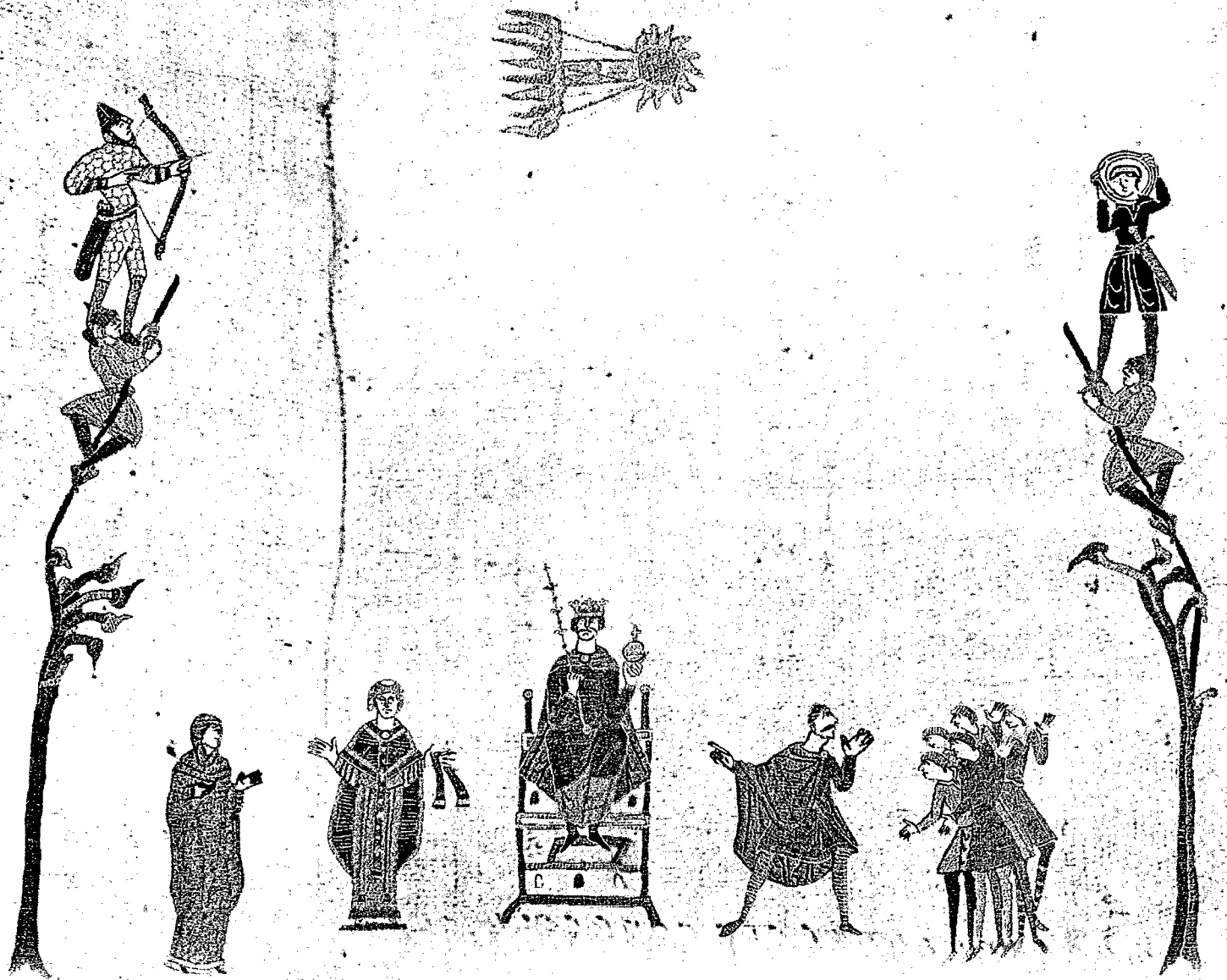




ASTRONOMICAL ODDS

A POLICY FRAMEWORK FOR
THE COSMIC IMPACT HAZARD

GEOFFREY S. SOMME

DISSERTATION

Astronomical Odds

A Policy Framework for the Cosmic Impact Hazard

Geoffrey S. Sommer

This document was submitted as a dissertation in June, 2004 in partial fulfillment of the requirements of the doctoral degree in public policy analysis at the Pardee RAND Graduate School. The faculty committee that supervised and approved the dissertation consisted of Steven Popper (Chair), Steven Banks, and Calvin Shipbaugh.

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Contents

Figures	vii
Tables	xi
Acknowledgments	xiii
Acronyms	xv

CHAPTER ONE

Introduction	1
Purpose	1
Society and the Impact Hazard	2
Organization of the Dissertation	4

CHAPTER TWO

Background	7
Historical Context	7
Physical Context	13
Geometries	13
Asteroids	15
Comets	20
Impact Effects	22
Confronting the Hazard	25
Mechanisms of Social Response	25
Survey: Surveillance	26
Survey: Tracking	30
Characterization	37
Mitigation	38
Genesis of the NEO Surveys	40
The Rise of the "Planetary Defenders"	43
Military Involvement	44
International Involvement	45
Discoveries	46
Warnings and Alarms	50
Warning Scales	55
Characterization Missions	57
Technological and Social Trends	58
Summary of Social Response	61

CHAPTER THREE

Literature Review	63
General	63
Methodologies	63
Analogous Cases	66
Perceptions vs. Reality	69
Specific	70
Impact Hazard Policy Analysis circa 1994	70
The Evolution of Impact Hazard Policy Analysis	72
Planetary Defense and the Military Perspective	73
Legal Perspectives	74

CHAPTER FOUR

Organizations and Their Policies	77
U.S. Government	77
White House	77
U.S. Congress	78
National Aeronautics and Space Administration	78
National Research Council	79
National Science Foundation	80
U.S. Air Force	80
Foreign Governments	80
United Kingdom	80
Australia	81
International Bodies	81
United Nations	81
Council of Europe	82
European Space Agency	82
Professional Societies, Private Organizations and Advocacy Groups	83
American Institute of Aeronautics and Astronautics	83
National Optical Astronomy Observatories	84
National Defense Industrial Association	84
International Astronomical Union	84
Spaceguard Foundation	85
Project B612	85
Cambridge Conference Network	86
Summary	86

CHAPTER FIVE

Toward a Comprehensive Policy Approach	87
Adding Complexity to a Simple Foundation	87
Previous Modeling Approaches	87
Costs of Alarm and Warning	89
Perceptions	96
Misunderstandings at Many Levels	99
Incorporating System Effects	101

Alternative Policy Interventions	103
Information Management and Uncertainty Reduction	103
Information Control	104
Project CARDINAL	107

CHAPTER SIX

Modeling the Policy Framework	113
Purpose of the Model	113
Foundation of the Model	113
SDT Model	113
Warning Rates	115
A New Model	116
Discount Rate	117
Cost per Life	119
Cost of Infrastructure (per Person)	119
Evacuation Factor	119
Evacuation Cost per Person	120
Active Mitigation Program (Interceptor) Costs	120
Warning Horizon	120
Program Structure (Baseline Case)	120
Program Structure (CARDINAL)	122
Interceptor System Reliability	123
Interceptor Effectiveness	124
Warning Rate	124
Warning Costs	125
Warning Rise Factor	126
Cost per Warning	126
Reassurance (CARDINAL Only)	126
Model Results	128
Nominal Cases	128
Maximum Cost per Life (\$12 million)	130
Minimum Cost per Life (\$10,000)	131
Fifty Percent Interceptor Effectiveness	132
Zero Interceptor Effectiveness	134
Maximum Cost per Warning (\$5 million)	135
Zero Warning Costs	136
Variation of Reassurance	138
Low Cost per Warning, High Warning Rise Factor	139
Shifted Warning Progression	141
Clipped Warning Progression	142
IRR vs. Warning Costs	144
Summary of Model Results	145

CHAPTER SEVEN

Conclusions	147
Summary of Analysis	147

Areas for Further Improvement	148
Implications for Other Policy Problems	148
APPENDIX	
A. Initial Impact Warning Rate Estimation	151
B. Armageddon in a Teapot	153
C. Project CARDINAL	169
D. Nominal Model Output	171
Bibliography	175

Figures

1.1. “Giggle Factor”	2
2.1. Meteorite believed to be from 1490 CE fall in China (ref. Table 2.1)	8
2.2. Moctezuma II sees comet as omen of doom	9
2.3. Tunguska blast zone	11
2.4. Barringer Meteor Crater, Arizona	12
2.5. Solar system out to Jupiter	14
2.6. Inclination of Wirtanen to the ecliptic plane	14
2.7. Impact hazard taxonomy	15
2.8. Earth “hemmed in by a sea of asteroids”	17
2.9. Eros from <i>NEAR Shoemaker</i>	17
2.10. Histogram of 300 NEAs	18
2.11. NEA population statistics	19
2.12. Nucleus of Comet Borrelly imaged by <i>Deep Space 1</i>	21
2.13. Hypothetical representation of the Oort cloud	22
2.14. Estimated fatalities vs. yield and NEA diameter	24
2.15. Detectability of C-class asteroids in the ecliptic plane	28
2.16. Detectability of 1 km diameter asteroid in the ecliptic plane	29
2.17. Density of known NEAs	30
2.18. Evolution of uncertainty ellipse with succession of future encounters	32
2.19. Evolution of uncertainty ellipse for a given encounter	33
2.20. Rate of initial warning, Earth-inclusive ellipse criterion	34
2.21. Initial impact warning rate estimation	36
2.22. Triangle of fear	37
2.23. Major survey sky coverage, $V=18$	48
2.24. Major survey sky coverage, $V=21$	48
2.25. Spatial distribution of NEA discoveries	49
2.26. Actual vs. theoretical discovery rates	49
2.27. Orbit of 1997 XF11	51
2.28. Uncertainty ellipse for 1997 XF11 in 26 October 2028 target plane	51
2.29. Keyhole in 2028 target plane to 2040 target plane	52
2.30. Tabloid asteroid	53
2.31. Asteroid alarms, 2000–2002	53
2.32. 2002 MN and the Internet	54
2.33. “Giggle factor” in satiric article	55
2.34. Torino scale	56
3.1. SETI Rio scale	68

3.2. “Giggle factor” within USAF study report	73
3.3. Cometary distant early warning	75
4.1. Emblem of the Spaceguard Foundation	85
5.1. Simple cost-benefit model	88
5.2. Adding the costs of alarm and warning	90
5.3. Costs of warning in many flavors	92
5.4. No child left unharmed?	94
5.5. Endless war, endless warning costs	94
5.6. Flaming death from the skies	98
5.7. “M” is for megalith	98
5.8. Pictures worse than a thousand words	100
5.9. Including social dynamics	102
5.10. Spin and scramble	105
5.11. Neosecrecy	106
5.12. Project CARDINAL	110
6.1. Estimated Torino warnings during SDT survey	116
6.2. Diminishing discount rate vs. constant rates	118
6.3. Truncation of discounted net benefits	119
6.4. Baseline acquisition profile	121
6.5. Derivation of expected annual mitigation costs	122
6.6. CARDINAL demonstrator acquisition profile	123
6.7. Torino Level 1 warnings, LEO 1-meter space telescope	124
6.8. Cost per warning with rise factor equal to five	125
6.9. Crescendo, then familiarization	127
6.10. Baseline nominal	129
6.11. CARDINAL nominal	129
6.12. Baseline (\$/life = \$12m)	130
6.13. CARDINAL (\$/life = \$12m)	130
6.14. Baseline (\$/life = \$10k)	131
6.15. CARDINAL (\$/life = \$10k)	132
6.16. Baseline (interceptor effectiveness = 0.5)	133
6.17. CARDINAL (interceptor effectiveness = 0.5)	133
6.18. Baseline (zero interceptor effectiveness)	134
6.19. CARDINAL (zero interceptor effectiveness)	134
6.20. Baseline (\$/T1 = \$5m)	135
6.21. CARDINAL (\$/T1 = \$5m)	136
6.22. Baseline (zero warning costs)	137
6.23. CARDINAL (zero warning costs)	137
6.24. Indifference curves	138
6.25. CARDINAL (Reassurance = 0.6)	139
6.26. CARDINAL (Reassurance = 0.3)	139
6.27. Baseline (cost per warning = \$50k, warning rise factor = 20)	140
6.28. CARDINAL (cost per warning = \$50k, warning rise factor = 20)	140
6.29. Baseline (no T1 warning costs, \$/T2 = 1m)	141
6.30. CARDINAL (no T1 warning costs, \$/T2 = 1m)	142
6.31. Baseline (no T1 warning costs, \$/T2 = 5m)	143

6.32. CARDINAL (no T1 warning costs, $\$/T2 = 5m$)	143
6.33. IRR vs. cost per warning, nominal	144
6.34. IRR vs. cost per warning, $\$/T1 = 0$	145
A.1. Uniform distribution of warning horizon	151
A.2. Skewed distribution of warning horizon	152
B.1. Drudge Report, 15 February 2003	154
B.2. CNN Quick Vote	154

Tables

2.1.	Supposed historical casualties due to cosmic impact	8
2.2.	Predicted economic and other effects of comets, ancient China	9
2.3.	Manifestations of 1910 comet scare	10
2.4.	Examples of asteroid types	18
2.5.	Impact effects as a function of NEO energy and size	23
2.6.	Impact hazard response	26
2.7.	Space telescope advantages and disadvantages	30
2.8.	Major NEO surveys	47
2.9.	Comet and asteroid alarms through 1999.....	50
2.10.	Comet and asteroid characterization missions.....	57
6.1.	Expected warnings by survey, Palermo and Torino scales	115
6.2.	Parametric variation	127

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Figure 5.8c on page 100 (an asteroid trajectory diagram from "A Close Asteroid Fly-By" by David Tytell from SkyandTelescope.com) is reproduced with permission of the publisher.

Acronyms

AAAS	American Association for the Advancement of Science
AANEAS	Anglo-Australian NEA Survey
AAS	American Astronomical Society
ABM	Anti-Ballistic Missile
ACTD	Advanced Concept Technology Demonstrator
AF	Air Force
AIAA	American Institute of Aeronautics and Astronautics
AU	Astronomical Unit
BBC	British Broadcasting Corporation
BCE	Before Common Era
BMD	Ballistic Missile Defense
BMDO	Ballistic Missile Defense Organization
CAPS	Comet/Asteroid Protection System
CARs™	Computer-Assisted Reasoning® system by Evolving Logic
CARDINAL	Comet/Asteroid Research and Development Interceptor Negating Alarms
CBA	Cost-Benefit Analysis
CBS	Columbia Broadcasting System
CCD	Charge-Coupled Device
CCNet	Cambridge Conference Network
CE	Common Era
CEAS	Confederation of European Aerospace Societies
CNN	Cable News Network
COPUOS	Committee on the Peaceful Uses of Outer Space
CSS	Catalina Sky Survey
CVM	Contingent Valuation Method
DARPA	Defense Advanced Research Projects Agency
D.C.	District of Columbia
DDR&E	Director, Defense Research and Engineering
DHS	Department of Homeland Security

DoD	Department of Defense
DoE	Department of Energy
ECA	Earth Crossing Asteroid
ECO	Earth Crossing Object
EKO	Edgeworth-Kuiper Object
EPA	Environmental Protection Agency
EPIC	Electronic Privacy Information Center
ESA	European Space Agency
EUNEASO	European NEA Search Observatories
EUNEOS	European NEO Survey
FY	Fiscal Year
GDP	Gross Domestic Product
GEODSS	Ground-Based Electro-Optical Deep Space Surveillance
IAA	International Academy of Astronautics
IAU	International Astronomical Union
IMPACT	International Monitoring Programs for Asteroid and Comet Threat
INAS	International NEA Survey
INGO	International Non-Governmental Organization
IP	Intermediate Period
IRR	Internal Rate of Return
ISHTAR	Internal Structure High-resolution Tomography by Asteroid Rendezvous
JPL	Jet Propulsion Laboratory
K-T	Cretaceous – Tertiary
KBO	Kuiper Belt Object
LANL	Los Alamos National Laboratory
LEO	Low Earth Orbit
LF	Lie Factor
LINEAR	Lincoln Laboratory NEA Research
LLNL	Lawrence Livermore National Laboratory
LONEOS	Lowell NEO Survey
LP	Long Period
LSST	Large-aperture Synoptic Survey Telescope
MIIV	Multiple Independently-targeted Interplanetary Vehicle
MIT	Massachusetts Institute of Technology
MOID	Minimum Orbital Intersection Distance
MPC	Minor Planet Center
MSNBC	Microsoft - National Broadcasting Corporation
MSSS	Maui Space Surveillance System

MT	Megaton
NASA	National Aeronautics and Space Administration
NDIA	National Defense Industrial Association
NEA	Near Earth Asteroid
NEAR	Near Earth Asteroid Rendezvous
NEO	Near Earth Object
NEPA	National Environmental Policy Act
NGO	Non-Governmental Organization
NMD	National Missile Defense
NOAO	National Optical Astronomy Observatories
NPV	Net Present Value
NRC	National Research Council
NRO	National Reconnaissance Office
NSIA	National Security Industrial Association
NSC	National Security Council
NSF	National Science Foundation
NSTC	National Science and Technology Council
OECD	Organization for Economic Cooperation and Development
OMB	Office of Management and Budget
OOSA	Office for Outer Space Affairs
OSD	Office of the Secretary of Defense
OSTP	Office of Science and Technology Policy
PACS	Palomar Asteroid and Comet Survey
PCAS	Palomar Planet-Crossing Asteroid Survey
PDD	Presidential Decision Directive
PHA	Potentially Hazardous Asteroid
PHO	Potentially Hazardous Object
POST	Parliamentary Office of Science and Technology
QALY	Quality-Adjusted Life Year
R&D	Research and Development
RFI	Radio Frequency Interference
ROI	Return On Investment
SAB	Scientific Advisory Board
SAIC	Science Applications International Corporation
SDT	Science Definition Team
SETI	Search for Extraterrestrial Intelligence
SIMONE	Smallsat Intercept Missions to Objects Near Earth
SOHO	Solar and Heliospheric Observatory

SP	Short Period
SSE	Space Science Enterprise
TBM	Theater Ballistic Missile
TL	Timeline
TNO	Trans-Neptunian Object
TNT	Tri-Nitro-Toluene
UCAS	United Kingdom Schmidt-Caltech Asteroid Survey
U.K.	United Kingdom
U.N.	United Nations
U.S.	United States
USAF	U.S. Air Force
VASIMR	Variable Specific Impulse Magnetoplasma Rocket
WGNEO	Working Group on NEOs
WH	Warning Horizon
WTP	Willingness-To-Pay

Introduction

Purpose

The phrase “astronomical odds” expresses the rarest of life’s experiences in terms of the unfathomable vastness of outer space. Ironically, this work examines the “astronomical odds” of a particular *astronomical* event, and shows how social responses to the prospect of the event are shaped by the inconceivability of those odds.

The event in question is a cosmic impact (collision of either a comet or an asteroid with the Earth, potentially destroying a city, a region, or all human civilization). This “impact hazard” is treated from the perspective of a policy analyst interested in the general category of low-probability-but-high-consequence events. Such extreme events have proven problematic, in terms of both the formulation and execution of public policy. Why should this be so, and what measures can be taken to surmount the difficulties?

There are cognitive barriers to serious consideration of very remote hazards, and these are nicely captured by the colloquial term “giggle factor.” These barriers on the individual level may aggregate into barriers on the organizational level, and thus serve to constrain policymaker action. The end result may be a less than socially-optimal level of resource allocation: in effect, the social system has a blind spot.¹

On the other hand, heuristics may operate that unjustifiably magnify the attention given to such hazards, and these heuristics may be susceptible to manipulation by interested stakeholders. The consequence would then be a greater than socially-optimal level of resource allocation.

The task is to first define how a socially-optimal level of resource allocation might be *derived*, and then to explore how such a level might be *maintained* in the face of policymaker aversion or rent-seeking behavior by stakeholders. If such a level cannot be maintained, then what is the constrained optimum?

Although as an outlying case the cosmic impact hazard can be expected to embody unique features that limit the general applicability of any resulting policy prescriptions, the very extreme nature of the case tends to throw these aforementioned difficulties of policy-making into sharp relief. In that sense, this is a case of interest for those considering threats of somewhat higher probability and somewhat lower consequence than a comet or asteroid

¹ “Resource allocation” refers to the distribution of scarce resources among competing needs. In the case of the impact hazard, examples of such resources are skilled labor (astronomers) and capital stock (telescope time). At a higher level, the funding of astronomical labor and capital represents an opportunity cost to society—there could well be a higher return on investment from expenditures on other programs. Resources are applied to the impact hazard largely from the public purse, in the U.S. and abroad, although there is a significant component of private investment.

strike. Such cases can be found outside the realm of natural hazards—the most relevant at the time of writing being the case of social reaction to terrorism.

To begin laying the foundations for subsequent analysis, the various dimensions of uncertainty associated with the impact hazard will be discussed. The complexity of the interacting physical, technical, and social systems will be characterized. The sensitivity of the problem to stakeholder manipulation will be addressed. Finally, a goal will be set: to provide a comprehensive policy framework (and a proposed implementation of such a framework) for the cosmic impact hazard that is robust to uncertainty, particularly to the uncertainties of social reaction.

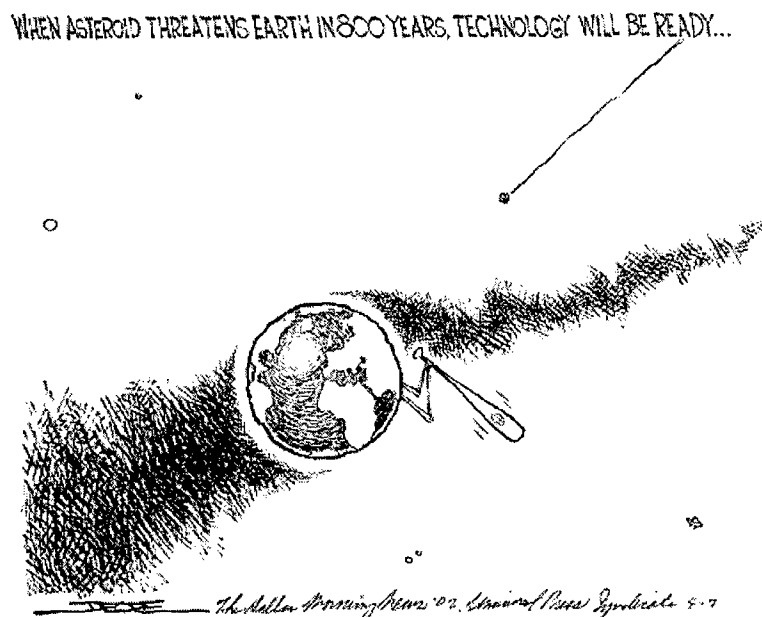
Society and the Impact Hazard

How does the threat posed to the Earth by comets and asteroids become the focus of a serious discussion of public policy? After all, for most people, the “cosmic impact hazard” is brought to us courtesy of Hollywood, with assistance now and then from sensationalized press treatments. For a number of reasons, we find it hard to contemplate the subject without an upwelling of humor—the “giggle factor,” typified by Figure 1.1.

Worthy of supermarket tabloids, perhaps, and light amusement in popular science magazines—but hardly worth serious thought when so many more pressing problems intercede in our daily lives. We experience the thrill and move on. Such at least has been the conventional wisdom.

The very features that cause us to trivialize or be jocular about the problem should serve as warning flags to the policymaker. The fear of ridicule serves as a deterrent to the

Figure 1.1
“Giggle Factor”



allocation of resources, even for the funding of analyses.² For the same reason, optimized policy responses may be impossible to implement. That so much may hinge on a possibly flawed aspect of human cognition is somewhat disturbing.

On the other hand, we could see vocal stakeholder groups distorting resource allocation by characterizing the problem to their benefit.³ In this case, these groups seek to alter the social perception of the hazard, magnifying the threat by means of "heuristic engineering." Both subjective probabilities and impressions of effect can be manipulated by means of semantic construction and graphic presentation—examples of each will be provided in a later chapter.

As mentioned above, the cosmic impact hazard represents an outlying case of an interesting, but somewhat intractable, set of problems: those of very low probability but high consequence. As is often the case with such problems, the impact hazard is characterized by uncertainty in many dimensions. This poses methodological difficulties for the policy analyst, and difficulties of implementation for the policymaker. Specifically, we have the very unlikely, but real, prospect of a cataclysmic event. However, the probabilities are uncertain; the threat populations are very diverse; and the expected effects are beyond human experience. Compounding these uncertainties in time and space, we have almost complete uncertainty in predicting society's response, either to specific policies or to the events themselves.

This dissertation will provide a comprehensive framework for developing a workable policy addressed specifically to the cosmic impact hazard. More generally, it should constitute an interesting reference for those addressing the larger set of low probability, high consequence problems.

There are various lenses through which one can view the problem. Cosmic impact can be viewed as an all-encompassing environmental policy issue, a scientific issue, a military or homeland defense issue, or as just a rare but severe natural disaster. It is also a political issue, involving the management of information and control of social reaction. Standing back, the impact hazard is a complex problem featuring the interactions of physical, technical and social systems under conditions of great uncertainty. The policymaker must decide whether and how to pull the levers of state power to address the problem, although the nature of the problem itself is alien to the means and mechanisms of such power.

In the absence of a comprehensive analysis that accounts for system effects and compounded uncertainty, we run the risk of misguided policy responses. As discussed above, we could see inaction or deferment as a result of policymaker fear of ridicule. Alternatively, we could see vocal stakeholder groups distorting resource allocation by characterizing the problem to their benefit. Of course, there is always the risk of the Gordian knot approach: a policymaker might respond to complexity with bold but uninformed action, attempting to impose his or her rules on the system.

² This quote from a U.S. defense industry newsletter is an example of such ridicule ("Cranberry Picking," *Inside the Pentagon*, 15 June 2000):

McCain [noted] that \$15 million was added to the bill for the Maui Space Surveillance System, ostensibly to improve the nation's ability to track asteroids. "I do not intend to minimize the importance of such activities, but only the cast of Star Trek could conceivably have looked at a list of military funding shortfalls and concluded that a total of \$19 million had to be in the fiscal year 2001 budget for this purpose," McCain said.

³ This could actually be altruistic behavior, in the sense that stakeholders may rationalize their conscious exaggeration of the threat by citing social benefit ("saving the world too blind to see"), the ends justifying the means.

Finally, uncertainty provides both pitfalls and opportunities for the policymaker. On the one hand, expert advisers may have a professional predilection to minimize, neglect, or spuriously collapse uncertainty. For an expert who is expected to know, it can be a hard thing indeed to give equal treatment to knowns and unknowns.⁴ On the other hand, a sophisticated grasp of uncertainty would allow the policymaker to take advantage of any corresponding *lack* of sophistication among stakeholders to successfully implement policy. That is, there is the possibility that the policymaker can choose a representation of the uncertainty that enhances social benefit.

To summarize, this work will attempt to define a framework for an impact hazard policy that is robust to the uncertainty inherent in this particular low probability, high consequence threat. It will be comprehensive in scope, including uncertainties of social reaction in particular. The work will consider issues of policy implementation, and will propose a specific policy approach to satisfy the requirements of robustness to uncertainty within social and institutional constraints. As a final note, while the differing points of view of national governments and subsidiary stakeholders will be addressed, the analysis is ultimately concerned with maximizing aggregate social benefit worldwide, however defined, as befits a problem of such global import.

Organization of the Dissertation

The following chapter, Chapter Two, introduces the reader to the impact hazard, first presenting the historical context and then progressing to a detailed physical description of the threat environment. It discusses the recent history of the international scientific community's response to the impact hazard, and reviews successes and failures in dealing with society's responses to warnings.

Chapter Three reviews the literature relevant to the cosmic impact hazard, drawing from diverse sources. It then focuses on those analyses that specifically treat the cosmic impact hazard from a public policy perspective. It discusses contributions of these works to the establishment of an impact hazard policy, as well as their failings. It will be evident by the end of the chapter that there is no shortage of technical papers dabbling in policy—nor is there a paucity of policy papers that gloss over the technical aspects of the hazard. There is, however, a lack of comprehensive and methodical policy analysis, and it is this gap that the present work hopes to fill.

Chapter Four progresses to a review of relevant organizations and their policies such as pertain to the impact hazard. This is done to gain an understanding of the institutional constraints that may bound the effectuation of any impact hazard policy, however derived. The chapter highlights non-governmental organizations and the unusually significant role of individual actors.

Chapter Five develops a framework for a comprehensive impact hazard policy, building on the work of previous researchers and picking up the threads of argument introduced in prior chapters. The purpose of Chapter Five is to provide the theoretical underpin-

⁴ "Experts tend not to flaunt their ignorance by being uninformative; the reverse is more the case, where experts may declare minimal uncertainty." Woo, G., *The Mathematics of Natural Catastrophes*, Imperial College Press, London, 1999, p.163.

ning for the structure of a new model to be presented in Chapter Six, and for the choice of parameters included therein.

The author selects a cost-benefit methodology, accommodating the limitations of the technique discussed at length in the literature. The chapter is structured around flow diagrams of progressively increasing model sophistication, and it discusses the added features and parameters at each step along the way.

The exposition begins with a simple flow diagram representing the characteristics of cost-benefit models in the literature of the impact hazard. Differences in metrics and valuations between these models are discussed.

First to be added to the simple model framework are the costs of alarm and warning. These are parameters of social response that have never before been included in an impact hazard model. The discussion highlights the difficulty of predicting such costs, and suggests an analytical "work-around" for the problem.

The chapter continues with a review of the factors affecting social perception and comprehension of this particular low probability, high consequence hazard. The previously discussed costs of alarm and warning will depend to a large degree on society's imperfect (if not severely distorted) view of reality.

Next to be added to the policy framework are system effects. Specifically, a loop of positive social feedback is introduced. The gains of this loop are dependent on the amplifying effects of several social actors who will be here identified. In short, a survey that generates an increasing number of warnings will in all likelihood result in increasing social pressure for even more capable surveys, which in turn will generate yet more warnings.

The chapter then presents and analyzes three different policy interventions, the features of which are depicted in corresponding system diagrams. These interventions exercise the policy levers of information management and control, investment in uncertainty reduction, and social reassurance by means of a demonstrated mitigation capability.

Chapter Six builds on the theoretical framework presented in the previous chapter by presenting a quantitative model of a comprehensive impact hazard policy. The model takes the latest available data from the scientific community on the physical aspects of the impact hazard, along with the costs and effectiveness of proposed telescopic survey programs, and adds a parametric variation in social response. The model is particularly suited to exploration of uncertainty in both warning rates and associated parameters of social response. The work contrasts two variants of the model. One is a baseline case, while the other explicitly models the policy implementation proposed at the end of Chapter Five. The discussion identifies regions of the policy space where the proposed approach is favored.

Finally, Chapter Seven distills the key points of the preceding chapters and compares what has been achieved with the goals set forth in Chapter One. It identifies areas of further research that would be enabling for future prescriptive policy analysis. Conclusions that may be relevant to other policy issues embodying high uncertainty, social effects of warnings, and low underlying probabilities (such as those concerned with the threat of terrorism) will be presented.

Background

This chapter presents the historical context of the cosmic impact hazard, with an emphasis on social reactions to warning. It then progresses to a detailed physical description of the threat environment: what asteroids and comets are; where they are; how many there are; and what their effects are when they impact the Earth. The recent history of the international scientific community's response to the impact hazard is then discussed and successes and failures in dealing with society's responses to warnings are reviewed. The resources, mechanics, and processes of survey programs are covered. We pay particular attention to the way that uncertainty (and thus estimated impact probability) evolves following an initial astronomical detection.

Historical Context

Asteroids and comets have threatened the Earth since the dawn of civilization—in fact, some smaller ones have actually impacted the planet. For most of recorded history, though, mankind remained in blissful ignorance of the asteroidal component of the threat, since such bodies are generally only visible from Earth with the aid of telescopes.¹ To be sure, meteorite falls represented asteroid impacts at the very small end of the scale, and the ancients were quite aware of their celestial origin.² Old records and folklore (of unavoidably doubtful accuracy) chronicle deaths and injuries resulting from “sky falls” (Table 2.1 and Figure 2.1).³ On the other hand, finds of meteoritic iron were arguably beneficial to society in the days before mining of iron ore. In any event, there was no suspicion that asteroids existed. The first asteroid, Ceres, was not discovered until 1801 CE; consequently there were no social effects due to asteroid *warnings*.⁴

In contrast, cometary appearances have had a deep effect on society for millennia. With their luminous comas and tails, comets were often visible across the inner reaches of

¹ One exception is the asteroid Vesta, which is occasionally visible to the naked eye. Another rare exception would be an asteroid passing very close to the Earth which would however be fleeting and unimpressive.

² As one piece of evidence, the Latin word *siderus* is derived from a word for star or constellation; the ancient Greek word for iron is *sideros*. Sagan, C., and Druyan, A., *Comet*, Random House, New York, 1997, pp. 343-344.

³ The meteorite shown in Figure 2.1 is about 12 centimeters across.

⁴ Serio, G., “Giuseppe Piazzi and the Discovery of Ceres,” in *Asteroids III*, Bottke *et al.*, editors, University of Arizona Press, Tucson, 2002, p.19.

Table 2.1
Supposed historical casualties due to cosmic impact⁵

1420 BCE	Israel – Fatal meteorite impact.
588 CE	China – 10 deaths; siege towers destroyed.
1321–68	China – People & animals killed; homes ruined.
1369	Ho-t'ao, China – Soldier injured; fire.
02/03/1490	Shansi, China – 10,000 deaths.
09/14/1511	Cremona, Italy – Monk, birds, & sheep killed.
1633–64	Milono, Italy – Monk killed.
1639	China – Tens of deaths; 10 homes destroyed.
1647–54	Indian Ocean – 2 sailors killed aboard a ship.
07/24/1790	France – Farmer killed; home destroyed; cattle killed.
01/16/1825	Oriang, India – Man killed; woman injured.
02/27/1827	Mhow, India – Man injured.
12/11/1836	Macao, Brazil – Oxen killed; homes damaged.
07/14/1847	Braunau, Bohemia – Home struck by 371 lb meteorite.
01/23/1870	Nedagolla, India – Man stunned by meteorite.
06/30/1874	Ming Tung li, China – Cottage crushed, child killed.
01/14/1879	Newtown, Indiana, USA – Man killed in bed.
01/31/1879	Dun-Lepoelier, France – Farmer killed by meteorite.
11/19/1881	Grossliebenthal, Russia – Man injured.
03/11/1897	West Virginia, USA – Walls pierced, horse killed, man injured.
09/05/1907	Weng-li, China – Whole family crushed to death.
06/30/1908	Tunguska, Siberia – Fire, 2 people killed.
04/28/1927	Aba, Japan – Girl injured by meteorite.
12/08/1929	Zvezvan, Yugoslavia – Meteorite hit bridal party, 1 killed.
05/16/1946	Santa Ana, Mexico – Houses destroyed, 28 injured.
11/30/1946	Colford, UK – Telephones knocked out, boy injured.
11/28/1954	Sylacauga, Alabama, USA – 4 kg meteorite struck home, lady injured.
08/14/1992	Mbole, Uganda – 48 stones fell, roofs damaged, boy injured.

Figure 2.1
Meteorite believed to be from 1490 CE fall in China (ref. Table 2.1)



⁵ Urias, J., *et al.*, "Planetary Defense: Catastrophic Health Insurance for Planet Earth," paper presented to Air Force 2025, October 1996, p.7.

Figure 2.2
Moctezuma II sees comet as omen of doom



the solar system, sparking public apprehension without the involvement of astronomers.⁶ Long before societies expressed any concern about planetary impact, comets were seen as portents of change or doom.⁷ Figure 2.2 depicts but one example among many, Moctezuma II of Mexico viewing a comet as an omen of disaster. That prediction, he later believed, came true with the arrival of Hernan Cortes in 1519 CE.⁸

Through history, cometary apparitions have been associated with wars and other dire events too numerous to discuss here. Nevertheless, it is interesting to review aspects of the ancient Chinese record of cometary visitations, which is unusually complete. Although at this stage the notion of cometary impact had yet to be voiced, social effects of cometary apparitions were predicted by Li Ch'un Feng, 602–667 CE, and are listed in Table 2.2 below.⁹

Notwithstanding the mystical attribute of the comet's celestial location, this table is notable for its prediction of widespread social effects, including economic effects, which extend beyond predicting the outcomes of wars or events in the lives of rulers.

It was not until 1694 CE that the possibility of cometary close passage or impact with the Earth was voiced by Sir Edmond Halley of Oxford University in a presentation to

Table 2.2
Predicted economic and other effects of comets, ancient China

Location of Comet Appearance	Effect
End of Big Dipper	Uprisings and war
Bowl of Big Dipper	Gold and gem prices crash
Virgo	Food shortages, cannibalism
Scorpio	Uprisings, rice prices rise
Pisces	Rice prices rise
Orion	Uprisings and war
Hydra	Rice, fish and salt prices rise People hate life and don't even want to speak of it
All	Whales die

⁶ The coma is a region of diffuse gas and particles surrounding a comet's nucleus.

⁷ Sagan, C., and Druyan, A., *Comet*, Random House, New York, 1997, pp. 14-15.

⁸ *Ibid*, pp. 31-32.

⁹ Sagan, C., and Druyan, A., *Comet*, Random House, New York, 1997, p.21.

the Royal Society of London. The same idea was raised two years later by William Whiston, also of England, by the French philosopher Comte de Buffon in 1745, and by Pierre Simon, the Marquis de Laplace in 1796.¹⁰ Laplace criticized humanity's irrational, mystic dread of comets but provided a rational, scientific basis for such dread.

The first worldwide comet scare was occasioned by Comet Halley's appearance in 1910. Although this returning comet was well known, it had previously been linked with specific events such as the Norman invasion of England in 1066 CE (appearing in the Bayeux tapestry) and the defense of Belgrade in 1456 CE, among others, rather than being the source of general social disturbance.¹¹ By the early 20th century, cyanogen (a chemical precursor of cyanide) had been detected in the comas and tails of many comets, including Comet Halley. Although the concentration of the gas was vanishingly small, and even the fact of the Earth's passage through that comet's tail in 1910 was in question, global pandemonium took hold. A number of astronomers, notably including one Camille Flammarion of France, added fuel to the fire. Flammarion, the author of a widely published popular astronomy text, was quoted as envisioning that the cyanogen gas would impregnate the atmosphere and possibly snuff out all life on the planet.¹² Table 2.3 presents some manifestations of the ensuing 1910 "panic."¹³

Note that this global social disruption spread across the civilized world, and took hold in industrialized nations with well-educated populations. Note also that the root cause of the event was the public miscommunication of a relatively innocuous scientific datum. Finally, note the key role of experts such as Flammarion in giving the concern scientific credence.¹⁴

As discussed above, by the end of the 17th century scientists had begun to consider the prospect of an actual cosmic impact. One such event finally occurred in 1908, when an object with an estimated diameter of 60 meters burst in the atmosphere over Tunguska in Siberia with the force of a small nuclear weapon; perhaps 10–15 megatons (MT) of energy

Table 2.3
Manifestations of 1910 comet scare

Location	Manifestation
Japan, Russia	National panics lasting for weeks
Constantinople	100,000 people on rooftops in nightclothes
Chicago	Rag-stuffing under doors
Kentucky	All-night prayer services
Rome	Pope Pius X condemns oxygen hoarding
Global	Suicides

¹⁰ *Ibid.*, pp. 31-32, 59-60, 276-277; and Steel, D., *Rogue Asteroids and Doomsday Comets*, John Wiley & sons, New York, 1995, pp. 15-16.

¹¹ Sagan, C., and Druyan, A., *Comet*, Random House, New York, 1997, pp. 30-32.

¹² *Ibid.*, p.149.

¹³ *Ibid.*, pp. 144-145.

¹⁴ Flammarion had some years previously written a novel about a cometary impact: Flammarion, C., *Omega: The Last Days of the World*, University of Nebraska Press, Lincoln, Nebraska (reprint), 1999. In 1922, Flammarion was made a Commander of the French Legion of Honor for his astronomical life-work.

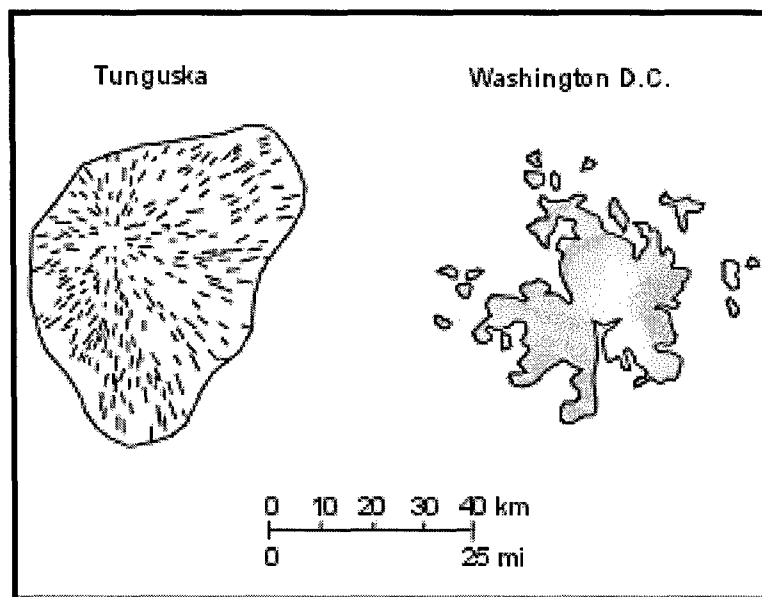
being released (Figure 2.3).¹⁵ However, it took many years until the cosmic provenance of the event was universally accepted, that delay to a large extent occurring because the airburst explosion left no crater. The remote Siberian forest took the brunt of the devastation.

Craters on the Earth that *had* been discovered were for a long time thought to be of volcanic origin. The impact origin of the Barringer Meteor Crater in Arizona (Figure 2.4) was not scientifically established until 1960.¹⁶ Regarding lunar craters, an impact origin was suspected. The author Ralph Baldwin wrote in his book *The Face of the Moon* (1949): "The explosion that caused the crater Tycho would, anywhere on Earth, be a horrifying thing, almost inconceivable in its monstrosity."¹⁷

Decades later, the impact origin of lunar craters was conclusively determined by lunar missions *in situ*.¹⁸

One of the greatest contributors to public awareness of the cosmic impact threat came in 1980. That year, the Alvarez impactor theory of dinosaur extinction was published in the journal *Science*.¹⁹ This theory proposed that an object of approximately 10–15

Figure 2.3
Tunguska blast zone



¹⁵ Morrison, D., *et al.*, "Dealing with the Impact Hazard," in *Asteroids III*, Bottke *et al.*, editors, University of Arizona Press, Tucson, 2002, pp. 741-742.

¹⁶ Shoemaker, E., *et al.*, "First natural occurrence of coesite from the Meteor Crater, Arizona," *Science*, Volume 132, 1960, pp. 220-222.

¹⁷ At the time of his writing, six Earth-crossing asteroids (ECAs, defined in the next section) had been discovered. Steel, D., *Rogue Asteroids and Doomsday Comets*, John Wiley & Sons, New York, 1995, pp. 21-22.

¹⁸ Steel, D., "Cometary impacts on the biosphere," in *Comets and the Origin and Evolution of Life*, Thomas, P., *et al.*, editors, Springer-Verlag, New York, 1997, p. 212.

¹⁹ Alvarez, L., *et al.*, "Extraterrestrial cause for the Cretaceous-Tertiary extinction," *Science*, Volume 208, 1980, pp. 1095-1108.

Figure 2.4
Barringer Meteor Crater, Arizona



kilometers in diameter impacted about 65 million years ago with an energy release of 10^8 MT, resulting in a layer of iridium in ancient deposits. When these deposits were associated with the remnants of a large crater of suitable age previously discovered at the edge of the Yucatán in Mexico (named Chicxulub), the theory entered the scientific mainstream, and the public consciousness.²⁰

In 1994, another pivotal event occurred. A disrupted comet (designated Shoemaker-Levy 9) was discovered on a collision course with Jupiter, in time for Earth-based and space-based telescopes to be trained on the resulting show. The results were spectacular and widely reported.

Finally, in 1998, two Hollywood “blockbuster” movies featuring cosmic impacts were released: *Deep Impact* and *Armageddon*.²¹ The international box office receipt total for these two movies (to date) is approximately \$900 million, a sum which dwarfs actual public expenditures dedicated to the impact hazard.²²

To summarize, the history of social awareness of these small cosmic bodies has shifted from a mystical or religious view of comets as portents of doom to a *scientific* view of both comets and asteroids as portents of doom. Given the almost universal interpretation of comets as baleful objects, it would be easy to argue that mankind would have been better off not knowing when comets passed nearby. Nowadays, we have both asteroids and comets to

²⁰ A much less publicized alternative theory is that a giant comet broke up in the inner solar system, and that Chicxulub was just one impact among many (of the resulting fragments) occurring over the course of about 100,000 years. Steel, D., *Rogue Asteroids and Doomsday Comets*, John Wiley & sons, New York, 1995, pp. 72-73.

²¹ These were not the first cosmic impact movies, just the most successful. Others included *Meteor* (1979) and *Night of the Comet* (1984).

²² www.boxofficeguru.com These are actual gate receipts, thus nominal dollars not adjusted for inflation.

give us cause for concern. The changed factor is that, unlike the ancients, we can apply science and technology to mitigate the harm of cosmic impactors, a real rather than imagined harm however slight the possibility. On the other hand, science and technology can also cause harm if improperly applied as foreshadowed by the prototypic case of the 1910 apparition of Comet Halley.

Physical Context

The focus of this dissertation is on social reactions to the impact hazard and the dependence of those reactions on perceptions of risk. The scope for social misperception of the impact risk is magnified by an almost complete lack of familiarity with the environment and scale of the solar system and with the rules governing its dynamics. Simply put, it is all far beyond everyday experience.

To properly evaluate these perceptions (or misperceptions), it is essential that the analyst understand the objective, physical basis of the risk. This section describes the threat environment: what asteroids and comets are; where they are; how many there are; and their effects when they impact the Earth.

Asteroids and comets are small compared to the planets and are distinguished by differences in dynamics, composition, and provenance. Asteroids are rocky bodies, sometimes referred to as minor planets, that are largely confined to an asteroid belt between the orbits of Mars and Jupiter. Comets are icy bodies that generally inhabit the far reaches of the solar system. A very small proportion of these asteroids and comets can be perturbed into orbits that result in their ejection from the solar system, collision with the Sun, or collision with a planet.²³

Geometries

Figure 2.5 depicts the inner planets, the asteroid belt, and the orbit of Jupiter. The orbit of the comet Wirtanen is shown for illustrative purposes.²⁴

Note the difficulty of representing three-dimensional space in a two dimensional image: while the depicted planets orbit close to the “ecliptic plane” (the plane of Earth’s rotation about the Sun), the asteroid belt in reality occupies a toroidal (doughnut-shaped) region. The comet shown has an inclined orbit (tilted with respect to the ecliptic plane), as is typically the case, although that tilt is impossible to determine from the figure.

An alternative and superior representation of Wirtanen’s orbit is shown in Figure 2.6. The plan view in Figure 2.6 is from the standpoint of an observer at the north ecliptic pole (“above” the Sun). The light gray area shows the portion of the comet’s orbit to the north of the ecliptic plane—the comet travels counterclockwise, crossing the ecliptic plane northbound at the “ascending node” (marked as Ω), and southbound at the “descending node” (unmarked, but opposite Ω).

²³ Jupiter in the case of Shoemaker-Levy 9, and the Earth in the case of the Tunguska and K-T impactors.

²⁴ Comet Wirtanen is notable for being the original intended target of the European Space Agency’s *Rosetta* comet probe. *Rosetta*’s new target is Comet Cheryumov-Gerasimenko (see Table 2.10).

Figure 2.5
Solar system out to Jupiter

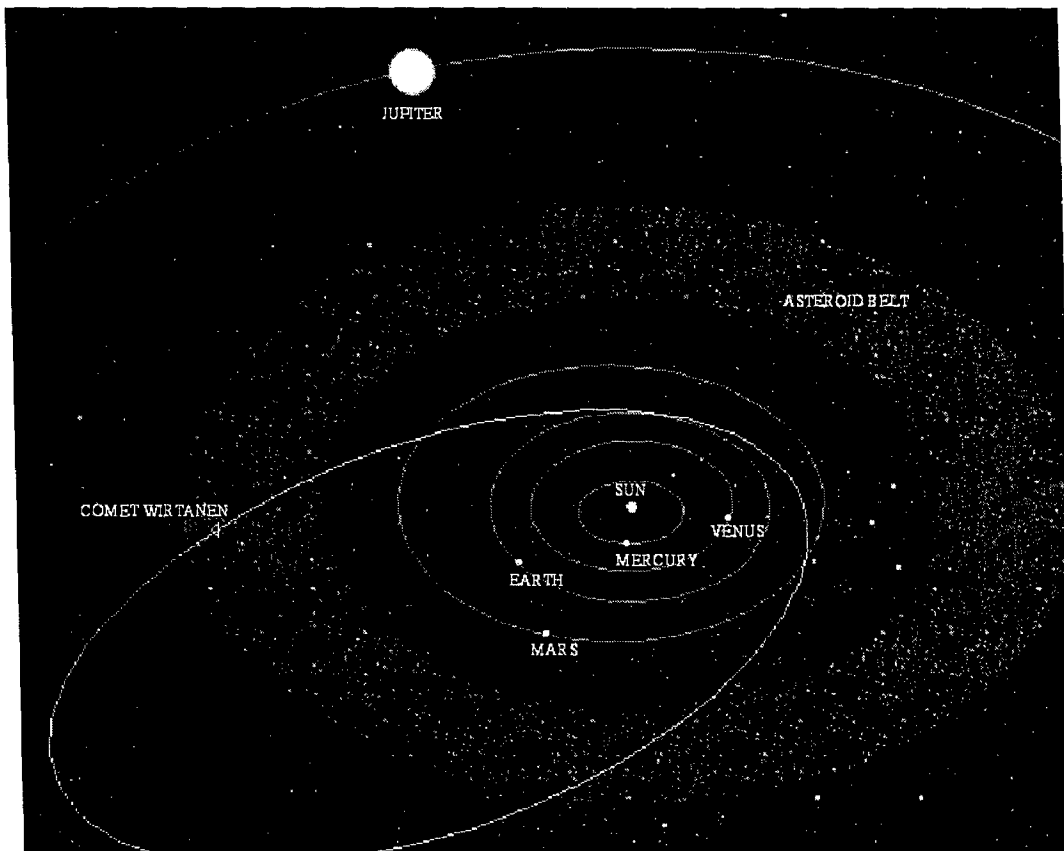
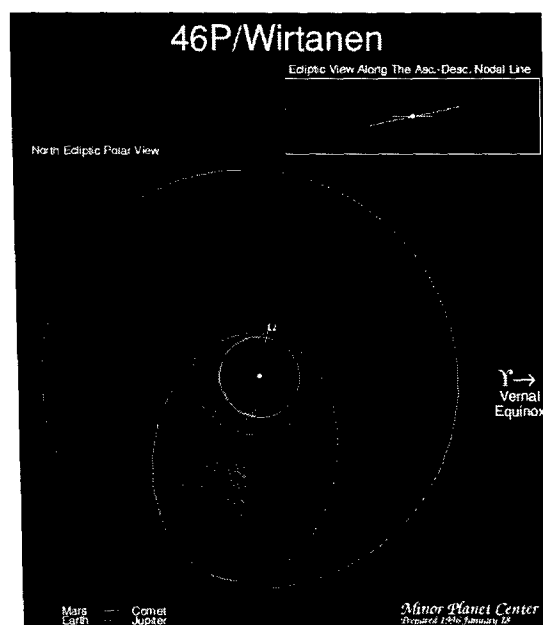


Figure 2.6
Inclination of Wirtanen to the ecliptic plane



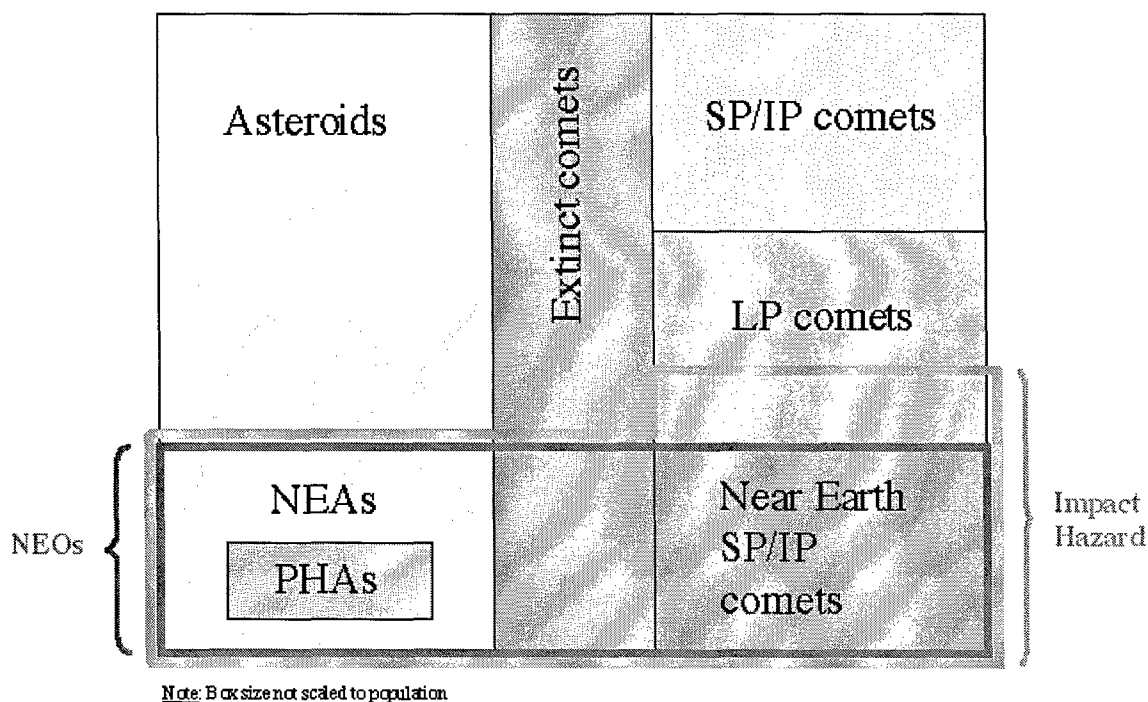
It follows from simple geometry that, for a cosmic collision of either a comet or asteroid with the Earth to occur, two conditions must be satisfied:

- The object must have either its ascending or descending node at the Earth's orbital radius; and
- The object must cross that node at the same time as the Earth.²⁵

Asteroids

Figure 2.7 depicts the “impact hazard taxonomy” associated with asteroidal (and cometary) bodies. Near Earth Asteroids (NEAs) are formally defined as those having a perihelion (closest approach to the Sun) of less than or equal to 1.3 Astronomical Units (AU), or an aphelion (furthest retreat from the Sun) of greater than or equal to 0.983 AU.²⁶ A subset of NEAs consists of Potentially Hazardous Asteroids (PHAs). PHAs are defined as those asteroids having a Minimum Orbital Intersection Distance (MOID), the minimum distance

Figure 2.7
Impact hazard taxonomy



²⁵ At first glance, Figure 2.6 seems to show that Wirtanen might pose a risk to the Earth, since its ascending node is close to the Earth's orbital radius. However, the node is separated from Earth's orbit by about 12 million kilometers, roughly 31 times the distance between the Earth and the Moon. This is a vast distance that appears tiny on the printed page. Furthermore, Figure 2.6 fails to capture the temporal dimension of potential collision. Nevertheless, with flawed or skewed delivery, even the simple Figure 2.6 could prompt a severe misperception of impact risk. The constraint of graphic presentation will be further explored later in this chapter and again in Chapter Five.

²⁶ Bottke, W., *et al.*, “An Overview of the Asteroids: The Asteroids III Perspective,” in *Asteroids III*, Bottke *et al.*, editors, University of Arizona Press, Tucson, 2002, p.11. One AU is equal to 149,597,871 kilometers, which equals the mean radius of Earth's orbit about the Sun.

between the orbits of two bodies, of less than 0.05 AU from an inner planet or 1.0 AU from Jupiter.²⁷ Close approaches to planets are a concern because an object can thereby be deflected onto an Earth-impacting path.

To add to the complexity, the term Earth Crossing Asteroids (ECAs) refers to those whose orbits cross the distance of Earth's orbital radius at some point. There are two families of asteroids whose orbits satisfy this condition: the Apollos and the Atens. The orbits of Apollos cross that of the Earth with a period of greater than a year (thus are largely outside the Earth's orbit). The orbits of Atens cross that of the Earth with a period of less than a year (thus are largely inside the Earth's orbit). The orbits of a third family, the Amors, lie entirely outside that of the Earth, with perihelia between 1.0167 and 1.3 AU. Consequently, Amors are not ECAs, but they *are* NEAs.²⁸

Asteroids are rocky bodies of widely varied composition, believed to have been products of the collision of an unknown number of minor planets, or subsequent collisions of the resulting fragments. The bulk of asteroid orbits lie in a "belt" between the orbits of Mars and Jupiter (between two and four AU from the Sun). Residing relatively close to the Sun, asteroids are generally devoid of the icy volatiles found in comets. With the exception of the asteroid Vesta, belt asteroids can be observed from Earth only with the aid of telescopes.²⁹

Various physical processes can cause belt asteroids to enter orbits with resonance to the orbits of the major planets (particularly Jupiter), and such bodies can thus be perturbed into paths that approach the Earth (these are the NEAs and PHAs of Figure 2.7). Figure 2.8 shows the orbits of all known NEAs (then about 800) as of early 2000. Light-colored orbits depict Amors (as above, NEAs but not ECAs), and dark-colored orbits depict Apollos and Atens (the ECAs).³⁰

Until recently, most of our beliefs about the composition of asteroids were inferred from the examination of meteorites. Lately, these estimates have been augmented with ground-based measurements by planetary radar (using facilities such as the radio telescope at Arecibo in Puerto Rico) and imaging of several asteroids by a variety of space probes. These observations have shown the targeted asteroids to be of highly irregular shape, and it is now believed that many asteroids are of "rubble pile" composition (that is, conglomerates only loosely bound by self-gravity). As scientific knowledge of asteroids increases, the extremely heterogeneous nature of this population of objects is becoming apparent. Figure 2.9 shows the NEA Eros, as imaged by the NASA asteroid-orbiter (and asteroid-lander) *NEAR Shoemaker* in the year 2000.

²⁷ *Bowell, E., and Muinonen, K., "Earth-Crossing Asteroids and Comets: Groundbased Search Strategies," in Hazards Due to Comets and Asteroids, Gehrels, T., editor, University of Arizona Press, Tucson, 1994, p. 179. The Jupiter constraint is often dropped from the definition. As of early April 2004, 589 PHAs were known to exist. See <http://neo.jpl.nasa.gov/orbits/> for a list of PHAs and interactive orbit tools.*

²⁸ ECAs and the three NEA families are omitted from Figure 2.7 for simplicity.

²⁹ Such is true for all asteroids except those passing extremely close to the Earth.

³⁰ Note immediately that such graphics give a misleading impression of crowded space; in reality the mean distance between asteroids even in the main belt is extremely large. This is the same constraint of graphic presentation that was addressed in the footnoted discussion of Figure 2.6.

Figure 2.8
Earth "hemmed in by a sea of asteroids"³¹

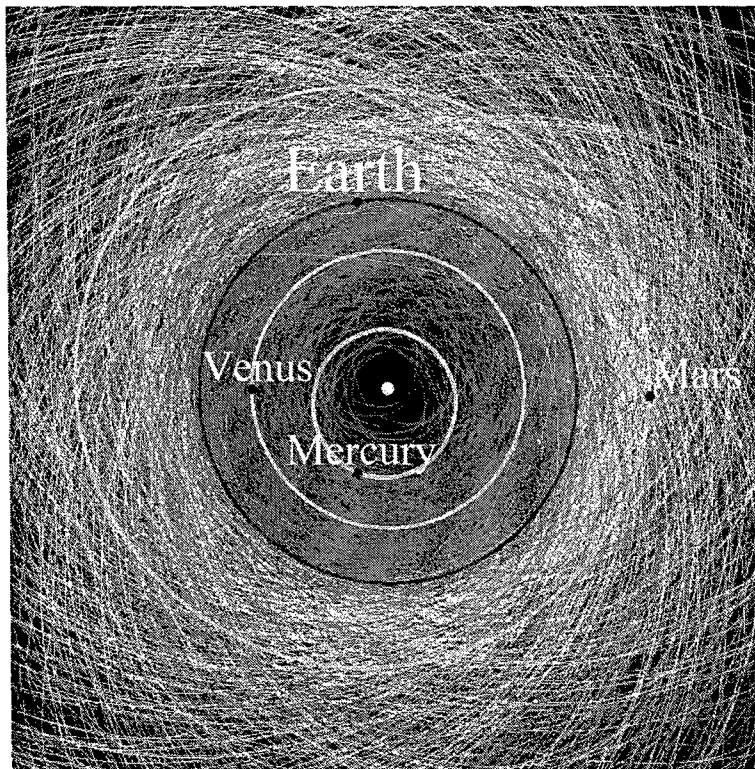
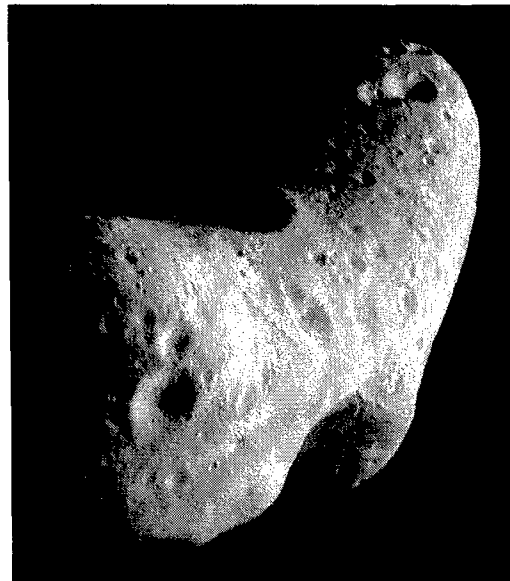


Figure 2.9
Eros from *NEAR Shoemaker*



³¹ This turn of phrase and the figure itself are taken from Atkinson, H., *et al.*, *Report of the Task Force on potentially hazardous Near Earth Objects*, September 2000, p.9. The original source of the figure is Steel, D., *Target Earth*, Reader's Digest Association, Pleasantville, New York, 2000, p.21.

Asteroids are sorted into a number of taxonomic classes according to their mineralogical composition. Figure 2.10 is a histogram of the classifications of a sample of 300 NEAs.³² Table 2.4 describes the better known of these classes: M, S, C, P, and D. Linkages have been made between types of asteroids and types of meteorites found on Earth. Spectroscopic classifications of main belt asteroids allows identification of NEA source regions (the regions of the asteroid belt from which the NEAs were perturbed).

NEAs have orbits of moderate eccentricity (up to 0.7 or so), with inclinations of plus or minus 30 degrees relative to the ecliptic plane.³³ Their velocities relative to Earth when crossing the Earth's orbit vary from about 12 to 40 kilometers per second.

Figure 2.11 presents the best scientific estimate of NEA population statistics, with expected impact intervals for each size of object.³⁴ Impact energies (yields, in the language of nuclear weapon effects) are shown assuming an average impactor velocity of 20 kilometers per second. The dot-and-dash curve shows objects actually discovered as of 28 January 2002, and is an absolute lower bound to the population estimates. The two curves with inflection points represent population estimates based on search statistics to date and the lunar crater-

Figure 2.10
Histogram of 300 NEAs

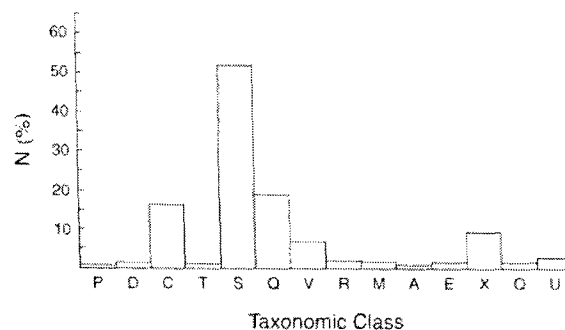


Table 2.4
Examples of asteroid types

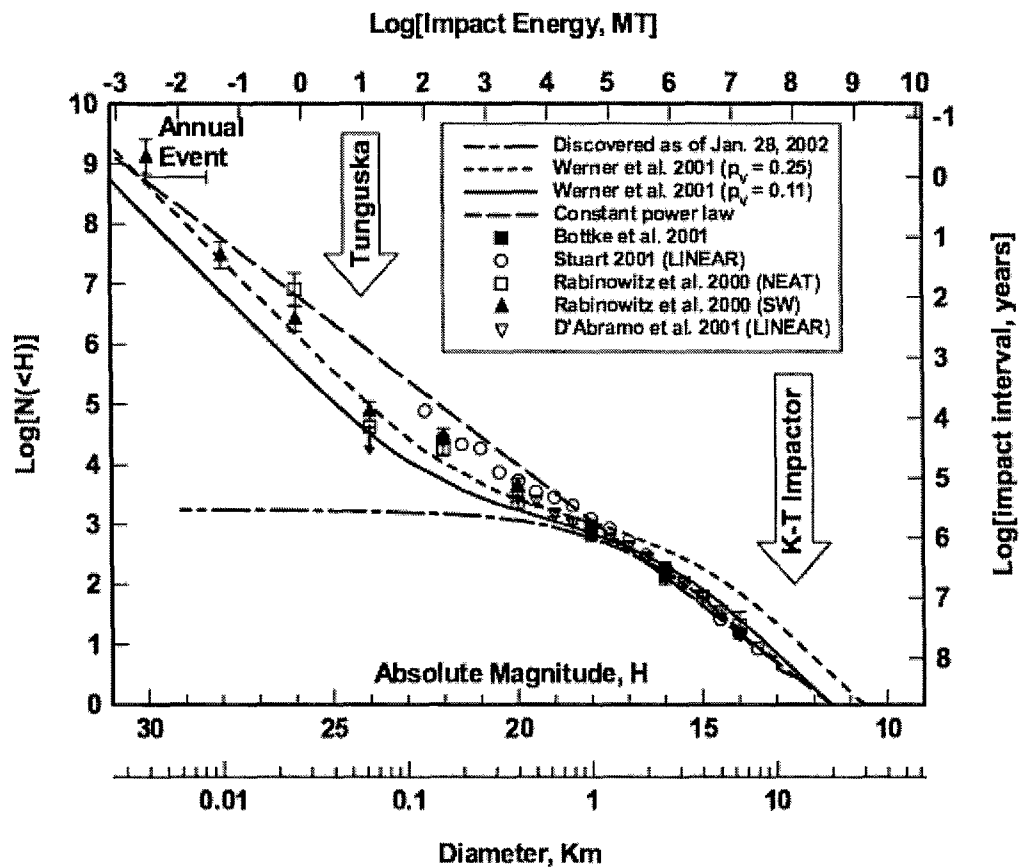
Type	Meteoritic Analog	Believed Source Region
M (metallic)	Iron-nickel, achondrites	Near inner belt
S (stony)	Chondrites & stony-irons	Inner belt
C (carbonaceous)	Carbonaceous chondrites	Outer belt
P, D	High carbon carbonaceous	Far outer belt

³² From "Physical Properties of Near-Earth Objects" by R. Binzel *et al.*, in *Asteroids III*, edited by W.F. Bottke Jr., A. Cellino, P. Paolicchi, and R. P. Binzel, p.262, © 2002 The Arizona Board of Regents. Reprinted by permission of the University of Arizona Press. No basis for the selection of this sample is noted.

³³ A circle has an eccentricity of zero, while an ellipse's eccentricity ranges from zero to one. The greater the eccentricity, the narrower the ellipse.

³⁴ Morrison, D., *et al.*, "Dealing With the Impact Hazard," in *Asteroids III*, Bottke *et al.*, editors, University of Arizona Press, Tucson, 2002, p. 745.

Figure 2.11
NEA population statistics



ing record, but each assuming a different average NEA albedo (reflectivity).³⁵ The straight diagonal dashed line represents a “power law” of the form $N=kD^b$, where N is the number of objects in a given size interval, D refers to diameter, and k and b are constants adjusted to fit the data.

Figure 2.11 shows that the population of NEAs of greater than one kilometer in diameter is estimated to be about 1,000, with a mean impact interval of several hundred thousand years.³⁶ The number of NEAs of greater than 60 meters in diameter (the estimated size of the Tunguska impactor) is somewhere between 100,000 and a million, with a mean impact interval of 1,000 to 10,000 years. The dip in the curve here is suspected to be an artifact of lunar cratering statistics, however, and estimates of a million objects and an interval of 1,000 years are preferred.³⁷

³⁵ A bimodal distribution of albedo is suspected, with smaller objects following the dashed red curve (high albedo, and thus intrinsically more reflective), and larger objects following the solid red curve (crossing over to low albedo at about the one kilometer diameter). Albedo is the source of the most uncertainty in estimating an object's size based on its brightness.

³⁶ The estimate is actually 1,000 plus or minus 200, but the error bar is not shown.

³⁷ From “Dealing With the Impact Hazard” by D. Morrison *et al.*, in *Asteroids III*, edited by W.F. Bottke Jr., A. Cellino, P. Paolicchi, and R. P. Binzel, p.748, © 2002 The Arizona Board of Regents. Reprinted by permission of the University of Arizona Press. Also, Stokes, G., *et al.*, “Study to Determine the Feasibility of Extending the Search for Near-Earth Objects to Smaller Limiting Diameters,” report of the NEO Science Definition Team, prepared at the request of the NASA Office of Space Science, Solar System Exploration Division, 22 August 2003, p.17.

The estimates of Figure 2.11 are for asteroids alone — the population of comets, and in particular, their total mass (and thus prospective impact energy) is highly uncertain.

Comets

Figure 2.7 refers to three types of comets:

- SP comets have “short periods” of less than 20 years.
- IP comets have “intermediate periods” of between 20 and 200 years.
- LP comets have “long periods” of over 200 years.³⁸

“Near Earth Objects” (NEOs) include the NEAs and those SP and IP comets that share the same characteristics of orbital proximity. The total impact hazard is that presented by NEOs and by some LP comets, which spend such a tiny fraction of their orbits in the inner solar system that they are not considered to be “near Earth” in any sense.³⁹

Comets are rich in volatiles, and these sublime as the comets approach the Sun, forming comas and tails, often making them visible from Earth with the naked eye. Some objects share characteristics of both asteroids and comets (again see Figure 2.7), and these may be extinct comets (comets having completely exhausted volatiles).

The typical comet is believed to be composed of a single or multiple nucleus, bound together by “dirty ice” (including water ice). It may or may not include a rocky core. A layer of dark dust surrounds the ice. As the comet approaches the sun, the volatiles begin to blow off through gaps in the dark dust crust, and the comet’s coma and tails form.⁴⁰ Comet densities are believed to be as low as 0.5 grams per cubic centimeter.⁴¹ However, comets are known to be extremely varied in behavior, and thus their basic composition may also vary widely. Space probes have flown past five comets: Giacobini-Zinner; Halley; Grigg-Skjellerup; Borrelly; and Wild-2.⁴² Figure 2.12 shows the nucleus of Comet Borrelly as observed by the NASA probe *Deep Space 1* in late 2001. The left-hand frame is over-exposed to show the volatiles and dust emanating from Borrelly’s surface, contributing to the comet’s coma and tails.

Comet orbits are typically of very high eccentricity (meaning their orbits are thin ellipses rather than circles). The distribution of LP and IP cometary inclinations is fairly uniform, but SP comets orbit close to the plane of the ecliptic and are prograde (that is, they orbit around the sun in the same direction as the planets, counterclockwise as seen from north of the ecliptic).

³⁸ A period is defined as the length of time to make one orbit of the Sun. An old classification (that is sometimes still used) defined LP comets as those with periods of greater than 200 years, and SP comets as those with periods of less than 200 years. Steel, D., *Rogue Asteroids and Doomsday Comets*, John Wiley & Sons, New York, 1995, p.284.

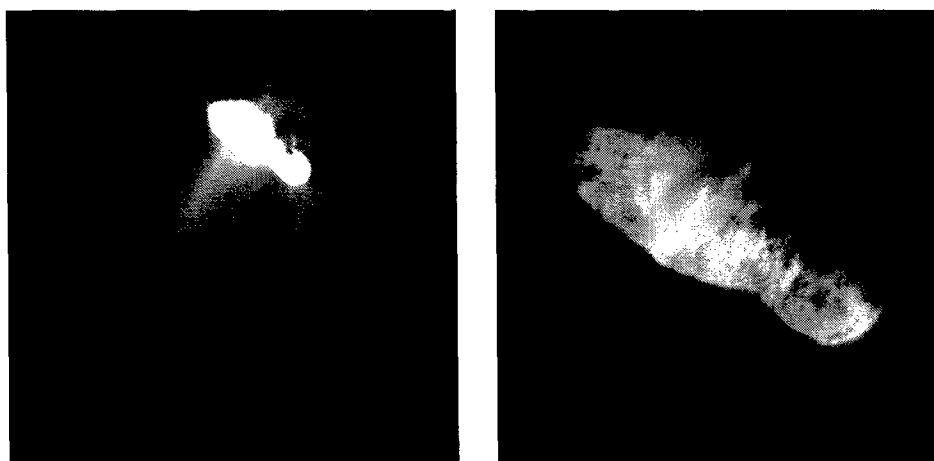
³⁹ Morrison, D., *et al.*, “The Impact Hazard,” in *Hazards Due To Comets and Asteroids*, Gehrels, T., editor, University of Arizona Press, 1994, p.61. The term Potentially Hazardous Object (PHO) includes PHAs and those near Earth SP/IP comets of Figure 2.7 that meet the PHA MOID constraint.

⁴⁰ There are usually separate dust and ion tails, although the variation of tail configuration from comet to comet is remarkable. Tails can be shed and regenerated during a single passage. Comets can also be disrupted—Shoemaker-Levy 9 (mentioned earlier in this chapter) is the most famous example.

⁴¹ Steel, D., “Cometary impacts on the biosphere,” in *Comets and the Origin and Evolution of Life*, Thomas, P., *et al.*, editors, Springer-Verlag, New York, 1997, p. 216.

⁴² This is shown in Table 2.10 below. The *Stardust* probe flew past Comet Wild-2 in January 2004, but will not return its sample of cometary material to Earth until 2006.

Figure 2.12
Nucleus of Comet Borrelly imaged by *Deep Space 1*



The source for comets is believed to be a spherical “Oort cloud” which lies far beyond the outer planets (out to about 100,000 AU). It is theorized that passing stars and molecular clouds perturb some comets into orbits that, like asteroids, can pass through the inner solar system. One theory is that some of these comets are preferentially sorted by perturbations from close passes by the outer planets into SP and IP orbits aligned to the ecliptic. Another theory holds that SP and IP comets originate from the Edgeworth-Kuiper belt, a torus of icy bodies, some approaching the size of small planets, beyond the orbit of Neptune again centered on the ecliptic.⁴³ Sometimes an inner Oort cloud is also conjectured. Figure 2.13 is one hypothetical representation of the cometary source region.

The orbital characteristics of LP and IP comets can result in extremely high velocities while in the inner solar system, up to 72 kilometers per second relative to the Earth. Comets also tend to be much larger than asteroids.⁴⁴ The prospect of these high speeds, large sizes, possibly high inclinations to the ecliptic and unheralded arrival in the inner solar system (depending on how far out the coma and tails start forming) makes these bodies a problematic and stressing component of the impact hazard.⁴⁵ How *large* a component of the impact hazard comets represent is highly uncertain, since the cometary population itself is poorly characterized (as noted in the discussion of Figure 2.11 above). One estimate is that comets represent about 5 percent of the hazard on an impact event basis, but up to 25 percent of the hazard on an energy-normalized basis (due to their much higher average velocities).⁴⁶ An ear-

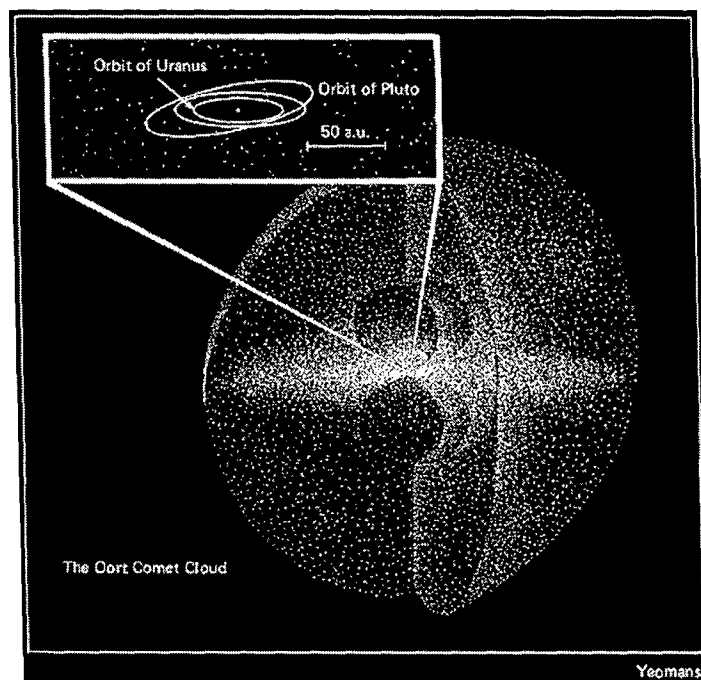
⁴³ In recent years, Edgeworth-Kuiper Objects (EKO) have been discovered with increasing frequency, providing experimental confirmation of that aspect of the hypothesis. They are also known as Kuiper Belt Objects (KBOs) or Trans-Neptunian Objects (TNOs). The planet Pluto is now considered to be a large EKO/KBO/TNO. There is no observational evidence for the existence of the Oort cloud.

⁴⁴ Thus the largest impact events will be due to cometary impacts. Steel, D., “Cometary impacts on the biosphere,” in *Comets and the Origin and Evolution of Life*, Thomas, P., et al., editors, Springer-Verlag, New York, 1997, p. 216.

⁴⁵ The possibly high inclination is a problem for those NEO survey programs that search on the ecliptic plane in an effort to maximize NEA discovery rates. Also, sublimation of cometary volatiles causes non-gravitational dynamic effects that make long-term orbit prediction impossible. These issues will be addressed in more detail below.

⁴⁶ Morrison, D., “The Contemporary Hazard of Cometary Impacts,” in *Comets and the Origin and Evolution of Life*, Thomas, P., et al., editors, Springer-Verlag, New York, 1997, p.245.

Figure 2.13
Hypothetical representation of the Oort cloud



lier estimate was that comets constitute about 10 percent of the flux of Earth impacts.⁴⁷ A more recent estimate is that “the threat from all...comets...is about 1% the threat from the NEA population.”⁴⁸

Impact Effects

The impact risk depends not just on the frequency of collision but also on the expected results of impact, these being highly dependent on the nature of the impactor. The mass, speed, and composition of the comet or asteroid are all critical.⁴⁹ There are many details to consider. The angle of entry into the atmosphere can be important (meteors often skip out of the atmosphere). Oceanic impacts can be particularly damaging due to the potential for tsunamis. The season of impact might be important if an “impact winter” occurs. In that phenomenon, dust raised into the atmosphere reduces solar irradiance, causing crop failures and mass starvation.⁵⁰

⁴⁷ *Spaceguard Survey Report*, NASA, January 1992.

⁴⁸ Stokes, G., *et al.*, “Study to Determine the Feasibility of Extending the Search for Near-Earth Objects to Smaller Limiting Diameters,” report of the NEO Science Definition Team, prepared at the request of the NASA Office of Space Science, Solar System Exploration Division, 22 August 2003, p.16. However, this last estimate was based on the ratio of LP comets to NEAs encountering the Earth in the interval 1900–2002. Since there were only two LP comet encounters in that period (and both occurred in 1983), the estimate is highly uncertain due to the statistics of small numbers.

⁴⁹ However, details of composition are less important for the higher energy impactors. Morrison, D., *et al.*, “The Impact Hazard,” in *Hazards Due To Comets and Asteroids*, Gehrels, T., editor, University of Arizona Press, 1994, p. 61.

⁵⁰ An “impact winter” is the analog of the “nuclear winter” predicted to follow a global thermonuclear war.

Nevertheless, it is possible to draw some general conclusions regarding the expected damage from impactors of different sizes, and these are presented in Table 2.5.⁵¹

Beyond the general consequences shown in this table, the most commonly presented measure of impact effects has been expected fatalities. These are estimated in Figure 2.14, both annualized and per event.⁵² The dotted line represents uncertainty in the efficiency of tsunami generation by impactors of different sizes. The gray area represents uncertainty in the yield threshold for the onset of global climatic effects. The major point is that expected annualized deaths are maximized for the impactor with a 1–2 kilometer diameter (the case represented in Table 2.5 by the shaded zone). This is because such an impact results in deaths not just from the mechanisms of blast, fire, or drowning, but also from the breakdown of a social system (in particular, the loss of food production). This systemic collapse is estimated to result in the demise of 25 percent of the global population.⁵³ The impacts of yet larger objects result in still more deaths but not in equal measure due to the reduced frequency of such events—hence annualized deaths decrease.

Table 2.5
Impact effects as a function of NEO energy and size

Yield (MT)	Interval (yrs)	NEO diam.	Crater diam.	Consequences
<10				Stones & comets detonate in upper atmosphere Only irons (<3%) penetrate to surface
10–10 ²	10 ³	75 m	1.5 km	Irons make craters (Meteor Crater) Stones produce airbursts (Tunguska) Land impacts destroy area the size of city
10 ² –10 ³	10 ^{3.6}	160 m	3 km	Irons & stones produce groundbursts Comets produce airbursts Land impacts can destroy large urban area
10 ³ –10 ⁴	10 ^{4.2}	350 m	6 km	Impacts on land produce craters, can destroy area the size of small state ^a Tsunamis become significant
10 ⁴ –10 ⁵	10 ^{4.8}	0.7 km	12 km	Tsunamis reach oceanic scales, exceed damage from land impacts Land impacts can destroy moderate state ^a
10 ⁵ –10 ⁶	10 ^{5.4}	1.7 km	30 km	Land impacts raise enough dust to affect climate, freeze crops Ocean impacts generate hemispheric scale tsunamis Land impacts can destroy large state ^a Global destruction of ozone
10 ⁶ –10 ⁷	10 ⁶	3 km	60 km	Both land and ocean impacts raise dust, change climate Impact ejecta are global, triggering fires Land impacts can destroy large nation
10 ⁷ –10 ⁸	10 ^{6.6}	7 km	125 km	Prolonged climate effects, global conflagration, probable mass extinction Continental-scale destruction
10 ⁸ –10 ⁹	10 ^{7.2}	16 km	250 km	Large mass extinction (K-T)
>10 ⁹				Threatens survival of all advanced forms of life

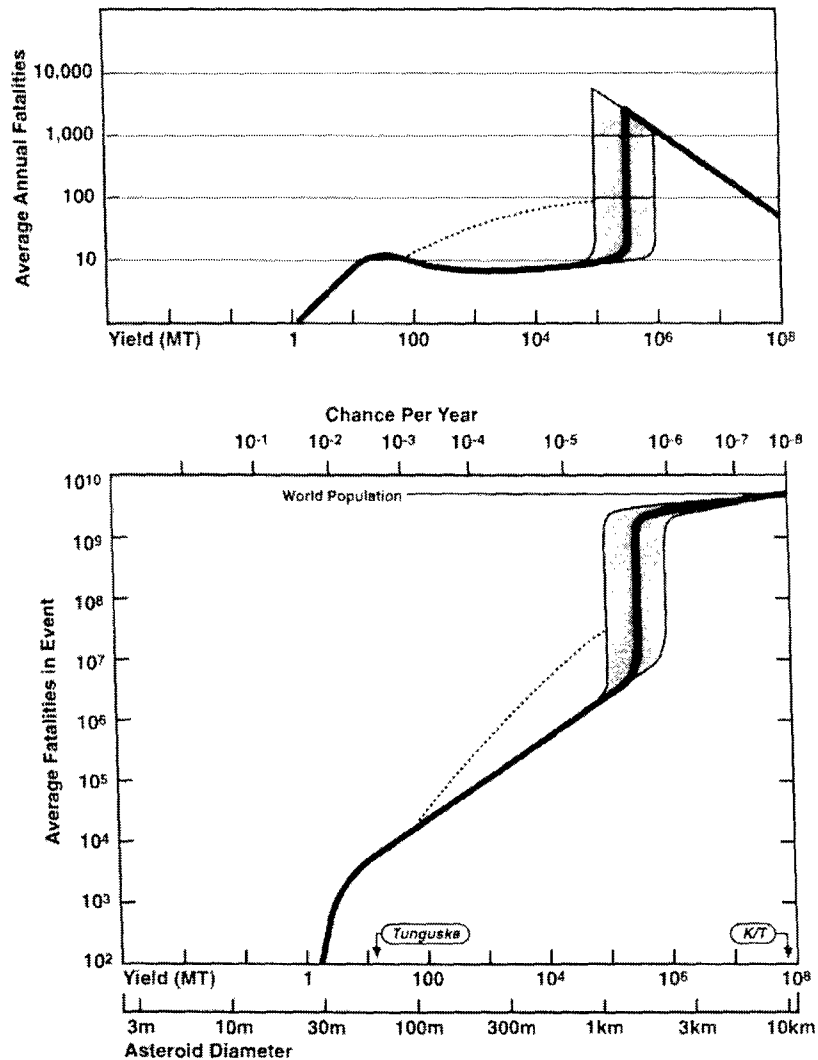
^a This refers to a state in the United States.

⁵¹ Morrison, D., *et al.*, "The Impact Hazard," in *Hazards Due To Comets and Asteroids*, Gehrels, T., editor, University of Arizona Press, 1994, pp.72-73.

⁵² From "The Impact Hazard" by D. Morrison *et al.*, in *Hazards Due To Comets and Asteroids*, edited by T. Gehrels, p.75, © 1994 The Arizona Board of Regents. Reprinted by permission of the University of Arizona Press.

⁵³ Morrison, D., *et al.*, "Dealing With the Impact Hazard," in *Asteroids III*, Bottke *et al.*, editors, University of Arizona Press, Tucson, 2002, p. 742.

Figure 2.14
Estimated fatalities vs. yield and NEA diameter



From a policy perspective, this discussion of the physical basis of the impact hazard demonstrates the enormously difficult task of communicating the threat, both to policymakers and to society at large. The aggregate threat is a function of a complicated interplay of arcane details of astrodynamics and planetary science, details of which are further shrouded by uncertainty. As a result, there is wide scope for societal misperception of the risk and for a consequently inefficient allocation of resources.

Confronting the Hazard

Mechanisms of Social Response

The previous section introduced the physical basis of the impact hazard: a very heterogeneous population of cosmic bodies with varying potentials of collision probability and impact effects. Due to the vastness of space, the mean interval between large impacts is well beyond the time scale of individual human experience. Likewise, the effects of the largest impacts (such as K-T or a smaller 1–2 kilometer civilization-ender) are beyond all experience. On the other hand, smaller impacts like the estimated once-per-thousand-year Tunguska, while still extremely rare occurrences, have nuclear blast effects as a referent.⁵⁴

Society's response to the impact hazard will be based on subjective probabilities and a subjective understanding of impact effects. While the experts (generally astronomers and planetary scientists) attempt to communicate frequentist probabilities and a scientific visualization of effects, it is society's perception and valuation of the hazard that has the greater likelihood of determining the social resources applied to the hazard.⁵⁵

Here it is important to note that there are diverse pathways for information flow between the NEO experts and the public.⁵⁶ The experts may communicate directly to the public, but more often their message is interpreted, amplified, and sensationalized by the news media. The experts may also communicate to policymakers, whose public pronouncements shape public opinion. Advocates have the potential to catalyze public concern, using the power of the Internet.⁵⁷ All of these actors have the ability to influence social perception of the impact hazard—sometimes out of altruism, sometimes for personal or organizational gain.⁵⁸

In principle, the baseline option for social response to the hazard is to do nothing. Indeed, for most of human history, mankind has been harmed not a whit by its failure to invest in NEO programs—*ex post facto*. It could be that doing nothing is still the right answer in certain circumstances involving specific social valuations and constraints of implementation.⁵⁹ In the absence of social considerations, however, it has been conventional wis-

⁵⁴ Note, however, that radiation effects are not an expected feature of a cosmic impact.

⁵⁵ A frequentist probability stems from long-run observations of the occurrence of an event, as distinguished from a subjective probability that represents a belief of the likelihood of an event. Stewart, T., "Uncertainty, Judgment, and Error in Prediction," in *Prediction—Science, Decision Making, and the Future of Nature*, Sarewitz, D., et al., editors, Island Press, Washington, D.C., 2000, p.42. Social valuation of the hazard probability is influenced by risk aversion or risk-seeking tendencies. Social valuation of the hazard effects includes a step function: Armageddon (or the end of everything) is qualitatively unlike any lesser effect.

⁵⁶ In this discussion, to avoid unwieldy construction, "NEO" is taken to include the LP comet case.

⁵⁷ These advocates can be "freelance," operating from an altruistic sense of social concern rather than from the usual stakeholder motivations. The Internet provides a forum for the unusually or even psychotically risk averse to potentially catalyze a social reaction. If these advocates are seen as disinterested (with no stake), their influence is potentially great. "In most instances, however, whether or not a source is arguing for personal gain *does* make a difference." Petty, R., and Cacioppo, J., *Attitudes and Persuasion: Classic and Contemporary Approaches*, Westview Press, Boulder, Colorado, 1996, p.64.

⁵⁸ Several characteristics of the NEO expert community make issues of communicating social hazards problematic. First, many observational astronomers are self-selected to enjoy separation from society, dwelling far from city lights and working at night, and usually studying objects as far from society as imaginable. Historically, it was the astrologers rather than the astronomers who had aspirations to achieve social effect. Second, the language of astronomical observation is complex and not easily communicated to the general public. Finally, as pure scientists, both astronomers and planetary scientists are naturally averse to information control; even information *management* is controversial. This will be further addressed in Chapter Five.

⁵⁹ The reasoning behind this assertion will be elaborated in Chapters Five and Six.

dom that *some* level of expenditure to reduce the impact hazard is appropriate and the debate has revolved about “how much,” not “whether.”

The implementation of society’s response to the impact hazard can take many forms, but in general can be divided into the functions shown in Table 2.6.

Table 2.6
Impact hazard response

Survey	Surveillance (ground and space-based) Tracking (optical and radar follow-up)
Characterization	Optical (spectrometry and occultations) ⁶⁰ Radar Space missions
Mitigation	Active (interception) Passive (civil defense) Consequence management

This division of functions is similar to that commonly found in the military sphere: a surveillance capability detects threats; a detected threat is tracked (and perhaps characterized); and measures are taken to neutralize that threat. In both cases, the purpose of the surveillance and tracking function is to provide support for the mitigation function—without a mitigation capability, the primary purpose of surveillance is vitiated. However, several aspects of the impact hazard are very different from the military case:

- The probability that a real threat will be detected is extremely low;
- Average warning times will be much longer; and
- The ratio of false warnings to accurate warnings will be much higher.

The first two of these considerations have led to an initial emphasis on NEO survey systems. It seems reasonable to argue that the expense of mitigation systems can be deferred until a real threat is detected. Nevertheless, there is always a remote chance that a seriously threatening NEO or LP comet will be detected with a short warning time. This has led some of the particularly risk averse to argue for more near term investment in a mitigation capability.

The third consideration regarding NEO impact warnings is only beginning to be appreciated. Warning rates are potentially high because predictions of impact in the far future are shrouded in great uncertainty. The purpose of an NEO surveillance system is to generate warnings that enable a mitigation response, to achieve a social benefit. On the other hand, false warnings carry social costs. These costs are determined by the frequency of such warnings; the distribution of warning horizon (time to possible impact); the length of time a warning state is in effect; and, least certain of all, the nature of social reactions to these warnings.

The following sections discuss each of the NEO response functions in more detail.

Survey: Surveillance

Surveillance is accomplished today by means of ground-based telescopic surveys. Most work in observational astronomy involves the examination of very distant objects that appear to be

⁶⁰ An occultation is the interruption of the light from a celestial body by the intervention of another celestial body.

motionless, so very large aperture telescopes with a narrow field of view are used. In contrast, NEO surveys place a premium on searching a large volume of space relatively close to the Earth in order to maximize detection rates. Survey telescopes thus have generally smaller apertures (currently 0.42 to 1.2 meters) but much wider fields of view (up to almost ten square degrees).⁶¹ For the performance requirements of NEO surveys to date, these telescope systems are relatively inexpensive and within the means of private observatories and even dedicated amateurs.⁶² This has decentralized and internationalized NEO survey efforts.

The problem of searching for fast moving celestial targets against a stellar background is shared by both NEO researchers and military organizations attempting to discover and track man-made objects in Earth orbit. This commonality of purpose has had a major effect on NEO survey achievements to date, and will be further discussed in this and later chapters.⁶³

For a ground-based survey program, detection rates are maximized by having telescopes in widely separated geographical zones (to minimize the effect of bad weather) and in both hemispheres (to see well below the ecliptic plane).⁶⁴ Geographic separation also enhances the effectiveness of "follow-up" efforts.⁶⁵ These factors cause professional astronomers to encourage open participation in NEO survey activities.

NEO detection rates depend upon telescope design and the survey observation strategy. Survey volumes (in terms of cubic AU) are a function of both aperture (which determines detection ranges) and field of view.⁶⁶ The survey observation strategy must take into account the variation of detection ranges with angle from the Sun (such angle being known as "solar elongation"), and also the expected densities of NEOs in the volume of space being searched.⁶⁷

As an example, Figure 2.15 shows the detection range of C-class asteroids of various diameters for a search telescope capable of seeing objects as faint as a limiting visual magni-

⁶¹ Stokes, G., *et al.*, "Near-Earth Asteroid Search Programs," in *Asteroids III*, Bottke *et al.*, editors, University of Arizona Press, Tucson, 2002, pp.49-51.

⁶² The 16 inch (0.41 meter) aperture Meade LX200 telescope is billed as the "ultimate personal telescope for the advanced amateur" (www.meade.com/catalog/lx/16_lx200gps.html). In the future, if NEO surveys are extended to smaller size objects requiring larger telescopes, these amateurs will inexorably be left behind.

⁶³ The USAF is currently the only military service in any country supporting NEO survey efforts, although this will not necessarily always be the case.

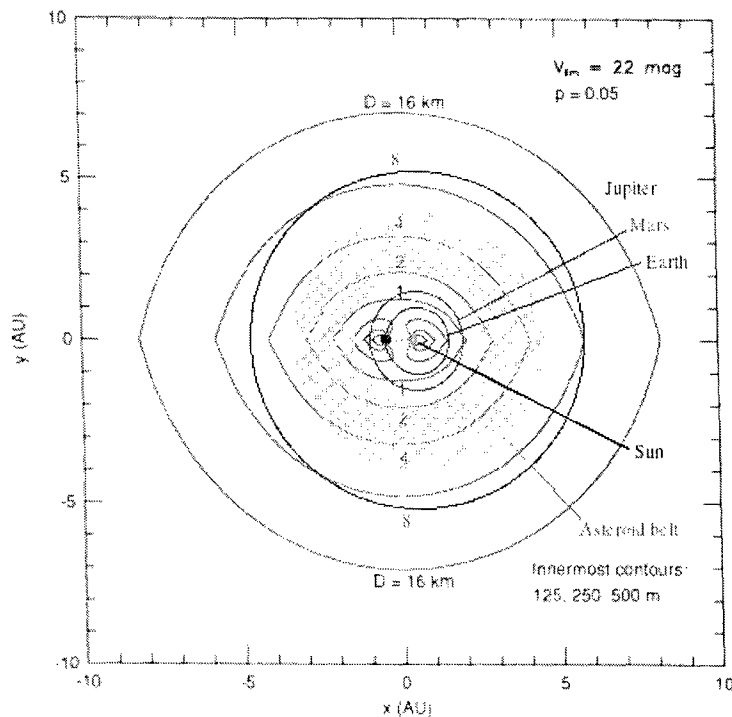
⁶⁴ The lower 20 percent or so of the celestial sphere is currently not covered. An NEO below the ecliptic plane will eventually move above it, but perhaps not until it is beyond the range of telescopes in the Northern Hemisphere. Eventually, though, even these NEOs will be in range, so it is a detection rate and survey completeness issue (particularly for smaller objects), not an "undiscoverable population" issue. Morrison, D., *et al.*, "Dealing With the Impact Hazard," in *Asteroids III*, Bottke *et al.*, editors, University of Arizona Press, Tucson, 2002, p. 746.

⁶⁵ Follow-up observations are those that enable the charting of an NEO orbit, and are discussed below.

⁶⁶ Increasing the integration time (analogous to increasing the exposure time for film-based systems) can also improve detection ranges, but at the cost of sky coverage over the course of a night. Sky coverage can be thought of as aggregated field of view.

⁶⁷ There are other subtleties. For example, lunar elongation (the angle subtended between the detected object and the Moon) is a factor. Also, it is very difficult to detect any moving object against the background of the Milky Way (*i.e.*, in the galactic plane).

Figure 2.15
Detectability of C-class asteroids in the ecliptic plane



tude (V_{lim}) of 22.⁶⁸ Such carbonaceous asteroids are very dark (Figure 2.15 assumes an albedo of 0.05), but on the other hand, a $V_{\text{lim}}=22$ optical system is very capable.⁶⁹ The detection range for a C-class asteroid of one kilometer diameter is 1.5 AU, if observed at opposition (that is, in a direction opposite the Sun, at 180 degrees of solar elongation). Figure 2.15 shows detection ranges on the ecliptic plane; ranges are diminished off the ecliptic.

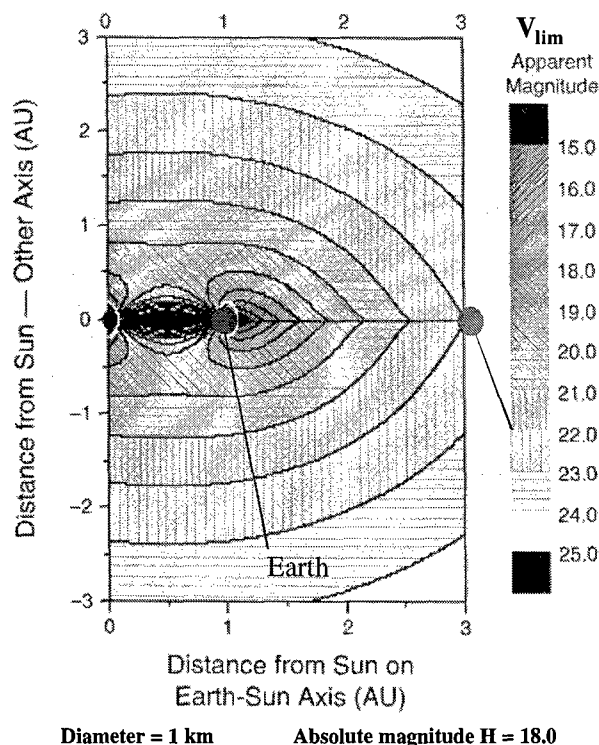
Figure 2.16 shows the detection range for a more typical asteroid (intrinsically brighter, with an absolute magnitude $H = 18.0$ and an assumed diameter of one kilometer).⁷⁰ The maximum range achievable with a $V_{\text{lim}}=22$ optical system is just over 2 AU.

⁶⁸ Visual magnitude (V) is the apparent brightness of an object, and depends on its distance from the Sun, distance from the observer, and phase angle (how much of the object's apparent disk is illuminated by the Sun). Figure 2.15 is adapted from "Earth-Crossing Asteroids and Comets: Groundbased Search Strategies" by E. Bowell and K. Muinonen in *Hazards Due To Comets and Asteroids*, edited by T. Gehrels, p.157, © 1994 The Arizona Board of Regents. Reprinted by permission of the University of Arizona Press.

⁶⁹ Current NEO search programs have a capability of between 19 and 22.6 V_{lim} . Stokes, G., *et al.*, "Near-Earth Asteroid Search Programs," in *Asteroids III*, Bottke *et al.*, editors, University of Arizona Press, Tucson, 2002, p.49.

⁷⁰ Absolute magnitude (H) is the brightness of an object, normalized to remove dependence on distances and phase angle. It is thus an inherent characteristic of the object. An $H = 18$ object of one kilometer diameter will have an average albedo of 0.11. This is consistent with the magnitude scale of Figure 2.11. Figure 2.16 is adapted from "Near-Earth Asteroid Search Programs" by G. Stokes *et al.*, in *Asteroids III*, edited by W.F. Bottke Jr., A. Cellino, P. Paolicchi, and R. P. Binzel, p.47, © 2002 The Arizona Board of Regents. Reprinted by permission of the University of Arizona Press.

Figure 2.16
Detectability of 1 km diameter asteroid in the ecliptic plane



Finally, the cumulative number of objects detected is a function of both telescope performance and target density. Figure 2.17 shows that the density of known NEAs is greatest near the orbit of the Earth, and that searches through the region of highest density (at solar elongations of up to 120 degrees) can be productive.⁷¹

Ideally, NEO search programs conduct all-sky surveys to maximize detection rate, rather than just searching at opposition on the ecliptic where detection ranges are greatest.⁷²

As a final note, over the years, different designs for space-based NEO survey telescopes have been proposed.⁷³ There are advantages and disadvantages, as listed in Table 2.7, and uncertainties will be resolved only with the launch of an actual system.⁷⁴ Although not specifically looking for NEOs, a space platform known as the Solar and Heliospheric Observatory (SOHO) has been the most prolific comet discoverer in history, finding over 750 new comets since 1996.⁷⁵

⁷¹ *Ibid.*, p.48.

⁷² This will be depicted in Figure 2.22.

⁷³ Wall, R., "New Military Space Telescope To Exploit Curved Electro-optics," *Aviation Week & Space Technology*, 26 August 2002, p.65. Also see www.space.com/scienceastronomy/astronomy/ness_asteroid_000824.html for the use of the proposed Canadian Near Earth Space Surveillance System (NESS) for NEO detection; and www.observer.co.uk/uk_news/story/0,6903,319399,00.html for the European Space Agency's proposed *Gaia* mission.

⁷⁴ The Hubble Space Telescope has been used to image asteroids, but it is not a dedicated survey telescope.

⁷⁵ See <http://ares.nrl.navy.mil/sungazer/> for an updated tally of SOHO comet discoveries.

Figure 2.17
Density of known NEAs

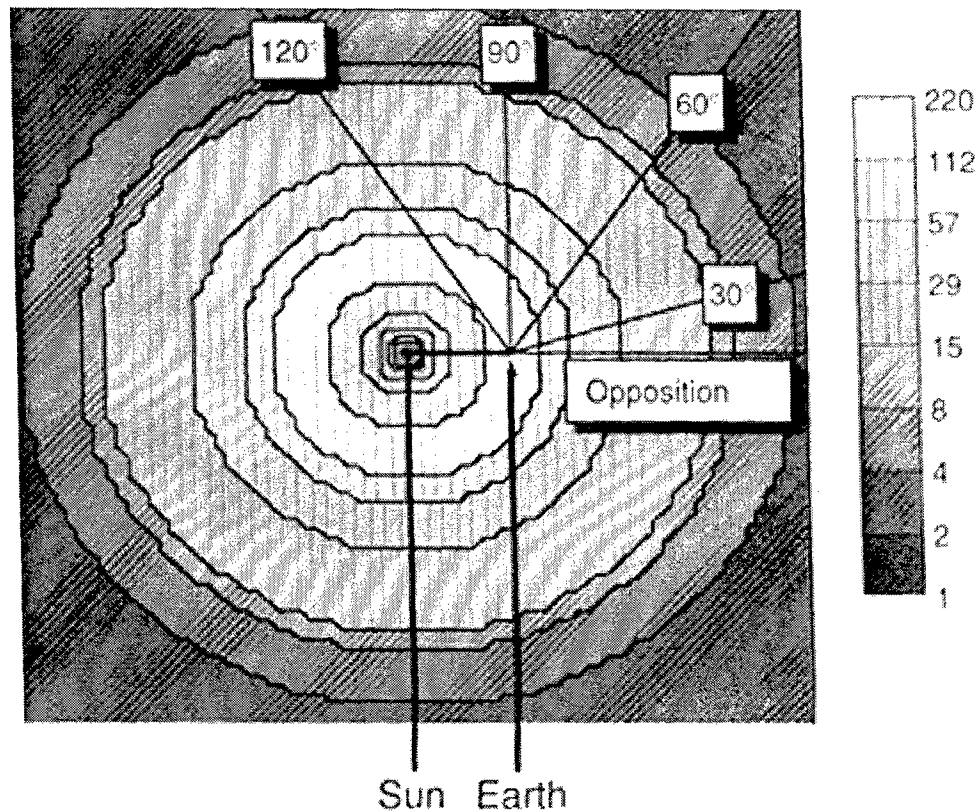


Table 2.7
Space telescope advantages and disadvantages

+	Apertures can be much smaller since atmospheric effects are nonexistent
+	Terrestrial weather effects are nonexistent
+	A single telescope can look both above and below the ecliptic plane, and if in a high inclination orbit, to the other side of the Sun
+	A telescope can be mounted as an adjunct payload on a larger spacecraft
-	A space survey telescope has never been built, hence entails risk
-	Space systems are inherently expensive
-	Space systems are difficult or impossible to maintain
-	Space systems have limited lifetimes

Survey: Tracking

The following discussion addresses the technical intricacies of NEO tracking, which is the source of the flow of hazard information that may ultimately be made available to society. NEO specialists must acquire this highly abstruse data and convert it into a form that society can use to assess the impact risk. This is a process that is fraught with difficulty, especially when the role of the news media as interlocutors is considered. To assess the efficacy of risk communication measures, the policy analyst must first understand the underlying processes that those measures are attempting to describe.

Stated somewhat simplistically, the purpose of tracking an NEO is to predict what its location will be each time that NEO passes close to the Earth. There is substantial uncertainty associated with determining the future position of an NEO, particularly as the time of interest extends further into the future.⁷⁶ This three dimensional position uncertainty is projected into a “target plane” including the Earth and normal to the NEO’s velocity vector, resulting in an uncertainty ellipse (arbitrarily of 3σ dimensions).⁷⁷

Figure 2.18 represents the propagation of an orbital uncertainty region using the orbit of a typical NEA, 2002 GO5, as an example.⁷⁸ The lighter part of the NEA’s orbit lies above the ecliptic plane, the darker part lies beneath. At time t_0 the notional asteroid is detected, and its position uncertainty lies largely along the line of sight to the object (since albedo, size, and thus distance are uncertain). As the object continues its orbit, an initial “arc of observation” is established, and a Minimum Orbital Intersection Distance (MOID) of less than 0.05 AU is calculated (shown in Figure 2.18 near the object’s descending node).⁷⁹ The asteroid is thus designated a PHA. For the purpose of this example, let us assume that the arc of observation then remains constant (that is, no “follow-up” observations are conducted).⁸⁰ Then the asteroid’s uncertainty region spreads out along its orbit as one looks into the future (t_2 and t_3 as seen from time t_1). At time t_n and subsequent times t_{n+a} and t_{n+b} , the asteroid has a close passage with Earth near its MOID locus.⁸¹ The lower panels of Figure 2.18 show the 3σ uncertainty ellipse (the projection of the three-dimensional uncertainty region) on the Earth target plane for each close encounter.⁸² Note how the uncertainty ellipse continues to grow in length over time. Eventually, the uncertainty region spreads around the entire asteroid orbit (looking ahead several decades into the future), and no further encounter predictions are possible.

An opposing tendency is for the uncertainty ellipse to shrink as the arc of observation is extended (by follow-up telescopic observations). The ellipse reduction can be accelerated rapidly by searching astronomical archives in the hope of making a “precovery.”⁸³ Another

⁷⁶ This discussion of NEO close encounter analysis is based on Milani, A., *et al.*, “Asteroid Close Approaches: Analysis and Potential Impact Detection,” in *Asteroids III*, Bottke *et al.*, editors, University of Arizona Press, Tucson, 2002, pp. 55-69; Chodas, P., and Yeomans, D., “Predicting Close Approaches and Estimating Impact Probabilities for Near-Earth Objects,” AAS/AIAA Astrodynamics Specialist Conference, AAS 99-462, Girdwood, Alaska, 16-19 August 1999; and conversations with Paul Chodas of JPL. Some definitions (such as that of the target plane) have been simplified for ease of comprehension.

⁷⁷ “ σ ” (sigma) denotes standard deviation.

⁷⁸ The size of the uncertainty region and the rapidity of its growth are greatly exaggerated here for illustrative purposes. The underlying asteroid orbit diagram is taken from <http://neo.jpl.nasa.gov/orbits/>.

⁷⁹ The arc of observation is the time between the earliest and most recent observations of an object. The number of observations is less important than the temporal baseline represented by the arc.

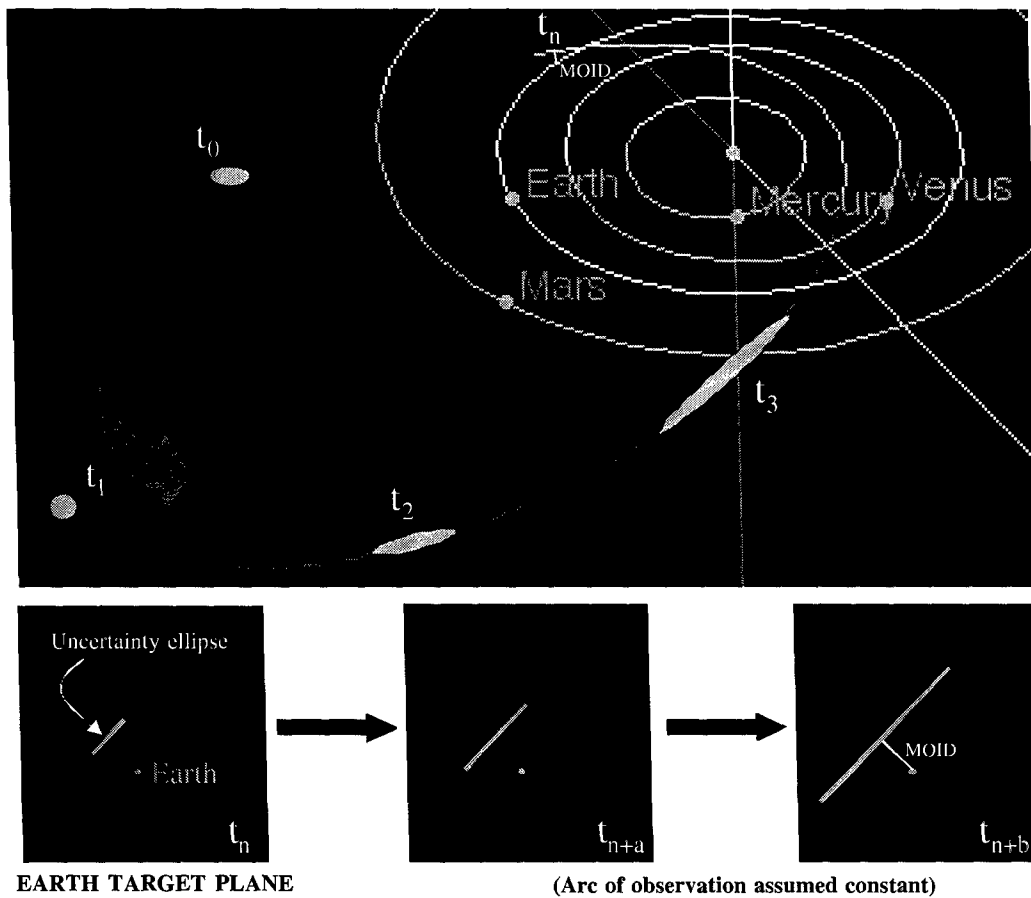
⁸⁰ A single detection with no follow-up is informally known as a “one night stand,” and results in the NEO’s position uncertainty being spread around the Earth’s orbit. The NEO can then easily be lost.

⁸¹ The subscripts n, a, and b represent those future orbits of the asteroid where a close encounter occurs (*i.e.*, where the Earth and the asteroid both happen to be close to their MOID loci at the same time).

⁸² The uncertainty ellipse appears as a line segment in each panel because it represents a transform of the temporal uncertainty of the asteroid in its orbit. That is, the orbit is well known (but not perfectly so, hence the ellipse has *some* thickness), but the asteroid’s position in that orbit is not. Thus, the asteroid’s eventual location on the uncertainty ellipse represents how early or late it was to the MOID.

⁸³ An initial observation of an asteroid (or comet) is sufficient to define a region of sky for subsequent follow-up observations to search. When the object is re-observed after a period of no sightings it is considered recovered. Hence an archival

Figure 2.18
Evolution of uncertainty ellipse with succession of future encounters



means of rapidly reducing the ellipse is to make a ground-based radar observation (for example, using the Arecibo or Goldstone radar telescopes), although this is not usually possible because of the limited range of planetary radars.⁸⁴

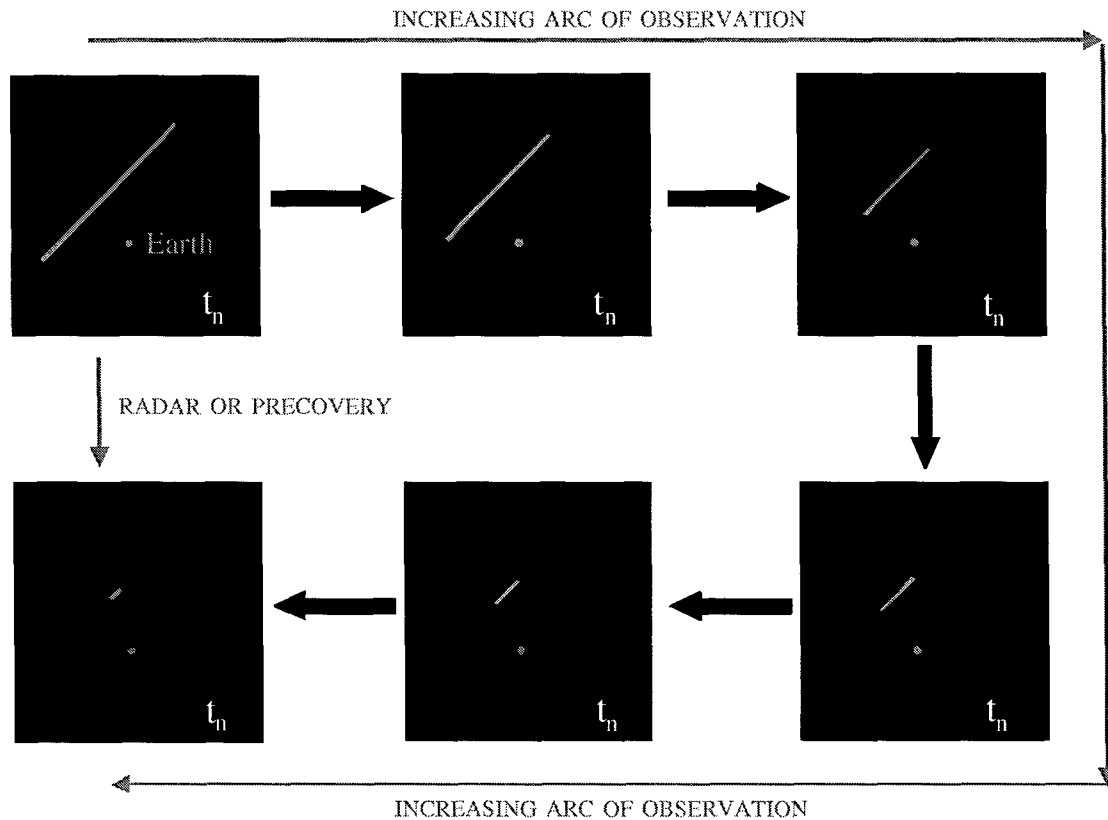
Figure 2.19 shows the process of uncertainty ellipse reduction as a function of increasing arc of observation. All panels show the same time of future encounter, time t_n . Note how radar observation or precovery can immediately shrink the ellipse.

A logical question would be why PHAs with nonzero MOIDs are considered hazardous, since such a MOID by definition implies zero probability of collision. The reason is that MOIDs can change over time, as a result of close approaches with the Earth or other plan-

“precovery” is a “previous recovery” serving the same purpose as a recovery—to extend the arc of observation. The difference is that the precovery observation can be from decades ago, so the arc of observation can lengthen immediately and immensely.

⁸⁴ Radar is effective because its observations have much less error than optical observations, particularly in measuring distances. The range limitation makes radar an unsuitable tool for NEO search, however. For an NEO of one kilometer in diameter, Arecibo has a range of about 0.24 AU, and Goldstone has a range of about 0.1 AU. Ostro, S., “The Role of Groundbased Radar in Near-Earth Object Hazard Identification and Mitigation,” in *Hazards Due to Comets and Asteroids*, Gehrels, T., editor, University of Arizona Press, Tucson, 1994, p.274.

Figure 2.19
Evolution of uncertainty ellipse for a given encounter



ets.⁸⁵ The PHA definition embodies a MOID sufficiently small that such perturbations could reasonably result in a zero MOID at some future encounter within human time scales.⁸⁶

To understand the nature and frequency of impact warnings it is necessary to know both the warning criteria and the time history of the uncertainty ellipses resulting from NEO discoveries. In principle, warnings could be issued whenever the Earth is determined to be in an uncertainty ellipse. Alternatively (and this is the procedure currently employed by the astronomical community), warnings could be issued whenever a threshold impact probability is reached.⁸⁷

⁸⁵ Prior close approach possibilities can result in a multiplicity of uncertainty ellipses (parallel ellipses with different MOIDs). MOIDs also change as orbits precess (the orientation of the orbits rotate in ecliptic longitude, in a "hula-hooping" motion). However, precession occurs over far longer than human time scales.

⁸⁶ This begs the question of why the NEO community has chosen to focus on NEO/NEA statistics (as in Figure 2.11) rather than the population subset of PHO/PHAs, which is more relevant to assessment of the impact hazard. In fact, this is beginning to change, with PHAs being tracked by the JPL NEO Program Office web site (<http://neo.jpl.nasa.gov/orbits/>). Likewise, PHAs rather than NEAs are the subject of analysis of the 2003 NASA Science Definition Team study (Stokes, G., *et al.*, "Study to Determine the Feasibility of Extending the Search for Near-Earth Objects to Smaller Limiting Diameters," report of the NEO Science Definition Team, prepared at the request of the NASA Office of Space Science, Solar System Exploration Division, 22 August 2003).

⁸⁷ Under the current warning protocol (discussed below), the Earth could be in an uncertainty ellipse (with zero MOID), yet with an impact probability too low to justify a formal warning. Publicity surrounding such a circumstance could make a formal warning moot, however, if a social alarm nevertheless occurs.

Uncertainty ellipses are populated by Monte Carlo methods, and there is no simple functional dependency on either the arc of observation or time to projected encounter. Consequently, warning rates associated with NEO survey programs are highly uncertain, whatever the choice of warning threshold.⁸⁸

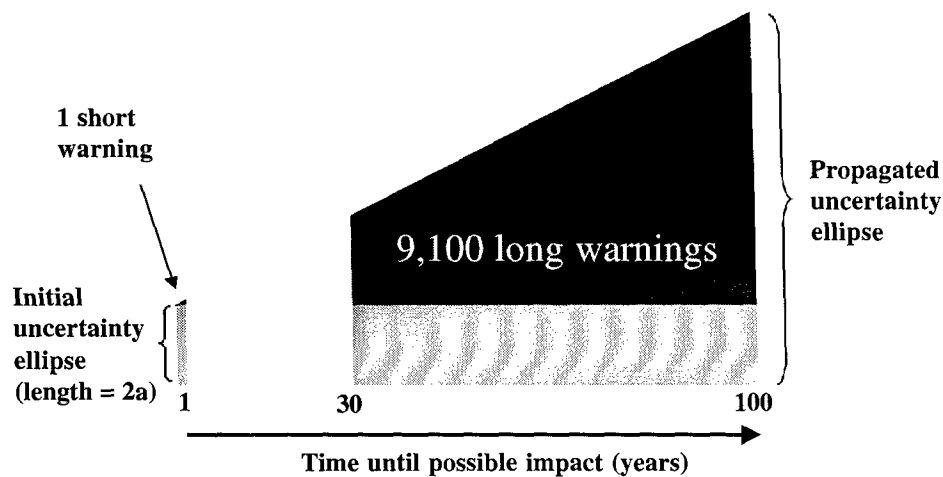
The distribution of warning horizon (time to possible impact) is important from two perspectives: the assessment of warning costs and the optimization of mitigation strategies.

There is a uniform distribution of impact probability—that is, the chance of impact from one year to the next is constant. Thus, one might expect that the chance of a possible impact being predicted, say, 30–100 years in advance is 70 times the chance of only one year's warning or less. In actual fact, if a warning is issued whenever the Earth is inside an uncertainty ellipse, then the propagation of the uncertainty ellipse with warning horizon ensures that long-range warnings will be relatively even more frequent. This is simply because there is a much greater chance of the Earth being inside a larger ellipse, as illustrated by Figure 2.20.⁸⁹

For any linear approximation of uncertainty ellipse propagation, there are up to 9,100 more 30–100 year warnings than one-year warnings.⁹⁰

The conclusion is that if the Earth-inclusive ellipse criterion is employed, long warning times will predominate, (except of course for LP comet threats, since those bodies cannot be detected until their final approach into the inner solar system). There will be many

Figure 2.20
Rate of initial warning, Earth-inclusive ellipse criterion



⁸⁸ Note also that in the case of LP comets, short arcs of observation and the non-gravitational effects of dust and volatile jets make position uncertainties potentially very large.

⁸⁹ In this figure, the effect of increasing arc of observation in reducing the ellipse is irrelevant, since only initial warnings are considered and there is no probability threshold involved.

⁹⁰ The ratio is less than 9,100 if an initial uncertainty ellipse length is assumed (as shown by the light blue area in Figure 2.20). Such would normally be the case, as an arc of observation would not yet have been established. The warning ratio is based on a ratio of triangles and is represented by the formula $(45.5 + 14a)/(1/200 + a/5)$ where a is the semi-major axis (half the longest dimension) of the initial uncertainty ellipse.

warnings, but as the bulk of the warnings will involve exceedingly low probabilities, familiarization (that is, the “cry wolf effect”) may actually serve to reduce social costs.

The other possibility (currently employed) is to issue a warning whenever a threshold impact probability is reached. A simple model serves to illustrate the effect of this criterion on the distribution of initial warning horizon, assuming a fifteen year survey (Appendix A). A population of 100 potential impactors is assumed. A power approximation is taken to represent the evolution of uncertainty ellipse length as a function of arc of observation and warning horizon, and probabilities of Earth impact are represented by the geometric ratio of the Earth’s diameter to this length.⁹¹ Horizon of initial warning is binned by decade. The two cases of Figure 2.21 reflect two different assumptions regarding the relative effect of arc of observation and time until encounter. It can be seen that the distribution of warning horizon is sensitive to these assumptions.

In this model, the greater the temporal propagation of the uncertainty ellipse (relative to its shrinking due to a longer arc of observation), the more short warnings occur. These would presumably entail higher social costs and perhaps different mechanisms by which those costs would be incurred.⁹²

Again, there is no simple functional dependency governing these effects—hence, there is no easy way of predicting either the frequency or character of impact warnings.

Finally, it is important to consider the length of time that a warning state would be in effect. As the uncertainty ellipse shrinks with increasing arc of observation (assuming that follow-up observations are conducted, which is likely to be the case if a worldwide NEO impact alert has been issued), it will in most cases shrink to exclude the Earth. Figure 2.22 shows an inclined triangular surface that represents possible impact warning outcomes.⁹³ The vertical scale is impact probability. An object is detected, and its initial uncertainty ellipse for a specific future encounter is large but includes the Earth (t_1). As the arc of observation is extended, the ellipse shrinks, but not yet sufficiently to exclude the Earth; hence the impact probability P_h rises (and the object climbs the triangular surface). At time t_2 , impact probability is at a maximum for this case (35 percent). At that point, the ellipse can shrink to exclude the Earth (t_3), or P_h can linger at 35 percent if the ellipse stays on the limb of the Earth, before falling off it completely (again to t_4).

As Figure 2.22 shows, in most cases, the ellipse shrinks to exclude the Earth. Still, the process takes time, and the social reaction to the object’s progress up the “triangle of fear” is highly uncertain. At the least, there will be conflicting pressures to start crash mitigation programs or to wait and see what happens.⁹⁴

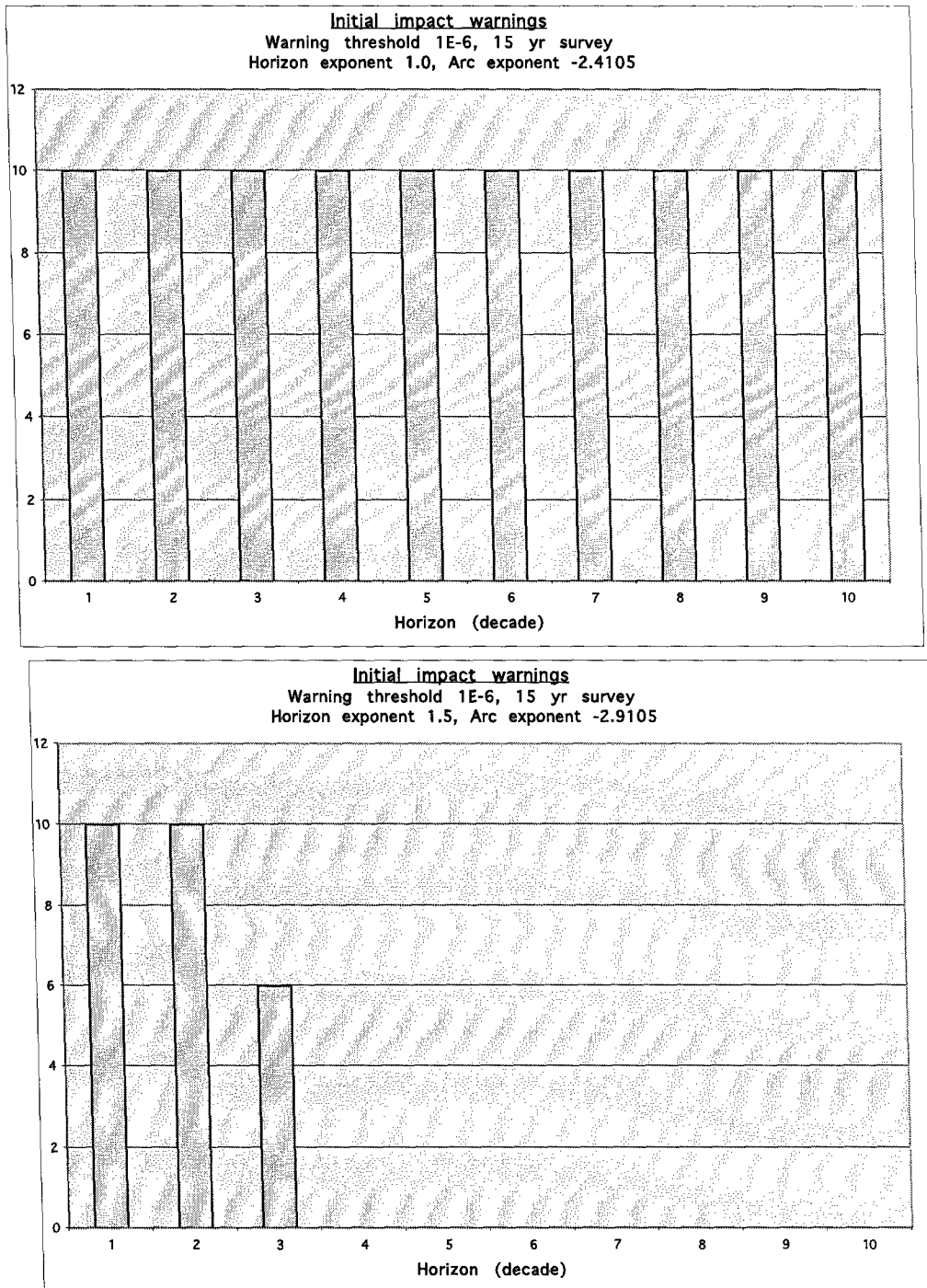
⁹¹ This power approximation is based on the results of an impact simulation presented by Paul Chodas, JPL, at the annual meeting of the Western Psychological Association, Irvine, California, 12 April 2002. It has unknown validity for any cases other than that simulation, and is used here for strictly illustrative purposes.

⁹² *e.g.*, acute social effects such as alarms and “panics” rather than chronic effects like economic malaise.

⁹³ The uncertainty ellipse must overlies the Earth (with zero MOID) before an object can climb this probability surface. The triangular surface is shown as smooth and equilateral only for clarity of presentation—in reality, the uncertainty ellipse does not necessarily shrink about its center, and can lack smoothness because of probability jumps. The ellipse can even shift beyond its original confines if there are systematic errors in the observations. This would result in a sinuous, pseudo-triangular probability surface. The probability surface is a concept of the author. Behavior of the uncertainty ellipse is per Paul Chodas, JPL.

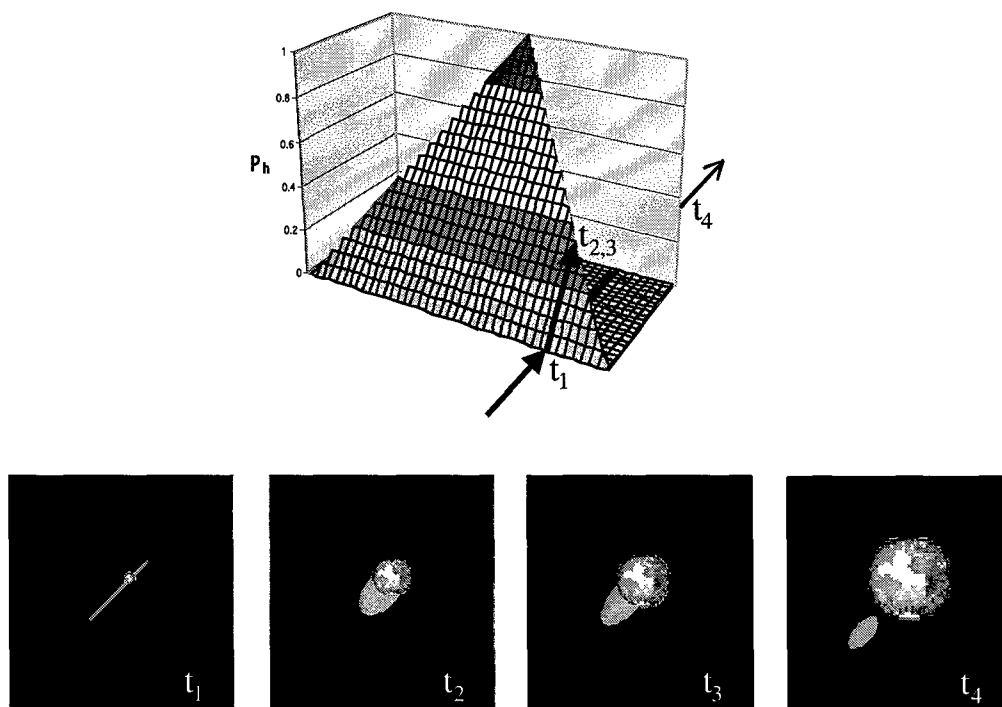
⁹⁴ The details of the uncertainty ellipse are not made available to the public, but the transient numeric probabilities of impact are, via the Internet (*e.g.*, at <http://newton.dm.unipi.it/cgi-bin/neodys/neoibo?riskpage:0;main>). The purpose of releasing such information is to encourage follow-up observations by astronomers, especially amateurs—but it is also done in

Figure 2.21
Initial impact warning rate estimation



the spirit of scientific openness. This is how the issue of warning threshold can become moot—an alarm can result even if a “confirmed warning” is not issued.

Figure 2.22
Triangle of fear



Characterization

NEOs can be characterized by optical means (measuring the spectrum of reflected light to infer mineralogical composition and estimating sizes by timing serendipitous passages in front of stars). Radar measurements can also be used for characterization. The ultimate method, though, is to inspect the NEO *in situ* with a space probe. Several asteroid and comet fly-by missions have already been conducted, and more are planned—these will be discussed later in this chapter.⁹⁵

From the standpoint of the impact hazard, characterization has two purposes:

- Understanding the makeup of a specific hazardous NEO can be of value in *designing and developing* mitigation responses for that NEO (assuming sufficient warning time exists); and
- Understanding the makeup of the NEO population as a whole can be of value in *planning* the operational effectiveness of mitigation alternatives.

Additionally, there is a scientific justification for NEO characterization that may well be judged as more important to society than the benefit to hazard mitigation: asteroids and comets are primitive bodies that bear witness to the conditions prevailing at the time of the solar system's formation.

⁹⁵ The probe *NEAR Shoemaker* is currently resting (inoperatively) on the surface of the NEA Eros.

Mitigation

Mitigation options include interception of the NEO for purposes of deflection or disruption, and civil defense measures including evacuation of populations. After an impact, losses can be mitigated by traditional means of disaster “consequence management,” at least for smaller impact events.

Interception systems generally involve the use of Earth-based rocket launchers carrying a nuclear device or some other non-nuclear means of deflecting or disrupting an NEO. The launchers must be much larger than a ballistic missile of equivalent payload, due to the need to achieve Earth escape velocity. For similar effect, it is usually considered that a launcher carrying a nuclear device can be much smaller than a non-nuclear interception system.

Nuclear interception would entail either fly-by detonation of a device, or rendezvous and emplacement. The former approach imparts much less energy to the object, but is easier to accomplish and requires a much smaller launch mass. The NEO’s orbit is altered primarily by radiation effects, since there are no blast effects in a vacuum. However, there is great uncertainty surrounding the coupling of nuclear energy into the NEO.

Non-nuclear means of NEO deflection could include hypothetical “mass driver” systems, attachment of ion engines, solar sails, and even beamed energy from the Moon.⁹⁶ They all suffer from difficult details of implementation. Since they are less energetic than nuclear methods, they are little suited for short warning scenarios. Still, since warning times will in all likelihood be ample, the development of such systems may be preferred.

Interception of NEOs has been a controversial topic for a number of reasons. An obvious negative is the sheer expense associated with interception systems, especially if they are designed for the most stressing threat (large, high velocity LP comets with little advance warning). Unlike characterization systems, interception systems have essentially no redeeming scientific value. Also, the use of nuclear devices in space is arguably banned by Article 4 of the Outer Space Treaty, and increases concerns over the militarization of space.⁹⁷ There is scientific concern over whether disruption of an asteroid by nuclear means might do more harm than good (causing a “shotgun” effect of smaller fragments hitting the Earth).⁹⁸ There is a concern that an NEO might be mistakenly deflected onto an Earth impacting trajectory when it was actually going to miss. Finally, there is fear about the “deflection dilemma”: the concern that a capability to deflect asteroids could be misused by the nefarious at some point in the future, creating a horrifying space strike weapon with effects far beyond those of any

⁹⁶ Mass drivers are hypothetical systems that would be deposited on an NEO to change its orbit over time by using the NEO’s own constituents as reaction mass. Solar sails would somehow be attached to a (probably spinning) NEO, and would rely on solar radiation pressure to change the NEO’s orbit. Another proposal is to “paint” an NEO with a light colored material, to change solar reflectivity and thus, over a long time, the NEO’s orbit. For beamed energy, see http://space.com/business/technology/technology/beamed_propulsion_021105.html, and also Mazanek, D., “Comet/Asteroid Protection System” (CAPS), Concept Summary Briefing to NASA Headquarters, 2 October 2001.

⁹⁷ The 1966 *Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies* entered into force on 10 October 1967. Commonly known as the “Outer Space Treaty,” Article IV of the treaty reads, in part: “States Parties to the Treaty undertake not to place in orbit around the Earth any objects carrying nuclear weapons or any other kind of weapons of mass destruction, install such weapons on celestial bodies, or station such weapons in outer space in any other manner.” It could be argued that a nuclear device intended for NEO interception is not a weapon, but a “peaceful” device akin to a demolition charge.

⁹⁸ www.space.com/business/technology/technology/nudging_not_nuking_000211.html

nuclear weapon in an Earth arsenal.⁹⁹ The logic is that the probability of this occurrence, however slight, might well outweigh the tiny probability of a natural Earth impact in the same time frame.

Given the nature of NEO impact warning and the evolution of uncertainty ellipses (discussed above), a key question when considering investment in an NEO interception system is determining what threshold level of impact probability justifies action. This threshold probability is difficult to establish since the error ellipse will eventually shrink to exclude the Earth in almost every case (as shown in Figure 2.22). A tension exists between the policymaker's desire to defer expenditures and the public's desire to mitigate a possibly unacceptable level of risk, occasioned by its perception of the threat.

In addition to active mitigation of NEO impacts through interception, passive mitigation is possible by means of evacuation of populations. This is, of course, relatively ineffective where the killing effects are global, involving civilization-ending impacts by large objects (greater than approximately one kilometer in diameter). For short warning impact scenarios with large uncertainty ellipses until just before impact, disaster response authorities may not know whether to expect a tsunami or a land impact of unknown location and might actually move populations into a more hazardous zone. For longer warning the key question will be determining the level of impact probability that justifies the costs of a planned social disruption. Another consideration is that the social disruption may be *unplanned* if populations self-evacuate based on a misperception of the threat. Indeed, in the case of smaller impactors it may be that any interception system will serve primarily to defend capital stock and infrastructure. People may not be sanguine about the probability of interception success and would quite possibly depart the perceived target zone on their own volition.

In the case of large, civilization-ending impacts, passive mitigation might consist of developing means of maximizing food production in the absence of normal solar irradiation.¹⁰⁰ The duration of an "impact winter" would be highly uncertain, depending on the season and the geographical location of the impact.

These, then, are the mechanisms of social response to the impact hazard. The discussion will now review the recent history of society's response to the new scientific awareness of the hazard. This includes the role of the international scientific community, the actions of policymakers to date, the establishment of NEO survey programs and characterization missions and the results so far. In particular, there is a review of difficulties of public communication that have already occurred and measures that the "NEO community" has taken to try to surmount these difficulties.¹⁰¹ The chapter concludes with a discussion of future trends. It reviews an ongoing effort to expand greatly the scope of survey and characterization efforts and to expend resources on mitigation capabilities. The discussion also considers the possible consequences of future technological advances.

⁹⁹ Harris, A., *et al.*, "The Deflection Dilemma: Use Versus Misuse of Technologies for Avoiding Interplanetary Collision Hazards," in *Hazards Due to Comets and Asteroids*, Gehrels, T., editor, University of Arizona Press, Tucson, 1994, pp. 1145-1155. Also, Preston, R., *et al.*, *Space Weapons—Earth Wars*, (Appendix C—"Natural Meteoroids As Weapons"), The RAND Corporation, Santa Monica, California, MR-1209-AF, 2002, pp. 173-183.

¹⁰⁰ Garshnek, V., *et al.*, "The mitigation, management, and survivability of asteroid/comet impact with Earth," *Space Policy*, 16 July 2000, Volume 16, Number 3, pp. 213-222.

¹⁰¹ The "NEO community" consists of professional and amateur astronomers, space scientists, planetary scientists, and assorted enthusiasts and hangers-on. It is an advocacy group that is informally bounded, with membership by self-selection.

Genesis of the NEO Surveys

Beginning in the 1970's, increasing scientific interest in NEOs led to the establishment of modest search programs. The participants labored in relative obscurity. However, public attention increased after the Alvarez K-T impactor theory was published in 1980, and then again after the collision of Shoemaker-Levy 9 with Jupiter in 1994.

Nevertheless, these early efforts were significant from the perspective of the community of observational astronomers. Asteroids, in particular, had been regarded as a nuisance rather than as fitting subjects for observation. They were given the sobriquet "vermin of the skies" since they had a habit of interposing themselves between the astronomer's telescope and the planet, star, or galaxy actually being observed.¹⁰² Now, for the first time, asteroids were deemed worthy of a coordinated program of observation (although, to this day, NEO efforts must compete with mainstream astronomical projects for funding and telescope time).

The first NEO search program was started in 1973 by Eugene Shoemaker and Eleanor Helin, and was known as the Palomar Planet-Crossing Asteroid Survey (PCAS). In 1983, Eugene and Carolyn Shoemaker began the Palomar Asteroid and Comet Survey (PACS). Other efforts included:

- The European NEA Search Observatories (EUNEASO) program;
- The U.K. Schmidt-Caltech Asteroid Survey (UCAS);
- The Anglo-Australian NEA Survey (AANEAS); and
- The International NEA Survey (INAS).

The first NEO search program to use modern charge-coupled device (CCD) and computer technology was the Spacewatch program of the University of Arizona, begun in 1984.¹⁰³ Previously, photographic emulsions had been used, along with human examination of the exposures—a laborious, time consuming process.¹⁰⁴

Scientific concern about the collision threat to Earth mounted as more NEOs were discovered. This concern was communicated to various national governments and international bodies, including in particular the U.S. Congress, the U.N., and the Parliamentary Assembly of the Council of Europe.

In early April 1989, observers at Palomar discovered a small asteroid that was given the designation 1989 FC (and later, the name Asclepius).¹⁰⁵ 1989 FC was notable for having the closest observed passage of an asteroid to the Earth up to that time. Scientists calculated that it had missed the Earth on 23 March 1989 by 0.00457 AU (or 427,289 miles).¹⁰⁶ 1989 FC was an estimated 210–470 meters in diameter, a size expected to impact Earth every 15,000 years or so and, according to Table 2.5, it was capable of generating a tsunami.¹⁰⁷

¹⁰² Steel, D., *Target Earth*, Reader's Digest Association, Pleasantville, New York, 2000, p.102.

¹⁰³ The CCD is the basis for modern consumer digital camera technology, and indeed for all digital imaging.

¹⁰⁴ Current NEO search programs are fully exploiting CCD and computer technology advances.

¹⁰⁵ <http://cfa-www.harvard.edu/iauc/04700/04767.html>

¹⁰⁶ As of June 2003, 20 asteroids had been observed passing closer to the Earth than did Asclepius. By April 2004, that number had increased to 31, testifying to the accelerating pace of NEO discoveries. <http://cfa-www.harvard.edu/iau/lists/Closest.html>

¹⁰⁷ On the other hand, it passed Earth at almost twice the Moon's mean distance, and the target cross section of a circle of that radius is about 12,000 times the earth's cross section. Hence the close passage itself was not unusual—it was such an object's *discovery* that was novel. The capture cross section of the Earth is actually somewhat larger than its geometric cross section because of gravitational focusing—some NEOs are "sucked in."

Impelled by the "close approach," the American Institute of Aeronautics and Astronautics (AIAA) released a position paper in April 1990, calling for the establishment of an asteroid search program and for a study of mitigation systems. It used vivid language:

An asteroid bigger than an aircraft carrier, traveling at 46,000 miles per hour, passed through Earth's orbit less than 400,000 [*sic*] miles away. Our planet had been at that point only six hours earlier. The asteroid was not detected until after it had passed. Had it struck the Earth, the energy released would have been equivalent to that of 1000 to 2500 megatons of TNT (or 1000 to 2500 one-megaton hydrogen bombs). In an area of high population density such as the northeast corridor of the U.S., Los Angeles, or Tokyo, millions of people would have died instantly.¹⁰⁸

In 1990, to no small degree in response to the AIAA advocacy, the Committee on Science, Space and Technology of the U.S. House of Representatives stated:

The Committee believes that it is imperative that the detection rate of Earth-orbit-crossing asteroids must be increased substantially, and that the means to destroy or alter the orbits of asteroids when they threaten collision should be defined and agreed upon internationally.¹⁰⁹

It further directed that NASA undertake two workshop studies to be completed within a year. Consistent with the language above, one study was to define a program to increase ECA detection rates (that is, a survey program) and the other was to define systems and technologies to deflect or destroy such asteroids (that is, an interception program).¹¹⁰

In response to the first part of the direction, NASA convened an International NEO Detection Workshop. This workshop proposed a "Spaceguard Survey" using six telescopes, each with an aperture of 2.5 meters, assigned the task of identifying "more than 90 percent of potentially threatening ECAs larger than 1 km in diameter, as well as detecting most incoming comets about a year before they approach the Earth."¹¹¹ The workshop projected that the survey could reduce the risk of cosmic impacts "by up to 75 percent over the next 25 years."¹¹² Costs were assessed at \$50 million (in FY93 dollars) for acquisition and \$10 million per year for operations—thus \$300 million in constant FY93 dollars.

The results of the two NEO workshops were presented to the Subcommittee on Space, of the Committee on Science, Space and Technology, U.S. House of Representatives,

¹⁰⁸ "Dealing with the Threat of an Asteroid Striking the Earth," AIAA Position Paper, April 1990. The language of this point paper is interesting to analyze, because it embodies a choice of presentation that influences risk perception. For example, the use of familiar scenarios maximizes the comprehension of impact effects. By using scenarios, the extreme rarity of the event is removed from consideration. Furthermore, converting the extremely large distance into a short time span (six hours) increases the perception of risk. The same conditional argument is made with respect to a recent high altitude meteor burst: "...if (the detonation) had occurred at the same latitude a few hours earlier, the result could have been much worse. Had the explosion occurred over India or Pakistan, the resulting panic could have sparked a nuclear war." <http://news.bbc.co.uk/1/hi/sci/tech/2246449.stm>

¹⁰⁹ *Spaceguard Survey Report*, NASA, January 1992. The language was included in the NASA Multiyear Authorization Act of 1990 of the U.S. House of Representatives (26 September 1990).

¹¹⁰ The interception study is addressed in the section on "planetary defense" below.

¹¹¹ The name was taken from an NEO survey featured in the science fiction novel *Rendezvous With Rama* by Sir Arthur C. Clarke. The Spaceguard Survey Report addressed the impact hazard from a strictly technical perspective. There was one transitory reference to "false alarms" due to the position uncertainty of comets discovered with short warning, but no social implications of the proposed survey were considered.

¹¹² The 75 percent estimate took into account the Spaceguard Survey's relative ineffectiveness against LP comets.

on 24 March 1993. In a staggering coincidence, Comet Shoemaker-Levy 9 was discovered the same day.

A little over a year later (July 1994), Shoemaker-Levy 9 impacted Jupiter. Reflecting great public interest in the event, the Committee on Science, Space and Technology gave additional direction to NASA before the month was out: "Identify and catalog within 10 years the orbital characteristics of all comets and asteroids that are greater than 1 km in diameter and are in an orbit around the Sun that crosses the orbit of Earth."¹¹³

To respond to this new direction, NASA established an NEO Survey Working Group. The new working group provided its report to Congress in August 1995. The recommended program would accomplish the objective of discovering 60–70 percent of short-period NEOs larger than 1 km diameter within one decade, but would need 15 years for 90 percent completeness unless U.S. Air Force (USAF) and international programs contributed to the effort. Two dedicated telescopes were required, each with an aperture of two meters, in addition to the use of two existing telescopes with apertures near one meter. Half-time usage of a 3–4 meter class telescope was requested for characterization efforts. Over a decade, the revised survey would require a budget of \$41.5 million (presumably in FY96 dollars), not including USAF or international contributions which were left unquantified.¹¹⁴

In transmitting the report to Congress, however, NASA recommended against funding the new survey effort, given "NASA's severely limited resources."¹¹⁵

There matters stood; yet NEOs continued to be discovered, and in 1997 public alarm was raised about newly discovered asteroid 1997 XF11. The Minor Planet Center (MPC, the global astronomical community's clearinghouse for observational data on asteroids and comets) released an invalid assessment of a future close passage: a prediction that XF11 would pass significantly closer than 30,000 miles from Earth in 2028.¹¹⁶ Not long after this event, NASA began to appreciate the public reaction to NEO warnings and an NEO Program Office was established in 1998 at the Jet Propulsion Laboratory (JPL) in Pasadena, California.¹¹⁷ The charter of the NEO Program Office was to:

¹¹³ *Near-Earth Objects Survey Workgroup Report*, NASA, Solar System Exploration Division, Office of Space Science, June 1995. Note the restricted timeline relative to the proposed Spaceguard Survey, and also the inclusion of comets (no doubt as a result of the recent Jovian spectacular). As with the Spaceguard Survey Report, the social implications of delivering NEO impact warnings were not addressed. Both reports discussed the need for follow-up observations to reduce uncertainty in only a technical context.

¹¹⁴ As a point of reference, at this time, NASA was allocating about \$1 million annually for NEO searches; hence this represented a quadrupling (or more) of effort.

¹¹⁵ Letter from Jeff Lawrence, NASA Associate Administrator for Legislative Affairs, to Robert Walker, Chair of the House Science Committee, 9 August 1995.

¹¹⁶ Chapman, C., "The Asteroid/Comet Impact Hazard: Homo Sapiens as Dinosaur?," in *Prediction—Science, Decision Making, and the Future of Nature*, Sarewitz, D., et al., editors, Island Press, Washington, D.C., 2000, pp. 109–116. Although the initial prediction was erroneous, archival precovery data from seven years prior had the greatest effect in shrinking the error ellipse well away from the Earth. This set the pattern for the typical sequence of events: an initial warning is "retracted" as the error ellipse shrinks to exclude the Earth (i.e., the object falls off the "triangle of fear" depicted in Figure 2.22). The "retraction" is then seen by the press and public as evidence of the astronomers' incompetence. The case of XF11 is treated in more detail below.

¹¹⁷ As of 1999, the two most frequent NASA-related subjects of constituent mail to Congress (and corresponding requests to NASA for information) were the "Face on Mars" and the cosmic impact hazard. Dr. Carl Pilcher, Science Director, Solar System Exploration, Office of Space Science, NASA, address at the International Monitoring Programs for Asteroid and Comet Threat (IMPACT) conference, Turin, Italy, 1 June 1999. Also recall that the movies *Deep Impact* and *Armageddon* were released in 1998.

- Coordinate NASA-sponsored efforts to detect, track, and characterize potentially hazardous asteroids and comets that could approach Earth;
- Focus on the goal of locating at least 90 percent of the estimated 2,000 asteroids and comets that approach the Earth and are larger than about 2/3-mile (about 1 kilometer) in diameter, by the end of the next decade; and
- Be responsible for facilitating communications between the astronomical community and the public should any potentially hazardous objects be discovered as a result of the program.”¹¹⁸

It was also decided that NASA-funded astronomers would keep such discoveries to themselves for 48 hours until detailed orbit calculations could be made. NASA headquarters would then hold the news for another 24 hours before making any public announcement.¹¹⁹

In consonance with the goal set for the NEO Program Office, NASA formally told Congress that it was “committed to achieving the goal of detecting and cataloging 90 percent of NEOs larger than 1 km in diameter within 10 years, and to characterizing a sample of these objects.”¹²⁰

This is today commonly referred to as the Spaceguard Survey goal, although the ten-year time frame was a feature of the later NEO Survey Working Group. Exclusive of the vastly more expensive NEO space characterization missions, funding was raised from \$1–1.5 million per year to about \$3 million per year.¹²¹ While it may seem curious that the original Spaceguard Survey goal was now to be accomplished in 40 percent of the time with 10 percent of the funding, advances in CCD and computer technology and the support of the USAF were to make the task much easier.

The Rise of the “Planetary Defenders”

An NEO Interception Workshop was established in response to the second part of the Congressional direction of 1990. It was chaired by NASA but hosted by the Los Alamos National Laboratory (LANL) of the Department of Energy (DoE). While not proposing a specific program, the workshop cited the need for two types of research missions:

- Precursor reconnaissance/sampling missions; and

¹¹⁸ “NASA NEO Program Office,” NASA press release 98-123. The estimate of 2,000 asteroids and comets was later reduced; the current estimate of 1,000 is shown in Figure 2.11.

¹¹⁹ Hotz, R., “NASA Orders 72-Hour Secrecy On Asteroid Threats,” *Los Angeles Times*, 14 May 1998, p.1. This first effort at information management was immediately controversial, and highlighted the dilemma faced by the policymaker: release of warning data helps to ameliorate the threat (in this case, by enabling follow-up observations that in essentially all cases will quickly end the state of alarm). Release of warning data is also indicated to forestall the (perhaps unquantifiable) costs of social distrust of government. On the other hand, release of warning data increases the social costs of warning, however quantified.

¹²⁰ Statement of Dr. Carl Pilcher, Science Director, Solar System Exploration, Office of Space Science, NASA, before the Subcommittee on Space and Aeronautics, Committee on Science, Space and Technology, U.S. House of Representatives, 21 May 1998.

¹²¹ The NASA NEO Observation Program was funded at a level of about \$4 million for FY04. Statement of Lindley Johnson, Program Manager, NASA NEO Observation Program, before the Senate Subcommittee on Science, Technology and Space, Commerce Committee, U.S. Senate, 7 April 2004.

- Missions aimed at diverting or fragmenting an NEO of any size.¹²²

There was a lack of consensus, however, on the need for such tests in the absence of an actual threatened impact. In particular, the question of nuclear versus non-nuclear interception was a matter of significant debate.¹²³

Although the Congressional direction of July 1994 (following Shoemaker-Levy 9) included no mandate for interception studies, this did not prevent the organizing of a “Planetary Defense Conference.” This conference was held at Lawrence Livermore National Laboratory (LLNL) in 1995.¹²⁴ The participants were primarily scientists from DoE laboratories (LLNL, LANL, and Sandia), the military, and their contractors. The conference was notable for two shifts of emphasis since the NEO Interception Workshop:

- A focus was placed on smaller NEOs (100 meters in diameter) that impact more frequently but could still result in regional damage, in particular from tsunamis. The supposed frequency of such objects was phrased in terms that had more human relevance than the usual annualized probability: “a probability of a few percent in the next century of the arrival of a stony asteroid [of] a hundred meters in diameter.”¹²⁵ By hypothesizing short-warning scenarios, interception tests (in the absence of an actual threatening NEO being discovered) seemed more justifiable.
- The second shift of emphasis was to highlight non-nuclear means of NEO interception: in the words of the conference, “non-threatening technologies.” Given the backgrounds and allegiances of the participants, however, it is not clear how much this was simply an effort to avoid controversy.

In what would become typical for these mitigation conferences, different scenarios for NEO interception were addressed: long warning; short warning; and very short warning.

Military Involvement

The USAF has been the only military service with an interest in the cosmic impact hazard. This interest has been comprehensive, but not widely based, stemming largely from the efforts of enthusiastic officers in certain key positions.

By far the most significant effect of USAF involvement has been in the shared use of military telescope facilities normally used for detecting and tracking man-made objects in Earth orbit. Two of the four large NEO survey efforts (discussed below) use telescopes acquired and maintained by the USAF, elements of the Ground-Based Electro-Optical Deep

¹²² Statement of Dr. John D. G. Rather, Assistant Director for Space Technology (Program Development), NASA, before the Subcommittee on Space, Committee on Science, Space and Technology, U.S. House of Representatives, 24 March 1993.

¹²³ Canavan, G., *et al.*, editors, *Proceedings of the Near-Earth-Object Interception Workshop*, Los Alamos National Laboratories, Los Alamos, New Mexico, LA-12476-C, February 1993.

¹²⁴ There was also a “Space Protection of the Earth” conference held in Snezhinsk, Russia, in September 1994.

¹²⁵ Teller, E., “The Need For Experiments on Comets and Asteroids,” in *Proceedings of the Planetary Defense Workshop*, Lawrence Livermore National Laboratory, Livermore, California, 22-26 May 1995. Note that this estimate is inconsistent with Figures 2.11 and 2.14 and Table 2.5. The cited 100-meter object is too small and its frequency is too high. For the 300-meter object associated with tsunami effects, these figures and the table show a chance per century of 1/1000—an order of magnitude less than Dr. Teller’s assertion. In more recent presentations by NEO advocates, impact frequencies are sometimes stated in terms of a time frame “in your lifetime or that of your children”—all in an effort to magnify the human relevance of very small probabilities.

Space Surveillance (GEODSS) system and the Maui Space Surveillance System (MSSS). As of February 2002, the largest of these surveys (the Lincoln Laboratory NEA Research or "LINEAR" program) had accounted for 62 percent of all NEA discoveries. The other program using a military telescope has been responsible for another 11 percent (albeit also using a non-military telescope at Palomar).

The USAF maintains an interest in NEO characterization and mitigation, although sometimes that interest is subsumed into other military objectives—notably, those relating to space control and missile defense. There is no explicit military requirement to "defend the planet."

In 1994, the USAF launched *Clementine*, a spacecraft that imaged the Moon and would have proceeded to a flyby of the NEA Geographos but for a software malfunction. This mission used Ballistic Missile Defense Organization (BMDO) sensors and was intended to "flight-qualify 23 advanced lightweight technologies." The NEA target was chosen because it "tested the functions required for intercepting a missile in mid-course." *Clementine* was widely praised for its streamlined development and low costs (\$80 million).¹²⁶

In 1997, the USAF sought funding for *Clementine II*, a mission that would have explicitly tested the technologies for interception of asteroids, in the process sending projectiles into the NEA Toutatis and two other asteroids. Although Congress allocated \$30 million of FY98 funding for the project, it fell victim to a line-item veto from President Clinton on 14 October 1997.¹²⁷ In justifying this decision, the White House cited concerns over compliance with the Anti-Ballistic Missile (ABM) Treaty and noted that its architecture for National Missile Defense (NMD) did not include space-based weapons.¹²⁸ It was clear that the White House saw asteroid defense as a "stalking horse" used by missile defense proponents to advance their agenda.

International Involvement

From the earliest days, it was recognized that international involvement in any response to the cosmic impact hazard was desirable, if not essential. For one thing, the civilization-ending impactors chosen as the focus of the Spaceguard Survey goal made stakeholders of all humanity. Furthermore, the nature of NEO surveillance and tracking places a premium on widely dispersed observatories—as one observatory rotates on the surface of the Earth toward daylight and the Sun, another observatory on the other side of the planet is rotating into darkness. Also, there will be less susceptibility to bad weather with widely dispersed observatories.

International involvement in characterization is also seen as beneficial, but NEO interception programs (even test programs) may defy international consensus, especially if nuclear means are involved. "Planetary defense" objectives get caught up with military space control and missile defense concerns.

The following paragraphs describe actions taken by a selection of international organizations (and one nation) with regard to the cosmic impact hazard.

¹²⁶ Rustan, P., "Clementine: Measuring the results," *Aerospace America*, February 1995, pp. 34-38.

¹²⁷ In fact, the Clementine Asteroid Intercept Technology Demonstration was one of the first two programs to ever suffer a line-item veto. The program was a Congressional add-on, *i.e.*, not in the President's budget.

¹²⁸ Raines, F., OMB Director, White House press briefing on the line-item veto, 14 October 1997, and Jaroff, L., "Dreadful Sorry, Clementine: Washington brushes off the asteroid threat," *Time Magazine*, 27 October 1997.

International Astronomical Union. In 1991, the International Astronomical Union (IAU) appointed an NEO working group (WGNEO) to coordinate international studies of NEOs and develop suitable strategies for detection, follow-up, and orbit prediction. This action was cited as evidence of “international sanction” in the Spaceguard Survey Report. In July 1998, in the wake of the XF11 affair, the IAU Executive Committee issued a policy statement on NEO research, charging the WGNEO with “draft[ing] a set of recommended procedures to be followed in case minor planets and comets are discovered that lead to predictions by the MPC of potential impacts.”¹²⁹

United Nations. The United Nations (U.N.) held an International Conference on NEOs in New York City in April 1995.¹³⁰ In July 1999, the Third United Nations Conference On The Exploration and Peaceful Uses of Outer Space (UNISPACE III) issued a “Vienna Declaration” that included the phrase “cooperative activities are called for, including consideration of a common strategy related to near-Earth objects.”¹³¹

Council of Europe and the Spaceguard Foundation. In 1996, the Parliamentary Assembly of the Council of Europe issued Resolution 1080 “on the detection of asteroids and comets potentially dangerous to humankind.” The resolution called for establishment of an “inventory of NEOs as complete as possible with an emphasis on objects larger than 0.5 km in size.” The resolution also called for “setting-up and development” of an international non-governmental organization (INGO), the Spaceguard Foundation.¹³²

United Kingdom. The U.K. Parliamentary Office of Science and Technology (POST) issued Report No. 126, “NEOs,” in April 1999. A “Task Force on Potentially Hazardous NEOs” was established, issuing its report in September 2000. As a consequence, the U.K. government funded the creation of an “NEO Information Centre,” to the disappointment of some NEO advocates who wanted a more active role for the U.K. in actual search programs.¹³³

Discoveries

The discussion will now address the consequence of society’s response to the impact hazard: the generation of NEO discoveries, and the coincident generation of warnings and alarms.

¹²⁹“Policy Statement on Near-Earth Object Research,” IAU Executive Committee, 4 July 1998. A review of the IAU’s current position on NEO research can be found at www.iau.org/IAU/FAQ/neo.html. The “recommended procedures to be followed” that were formulated by the WGNEO are discussed below, and can also be found at <http://web.mit.edu/rpb/wgneo/TechComm.html>.

¹³⁰ “Report of the Committee on the Peaceful Uses of Outer Space,” U.N. General Assembly, Official Records—Fiftieth Session, Supplement Number 20, A/50/20, 15 September 1995, p.11.

¹³¹ www.oosa.unvienna.org/unisp-3/pressrel/e30pm.htm. No matter how passing the reference or inconsequential the effect, such affirmations are naturally of great value to outsider stakeholder groups in advancing their agendas. Sometimes it is less a matter of sanction than of unctio.

¹³² The Spaceguard Foundation, headquartered in Italy with affiliates in several other countries, has no connection with the NASA Spaceguard Survey, other than a sharing of general objectives. It is a “private organization that groups observers, both professional and amateur, as well as people and organizations with no particular astronomical background who want to contribute to the activity of the Foundation.” (<http://spaceguard.rm.iasf.cnr.it/>)

¹³³ www.near-earth-objects.co.uk Although the establishment of an “information centre” seemed like a weak response to the impact hazard in the minds of many NEO advocates, it is worth noting that it reflects an implicit valuation by the UK government. Specifically, it can be inferred that the government considers the social consequences of NEO data to have a relatively high valuation compared with the expected losses from actual impacts. Recall that NASA established the NEO Program Office at JPL only in response to the social consequences of NEO data (*i.e.*, the XF11 alarm).

Table 2.8 lists the four major NEO survey programs that are in operation today. These surveys are all based on CCD technology. Two smaller programs, the Catalina Sky Survey (CSS) and Bisei Spaceguard in Japan, are more recent and have yet to hit their stride.¹³⁴

Figures 2.23 and 2.24 show sky coverage of the four survey programs of Table 2.8 during a sample period (18 May 2003 through 17 June 2003).¹³⁵ Figure 2.23 shows that the survey effort is essentially all-sky (within limits established by solar elongation and the lack of an observatory in the Southern Hemisphere). However, Figure 2.24 shows that at higher limiting visual magnitudes, only the Spacewatch program had coverage, and that was very spotty (in this time period, at least). Referring back to Figures 2.15 and 2.16, the bulk of the survey effort is only reaching out to the orbit of Mars (0.5 AU) at opposition; Spacewatch is reaching into the asteroid belt (1.5 AU) at opposition.

Figure 2.25 shows the celestial distribution of NEAs at time of discovery.¹³⁶ Note that smaller NEAs are preferentially discovered close to opposition.

Considered together, Figure 2.17 and Figures 2.23 through 2.25 show that there is much room for higher detection rates, especially for smaller NEOs (under one kilometer in diameter). More powerful telescopes can increase deep survey coverage at opposition, and can find many more of the smaller objects away from opposition.

The left panel of Figure 2.26 shows NEA discovery totals as of November 2003, for all NEAs and for "large" NEAs (greater than one kilometer in diameter). Roughly halfway through the Spaceguard Survey, it appears that over half of the estimated population of one-kilometer NEAs has been discovered. As the population gets fully sampled, the discovery rate for these large NEAs will naturally diminish. The discovery rate for smaller NEAs is exponential, however, as predicted by the right panel of Figure 2.26, which shows the results of a survey simulation for five different limiting visual magnitudes.¹³⁷

Table 2.8
Major NEO surveys

Survey		Year started	Aperture (meters)	V_{lim}
Spacewatch (University of Arizona)		1980	0.9, 1.8	21.7, 22.6
NEA Tracking (Maui & Palomar)	NEAT	1995	1.2, 1.2	19.5, 21.0
Lowell NEO Survey (Arizona)	LONEOS	1998	0.6	19.3
Lincoln Laboratory NEA Research (New Mexico)	LINEAR	1996	1.0, 1.0	19.2, 19.2

¹³⁴ Together, CSS and Bisei have accounted for 3 percent of the NEAs detected through February 2002. Stokes, G., *et al.*, "Near-Earth Asteroid Search Programs," in *Asteroids III*, Bottke *et al.*, editors, University of Arizona Press, Tucson, 2002, pp. 49-51.

¹³⁵ <http://scully.harvard.edu/~cgi/SkyCoverage.html>

¹³⁶ From "Near-Earth Asteroid Search Programs" by G. Stokes *et al.*, in *Asteroids III*, edited by W.F. Bottke Jr., A. Cellino, P. Paolicchi, and R. P. Binzel, p.52, © 2002 The Arizona Board of Regents. Reprinted by permission of the University of Arizona Press.

¹³⁷ From "Earth-Crossing Asteroids and Comets: Groundbased Search Strategies" by E. Bowell and K. Muinonen in *Hazards Due To Comets and Asteroids*, edited by T. Gehrels, p.171, © 1994 The Arizona Board of Regents. Reprinted by permission of the University of Arizona Press.

The right panel of Figure 2.26 does not consider technology advances within the period of the survey.

Figure 2.23
Major survey sky coverage, $V=18$

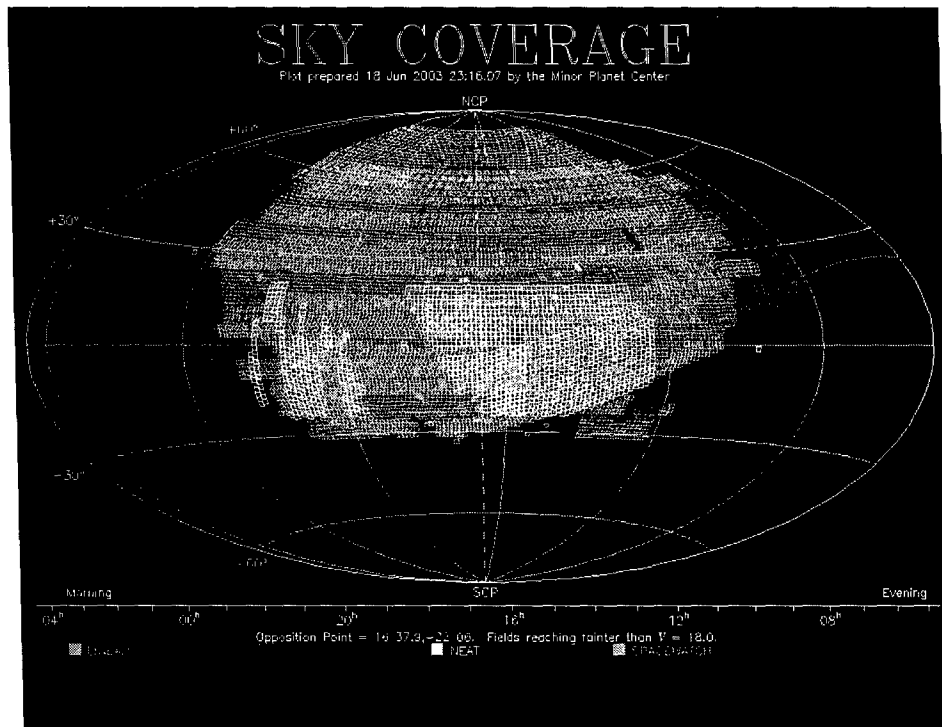


Figure 2.24
Major survey sky coverage, $V=21$

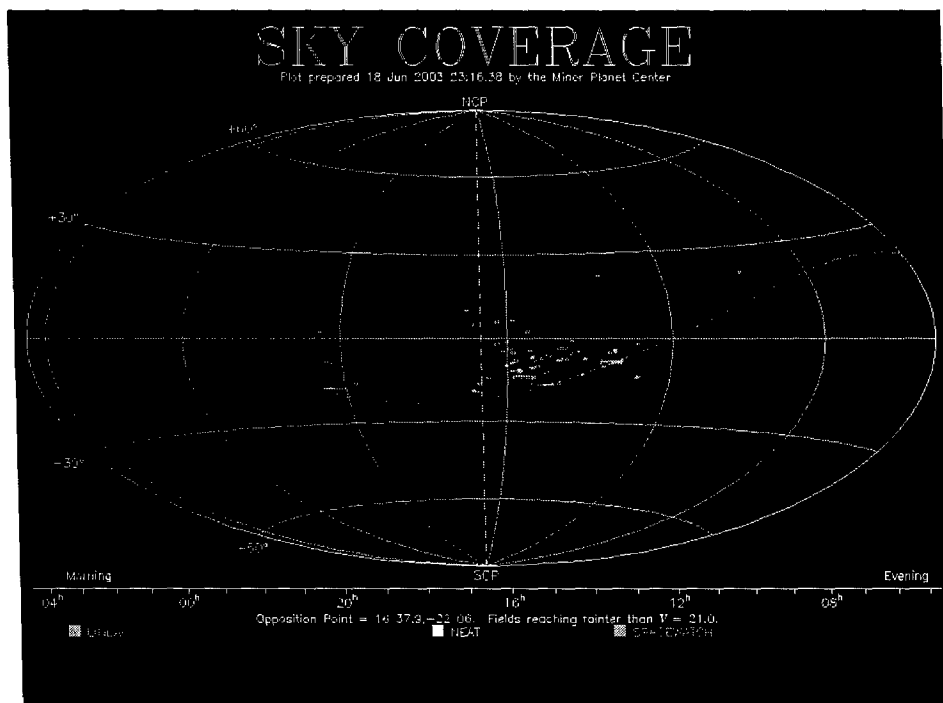


Figure 2.25
Spatial distribution of NEA discoveries

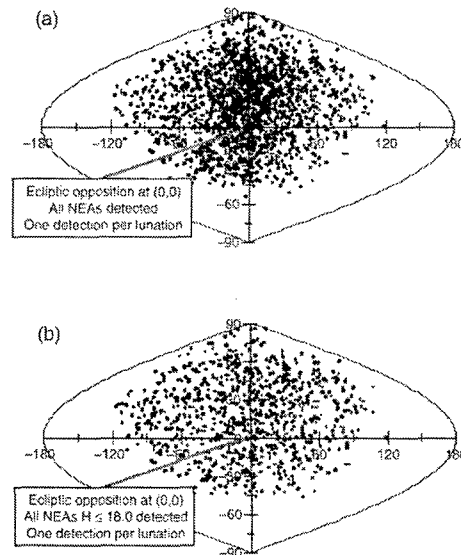
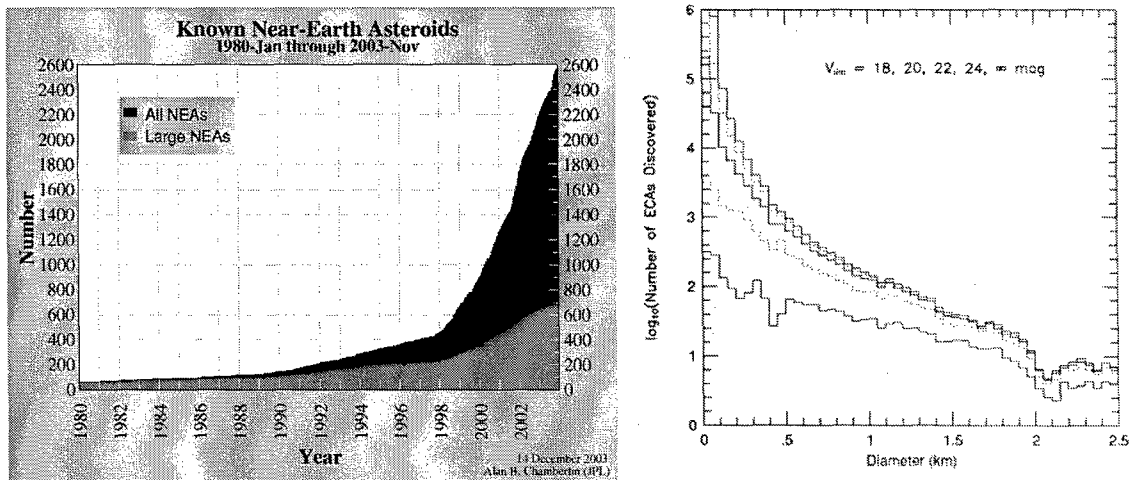


Figure 2.26
Actual vs. theoretical discovery rates



The purpose of this discussion is to show the consequences (in terms of discovery rates) of either technological advances or simple increases of effort that may result from expanding the Spaceguard Survey to smaller objects. The consequences for warning rates are less clear, since that question depends on the means of follow-up observation and the warning threshold, however defined.

Warnings and Alarms

The procedure currently employed by the astronomical community is to issue a warning whenever a threshold impact probability is reached. The IAU WGNEO adopted as a threshold “the prediction of impacts with probability larger than one in a million (10^{-6}) in the near future (less than 100 years).”¹³⁸ In practice, the IAU leaves any decision about public release of a warning to the discoverer of the threat. Finally, as noted previously, it must be recognized that social alarms may well occur whether or not a “confirmed warning” is ever issued.¹³⁹

Table 2.9 lists five “cosmic alarms,” beginning with the case of Comet Halley discussed at the beginning of this chapter. 1989 FC is the “near miss” that occasioned the AIAA position paper that eventually resulted in the Spaceguard Survey. The case of 1997 XF11 will be examined in more detail as it is a good example of the evolution of uncertainty first raised in the discussion of Figures 2.18 and 2.19.

Figure 2.27 shows the orbit of 1997 XF11, with a collision possibility at the object’s descending node (coincident with the Earth’s orbital radius).¹⁴⁰

Figure 2.28 shows the uncertainty ellipse in the Earth target plane for a close passage on 26 October 2028, on the left with an 88-day arc of observation, on the right with archival precovery extending the arc of observation back to 1990. Note that the Earth was never in the uncertainty ellipse; that is, the MOID was always non-zero.

The left side of Figure 2.29 shows a close-up of the Monte Carlo points that populate the uncertainty ellipse. An object that passes through the “keyhole” will have a close encounter with the Earth at a future date—in the case of XF11, about 12 years later. The new uncertainty ellipse has a zero MOID, since it passes through the Earth. In this case, the impact probability becomes a compound of the probability of the object passing through the “keyhole” and the probability that the secondary error ellipse will shrink onto the Earth.

The 1997 XF11 alarm listed in Table 2.9 was based on an erroneous prediction that the NEA would pass “significantly closer than 30,000 mi. in 2028.” However, the 1999 AN10 alarm was based on the innocent publication on a web page of an impact scenario that

Table 2.9
Comet and asteroid alarms through 1999

Object	Alarm	Date of alarm
Comet Halley	Cyanide poisoning of Earth	1910
1989 FC (Asclepius)	Unseen “near miss” (427,289 mi.)	1989
Comet Swift-Tuttle	Impact chance 1/10,000 in 2126	1992
1997 XF11	Significantly closer than 30,000 mi. in 2028	1997
1999 AN10	Impact chance one in a billion in 2039	1999

¹³⁸ Morrison, D., *et al.*, “Dealing With the Impact Hazard,” in *Asteroids III*, Bottke *et al.*, editors, University of Arizona Press, Tucson, 2002, p. 749.

¹³⁹ For the benefit of observers who conduct follow-up, web pages are maintained that list “Earth Impact Possibilities” for objects that have a “non-zero probability of collision.” In this manner, an alarm could be generated without a causative “warning.” See the NeoDys “risk page,” <http://newton.dm.unipi.it/cgi-bin/neodys/neoibo?riskpage=0;main>.

¹⁴⁰ Figures 2.27 through 2.29 are taken from Chodas, P., and Yeomans, D., “Predicting Close Approaches and Estimating Impact Probabilities for Near-Earth Objects,” AAS/AIAA Astrodynamics Specialist Conference, AAS 99-462, Girdwood, Alaska, 16-19 August 1999.

Figure 2.27
Orbit of 1997 XF11

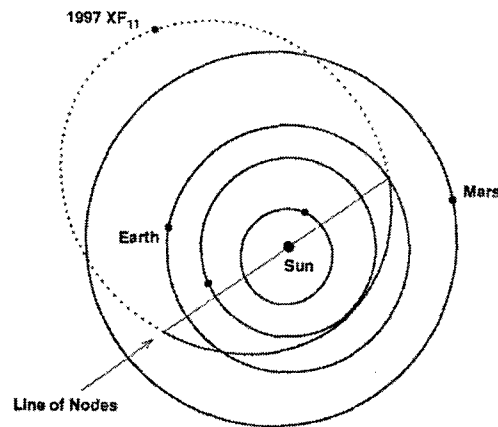
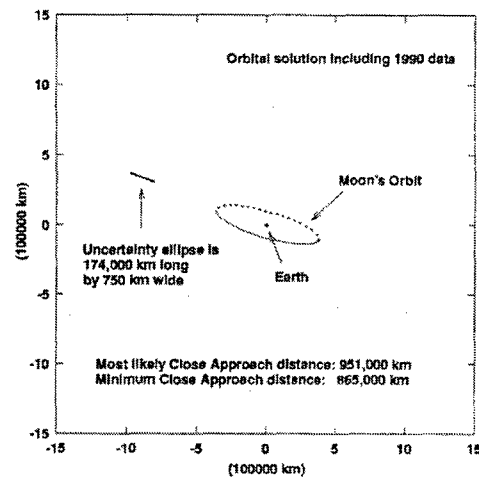


Figure 2.28
Uncertainty ellipse for 1997 XF11 in 26 October 2028 target plane



required the NEA to pass through two consecutive keyholes—hence the miniscule “one in a billion” possibility. Nevertheless, the moderator of an Internet NEO discussion forum discovered the web page, charged “cover-up,” and sparked an ensuing media frenzy.¹⁴¹

The lesson is that the most arcane details of orbital analysis and the most extremely remote impact possibilities can result in wild headlines, whatever the astronomical community (or policymakers) have adopted as a “warning threshold.”

¹⁴¹ Chapman, C., “The Asteroid/Comet Impact Hazard: Homo Sapiens as Dinosaur?,” in *Prediction—Science, Decision Making, and the Future of Nature*, Sarewitz, D., et al., editors, Island Press, Washington, D.C., 2000, pp. 116-117.

Figure 2.29
Keyhole in 2028 target plane to 2040 target plane

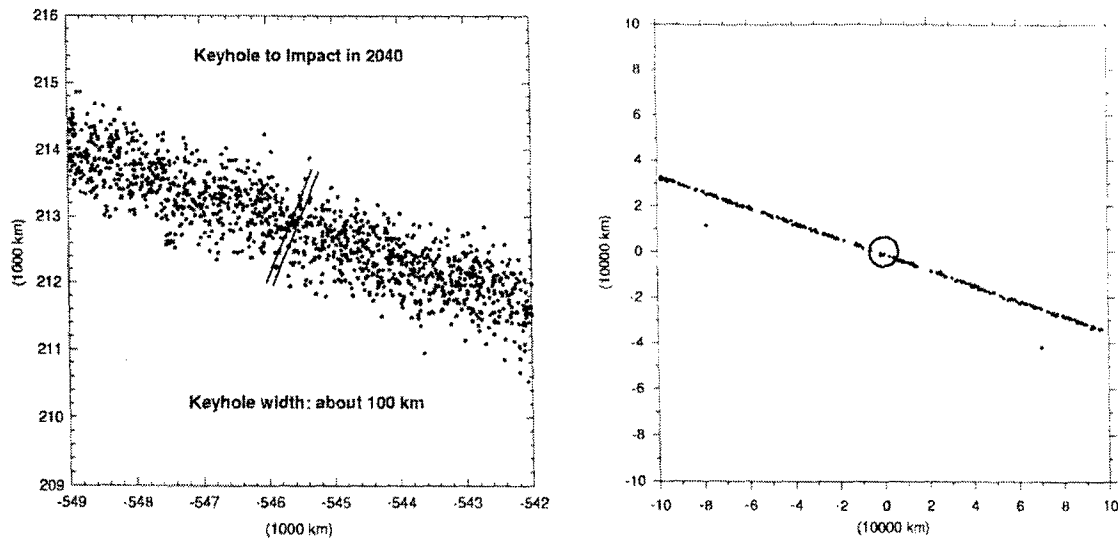


Figure 2.31 lists news headlines for the period 2000 to 2002 generated by specific NEAs. Some interesting facts emerge. As one might expect, the tabloid press is well represented. However, so are more respectable outlets like the BBC News (responsible for the egregious headline “Space Rock ‘On Collision Course’,” remarkably similar to the “Killer Asteroid Headed for Earth” headline of Figure 2.30 below).¹⁴²

It is apparent that there are two general sources for alarm (not including those alarms that may be self-generated by the news media), as follows:

- A statement of impact probability (or impact certainty, in the case of BBC News); and
- A “near miss,” especially a near miss that was not observed or that came from a “blind spot” (usually referring to an approach from the direction of the Sun).

Figure 2.32 shows how an asteroid alert can get top billing, even if only on an Internet web site such as the Drudge Report (this example is from 20 June 2002, representing the case of asteroid 2002 MN).

Finally, Figure 2.33 shows that the increasing scientific and social legitimacy of asteroid warnings has not eliminated the “giggle factor” first raised as a deterrent to policy action in Chapter One. This illustration accompanied a satiric article titled “Scientists to study giant asteroids by steering them into Earth—Are major asteroids as dangerous as predicted? The answer comes in 2003.”¹⁴³

¹⁴² Nothing better illustrates the chasm that can exist between the narrow interests of the media and the welfare of society than the following: this alarmist BBC News article won the 2003 European Online Journalism award for the “best news story broken on the net.” <http://news.bbc.co.uk/1/hi/technology/3042910.stm>

¹⁴³ www.satirewire.com/news/jan02/asteroid.shtml, prompted by the “near miss” of asteroid 2001 YB5.

Figure 2.30
Tabloid asteroid¹⁴⁴



Figure 2.31
Asteroid alarms, 2000–2002

NEA: 2000 SG344

- "Asteroid Threatens Major Impact With Earth" (Sydney Morning Herald, 6 November 2000)
- "Sept 21, 2030: 500/1 It's The End Of The World" (Mirror, 6 November 2000)
- "Asteroid On Collision With Earth" (Sky News, 7 November 2000)
- "Experts Predict Asteroid Coming in 2030" (Australian Broadcasting Corporation, 7 November 2000)
- "Asteroid Due For Close Encounter In 2030" (Irish Times, 6 November 2000)
- "Alert Over Asteroid Threat" (Daily Express, 6 November 2000)
- "Whew! Asteroid Collision Delayed 41 Years, To 2071—New Calculations Show Astronomers Were Wrong Again On First Prediction" (Seattle Post Intelligencer, 7 November 2000)

NEA: 2001 PM9

- "Asteroid No Threat, Despite Rumors of Earth Impact" (Space.com, 23 August 2001)

NEA: 2001 YB5

- "Space Rock Hurtles Past Earth" (BBC News, 7 January 2002)
- "Asteroid Near Miss For Earth" (Ananova.com, 7 January 2002)
- "Earth Escapes Brush With Killer Asteroid" (CNN, 7 January 2002)
- "Asteroid Misses Earth By 4 hours" (New Zealand Herald, 9 January 2002)
- "Asteroid Big Enough To Raze France Zips By Earth" (Seattle Times, 9 January 2002)

¹⁴⁴ "Killer Asteroid Headed for Earth!," *Weekly World News*, 22 March 2004, p.1.

Figure 2.31 (continued)

NEA: 2002 EM7

"Whew! Stealth Asteroid Nearly Blindsides Earth" (CNN, 19 March 2002)
 "Asteroid Buzzes Earth From "Blind Spot" (New Scientist, 15 March 2002)
 "Close Call Asteroid Causes More Worries" (Sky & Telescope, 21 March 2002)

NEA: 1950 DA

"Asteroid Could Hit Earth in 2880" (BBC News, 5 April 2002)
 "Asteroid On Possible Collision Course, in 900 Years" (CNN, 5 April 2002)
 "There's a Rock Headed Our Way" (Space Daily, 5 April 2002)

NEA: 2002 MN

"A Close Asteroid Flyby" (Sky & Telescope, 19 June 2002)
 "Space Rock's Close Approach" (BBC News, 20 June 2002)
 "Earth Has 'Close Shave' From Large Asteroid" (Daily Telegraph, 21 June 2002)

NEA: 2002 NT7

"Space Rock 'On Collision Course' (BBC News, 24 July 2002)
 "Asteroid Could Wipe Out a Continent in 2019," (Ananova.com, 24 July 2002)
 "NASA Dismisses Asteroid Collision Claim," (Guardian, 24 July 2002)
 "Mile-Wide Asteroid Heading Towards Earth Poses Greatest Threat Yet, Scientists Warn" (Independent, 25 July 2002)
 "Asteroid Could Mean End Of Life As We Know It...But It's 60,000 To One" (Guardian, 25 July 2002)
 "The World Ends On February 1, 2019 (Possibly)" (Daily Telegraph, 25 July 2002)
 "The Armageddon Asteroid Is Coming" (Mirror, 25 July 2002)
 "Astronomers Warn Of Possible Hit By New-Found Asteroid" (Christian Science Monitor, 26 July 2002)
 "Slim Chance Of Asteroid Collision With Earth In 2019: Astronomers" (Xinhua, 26 July 2002)
 "Caveat Impactor—An Asteroid With Almost No Chance Of Hitting Earth Made Big Headlines This Week" (NASA Science News, 26 July 2002)

Figure 2.32
 2002 MN and the Internet

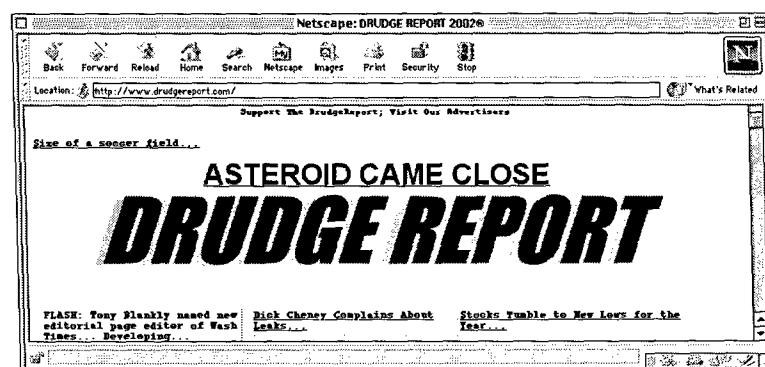
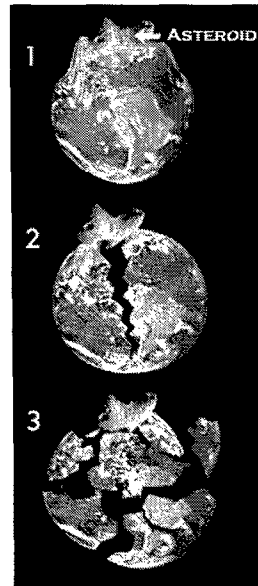


Figure 2.33
"Giggle factor" in satiric article



Warning Scales

In 1999, the IAU WGNEO attempted to address the emerging difficulties of public communication by adopting an NEO hazard warning scale. This "Torino scale" is depicted in Figure 2.34.¹⁴⁵ At the time, some scientists opined that the scale was of little use, since a lifetime could go by before any objects progressed beyond level one. That, however, was the point of the scale: to put impact probabilities in proper context in the public mind.

The Torino scale was intended for public consumption. However, it lacks any embodiment of the warning horizon (time to impact). Consequently, it is of little value as a tool for prioritizing discoveries for observational follow-up. Accordingly, a new scale was developed for the use of astronomers: the Palermo scale, where a positive value represents an impact threat above the background level (the threat represented by an unknown and undetected object colliding with the Earth).¹⁴⁶

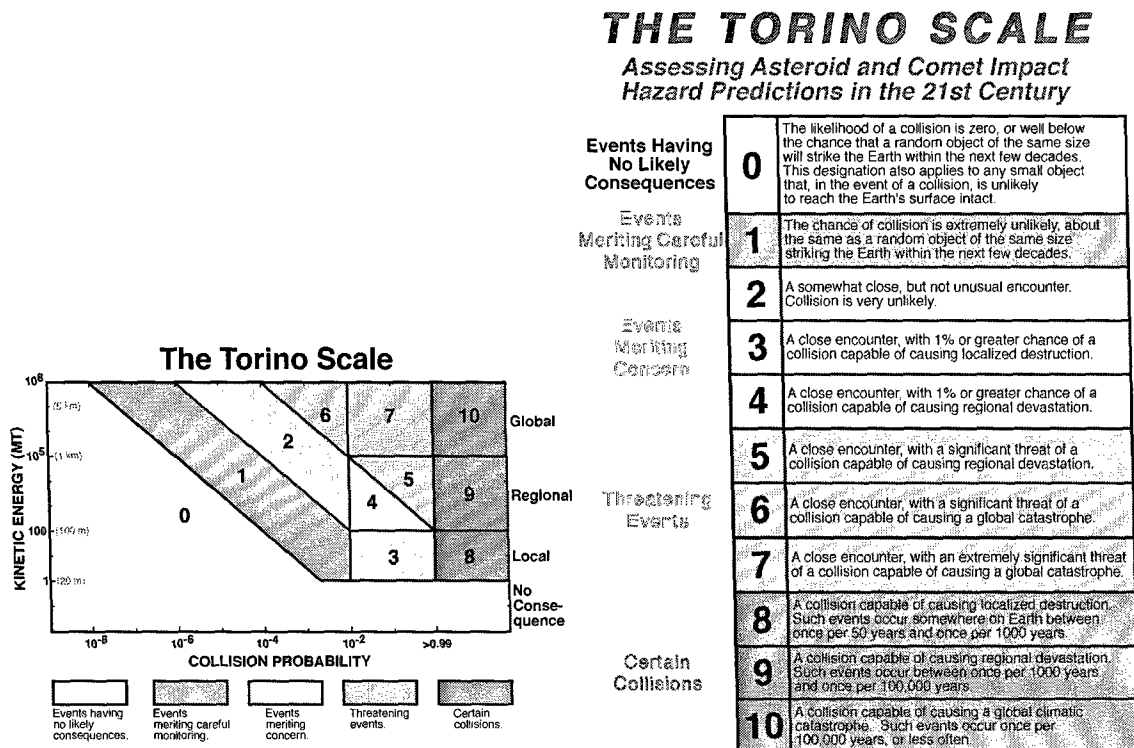
Very soon, the predictable happened: an object was detected (2002 NT7 in Figure 2.31) that was assigned a positive Palermo value and that fact was trumpeted by an Internet NEO enthusiast web site.¹⁴⁷ The media frenzy was accelerated by the misuse of a scale intended for the use of astronomers. Of course, the same object rated only a "one" on the Torino scale—but that would not have sold as many newspapers.

¹⁴⁵ <http://128.102.32.13/impact/torino.cfm>

¹⁴⁶ Chesley, S., *et al.*, "Quantifying the risk posed by potential Earth impacts," *Icarus*, Volume 159, Number 2, October 2002, pp. 423-432.

¹⁴⁷ <http://abob.libs.uga.edu/bobk/cc072302.html> "First ever positive Palermo scale" is more impressive when the reader is unaware that the scale was only recently developed.

Figure 2.34
Torino scale



In concert with the development of the Torino and Palermo warning scales, the IAU WGNEO established a voluntary procedure for technical review of NEO impact warnings, and suggested its use for objects assigned a positive Palermo scale value. The procedure specified that:

In most cases, such events will fall at a value of 1 or higher on the 0–10 point Torino Scale, a scale intended for public communication of impact hazard risks. Information leading to an impact prediction...should be transmitted for confidential review to the chair of the [IAU WGNEO], the President of IAU Division III, the General Secretary of the IAU, and the members of the NEO Technical Review Team (see below), before any announcement and/or written document on the subject be made public via any potentially nonprivate communication medium, including the World Wide Web. The individual members of the NEO Technical Review Committee shall review the work for technical accuracy and shall communicate under most circumstances within 72 hours the results of their reviews to the chair of the WGNEO and directly to the authors of the report or manuscript.¹⁴⁸

In practice, however, the peer review intended by the IAU technical review procedure is becoming redundant due to the automation of NEO impact hazard predictions. There are two independent systems that have been consistently in close agreement:¹⁴⁹

¹⁴⁸ <http://web.mit.edu/rpb/wgneo/TechComm.html>

¹⁴⁹ See <http://newton.dm.unipi.it/cgi-bin/neodys/neoibo> and <http://neo.jpl.nasa.gov/risk/doc/sentry.html> for NEOdys and Sentry, respectively.

- NEO Dynamic Site (NEODys) – operated by the University of Pisa in Italy; and
- Sentry – operated by JPL.

Finally, it is worth noting that as the pace of NEO discovery increases (particularly if a new, more-challenging post-Spaceguard Survey goal is adopted), the Torino scale will likely remain the primary tool for communicating impact risk to the public. The NEO community may then find objects “climbing the scale” and generating alarms much more frequently than ever envisioned at the time of the Torino scale’s creation.

The preceding sections have discussed two aspects of society’s response to the impact hazard. The genesis, conduct, and outcomes of NEO surveys have been covered in detail. Attempts to initiate mitigation programs were exemplified by the several “planetary defense” conferences and the stillborn *Clementine II* program. Yet to be discussed is characterization, which to date has not been a response to the impact hazard, but has instead been driven by basic space science objectives.

Characterization Missions

Table 2.10 lists space science missions to comets and asteroids—some of the bodies are NEOs and some are not.¹⁵⁰ The primary purpose of these missions has been to accumulate basic scientific knowledge. However, this knowledge provides useful data for future mitigation efforts if ever needed. Furthermore, it can help quantify the supposed benefits of asteroidal and cometary resource exploitation (that is, the extraction of water and minerals from comets and asteroids). Such “mining” of these objects has been proposed as a way to facilitate future human exploration of the Solar System.¹⁵¹

Table 2.10
Comet and asteroid characterization missions

Mission	Target	Date at target
International Cometary Explorer (NASA)	Comet Giacobini-Zinner	1985
	Comet Halley	1986
Suisei & Sakigake (Japan)	Comet Halley	1986
Vega 1 & 2 (USSR)	Comet Halley	1986
Giotto (ESA)	Comet Halley	1986
	Comet Grigg-Skjellerup	1992
Galileo (NASA)	Gaspra, Ida	1991
NEAR Shoemaker (NASA)	Mathilde, Eros	1997, 2000
Deep Space 1 (NASA)	Comet Borrelly	2001
Stardust (NASA)	Comet Wild-2	2004
Deep Impact (NASA)	Comet Tempel 1	2005
Hayabusa (Japan)	1998 SF36	2005
Rosetta (ESA)	Steins, Lutetia, Comet Cheryumov-Gerasimenko	2008, 2010 2014
Dawn (NASA)	Vesta, Ceres	2010, 2014

¹⁵⁰ Failed missions are not listed.

¹⁵¹ Lewis, J., *Mining the Sky*, Addison-Wesley Publishing Company, New York, 1996. Advocates for space resource exploitation hail from the space science and engineering communities, and they focus on technical aspects of resource extraction rather than economic feasibility.

It is far more expensive to fly space probes than to conduct NEO surveys, of course. Each mission usually consumes hundreds of millions of dollars of funding, but the acquisition of scientific knowledge is considered ample justification for that expenditure.

It is worth noting that ground-based NEO survey and characterization efforts assist in the planning and execution of these space missions: orbits, gross composition, spin state, and even shapes of target bodies can be determined from the ground by optical and radar means. This confluence of purpose is assisted by the fact that the space scientists involved in the missions are often active in the NEO community.

Technological and Social Trends

A number of trends will affect the nature and scope of society's response to the impact hazard in the future. Internal to the NEO community, there is a realization that the Spaceguard Survey goal will be met, if not within the allotted ten years, then shortly thereafter. Two related imperatives are commonly voiced: one to extend the survey efforts to ever-smaller objects (sub-kilometer, in the extreme down to Tunguska-sized impactors of 60 meters in diameter); the other to begin interception experiments.¹⁵² These potential new goals are now being proposed in the context of a likely more risk-averse society, stemming from the terrorist attacks of 11 September 2001.¹⁵³

Although the Spaceguard Survey goal addressed NEOs of one kilometer in diameter or larger, there were early references to a possibly lower size threshold. As previously noted, the advocates of NEO interception were concerned with objects down to a size of 100 meters.¹⁵⁴ In 1996, the Parliamentary Assembly of the Council of Europe called for establishment of an inventory of NEOs as complete as possible with an emphasis on objects larger than 500 meters in size. More recently, the U.K. Task Force on Potentially Hazardous NEOs (2000) recommended a survey of "substantially smaller objects than those now systematically observed by other telescopes."¹⁵⁵ It also stated "the aim should be to measure over the coming years the orbits of all objects down to diameters of 300 meters, by the use of larger telescopes than those currently employed."¹⁵⁶

In 2001, the Space Studies Board of the U.S. National Research Council (NRC) issued a report titled *Astronomy and Astrophysics in the New Millennium*. This report called for a Large-aperture Synoptic Survey Telescope (LSST), a primary purpose of which was to "detect 90 percent of the near-Earth objects larger than 300 m[eters] in diameter within a decade," and producing "a terabyte of data per night, all of which will be accessible to scientists and the public alike through the National Virtual Observatory."¹⁵⁷

¹⁵² These are related in the sense that interception (and deflection or disruption) of smaller NEOs is comparatively easier. This was a factor in the shift of emphasis of the 1995 LLNL Planetary Defense Conference to such small bodies.

¹⁵³ The risk aversion of society to rare events (such as large terrorist attacks) is very pertinent to this discussion, and will be addressed further in Chapter Five.

¹⁵⁴ Teller, E., "The Need For Experiments on Comets and Asteroids," in *Proceedings of the Planetary Defense Workshop*, Lawrence Livermore National Laboratory, Livermore, California, 22-26 May 1995.

¹⁵⁵ *Report of the Task Force on Potentially Hazardous Near Earth Objects*, (Recommendation 1), Information Unit, British National Space Centre, London, September 2000, p.7.

¹⁵⁶ *Report of the Task Force on Potentially Hazardous Near Earth Objects*, Information Unit, British National Space Centre, London, September 2000, pp. 20-21.

¹⁵⁷ *Astronomy and Astrophysics in the New Millennium*, Astronomy and Astrophysics Survey Committee, Board on Physics and Astronomy, Space Studies Board, Commission on Physical Sciences, Mathematics, and Applications, National Research

In July 2002, the Space Studies Board issued a report titled *New Frontiers in the Solar System—An Integrated Exploration Strategy*. In this report, the Board recommended “that dedicated and powerful ground-based facilities for the detection and physical study of near-Earth objects be implemented, together with the data handling and analysis capabilities that large-scale surveys will require.”¹⁵⁸ It also stated that “Assessment of the NEO population down to 300-meter scales...is recognized as a high priority for NASA’s solar system exploration program.”¹⁵⁹

On 3 October 2002, the Committee on Science of the U.S. House of Representatives held a hearing on “The Threat of Near-Earth Asteroids.” The hearing “explored the question of next steps beyond this [Spaceguard] survey goal, including the costs, benefits, and technical challenges of extending the survey to include smaller, yet potentially very hazardous, objects.” All but one of the witnesses testifying before the Committee supported such an expansion of NEO survey efforts, the two NRC reports were cited as justification, and the proposed LSST was endorsed. The exception was Dr. Edward Weiler, the Associate Administrator for Space Science at NASA Headquarters, who stated:

I feel that it is premature to consider an extension of our current national program to include a complete search for smaller-sized NEOs...

Two groups that wish to build large survey systems have argued that the search goal should extend to 300 m[eters]. NASA has at least two concerns with this proposition. First, we do not possess a non-advocate trade study to tell us how best to do such a search...

Second, why 300 m[eters]? The present limiting diameter of 1 km was the product of a broad public discussion. When we have another broad public discussion, the answer could be: “Leave the present limiting diameter as it stands”...

Within the Office of Space Science, the Solar System Exploration Division Director has appointed a small Science Definition Team (SDT) to consider the technical issues related to extending the search for NEOs to smaller sizes. The goal of the SDT is to evaluate what is technologically possible today. The scope of the SDT does not include consideration of any change to our present NEO search goal.¹⁶⁰

After the hearings, the National Optical Astronomy Observatories (NOAO), attempted to buttress the case of the NEO survey advocates, strongly supporting an expanded NEO survey in a statement provided to the Science Committee.¹⁶¹

Council, 2001, pp. 38-39. LSST would be a large telescope (8.4 meters of aperture), with a wide field of view, vastly more powerful than existing NEO survey instruments (www.lsst.org). LSST costs are estimated at \$125 million for acquisition and five years of operation (Cornell University press release, 3 October 2002). Another proposed high-performance survey telescope is the Panoramic Survey Telescope & Rapid Response System (Pan-STARRS), and its use in expanded NEO surveys is discussed at <http://pan-starrs.ifa.hawaii.edu/public/asteroids/near-earth.html>. The National Virtual Observatory is a U.S. program to place astronomical databases on the Internet (www.us-vo.org/). As a consequence, professionals, amateurs, and the casually interested may one day be poring through LSST data all looking for Earth-threatening NEOs in the same way that amateur comet-hunters scan data on the SOHO web page (<http://ares.nrl.navy.mil/sungazer/>).

¹⁵⁸ *New Frontiers in the Solar System—An Integrated Exploration Strategy*, Solar System Exploration Survey, Space Studies Board, National Research Council, 9 July 2002, p.35.

¹⁵⁹ *Ibid*, p.340.

¹⁶⁰ Hearing on “The Threat of Near-Earth Asteroids,” Committee on Science, U.S. House of Representatives, 3 October 2002.

¹⁶¹ “The Hazard Presented By Small Asteroids and Strategies For Detecting Them,” NOAO, October 2002.

The advocacy for survey expansion continued into 2003. An example is an article published in the “Policy Forum” section of the journal *Science*, in which it was stated:

In my opinion, the scientific community should take upon itself the duty to investigate the NEO population at the level of knowledge necessary to identify all possible impactors, down to the size compatible with available technology and with the public perception of acceptable risk. In the next decade, this should go well beyond the Spaceguard goal, with the help of sky surveys by large telescopes now being developed.¹⁶²

It is notable that all of these reports, articles, and hearings failed to consider the NEO impact hazard in its social context, as a problem where technical capabilities are only an input to the solution, and in fact may themselves cause other social problems.¹⁶³ In this sense, nothing has changed since the days of the Spaceguard Survey Report.

This agitation for an expanded NEO survey has been accompanied by a renewed focus on mitigation capabilities (primarily addressing NEO interception, and deflection or disruption). In essence, the arguments of the LLNL Planetary Defense Conference of 1995 are being dusted off, hopefully to a more receptive audience. A “NASA Workshop on Scientific Requirements for Mitigation of Hazardous Comets and Asteroids” was held in September 2002, and a 25-year program requiring \$5–6 billion of funding was recommended in the workshop’s final report.¹⁶⁴ The conference organizers sent a letter to NASA Headquarters in April 2003, arguing that “a new program needs to be started at NASA to create an adequate scientific basis for a future mitigation system and, simultaneously, to learn how to apply future collision mitigation technologies.” In this letter, they referenced NASA’s “newly stated objective of ‘...Protecting the Home Planet...As only NASA can!’.”¹⁶⁵

Other mitigation advocacy includes the organizing of a non-profit foundation dedicated to supporting a specific interception effort (known as Project B612, after the asteroid found in *The Little Prince* by Antoine de Saint-Exupéry), and the scheduling of a Planetary Defense Conference that was held in Los Angeles in February 2004.¹⁶⁶

On 22 August 2003 the NEO Science Definition Team (referred to by Dr. Weiler in his Congressional testimony) released its study report. This report represents the most comprehensive *technical* assessment of expanded NEO survey objectives yet published. It recom-

¹⁶² Milani, A., “Extraterrestrial Material—Virtual or Real Hazards?,” *Science*, Volume 300, 20 June 2003, pp. 1882–1883.

¹⁶³ In fairness, the U.K. NEO Task Force did implicitly consider social effects, as shown by its recommendation to establish a British Centre for Near Earth Objects. One of the most important functions of this centre was to “give balanced information in clear, direct and comprehensible language.” Social effects of actual impacts were explicitly addressed in a separate recommendation. *Report of the Task Force on Potentially Hazardous Near Earth Objects*, (Recommendations 8, 13 and 14), Information Unit, British National Space Centre, London, September 2000, p.8.

¹⁶⁴ www.noao.edu/meetings/mitigation/report.html

¹⁶⁵ Letter from “Michael Belton and the Mitigation Workshop team” to Mr. Gary L. Martin, NASA Space Architect, NASA Headquarters, Washington, D.C., 4 April 2003.

¹⁶⁶ For B612, see www.b612foundation.org/ and for the Planetary Defense Conference, see www.aero.org/conferences/planetdef/. The Planetary Defense Conference was interesting because it sidestepped the most problematic issue of mitigation planning (the extremely low probabilities involved) by structuring the format of the conference around notional “Defined Threat Scenarios.” This author compared the *ex post* perspective with an *ex ante* approach in a presentation to the attendees: “Project CARDINAL: A Policy-Relevant NEO Hazard Mitigation System,” AIAA Planetary Defense Conference, Garden Grove, California, 25 February 2004.

mends a new goal of surveying the population of 140-meter or larger PHOs to a completeness of 90 percent.¹⁶⁷

The present work will significantly modify the cost and effectiveness model at the core of the SDT study, expanding it to include predicted warning rates and uncertainty in several parameters of social response (those parameters being discussed in Chapter Five). The new model will be presented in detail in Chapter Six.

Summary of Social Response

The recent history of society's response to the impact threat is characterized by the rapid progress of NEO survey efforts, and a reluctance to invest resources in NEO mitigation in the absence of a specific defined threat.

With increases in the number of NEO detections, however, has come an increase in the number of unwarranted alarms. In at least two instances (1989 FC and 1997 XF11), these have attracted the concern of policymakers, leading to organizational responses and eventual increases in funding. This is a classic example of a positive feedback loop: more discoveries result in more false positives, which result in more funding to generate yet more discoveries—and perhaps, to initiate mitigation programs.¹⁶⁸ This will be discussed in much more detail in Chapter Five.

From the standpoint of a stakeholder in the NEO community, the alarms can be seen as either positive or negative. They are positive in the sense that they increase “public awareness of the threat” and consequent increases in public resources applied to the hazard. They are negative if they result in a public perception that the community is incompetent, or rash.

From the standpoint of society, alarms carry costs. The alarms that have occurred to date have had little social effect. However, they have been alarms associated with misperceptions about supposed “near misses” and vanishingly remote odds. The social costs associated with the first ever scientifically-blessed warning of impending doom, whenever it occurs, are unknown and unpredictable—it is possible, however, to outline some mechanisms of how social cost might be incurred, and these are covered in Chapter Five. We would like to think that modern industrialized society is no longer susceptible to the mass fear engendered by the passage of Comet Halley in 1910, but we live in an era of globalization. We have tightly coupled organs of mass communication and highly interdependent economies, and these may make us more, not less, vulnerable to such alarms.

The root of the problem is that the programs to generate NEO discoveries were not conceived with social responses in mind—only after the surveys began to pick up speed was it recognized that false positives would be a significant issue.¹⁶⁹ This was a natural consequence of the fact that those bringing the NEO threat to society's attention were technologists, rather than social scientists or hazard managers. However, warning is a social function,

¹⁶⁷ Stokes, G., *et al.*, “Study to Determine the Feasibility of Extending the Search for Near-Earth Objects to Smaller Limiting Diameters,” report of the NEO Science Definition Team, prepared at the request of the NASA Office of Space Science, Solar System Exploration Division, 22 August 2003.

¹⁶⁸ An extensive discussion of positive feedback in the social sciences is found in Jervis, R., *System Effects—Complexity in Political and Social Life*, Princeton University Press, Princeton, New Jersey, 1997, pp. 146-165.

¹⁶⁹ Neither the 1992 Spaceguard Survey Report nor the 1995 NEO Survey Workgroup Report addressed the social implications of impact warnings. Both reports discussed the need for follow-up observations to reduce uncertainty in only a technical context.

not a technical function, and this was not appreciated at the time.¹⁷⁰ Effective warning systems involve four components:¹⁷¹

- A technical analysis of the potential risks of issuing warnings;
- An establishment of priorities;
- A clear understanding of public beliefs and values; and
- An evaluation of the outcomes of warnings that are issued.

It is only now that these considerations are beginning to be addressed, some by the present work.

This is not to say that the many backers of NEO surveys (and mitigation programs) were misguided, or ill intentioned. On the contrary, the NEO impact hazard is real, albeit remote, and major strides have already been taken to address the threat. From a policy perspective, though, the question is how to ensure that a socially desirable level of resources is applied to the hazard given the sensitivity of society to the manner in which the hazard information is presented. This is a particularly timely question, given the efforts now underway (in interested quarters) to greatly expand the scope of society's response to the cosmic impact hazard.

¹⁷⁰ Ideally, a collective scientific opinion is communicated through a hazard operational scientist or manager to a civil defense officer, not directly to society. Woo, G., *The Mathematics of Natural Catastrophes*, Imperial College Press, London, 1999, pp. 140-141.

¹⁷¹ Fischhoff, B., Carnegie Mellon University, cited in *RAND Review*, The RAND Corporation, Santa Monica, California, Spring 2003, p.10.

Literature Review

This chapter presents an overview of the literature relevant to the cosmic impact hazard. The reader will note that many sources have already been cited in the footnotes of preceding chapters, and Chapter Five in particular will return to many of the works listed here. Some advocacy pieces, point papers, position papers, and so forth are left for discussion in Chapter Four, Organizations and Their Policies. An even more expansive set of sources is found in the Bibliography, which includes a number of works used by the author to establish the intellectual framework for this analysis.

As noted in Chapter One, analysis of the cosmic impact hazard can be approached from several possible directions, and this review will begin by presenting examples of these different general approaches, discussing their merits and shortcomings as appropriate.

The review then narrows its focus. It examines those policy papers, studies, and the like that specifically address the cosmic impact hazard. Such analyses are often embedded in larger works addressing scientific and technical aspects of the impact hazard, and have had little if any exposure in the more general, policy-oriented literature.¹

General

Methodologies

These selected works consider the analysis tools that are applied to problems with varying degrees of relevance to the cosmic impact hazard. The more comprehensive works address the ethical and value assumptions that underlie the use of these tools.

An overview of the theory of risk management is found in B. Fischhoff, *et al.*, *Acceptable Risk*.² While oriented toward the risk posed by technologies, this work has much more general applicability. Fischhoff lays out dimensions of consequences for characterizing the attractiveness of options, including economic, physical, ecological, political/ethical, and psychological factors. Among the questions addressed in the last two categories are those that

¹ Why this should be so is itself a matter of academic interest. The impact hazard policy literature, such as exists, is almost exclusively the product of technical specialists lacking training in policy analysis. It is characterized by either implicit or arbitrary assumptions on the acceptability of risk, and is colored by advocacy. On the other hand, policy "professionals" have refrained from conducting any serious analysis, perhaps because:

- The issue is seen as peripheral and beneath their notice;
- The technical underpinnings of the hazard are too difficult to grasp; or
- They fear a taint on their careers from the "giggle factor" (introduced in Chapter One).

have received short shrift in discussions of the impact hazard to date; namely, intergenerational equity, worry, anxiety, and confidence in the future. Fischhoff addresses difficulties of valuation and perception, takes note of the fallibility of experts, and outlines three types of approach to acceptable-risk problems. These are: formal analysis (including cost-benefit analysis); bootstrapping approaches (inferring the threshold of acceptability of one hazard from society's level of risk tolerance for a second hazard); and professional judgment. All of these approaches have been used in prior analyses of the impact hazard. Finally, Fischhoff recognizes that issues of implementation must be considered, including "political acceptability" and "compatibility with institutions" in his criteria for evaluating the acceptability of approaches to acceptable risk.³

A Primer for Policy Analysis, by E. Stokey and R. Zeckhauser provides a comprehensive overview of fundamentals.⁴ Two of its chapters in particular are germane to the present work: one on cost-benefit analysis and the other on discounting. The book discusses difficulties of valuation, and highlights the importance of estimating "intangible" costs and benefits. It considers the grave difficulties associated with choice of discount rate, and argues strongly against the use of a single discount rate as opposed to a range ("when we get down to discussing real numbers, most of the voluminous discount rate literature becomes suddenly vague").⁵ It identifies the pitfalls of choosing the capital market's rate of return as a discount rate. It notes that some think "the choice of a discount rate should be used deliberately to apportion costs and benefits among income groups and among present and future time periods, and hence generations, according to the values held by society."⁶ On the other hand, it points out one common argument *against* using low discount rates for purposes of intergenerational equity: "If per capita income continues to grow as it has over the last two centuries, our children's children will be far better off financially than we are. Any sacrifice for the benefit of future generations would be made by the not-very-poor for the benefit of the even-less-poor."⁷

A comprehensive examination of the issues associated with cost-benefit analysis as applied to environmental problems is found in the compilation *Cost-Benefit Analysis*, edited by K. Puttaswamaiah. Two of the papers therein are of particular interest: "Cost-Benefit Analysis, Ethics and the Natural Environment" by S. Lumley, and "Challenges and Pitfalls of Cost-Benefit Analysis in Environmental Issues" by J. Van der Straaten.⁸

The Lumley paper addresses the difficulties of placing a value on intangibles. It makes reference to the Contingent Valuation Method (CVM), the hedonic pricing technique, the travel cost method, and other shadow pricing techniques. These methods allow the quantification of intangibles within a cost-benefit framework, although their practical application can be very controversial. Lumley addresses the ethical dimensions of cost-benefit

² Fischhoff, B., *et al.*, *Acceptable Risk*, Cambridge University Press, Cambridge, 1981.

³ *Ibid*, p.60.

⁴ Stokey, E., and Zeckhauser, R., *A Primer For Policy Analysis*, W.W. Norton and Company, New York, 1978.

⁵ *Ibid*, p.172.

⁶ *Ibid*, p.173.

⁷ *Ibid*, p.174.

⁸ Lumley, S., "Cost-Benefit Analysis, Ethics and the Natural Environment," and Van der Straaten, J., "Challenges and Pitfalls of Cost-Benefit Analysis in Environmental Issues," in *Cost-Benefit Analysis*, Puttaswamaiah, K., editor, Transaction Publishers, New Brunswick, U.S., 2002, pp. 95-114 and pp. 323-346, respectively.

analysis (specifically addressing intergenerational equity) but is contradictory in that regard. On the one hand, she states that "ethics has at least two points of relevance to the use of CBA [cost-benefit analysis]." On the other hand, she asserts unequivocally (within the same paragraph) that cost-benefit analysis "is based on efficiency not equity considerations. As such, outside of utilitarian ethics, it has no moral context and pays no heed to the possible distributional consequences of project proposals."⁹

The Van der Straaten paper introduces the concept of critical load, a threshold of acceptable environmental stress.¹⁰ It discusses quasi-option value (the value of avoiding the irreversible damage associated with a certain project in the light of potential future knowledge), and notes that its use could cause the repeated postponement of a project since "new and relevant information in the future" might always become available.¹¹ It links the use of quasi-option values to the precautionary principle, going so far as to advocate the application of that principle in cases where parametric uncertainty renders cost-benefit analysis problematic.¹² Van der Straaten concludes by characterizing choice of discount rate as a yet-unsolved problem. He states that "every choice of every rate is based on ethical and political opinions about the relevance of future generations and the seriousness of the problems in the field of nature and the environment."¹³

The thorny issue of selection of discount rate is again examined in four papers on time discounting for the far future. Two papers are by T. Schelling ("Intergenerational Discounting" and "Intergenerational Time Discounting—Preliminary synthesis, with questions"). The other two of the selected papers are by M. Weitzman ("Gamma Discounting" and "Why the Far-Distant Future Should Be Discounted at Its Lowest Possible Rate").¹⁴

Schelling comes to the conclusion that intergenerational discounting is not a problem of time preference, but rather of income redistribution in a temporal sense. He advances the usual arguments against transferring wealth from the well-off to the even better-off, and makes a strong argument for consideration of opportunity cost, the point being that direct investment in the economic improvement of less developed countries *today* should be considered in any cost-benefit framework.¹⁵

⁹ Lumley, S., *op. cit.*, p.109.

¹⁰ This is relevant to the impact hazard as viewed through the lens of environmental policy: the threshold of critical load could be the threshold of the Spaceguard Survey goal (*i.e.*, that corresponding to the end of human civilization); or it could be the more calamitous "extinction-level event" (as in Table 2.5), all depending on one's valuations.

¹¹ Van der Stratten, J., *op. cit.*, p.332. With reference to the impact hazard, this is distinct from, but related to, the issue of the affluence of future generations. In the future, it might be expected that technologies to survey and intercept threatening NEOs would be far in advance of our own, so it could be argued that expenditures on such efforts should be deferred (to the extent that we value posterity and not "our own skins").

¹² Van der Stratten, J., *op. cit.*, p.338.

¹³ Van der Stratten, J., *op. cit.*, p.343.

¹⁴ Schelling, T., "Intergenerational Discounting," *Energy Policy*, Volume 23, Number 4/5, 1995, pp. 395-401, and "Intergenerational Time Discounting—Preliminary synthesis, with questions," unpublished manuscript, received by facsimile from that author on 10 May 2001; Weitzman, M., "Gamma Discounting," *The American Economic Review*, Volume 91, Number 1, March 2001, pp. 260-271, and "Why the Far-Distant Future Should Be Discounted at Its Lowest Possible Rate," *Journal of Environmental Economics and Management*, Volume 36, Number 3, November 1998, pp. 201-208.

¹⁵ Schelling frames his arguments in the context of climate change policy, and they are relevant to the present discussion to the extent that the impact hazard is global in nature. The main difference, of course, is that the impact hazard is the result of a Poisson process, so there is a uniform distribution of risk across time. Hence there is indeed a significant component of time preference applicable to the impact hazard, even if in Schelling's view that is not the case in the climate change policy arena.

Weitzman's two papers construct a theoretical basis for a discount rate that declines over time to the "lowest possible rate," that being the lower bound of the range of uncertainty in discount rate. He concludes his paper on "Gamma Discounting" by stating that "society should be using effective discount rates that decline from a mean value of, say, around 4 percent per annum for the immediate future down to around zero for the far-distant future."¹⁶

A paper by D. Kenkel entitled "Using Estimates of the Value of a Statistical Life in Evaluating Regulatory Effects" is of particular interest inasmuch as it informs the life valuations of the SDT study report that will be reviewed in detail in Chapter Six.¹⁷ Kenkel examines the diverse methodologies used by U.S. government agencies to assess the value of human lives. He addresses the willingness-to-pay (WTP) approach, along with the difficulties of eliciting WTP; the human capital approach; and hybrid approaches. His paper concludes by calling for life valuations that are consistent and specific to the risks and populations at issue. With certain caveats of implementation, Kenkel favors a monetized quality-adjusted life year (QALY) metric, which yields specific statistical life valuations depending on age, health state, and cause of death.

Finally, a paper by L. Thiele ("Limiting Risks: Environmental Ethics as a Policy Primer") incorporates a good review of the precautionary principle as applied to environmental policy. The precautionary principle is relevant to the impact hazard in the sense that the hazard is surrounded by scientific uncertainty, and the principle holds that such uncertainty should not be a deterrent to action. On the other hand, the principle could be seen as a two-edged sword in the context of the NEO hazard. It is usually applied to questions of risk generated by human activities, not to natural hazards, and any interception of a threatening NEO carries the potential for making matters worse (as first discussed in Chapter Two).¹⁸

Analogous Cases

Although the cosmic impact hazard is unique in its specifics, other threat cases have varying degrees of relevance. Specifically, an extensive literature on natural disasters is worth examining, as is an evolving literature on social responses to terrorism.

It is interesting to observe that scientific communities associated with differing natural hazards have varying degrees of sophistication in communication of uncertainty to society. Two useful overviews are *Prediction—Science, Decision Making, and the Future of Nature*, edited by D. Sarewitz *et al.*, and *The Mathematics of Natural Catastrophes* by G. Woo.¹⁹ The Sarewitz volume includes a chapter on the NEO hazard in particular, and has a good introductory discussion of the problem of false positives. The book by Woo also addresses warning. Its discussion of warning centers on volcanic hazards, however, and addresses the NEO hazard only in passing.

¹⁶ Weitzman, M., "Gamma Discounting," *The American Economic Review*, Volume 91, Number 1, March 2001, p. 270.

¹⁷ Kenkel, D., "Using Estimates of the Value of a Statistical Life in Evaluating Regulatory Effects," Session 1, "Valuing Statistical Lives," *Valuing the Health Benefits of Food Safety: A Proceedings*, Kuchler, F., editor, U.S. Department of Agriculture Economic Research Service, MP1570, April 2001.

¹⁸ Thiele, L., "Limiting Risks: Environmental Ethics as a Policy Primer," *Policy Studies Journal*, Volume 28, Number 3, 2000, pp. 540-557.

¹⁹ Sarewitz, D., *et al.*, editors, *Prediction—Science, Decision Making, and the Future of Nature*, Island Press, Washington, D.C., 2000; and Woo, G., *The Mathematics of Natural Catastrophes*, Imperial College Press, London, 1999.

A classic example of a scientific community utterly devaluing the costs of warning is presented (unintentionally) in "Fostering Public Preparations for Natural Hazards—Lessons from the Parkfield Earthquake Prediction," a paper by D.S. Milet *et al.* in the journal *Environment*.²⁰ An earthquake prediction was communicated to the residents of the towns of Coalinga, Paso Robles, and Taft in California. A large proportion of the public ignored the warning.²¹ The experiment was judged to have been successful as measured by those who *did* take action to prepare for the earthquake that never happened. The lesson that appeared to be lost on the scientific community was that, *sans* earthquake, those inhabitants that either did not receive the warning or ignored it were those that avoided unnecessary social costs.

A key reference for assessing natural disasters from an economic perspective is a report by the U.S. National Research Council (NRC), entitled *The Impacts of Natural Disasters—A Framework for Loss Estimation*.²² This report highlighted the significant difficulties associated with quantification of losses, particularly uninsured losses. An important finding was that net economic losses associated with natural disasters may well be zero, due to positive effects outside the zone of immediate destruction.²³

In a similar vein, in 2002 the Joint Economic Committee of the U.S. Congress issued a report entitled *The Economic Costs of Terrorism*.²⁴ While the costs of natural disasters are relevant to the *ex post* costs of NEO impacts, the indirect costs of terrorism may well be similar to those *ex ante* costs incurred by NEO impact warnings. Specifically, *The Economic Costs of Terrorism* addresses the effects of uncertainty on consumer and investor behavior, and associated retrenchment of specific industries or localities. It also considers the "hard to measure" long-run costs of added anxiety, stress, and mental disorders accompanying a very uncertain yet permanent threat.²⁵

For more on the economics of disasters, a classic text is *Economic Behavior in Adversity* by J. Hirshleifer, particularly its chapters on disaster and recovery.²⁶ This book contains much that is relevant to the *ex post* costs of NEO impacts, including an analysis of the economic effects of the Black Death in Western Europe. As in the NRC's report *The Impacts of Natural Disasters—A Framework for Loss Estimation*, the point is made that every dark cloud has a silver lining—for some.²⁷

An interesting and relevant literature addressing another low probability, high consequence event is that concerned with the Search for Extraterrestrial Intelligence (SETI). In 1960, the Brookings Institution issued a study report entitled *Summary of Proposed Studies on the Implications of Peaceful Space Activities for Human Affairs*.²⁸ This report was concerned

²⁰ Milet, D. S. *et al.*, "Fostering Public Preparations for Natural Hazards—Lessons from the Parkfield Earthquake Prediction," Volume 34, Number 3, *Environment*, 1 April 1992, pp.16-20 and 36-39.

²¹ Apparently about half of the population took no action, although it is difficult to determine from Milet *et al.*

²² *The Impacts of Natural Disasters—A Framework for Loss Estimation*, National Research Council, National Academy Press, 1999.

²³ *Ibid.*, p.38.

²⁴ Saxton, J., Chairman, *The Economic Costs of Terrorism*, Joint Economic Committee, U.S. Congress, May 2002.

²⁵ *Ibid.*, pp. 3-4.

²⁶ Hirshleifer, J., *Economic Behavior in Adversity*, University of Chicago Press, Chicago, 1987.

²⁷ *Ibid.*, p.103.

²⁸ Mitchell, D., *Summary of Proposed Studies On The Implications Of Peaceful Space Activities For Human Affairs*, Brookings Institution, December 1960.

with the social effects of the possible fruits of space exploration, including possible contact with alien civilizations.²⁹ In contrast to the NEO community, the SETI community has been sensitive to the social implications of their activities from the start. On the Internet can be found web pages titled “Cultural Aspects of SETI,” and “What Are the Possible Societal Effects of a SETI Success?”³⁰ The SETI community has a protocol for communicating a SETI detection to society, and even a warning scale (the “Rio” scale) for use in cases of uncertainty (Figure 3.1).³¹

Figure 3.1
SETI Rio scale

Rio Importance	
10	Extraordinary
9	Outstanding
8	Far-reaching
7	High
6	Noteworthy
5	Intermediate
4	Moderate
3	Minor
2	Low
1	Insignificant
0	None

²⁹ “The implications of a discovery of extraterrestrial life,” *Ibid*, p.182.

³⁰ www.seti.org/site/pp.asp?c=ktJ2J9MMIsE&b=179289 and www.seti.org/site/pp.asp?c=ktJ2J9MMIsE&b=179288

³¹ As was the case with the NEO community’s Torino scale (Chapter Two), the Rio Scale was named after the city where it was formally introduced in October 2000 (Rio de Janeiro). It is interesting that the creators of the Rio Scale used the antecedent Torino scale as a referent. (www.setileague.org/iaaseti/rioscale.htm)

Perceptions vs. Reality

Naturally, the costs associated with warnings, however measured, are a function of how the warnings are presented and how they are perceived by society. Here we turn to the extensive literature on persuasion and perception, including the presentation of information for effect.

A general reference is *Attitudes and Persuasion: Classic and Contemporary Approaches*, by R. Petty and J. Cacioppo.³² A section on "determinants of attitude change in persuasive communications" is relevant to this analysis. In particular, a discussion of issues associated with communicator credibility is quite useful.³³

A report for FEMA entitled *Emergency Management: The Human Factor*, by T. Drabek, addresses sociological issues from a hazard perspective.³⁴ Drabek notes that "there appears to be a minimal correlation between perceived risk and scientifically-assessed risk."³⁵ He considers social responses to warning, but is concerned only with fashioning the warning messages to "substantially affect the success of the warning effort" and does not consider the question of the costs associated with false alarms. This failing is encountered time and again in the disaster management literature.

Very relevant to hazard communication is a classic book by E. Tufte entitled *The Visual Display of Quantitative Information*.³⁶ A central theme of this work is that flawed graphic presentation will distort human perceptions of the underlying data. The author defines a "Lie Factor," as shown in Equation 3.1. Tufte states that "in practice almost all distortions involve overstating, and Lie Factors of two to five are not uncommon," and he gives examples of Lie Factors up to about fifteen (an "extreme example").³⁷ Tufte's Lie Factor will be revisited in Chapter Five and applied to past examples of NEO hazard communication.

$$\text{Lie Factor} = \frac{\text{size of effect shown in graphic}}{\text{size of effect in data}} \quad (3.1)$$

For perceptions of low probability events, we first review a paper by A. Tversky and D. Kahneman, the classic "Judgment under Uncertainty: Heuristics and Biases."³⁸ A number of the heuristics addressed therein are very relevant to public perceptions of the impact hazard. For example, it is probably easier for the average person to imagine a city being destroyed than to mentally grasp the end of civilization (at least, it was until movies like *Deep Impact* and *Armageddon* were released). After all, cities have been destroyed by war and calamity, but human civilization has endured. This calls into play the availability heuristic, which would increase the subjective probabilities associated with small impacts. Another relevant heuristic is representativeness, as demonstrated by an insensitivity to sample size. It

³² Petty, R., and Cacioppo, J., *Attitudes and Persuasion: Classic and Contemporary Approaches*, Westview Press, Boulder, Colorado, 1996.

³³ *Ibid*, pp. 60-69.

³⁴ Drabek, T., *Emergency Management: The Human Factor*, FEMA National Emergency Training Center Monograph Series, Volume 2, Number 3, 1985.

³⁵ *Ibid*, Abstract.

³⁶ Tufte, E., *The Visual Display of Quantitative Information*, Graphics Press, Cheshire, Connecticut, 1983.

³⁷ *Ibid*, p.57.

³⁸ Tversky, A., and Kahneman, D., "Judgment under Uncertainty: Heuristics and Biases," *Science*, Volume 185, Number 4157, 27 September 1974, pp. 1124-1131.

was seen in Chapter Two that even experts can fall prey to this cognitive error (in that case, projecting the cometary component of the impact hazard from a sample size of two).

The second paper with obvious relevance to the subject at hand is “Decision Processes for Low Probability Events: Policy Implications” by C. Camerer and H. Kunreuther.³⁹ As with the previous work, this paper highlights biases in judgments about risks and probabilities. It reviews prospect theory and regret theory, and argues that “normative models of choice, such as expected utility theory, are inadequate descriptions of individual choices.”⁴⁰ The authors note that “many policy problems arise when people ignore risks with low probabilities,” and suggest that “if probabilities were aggregated over time or groups of people to make them seem larger, people might protect themselves more often.”⁴¹ They also offer a “cure” for the hindsight bias that leads to inappropriate regret. This is simply to “ask people to record causal sequences which did *not* lead to the event.”⁴²

Specific

This review now proceeds to examine the literature that specifically addresses policy issues associated with the cosmic impact hazard. This literature is largely the product of the NEO community rather than of policy generalists, and is rife with implicit valuations and other unstated assumptions. Nevertheless, there is much that is useful. Indeed, one of the most recent of these studies (the SDT study, first mentioned in Chapter Two) is used as an essential foundation for the present work.⁴³

Much of the NEO literature is clouded by advocacy, with appeals to emotion, as one might expect from a marginal but vocal stakeholder community. Many works representative of this type are included in the Bibliography. The present review limits itself to those works that offer a distinct viewpoint, or attempt a quantitative analysis.

Impact Hazard Policy Analysis circa 1994

A compilation edited by T. Gehrels entitled *Hazards Due To Comets And Asteroids* includes a cost-benefit analysis authored by the physical scientist G. Canavan (“Cost and Benefit of Near-Earth Object Detection and Interception”).⁴⁴ Canavan concluded that all sizes of NEOs “make contributions to expected losses large enough to justify their detection.”⁴⁵ He attempted an optimization by equating marginal costs with marginal benefits, determined the detection ranges and deflection characteristics of “affordable defensive systems,” and es-

³⁹ Camerer, C., and Kunreuther, H., “Decision Processes for Low Probability Events: Policy Implications,” *Journal of Policy Analysis and Management*, 1989, Volume 8, Number 4, pp. 565-592.

⁴⁰ *Ibid*, Abstract.

⁴¹ *Ibid*, p.570. As an example, recall the presentation of impact frequencies using the formulation “in your lifetime or that of your children” (Chapter Two).

⁴² *Ibid*, p.576. From an *ex ante* perspective, this would take the form of “anticipated regret” and consideration of causal sequences that *will* not lead to the event. An example in the NEO literature that serves this purpose (perhaps unintentionally) is discussed later in this chapter.

⁴³ The SDT study will be discussed in much more detail in Chapter Six, and so is not addressed further in this chapter.

⁴⁴ Canavan, G., “Cost and Benefit of Near-Earth Object Detection and Interception,” *Hazards Due To Comets And Asteroids*, Gehrels, T., editor, University of Arizona Press, Tucson, Arizona, 1994, pp. 1157-1189.

⁴⁵ *Ibid*, p.1157.

timated the maximum object size for which defenses are "cost effective."⁴⁶ A single constructed parameter was varied in a limited sensitivity analysis.⁴⁷

Canavan chose to quantify impact losses by scaling the Earth's total gross product as a function of impactor energy. He assumed a real interest rate of five percent, and then made the unsupported assertion that such a value "is appropriate to discount or capitalize losses of comparable uncertainty."⁴⁸ He then assumed a recovery time of twenty years for impact zones associated with all NEO diameters, on the somewhat mystifying grounds that twenty is the reciprocal of the five percent interest rate.⁴⁹ His analysis assumed that no lives would be lost as the result of an impact of any size, an assumption that is unique in the literature and has an obviously large effect on results. Costs of evacuation and the effects of false alarms (that is, the social costs of warning) were not recognized. Uncertainty in many areas was not addressed—for example, economic valuation, impact effects, interceptor reliability, and interceptor effectiveness.

Another relevant paper in *Hazards Due To Comets And Asteroids* is "The Comet and Asteroid Impact Hazard in Perspective," by P. Weissman.⁵⁰ This paper treated the opportunity costs associated with the impact hazard—for example, whether resources would be better applied to combating disease or nuclear proliferation. It put the hazard in a social context, raising questions of perceptions and credibility. However, the social cost of warning was not discussed; the asteroid alarms reviewed in Chapter Two (1997 XF11, 1999 AN10, and those listed in Figure 2.31) were yet to occur at the time of writing. Nevertheless, for a paper originating within a community of advocacy, this was a remarkably even-handed treatment of the impact hazard.

Yet another interesting paper in *Hazards Due To Comets And Asteroids* is "The Deflection Dilemma: Use Versus Misuse of Technologies for Avoiding Interplanetary Collision Hazards," by A. Harris *et al.*⁵¹ The concern of the authors was that an NEO interception system could be used by the malevolent to deflect an asteroid *into* a target on the Earth. In effect, a horrifying new space-strike capability would have been created.⁵²

A short paper that considers the institutional issues associated with response to the impact hazard is "A plan for worldwide protection against asteroid impacts," by W. Tedeschi

⁴⁶ Canavan's casual use of the term "cost effective" is not to be confused with the standard definition, where benefits are calculated using a non-monetized effectiveness parameter.

⁴⁷ This parameter is discount rate times the derivative of cost with respect to NEO diameter.

⁴⁸ Stokey and Zeckhauser (*op. cit.*, pp. 170-176) make it clear that choosing the interest rate prevailing in a financial market as a discount rate is problematic, especially in an analysis where difficulties of valuation exist.

⁴⁹ Entire cities devastated by bombing in World War II were rebuilt in far less than twenty years. Hirshleifer (*op. cit.*, p. 78) presents an argument that "speed and success of recovery in the observed historical instances have been due in large part to the proportionately smaller destruction of population than of material resources." Thus it seems that Canavan, who assumed no loss of life for any impact event, should have used a shorter recovery period. This would have created problems, however, as the reciprocal of a shorter recovery period (using his unclear logic) would have resulted in an extraordinarily high interest rate (assuming that interest rate is an appropriate discount rate, which in a problem such as this it is not).

⁵⁰ Weissman, P., "The Comet and Asteroid Impact Hazard in Perspective," *Hazards Due To Comets and Asteroids*, Gehrels, T., editor, University of Arizona Press, 1994, pp. 1191-1212.

⁵¹ Harris, A., *et al.*, "The Deflection Dilemma: Use Versus Misuse of Technologies for Avoiding Interplanetary Collision Hazards," in *Hazards Due to Comets and Asteroids*, Gehrels, T., editor, University of Arizona Press, Tucson, 1994, pp. 1145-1155.

⁵² The same subject is addressed in a RAND report entitled *Space Weapons—Earth Wars*, Preston, J., *et al.*, (Appendix C—"Natural Meteoroids As Weapons"), The RAND Corporation, Santa Monica, California, MR-1209-AF, 2002, pp. 173-183) and was treated in the discussion of mitigation in Chapter Two.

and E. Teller.⁵³ It suggested that a “Special Branch” of the U.N. be established to deal with the threat. Arguments offered to support this position included “the United Nations has the great advantage that it exists” and (somewhat ironic in the light of subsequent history) “...it has shown that it is capable of effective action as in the case of Iraq.”

The Evolution of Impact Hazard Policy Analysis

Three papers take remarkably similar approaches to the impact hazard, using a disaster management framework and considering issues of institutional implementation (although at the “organizational chart” level of sophistication). These are: “The mitigation, management, and survivability of asteroid/comet impact with Earth,” by V. Garshnek *et al.*; “Response to Sub-Critical Cosmic Impacts” by M. Gerrard and J. Remo; and “The Comet/Asteroid Impact Hazard: A Systems Approach” by C. Chapman *et al.*⁵⁴ The disaster management approach results in a failure to address the implications of the extremely low *ex ante* probabilities that make this hazard different from the average disaster. There are nods to the social costs of warning: the Garshnek paper places a hopeful reliance on the Torino scale to “avoid unnecessary confusion or panic,” and the Chapman paper includes the statement “much may have to be done to calm public fear and panic arising from the prediction itself.”⁵⁵

A book entitled *Comet and Asteroid Impact Hazards on a Populated Earth* by J. Lewis presents the results of a Monte Carlo simulation of NEO impacts with the Earth.⁵⁶ The work includes the code of the simulation itself, allowing the reader to personally set up runs spanning various time periods. This exercise is valuable for two reasons:

- It very effectively demonstrates the extreme idiosyncrasy of individual impact events (thus providing a context for questioning the assumptions of scenario-based analyses that have been conducted in this field); and
- It provides a “cure” for the hindsight bias addressed by Camerer and Kunreuther in their work “Decision Processes for Low Probability Events: Policy Implications” (reviewed above). For most runs of reasonable duration, nothing much happens, and the true meaning of the very low probabilities begins to sink in.

The primary measure of loss in this simulation is human life, with no attempt made at monetization. However, the program does report impact energies and several other interesting parameters.

Finally, the book *Asteroids III* (edited by W. Bottke *et al.*) includes a chapter titled “Dealing With the Impact Hazard.”⁵⁷ That chapter includes sections written by this author discussing the societal context for NEO surveys and the influence of that context on mitiga-

⁵³ Tedeschi, W., and Teller, E., “A plan for worldwide protection against asteroid impacts,” *Space Policy*, August 1994, pp.183-184.

⁵⁴ Garshnek, V. *et al.*, “The mitigation, management, and survivability of asteroid/comet impact with Earth,” *Space Policy*, 16 July 2000, Volume 16, Number 3, pp. 213-222; Gerrard, M., and Remo, J., “Response to Sub-Critical Cosmic Impacts,” *Journal of the British Interplanetary Society*, Volume 52, 1999, pp. 115-120; and Chapman, C. *et al.*, “The Comet/Asteroid Impact Hazard: A Systems Approach,” 24 February 2001 (www.boulder.swri.edu/clark/neowp.html).

⁵⁵ Chapman, *op. cit.*, p.18.

⁵⁶ Lewis, J., *Comet and Asteroid Impact Hazards on a Populated Earth*, Academic Press, San Diego, California, 1999.

⁵⁷ Morrison, D., *et al.*, “Dealing With the Impact Hazard,” Bottke, W., *et al.*, editors, *Asteroids III*, University of Arizona Press, Tucson, 2002, pp. 739-754.

tion programs and institutions. Many of the concepts included therein are addressed in much more detail in the present work.

Planetary Defense and the Military Perspective

"Planetary defense" is a term that invokes a military conceptual framework: the "mission" being to defend the Earth by detecting and then destroying threatening objects. Recall from Chapter Two, however, that the nature of the impact hazard is very alien to the military.

Specifically:

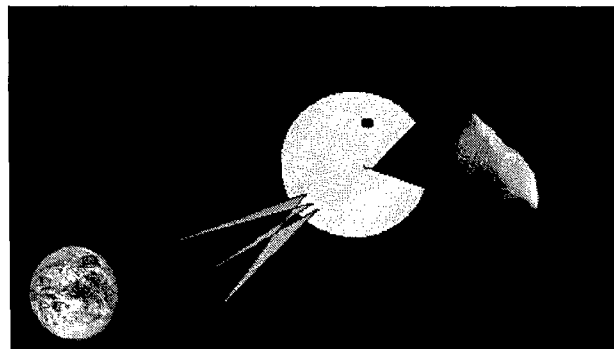
- The probability that a real threat will be detected is extremely low;
- Average warning times will be extremely long; and
- The ratio of false warnings to accurate warnings will be very high.

We now proceed to review a selection from the literature of planetary defense, consisting of several studies undertaken by the USAF and NASA. The degree to which these studies recognize the alien nature of the impact hazard remains to be seen.

A USAF study effort known as "Air Force 2025" included a paper authored by J. Urias *et al.*, entitled "Planetary Defense: Catastrophic Health Insurance for Planet Earth."⁵⁸ This paper outlines the architecture of a "planetary defense system," analyzes technical alternatives, examines command structures, and proposes acquisition timelines. A chapter on "social, economic, and political implications" dwells on impact effects, asserts that "a modest but prudent program is justified" without any quantitative analysis, and reviews the status of international space cooperation and treaty constraints. There is no serious consideration of the consequences of the extremely low probabilities involved, nor is there any recognition of the social costs of warning.

The Urias paper is notable for its inclusion of the graphic shown in Figure 3.2, which is presented as an example of a Biological, Chemical, Mechanical Earth Crossing Object (ECO) Eater.⁵⁹ When even the military officers analyzing planetary defense in an official study embrace the "giggle factor," hopes for any programmatic implementation are dim indeed.

Figure 3.2
"Giggle factor" within USAF study report



⁵⁸ Urias, J., *et al.*, "Planetary Defense: Catastrophic Health Insurance for Planet Earth," paper presented to Air Force 2025, October 1996.

⁵⁹ *Ibid*, Figure 3-5a., p.43.

The USAF Scientific Advisory Board (SAB) issued a report on "Space Surveillance, Asteroids and Comets, and Space Debris," one volume of which dealt specifically with the impact hazard.⁶⁰ There was little if any new ground covered, but the "Ad Hoc Committee on Space Surveillance, Debris, and Asteroids and Comets" recommended that USAF "mount a ground-based search program for large NEOs with upgraded GEODSS telescopes," foreshadowing LINEAR's subsequent successes. The analysis relies heavily on G. Canavan's cost-benefit analysis in the book *Hazards Due To Comets And Asteroids* (reviewed above), which is not surprising since Canavan was chair of the "Asteroids and Comets Panel" in this new study effort. A technique is used which has become something of a theme in planetary defense studies: to consider scenarios with different warning horizons, without any analysis of how often those scenarios would actually occur. The scenarios used in the SAB report are Long Warning, Short Warning, and Very Short Warning. "Strawman programs" are proposed for each of the scenarios.

A report authored by a professional services contractor was provided to U.S. Space Command entitled "Concept of Operations for Natural Impact Warning Clearinghouse."⁶¹ This report outlines the command relationships and operational responsibilities of a center that would review impactor threat data acquired from the whole gamut of NEO surveillance assets, including those under USAF control. The center would then provide the filtered data to "U.S. civil and military authorities at the highest levels."⁶² The center is visualized as a command and control node in the military sense. The extremely low probabilities associated with actual impacts would mean that such a center would be doing very little for most of its existence *provided that* warning rates are low, which may well not be the case. The "Clearinghouse" report is concerned about small objects entering the Earth's atmosphere that could be mistaken for nuclear events. It does not consider the longer-term warnings that will be an unavoidable consequence of any expanded NEO survey.

A report entitled "SHIELD—A Comprehensive Earth Protection System" by R. Gold was provided to the NASA Institute for Advanced Concepts.⁶³ This study is a strictly technical analysis of space-based NEO detection and interception alternatives. It does not include any cost analysis, and is presented here as a good example of the extreme level of risk aversion that characterizes the advocates of planetary defense. Figure 3.3 depicts a "long period comet distant early warning system" consisting of eighteen "Sentry" spacecraft sharing Jupiter's orbit. These eighteen provide coverage only in the ecliptic—many more would be required for all-sky surveillance.

Legal Perspectives

There is a reasonably complete literature on the legal issues associated with the NEO impact hazard. In fact, the ground has been covered so well that the present work will not attempt to improve upon it—the reader is referred to the sources discussed below.⁶⁴

⁶⁰ "Report on Space Surveillance, Asteroids and Comets, and Space Debris—Volume 2: Asteroids and Comets," USAF Scientific Advisory Board SAB-TR-96-04, June 1997.

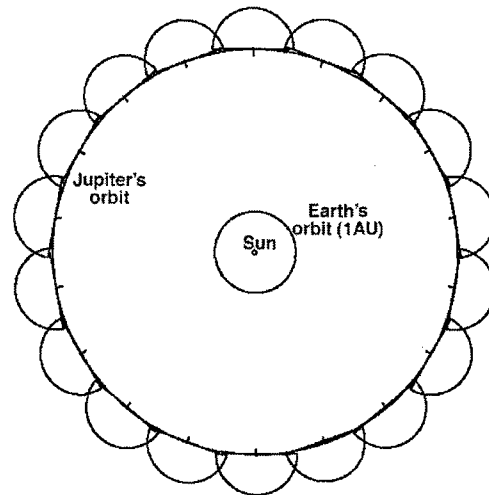
⁶¹ "Concept of Operations for Natural Impact Warning Clearinghouse," SAIC report EADDII-21-10152, 14 June 2002.

⁶² *Ibid.*, p.5.

⁶³ Gold, R. E., "SHIELD—A Comprehensive Earth Protection System," Phase I Report to the NASA Institute for Advanced Concepts, 28 May 1999. "SHIELD" is not an acronym.

⁶⁴ Chapter Four will, however, discuss the "five treaties," the international treaties that collectively form the basis of international space law.

Figure 3.3
Cometary distant early warning



A paper by J. Remo entitled "Policy perspectives from the U.N. international conference on near-Earth objects" includes a brief outline of the relationship of NEOs to U.N. law and treaties.⁶⁵ International space law is also reviewed in K. Sweet, "Planetary preservation: the need for legal provision."⁶⁶

M. Gerrard and A. Barber address requirements of the National Environmental Policy Act (NEPA) in their paper "Asteroids and Comets: US and International Law and the Lowest-Probability, Highest Consequence Risk."⁶⁷ They pay particular attention to the legal consequences of a failed interception attempt, and they provide yet another review of international space law.

Finally, we have two papers by E. Seamone: "When Wishing on a Star Just Won't Do: The Legal Basis for International Cooperation in the Mitigation of Asteroid Impacts and Similar Transboundary Disasters" and "The Duty to 'Expect the Unexpected': Mitigating Extreme Natural Threats to the Global Commons Such as Asteroid and Comet Impacts with the Earth."⁶⁸ Seamone takes the position that states have an absolute duty to protect themselves, discussing "the historically entrenched right to global survival," the "duty of self-preservation," "nation's duties to cooperate in preserving their subjects' survival," "duties to warn of impending danger," and "duties to act beyond warning." The weakness of his construction lies in its ethical foundation. Specifically, an absolute risk aversion to one particular hazard carries with it a valuational choice that has unavoidable ethical ramifications. As but

⁶⁵ Remo, J., "Policy perspectives from the U.N. international conference on near-Earth objects," *Space Policy*, February 1996, pp.13-17.

⁶⁶ Sweet, K., "Planetary preservation: the need for legal provision," *Space Policy*, Volume 15, 1999, pp. 223-231.

⁶⁷ Gerrard, M., and Barber, A., "Asteroids and Comets: US and International Law and the Lowest-Probability, Highest Consequence Risk," *New York University Environmental Law Journal*, Volume 6, Number 1, 1997.

⁶⁸ Seamone, E., "When Wishing on a Star Just Won't Do: The Legal Basis for International Cooperation in the Mitigation of Asteroid Impacts and Similar Transboundary Disasters," *Iowa Law Review*, Volume 87, Number 3, March 2002, pp. 1091-1139; and "The Duty to 'Expect the Unexpected': Mitigating Extreme Natural Threats to the Global Commons Such as Asteroid and Comet Impacts with the Earth," *Columbia Journal of Transnational Law*, Volume 41, 2003, pp. 735-794.

one example, consider the opportunity cost argument of T. Schelling in his works reviewed earlier in this chapter.

Seamone chooses an intellectual framework that supports his argument, and neglects those that do not. For example, he uncritically accepts the precautionary principle (since it is essential for his argument) and leaves the impression that it is the *only* valid foundation for environmental policy.⁶⁹ Such a position of legal advocacy is inconsistent with disinterested policy analysis.

⁶⁹ The following quote from Seamone makes this clear: a scholarly debate is cast aside due to the existence of international agreements.

Thus, while scholars and courts engage in lengthy debates over the status of the precautionary principle as customary international law or its binding nature, the virtual cornucopia of international agreements adopting the precautionary principle further supports the international salience of obligations to take preventive and anticipatory action.

Seamone, E., "The Duty to 'Expect the Unexpected': Mitigating Extreme Natural Threats to the Global Commons Such as Asteroid and Comet Impacts with the Earth," *Columbia Journal of Transnational Law*, Volume 41, 2003, p.761.

Organizations and Their Policies

Any future policy response to the impact hazard will be shaped by the nature of extant organizations, their constraints, motivations, and structures. This chapter reviews the principal organizations having an interest or involvement in addressing the cosmic impact hazard. Many of these organizations have been discussed previously, but are brought together here for the purpose of establishing an institutional baseline. Some have had reluctant involvement, some contain cadres of advocates, and some have been created for the specific purpose of impact hazard reduction. Both governmental and non-governmental organizations are listed.

Key to an understanding of the role of institutions is the unusually significant role of highly motivated individuals, both within and without the institutional framework. Why this should be so is discussed in Chapter Five. For now, it is sufficient to note the locations and actions of those interested individuals.

U.S. Government

White House

Outside of the movies, no U.S. Administration has yet had the misfortune to be forced to address the cosmic impact hazard. It is likely that President Clinton's 1997 veto of the *Clementine II* asteroid interceptor program (discussed in Chapter Two) simply revealed a preference for the avoidance of space weaponization as opposed to lack of concern for NEO threat reduction. Naturally, a subsequent Administration may chart a different course.

Insofar as the implementation of NEO mitigation programs is perceived, rightly or wrongly, as a "stalking horse" for space weaponization, the National Space Policy is relevant.¹ This policy document, known alternatively as Presidential Decision Directive National Science and Technology Council 8 (PDD/NSTC-8) and Presidential Decision Directive National Security Council 49 (PDD/NSC-49) was issued in 1996 by the Clinton Administration. While it fails to consider the impact hazard specifically, there are some pronouncements relevant to NEO mitigation.² The United States is "committed to the exploration and use of outer space by all nations for peaceful purposes and for the benefit of all humanity," al-

¹ "Fact Sheet—National Space Policy" (PDD/NSTC-8, PDD/NSC-49), White House, 19 September 1996. See www.ostp.gov/NSTC/html/pdd8.html

² While the Bush Administration has been conducting an extended review of space policy, it has failed, as of this writing, to issue any documentation supplanting the Clinton-era policy. This is likely because no urgent need to do so is perceived, as the Clinton space policy is much more enabling for the military uses of space than is commonly appreciated.

though it is noted that “‘peaceful purposes’ allow defense and intelligence-related activities in pursuit of national security and other goals.” A fundamental goal of the U.S. space program is to “promote international cooperation to further U.S. domestic, national security, and foreign policies.” Finally, and relevant to the means and methods of NEO mitigation, space “control” (a more ambiguous term than space “weaponization”) is explicitly supported.

U.S. Congress

Historically, Congressional interest in the NEO impact hazard has been centered in the House Committee on Science (formerly the Committee on Science, Space, and Technology), and its Subcommittee on Space and Aeronautics (formerly the Subcommittee on Space). Committee member (and two-time Chairman) Representative George Brown, Jr. (D, CA) took a personal interest in the NEO hazard, and was considered a staunch friend of the NEO community until his death in 1999. Recently, the most active and vocal member of the House with respect to the NEO impact hazard has been Representative Dana Rohrabacher (R, CA), the current Subcommittee Chairman.

A House hearing on “The Threat of Near-Earth Asteroids” was held in 2002 (and was discussed at the end of Chapter Two). The purpose of this hearing was to “examine the status of the current national survey of [NEOs], the threat of a NEO impact, future goals for the survey, and the national policy regarding NEOs.”³

National Aeronautics and Space Administration

Chapter Two reviewed NASA’s response to congressional direction regarding the NEO impact hazard. NASA established the NEO Program Office at JPL in 1998. Also that year, NASA committed to the Spaceguard Survey goal in congressional testimony. This was in contrast to NASA’s earlier position that “new survey efforts” should not be funded, given “NASA’s severely limited resources.”⁴

A Steering Group was established for the new NEO Program Office. This group coordinated NASA and USAF cooperation in pursuit of the Spaceguard Survey Goal. The wider aspects of the NEO hazard, such as mitigation plans or programs, were not within this group’s purview.⁵

For an understanding of current NASA policy on the NEO impact hazard, it is useful to consult NASA’s 2003 Strategic Plan. The impact hazard is addressed in Mission 1, Goal 1.⁶ The Strategic Plan states “We study the population and dynamics of [NEOs] to understand the probabilities and possible effects of future impacts better” and (in excerpt):

Objective 1.4: Catalogue and understand potential hazards to Earth from space. NASA is working toward a congressionally mandated goal to discover, by 2008, at least 90 percent of asteroids and comets larger than 1 kilometer in diameter that

³ Hearing on “The Threat of Near-Earth Asteroids,” Committee on Science, U.S. House of Representatives, 3 October 2002.

⁴ NASA Associate Administrator for Legislative Affairs, letter to Chair of the House Science Committee, 9 August 1995.

⁵ http://128.102.32.13/impact/news_detail.cfm?ID=22

⁶ Mission 1 is to “Understand and Protect Our Home Planet,” and Goal 1 is to “Understand Earth’s system and apply Earth-system science to improve the prediction of climate, weather, and natural hazards.”

could come near Earth and determine their orbits with sufficient accuracy to predict whether any of them pose a threat to Earth.⁷

The Strategic Plan addresses the scientific exploration of comets and asteroids, such activity falling under Mission 1, Goal 5.⁸ The relevant objective under Goal 5 is:

Objective 5.1: Learn how the solar system originated and evolved to its current diverse state. Major NASA missions will gain an understanding of the evolution of our solar system through...surface exploration of and sample return from the inner planets and small bodies.⁹

The *characterization* of comets and asteroids for hazard-related purposes is not mentioned, but is implicit when taking Goal 1 into account. Objectives 1.4 and 5.1 are assigned to the NASA Space Science Enterprise (SSE), specifically, the Solar System Exploration "Theme."¹⁰

NASA's FY 2004 budget request includes \$1.359 billion for the Solar System Exploration Theme. The *Dawn* asteroid mission and the *Deep Impact* comet mission account for \$145.5 million of that sum, and \$5.3 million is required for operational support of the *Stardust* cometary encounter (Table 2.10). The total NASA Budget Request is for \$15.469 billion. Thus, including the comet and asteroid probes, funding for efforts related to the impact hazard represent about 11 percent of NASA's FY2004 Solar System Exploration budget request, and one percent of the total NASA request for that year.¹¹ NEO survey funding (that is, not including the "characterization" missions) amounts to \$4.062 million, thus about 0.3 percent of the Solar System Exploration request, and 0.026 percent of the total NASA request.

Any NASA interest in NEO hazard mitigation is conspicuously absent. As mentioned at the end of Chapter Two, NEO advocates are hoping to change that.

National Research Council

The involvement of the NRC in shaping U.S. NEO policy has been largely a matter of issuing various pertinent reports. As discussed in Chapter Two, the Space Studies Board of the NRC issued two reports that were relevant to the future of NEO survey efforts: *Astronomy and Astrophysics in the New Millennium* (2001) and *New Frontiers in the Solar System—An Integrated Exploration Strategy* (2002). These reports supported expansion of the Spaceguard Survey to address smaller NEOs, and a program to facilitate such expansion (LSST).

Earlier, the NRC Space Studies Board released a document entitled *The Exploration of Near-Earth Objects* (1998). This report addressed the scientific rationale, rather than the

⁷ NASA 2003 Strategic Plan, pp. 12-14 and Appendix III, p. A-10.

⁸ Goal 5 is to "Explore the Solar System and the universe beyond, understand the origin and evolution of life, and search for evidence of life elsewhere."

⁹ NASA 2003 Strategic Plan, Appendix III, p. A-11.

¹⁰ NASA is organized into 18 "themes," which represent its structure for budget planning, management, and performance reporting purposes. The reader should recall from Chapter Two that it was the Science Director for Solar System Exploration in the NASA Office of Space Science who committed to the Spaceguard Survey goal in 1998 congressional testimony. The NEO Program Office at JPL reports to that same Science Director.

¹¹ NASA FY2004 Budget Request, www.nasa.gov/about/budget/AN_Budget_04_detail.html

hazard-related rationale, for NEO science. Notably, the report expressed a concern about the social effects of NEO impact warnings.¹²

National Science Foundation

The National Science Foundation (NSF) provides about two thirds of the federal support for U.S. ground-based astronomy, and almost all support for radio astronomy. In contrast, NASA provides about 75 percent of the funding for all astronomy (since space-based astronomy using platforms like the Hubble Space Telescope is so expensive).¹³ Consequently, NASA funding such as exists for ground-based NEO surveys is something of an anomaly as is its funding of NEO radar studies using radio telescopes (as discussed in Chapter Two). This type of overlap in agency involvement can sometimes lead to problems such as occurred in 2001 when NEO-associated funding of the Arecibo radio telescope was cut by NASA and then quickly restored after a storm of protest.¹⁴

Finally, the NSF is the sponsor of the National Virtual Observatory program (discussed in Chapter Two in connection with the LSST).

U.S. Air Force

Chapter Two discussed in detail the role of the USAF in supporting the Spaceguard Survey, primarily by sharing the use of military telescope facilities. The Steering Group overseeing the NEO Program Office included USAF participation, and was discussed earlier in this chapter. At a higher level, NEO survey cooperation became an occasional issue for the Partnership Council, a group established in 1995. The Partnership Council originally included the NASA Administrator and the commander of the Air Force Space Command. It was later expanded to include the National Reconnaissance Office (NRO), the U.S. Strategic Command, and the Department of Defense (DoD) Director, Defense Research and Engineering (DDR&E).¹⁵

As noted in Chapter Two, there is no explicit military requirement for “planetary defense.” This has not deterred the generation of multiple studies under USAF auspices, however. These studies were reviewed in Chapter Three.

Foreign Governments

United Kingdom

Outside the United States, the U.K. is the only national government to take a direct and continuing interest in the NEO impact hazard. In the United States, the interest of key members of Congress was noted above. In the U.K., a particular Member of Parliament (MP), Lembit Öpik (Liberal Democrat, Montgomeryshire), helped to spearhead the government’s interest.¹⁶ As discussed in Chapter Two, the U.K. government funded the creation

¹² *The Exploration of Near-Earth Objects*, Committee on Planetary and Lunar Exploration, Space Studies Board, Commission on Physical Sciences, Mathematics, and Applications, National Research Council, 1998, p. 18.

¹³ www.aaas.org/spp/rd/04pch15.htm

¹⁴ www.space.com/scienceastronomy/astronomy/arecibo_nasa_011220.html

¹⁵ www.hq.nasa.gov/office/codea/codeac/WWW/partnership.html and www.space.com/news/nasa_townhall_021008.html

¹⁶ By no coincidence, the father of this MP was Ernst Öpik, a luminary in the field of NEO science.

of an "NEO Information Centre" which commenced operations in 2002. Little of note has happened since then.

Australia

In 1995, Australia terminated its involvement in the Anglo-Australian NEA Survey (AANEAS), based in Siding Springs, Australia, and mentioned in Chapter Two. The NEO Survey Workgroup Report had cited this project as "one of the strongest on-going efforts" so its cancellation came as a rude shock to the NEO community.¹⁷ It was particularly valuable for astrometric follow-up, and was the only NEO survey based in the Southern Hemisphere.

In 2002, the international NEO community initiated a lobbying campaign to reverse the Australian decision, sending an "open letter" to the Australian Minister of Science. The letter was signed by 45 NEO specialists from around the world.¹⁸ The effort backfired, however, as the Minister, under pressure, publicly pronounced that he was "not going to be spooked or panicked into spending scarce research dollars on a fruitless attempt to predict the next asteroid." He characterized the NEO survey as a "fruitless, unnecessary, self-indulgent exercise," and went on to say that he was "just not convinced that the hype and alarm and even fear-mongering is enough to justify an instant investment."¹⁹ The funding was not restored.

International Bodies

United Nations

Chapter Two discussed past U.N. involvement in the NEO hazard issue. This has consisted of one co-sponsored conference devoted to the subject in 1995 and a passing mention included in the final declaration of the UNISPACE III conference in 1999. Should activities related to NEO mitigation gain momentum, it could be expected that issues associated with the militarization of space would become contentious. The U.N. forum for resolving these issues would be the Committee on the Peaceful Uses of Outer Space (COPUOS), with its executive arm, the U.N. Office for Outer Space Affairs (OOSA), located in Vienna. COPUOS is the body responsible for interpretation of the "five treaties," the international treaties that collectively form the basis of international space law. The U.N. Conference on Disarmament in Geneva has higher oversight over space militarization issues, however.²⁰

Of the five treaties, the ones most relevant to the NEO impact hazard (specifically, interception of threatening NEOs) are the Outer Space Treaty (discussed in Chapter Two in connection with the use of nuclear devices or "warheads" in space) and the Liability Convention. The latter "provides that launching States are liable for damage caused by their space objects on the Earth's surface" and could become relevant if an interception attempt

¹⁷ *Near-Earth Objects Survey Workgroup Report*, (Chapter 8), NASA, Solar System Exploration Division, Office of Space Science, June 1995.

¹⁸ "An Open Letter to the Australian Federal Government from International Scientists—Australia's Contribution to Spaceguard," 29 January 2002.

¹⁹ Australian Science Minister Peter McGauran, speaking on Australian television program "60 Minutes," 17 March 2002. (www.space.com/scienceastronomy/solarsystem/asteroids_australia_020319.html)

²⁰ www.oosa.unvienna.org/OOSA/oosa.html

(or experiment) results in fragments of a disrupted NEO impacting the Earth absent some type of “hold harmless” agreement.²¹

Should NEO resource exploitation (mining of asteroids and comets for their metal or mineral content) ever approach reality, the Moon Treaty would become relevant. This treaty sets up the basis for the future regulation of the exploration and exploitation of space resources. Although considered to be in force as a matter of international law, among the spacefaring nations only India has signed the treaty.²²

Council of Europe

As noted in Chapter Two, the Parliamentary Assembly of the Council of Europe issued a resolution “on the detection of asteroids and comets potentially dangerous to humankind” in 1996. The resolution also called for “setting-up and development” of the Spaceguard Foundation (addressed below).

European Space Agency

As is the case with NASA, the bulk of ESA’s support of projects related to the NEO impact hazard has taken the form of space missions. The European *Rosetta* spacecraft is enroute to Comet Cheryumov-Gerasimenko, with an encounter in 2014.²³ The spacecraft *Giotto* imaged comets Halley and Grigg-Skjellerup in 1986 and 1992, respectively (Table 2.10).

In July 2002, ESA provided funding for preliminary studies on six proposed space missions specifically designed to address the NEO impact hazard:²⁴

- **Don Quijote.** Two spacecraft test technologies required to deflect an asteroid heading towards Earth. One impacts a 500-meter asteroid at a relative speed of 10 kilometers per second while the other delivers sensors to the asteroid surface and observes what happens during and after the collision. Data on the asteroid’s internal structure is gathered.
- **Earthguard 1.** A ‘hitchhiker’ telescope is mounted on a spacecraft en route to the inner Solar System; for example, ESA’s *BepiColombo* Mercury orbiter. The telescope would detect ECAs larger than about 100 meters.
- **European NEO Survey (EUNEOS).** A medium-sized space telescope searches for NEOs from inside the orbit of Venus. Its main goal is to detect 80 percent of the potentially hazardous objects down to a few hundreds of meters in size within five years. Systematic re-detection of the objects ensures that their orbits are determined with high accuracy.
- **Internal Structure High-resolution Tomography by Asteroid Rendezvous (ISHTAR).** The mass, density and surface properties of an NEO are measured *in*

²¹ The 1971 *Convention on International Liability for Damage Caused by Space Objects*, entered into force on 1 September 1972.

²² The 1979 *Agreement Governing the Activities of States on the Moon and Other Celestial Bodies* entered into force on 18 December 1979.

²³ *Rosetta*’s costs approach one billion euros, increasing as a result of program delays (www.planetary.org/html/news/articlearchive/headlines/2003/rosetta_delay-threatens-mission.html).

²⁴ www.esa.int/export/esaCP/SEMI919YFDD_index_0.html

situ, and its interior is probed using radar tomography in order to study its structure and internal strength.

- **Smallsat Intercept Missions to Objects Near Earth (SIMONE).** Five microsatellites fly by or orbit different types of NEO. Each spacecraft carries a suite of scientific instruments that provides insights into the nature of large asteroids (400–1,000 meters in diameter) with different physical and compositional properties.
- **Remote observation of NEOs from Space.** A space telescope carries out remote sensing and detects physical characteristics of NEOs, such as size, composition and surface properties.

While these competing proposals are not yet funded beyond the initial study phase, they do give an indication of the European interest in addressing the NEO impact hazard. Perhaps more tangible is the fact that an NEO-spotting telescope is under consideration for addition to ESA's *Gaia* mission, planned for launch in 2010.²⁵

Professional Societies, Private Organizations and Advocacy Groups

American Institute of Aeronautics and Astronautics

The AIAA is a professional society for aerospace engineers and scientists. The pivotal role of the 1990 AIAA position paper, "Dealing with the Threat of an Asteroid Striking the Earth," was discussed in Chapter Two. In 1995, the AIAA issued an updated position paper entitled "Responding to the Potential Threat of a Near-Earth-Object Impact."²⁶ The update had four recommendations:

- Accelerate the detection of NEOs;
- Establish a systems engineering and analysis program to plan follow-on activity;
- Perform experiments in accordance with the results of the above; and
- Establish a management focal point to coordinate the domestic and international activity.

In March 2001, the AIAA organized the 6th International Space Cooperation Workshop. The Executive Summary of the Workshop report included the following language regarding the NEO impact hazard:

An international study should be initiated on how the world's current space-flight capabilities, properly augmented with interceptors and effectors, might be used to counter a near-term NEO threat. Such a capability may, in the long term, evolve into a dedicated International Planetary Defense System.²⁷

The Workshop report also demonstrated unequivocal support of NEO space telescopes:

²⁵ www.spacedaily.com/news/deepimpact-02g.html

²⁶ "Responding to the Potential Threat of a Near-Earth-Object Impact," AIAA Position Paper, 1995.

²⁷ 6th *International Space Cooperation Workshop Report*, AIAA International Activities Committee, Seville, Spain, March 2001, p. 2. The Workshop was co-sponsored by the U.N. OOSA, the Confederation of European Aerospace Societies (CEAS), and the International Academy of Astronautics (IAA).

A NEO-dedicated 1-m[eter]-class near-infrared space telescope facility should be stationed at the L2 Lagrangian point. In addition, several 25-m[eter]-class optical telescopes should be placed in space to detect long-period comets with adequate warning time for action to be taken.²⁸

It seems clear that the response of the Workshop participants to the low probability aspect of the NEO impact hazard was, for whatever reason, to display an essentially absolute aversion to risk.

National Optical Astronomy Observatories

From their web site, “NOAO’s purpose is to provide the best ground-based astronomical telescopes to the nation’s astronomers, to promote public understanding and support of science, and to help advance all aspects of US astronomy.”²⁹ NOAO receives its funding from the NSF and strongly supports expanding the NEO Spaceguard Survey goal, as discussed in Chapter Two.³⁰

National Defense Industrial Association

NDIA (formerly the National Security Industrial Association or NSIA) is a U.S. defense industry advocacy group. From their web site:

Our Government Policy business center works to strengthen the government-industry partnership through dialogue, education, and interaction. The center monitors legislative and regulatory issues and interacts with Congress and federal agencies, as well as a number of industry working groups.³¹

In 1996, NSIA released an Issue Brief on Planetary Defense. This “brief” simply alerted the NSIA membership to the prospect of government expenditures for “planetary defense” research and development (R&D):

Any development of a planetary defense program will most likely concentrate on high-tech R&D in areas similar to ballistic missile defense. In addition, deep space tracking and surveillance systems and high endurance propulsion systems would be integral parts of any program. Companies specializing in these areas could receive a boost in their R&D efforts.³²

International Astronomical Union

The mission of the IAU is to “promote and safeguard the science of astronomy in all its aspects through international cooperation.” Its individual members are “professional astronomers at the Ph.D. level or beyond and active in professional research,” although the IAU “maintains friendly relations also with organizations that include amateur astronomers in

²⁸ *Ibid*, p.15.

²⁹ www.noao.edu/outreach/aboutnoao.html

³⁰ www.noao.edu/outreach/press/pr03/pr0303.html

³¹ www.ndia.org/Content/NavigationMenu/Resources1/Mission_Statement.htm

³² Issue Brief on Planetary Defense, 104-53, NSIA, November 1996.

their membership.”³³ The past actions of the IAU and its NEO working group (the WGNEO) with respect to the NEO impact hazard were discussed extensively in Chapter Two.

Spaceguard Foundation

As noted in Chapter Two, the Spaceguard Foundation is a “private organization that groups observers, both professional and amateur, as well as people and organizations with no particular astronomical background who want to contribute to the activity of the Foundation.”³⁴ The official emblem of the Foundation is depicted in Figure 4.1.³⁵ While headquartered in Italy, affiliated “Spaceguard Foundations” exist in the U.K., Japan, Croatia, and Germany. The Foundation’s purpose is:

- To promote and co-ordinate activities for the discovery, pursuit (follow-up) and orbital calculation of the NEO at an international level;
- To promote study activities—at theoretical, observational and experimental levels—of the physical-mineralogical characteristics of the minor bodies of the solar system, with particular attention to the NEO; and
- To promote and co-ordinate a ground network (the Spaceguard System), backed up by possible satellite network, for the discovery observations and for astrometric and physical follow-up.³⁶

Project B612

Introduced at the end of Chapter Two, Project B612 is a non-profit, private foundation dedicated to supporting an interception effort: to “significantly alter the orbit of an asteroid

Figure 4.1
Emblem of the Spaceguard Foundation



³³ www.iau.org

³⁴ The Spaceguard Foundation has no connection to the NASA Spaceguard Survey, other than a sharing of general objectives. (<http://spaceguard.rm.iasf.cnr.it/>)

³⁵ In translation, the motto of the Spaceguard Foundation reads "...neither with the certainty to find the truth, nor without hope" (Lucius Annaeus Seneca, *Quaestiones Naturales*, Book VII, "de Cometis" [29,3]).

³⁶ <http://spaceguard.rm.iasf.cnr.it/SGF/INDEX.html>

in a controlled manner by 2015.”³⁷ It was established in October 2002. Tax-exempt contributions to support the project are solicited from visitors to the B612 web site.

Cambridge Conference Network

The Cambridge Conference Network (CCNet) is an Internet NEO discussion forum that bills itself as a “scholarly electronic network” with the aim of disseminating information and research findings related to:

- Geological and historical neo-catastrophism;
- NEO research and the hazards to civilization due to comets, asteroids and meteor streams; and
- The development of a planetary civilization capable of protecting itself against cosmic disasters.³⁸

Unfortunately, CCNet has played a key role in magnifying errors in communication surrounding past NEO discoveries (such as the 1999 AN10 asteroid scare discussed in Chapter Two). This is partly due to its format (a very loosely moderated, freewheeling interaction resulting in truly prodigious amounts of noise with occasional signal). It is also partly due to the variety of its open membership (ranging from NEO scientists through experienced amateurs to inhabitants of the social fringe, including many representatives of the international news media).

Summary

This chapter has briefly reviewed those organizations that have had a role in shaping society’s response to the cosmic impact hazard to date. By now, some common themes should be evident to the reader. Interested stakeholders have had a key role in driving the issue into the ken of policymakers. Sometimes these stakeholders have gone directly to the public in an attempt to impel policymaker action. Some organizations have resisted having their charters expanded to include responsibility for this remote hazard. On the other hand, some have begun to notice the almost guaranteed public interest in the hazard and have proposed new programs (or re-cast programs) to benefit from that interest. NEO advocates (especially “planetary defense” advocates) display, for whatever reason, a much higher level of risk aversion to the hazard than evinced by the general public. Finally, unusually high leverage is enjoyed by those interested parties with a high level of power (*e.g.*, legislators, by society’s design) or influence (*e.g.*, Internet discussion group moderators, by society’s default). This leverage is symptomatic of an imbalance between public interest and public expenditure and will be the subject of further discussion.

³⁷ www.b612foundation.org/

³⁸ <http://abob.libs.uga.edu/bobk/cccmenu.html>

Toward a Comprehensive Policy Approach

This chapter develops a framework for a comprehensive impact hazard policy, building on the work of previous researchers and picking up the threads of argument introduced in prior chapters. The purpose of Chapter Five is to provide the theoretical underpinning for the structure of a new model to be presented in Chapter Six, and for the choice of parameters included therein.¹

A cost-benefit methodology is chosen. The limitations of that technique were addressed in Chapter Three, particularly its sensitivity to valuations and discounting assumptions. Chapter Six will demonstrate how those sensitivities can be accommodated, if not resolved, by a quantitative exploration of the parameter space.

Among the reasons for choosing cost-benefit are the following:

- Cost-benefit analysis is a technique known to practitioners in many different fields. The present study is multidisciplinary in scope, and the use of an analytical *lingua franca* enables its arguments to be made to the widest possible audience.
- The new model to be presented in Chapter Six will be based on the foundation of an existing cost-benefit analysis (the SDT model).
- The methodology is quite adequate for the illustrative purpose intended.

This chapter is structured around flow diagrams of progressively increasing model sophistication. It will analyze three different policy interventions. The last of these will feature in the model presented in Chapter Six (for reasons that will become apparent).

Adding Complexity to a Simple Foundation

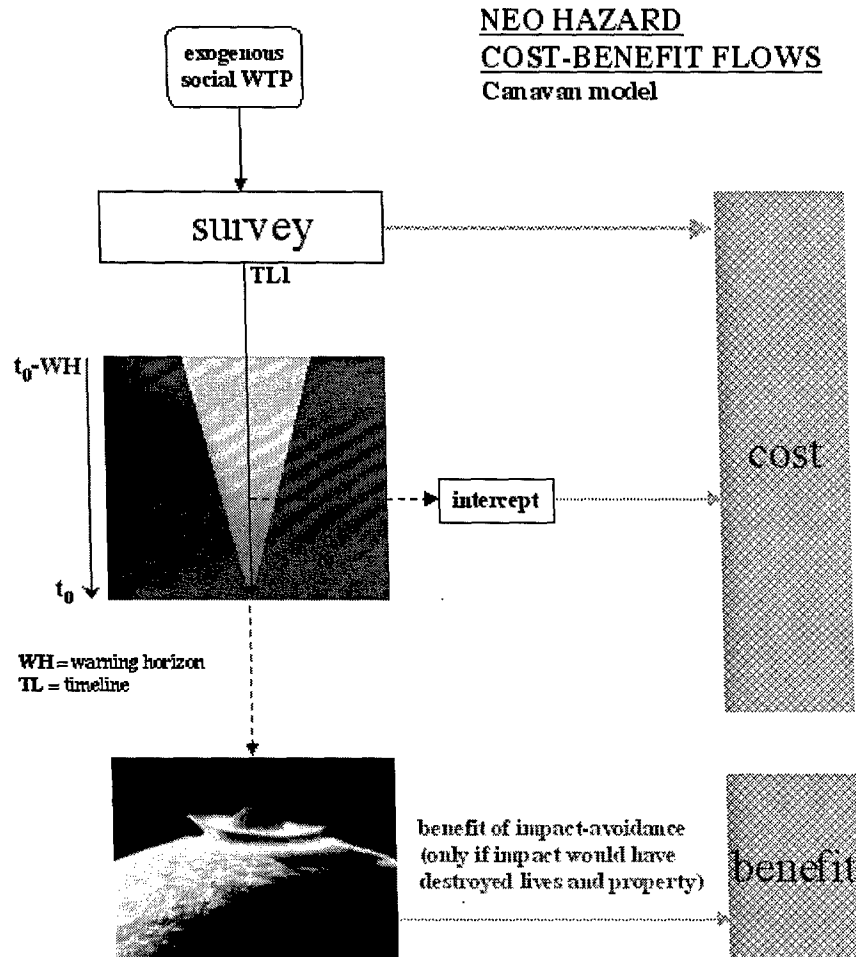
Previous Modeling Approaches

The simple flow diagram shown in Figure 5.1 is a functional representation of the Canavan cost-benefit model reviewed in Chapter Three.² Society has a willingness-to-pay (WTP) for

¹ In fact, this chapter goes beyond the static model presented in Chapter Six, concluding with dynamic frameworks that incorporate system effects. A static model suffices to illustrate the main points made in this and preceding chapters, but a dynamic model would clearly be superior for a prescriptive purpose.

² Canavan, G., "Cost and Benefit of Near-Earth Object Detection and Interception," *Hazards Due To Comets And Asteroids*, Gehrels, T., editor, University of Arizona Press, Tucson, Arizona, 1994, pp. 1157-1189.

Figure 5.1
Simple cost-benefit model



NEO survey efforts that originates outside the model and thus is exogenous. These NEO survey efforts incur a direct cost (indicated by the solid line leading to the right).³

The gray square with an inverted light gray triangle is a timeline representation of the "triangle of fear" shown in Figure 2.22 (here we can call the triangle the "nabla of fear" after one of the mathematical names for an inverted delta).⁴ The upper edge (base) of the nabla corresponds to the time that a threatening object is discovered, the lower point (apex) is an impact event at time t_0 . The vertical extent of the nabla is thus the warning horizon. Object timelines take the form of perpendiculars dropped from the survey box. A timeline that only drops through a dark gray area is discovered but is never threatening, and thus never generates a warning. A timeline that drops through the base of the nabla offset from the apex generates an initial warning, but when it leaves the nabla into the dark gray zone, the "all clear"

³ In these flow diagrams, the thicker the arrow, the greater the flow. Solid arrows are certain, dashed arrows are probabilistic. The rounded box indicates a start point, and the square boxes indicate a process (both being standard flowchart symbols).

⁴ "Nabla" is the ancient Aramaic word for harp, an instrument that the inverted delta resembles.

is sounded. Figure 5.1 includes only one timeline (TL1), since no warning costs are considered in the Canavan model.

A probabilistic dashed line leads to the right from TL1. This line represents an interception attempt. In the Canavan model, all interception attempts are successful, and no interceptors are launched at objects that are not eventual impactors.

Finally, we have a probabilistic dashed arrow extending from TL1 to a picture of an impact event. A line extends to the right, depicting the benefit of impact-avoidance. In the bookkeeping used for these models, costs and benefits are defined as zero if no action is taken, and the lives or property saved by interception are put on the "benefit" side of the ledger.

In the Canavan model, no benefit is accrued from lives saved. As noted in Chapter Three, he quantifies all benefits in terms of an energy-scaled total global product.

It is interesting to note that the SDT model, which is to be more fully described in Chapter Six, has the same flow diagram as the Canavan model except that the interception contribution to cost is absent. In other words, credit is taken for lives and property saved without accounting for the means of their delivery from harm.

The SDT model differs from that of Canavan also in its measurement of benefit, accounting for both lives and property. The estimate for the latter borrows from Canavan, assumes that people and their possessions are generally co-located, and scales total global product by the ratio of human casualties to global population. For the value of human life, the SDT study turns to the work by D. Kenkel reviewed in Chapter Three: "Using Estimates of the Value of a Statistical Life in Evaluating Regulatory Effects."⁵ This will be discussed further in Chapter Six.

Costs of Alarm and Warning

Figure 5.2 shows the addition of costs of alarm and warning to the model representation of Figure 5.1.⁶ In addition, the costs of evacuation from an impact target zone are added (these costs are not considered by either the Canavan or SDT models).

We still have a static model with an exogenous WTP. However, there are two additional timelines extending down from the survey box. TL2 shows an object that generates a warning as it enters the nabra of fear. After a while, alarm in the population and amongst policymakers rises to the point that society incurs a needless cost: an interceptor is launched toward an object that is destined to never hit the Earth. The dashed arrow leading to the right from this point shows the "technical costs of warning." After the interceptor is launched, TL2 either ends (that is, the object is destroyed or deflected) or continues into the dark gray zone, where the object is no longer a major concern.

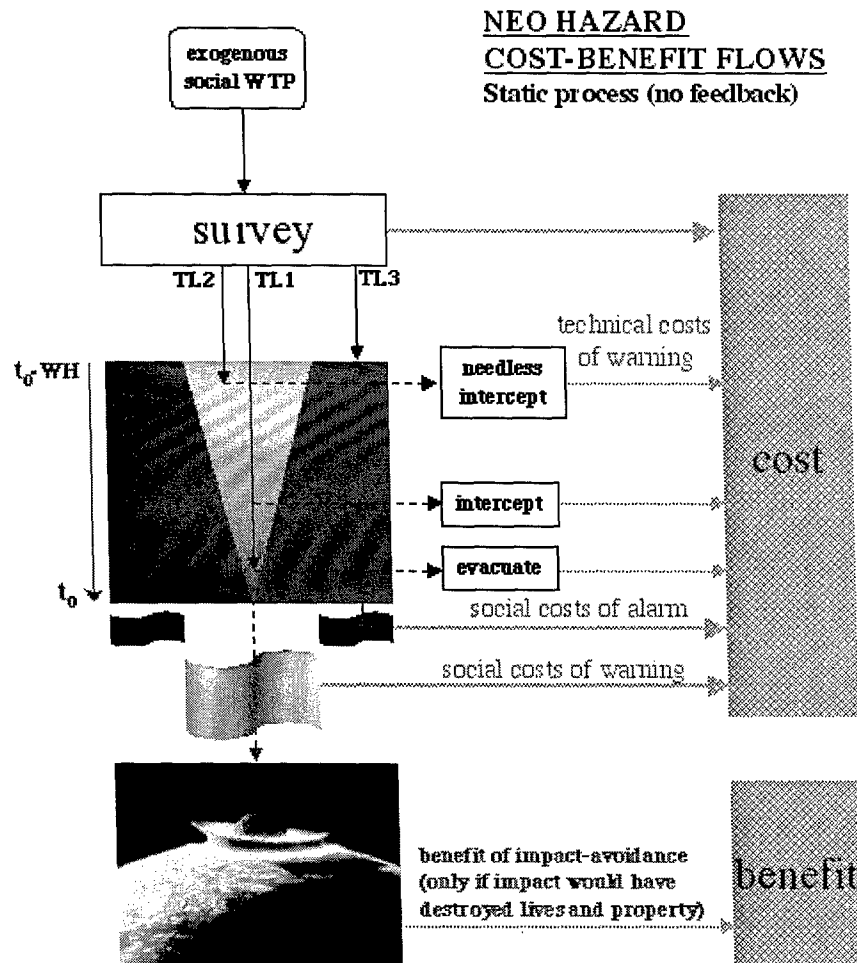
TL1 is the same timeline that was shown in Figure 5.1, but with an arrow to the right showing a probabilistic evacuation (following a probabilistic interception attempt).

Below the nabra of fear, we see a light gray glyph that depicts the accumulated costs of warning for all timelines within the base of the nabra. On either side of this glyph there

⁵ Kenkel, D., "Using Estimates of the Value of a Statistical Life in Evaluating Regulatory Effects," Session 1, "Valuing Statistical Lives," *Valuing the Health Benefits of Food Safety: A Proceedings*, Kuchler, F., editor, U.S. Department of Agriculture Economic Research Service, MP1570, April 2001.

⁶ The semantic convention used for "alarm" and "warning" is consistent in this work. A government or other competent authority issues a "warning." A warning is sufficient but not necessary for a social "alarm" to result.

Figure 5.2
Adding the costs of alarm and warning



are two similar dark gray ones. These represent the accumulated costs of alarm—those costs that are incurred in the absence of an official government warning and which would result from social misperception or misunderstanding (to be addressed later in this discussion). TL3 is a timeline that results in alarm costs, but no warning costs.

Before proceeding to the next model “upgrade,” it is worthwhile to consider these costs of alarm and warning in more detail. Chapter Two established the physical and institutional processes by which NEO survey programs generate shocks to social equanimity. We now examine the question of social response.

Table 2.9, Figures 2.27 through 2.32, and their associated discussions enumerate many cases in which asteroids and comets induced alarm in the population. Why should we have concern for the future in this regard? There are a number of reasons:

- NEO survey efforts will in all likelihood continue to expand, as a result of advocacy group pressure coupled with public receptiveness.
- Impact scares of the recent past were sparked by astronomers who were clumsy in explaining the risk, or were amplified by those who stood to gain from an exaggerated

social response (scientists seeking attention, sensationalist news media, and so forth). However, there is an almost complete uncertainty regarding society's response to a scientifically-blessed warning of impending doom.

- Unlike the direct and quantifiable (although still somewhat uncertain) technical costs associated with the impact hazard, the social costs may well be indeterminate before the fact. Even after the fact, it may be impossible to separate the "signal from the noise." It does not take much of a decline in the stock market or reduction in global economic output to utterly swamp the putative benefits of a survey program. If such effects occurred, they might never be attributed to the impact scare, given other factors at play in the economy. However, an effect's insusceptibility to measurement does not negate its existence.

Notwithstanding the uncertainty of social costs, in the discussion that follows it must be remembered that the primary purpose of an NEO survey is to enable a mitigation response should one be required.⁷ Conversely, the survey's purpose is vitiated without an ability to mitigate the threat *at some point*. The purpose is *not* to warn the public except to the extent that scientists presume to apply pressure thereby to policymakers.⁸

There are two avenues of inquiry regarding the social costs of warning. One is to review social experience using analogous cases. The second is to examine the policy literature, considering the theoretical mechanisms by which such costs might be incurred.

Figure 5.3 shows a pastiche of the warnings and alarms experienced in four analogous cases. In each case, the social costs are apparent. In each case, the social costs have not been measured and will likely never be measured. Especially in the two warning cases (Figures 5.3a and 5.3d), there is good reason to believe that the social costs far outweigh the benefits of warning.

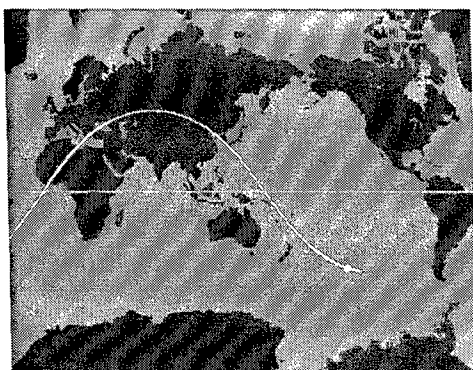
Figure 5.3a shows the ground track and impact zone for the Russian *Mir* space station, de-orbited by flight controllers in March 2001. The spacecraft impacted in the ocean between New Zealand and South America. Of relevance to this discussion, the chairman of the Japanese National Public Safety Commission, Bunmei Ibuki, told the inhabitants of the southernmost Japanese islands that "during the dangerous forty minutes, you had better stay home." He then stated that the probability of *Mir* debris falling on Japan was "one in 100 million" although the analytical basis for his remark was unclear.⁹ The true probability may well have been less than that. Although *Mir* passed over Japan in its last orbit, physics dictates that only two circumstances could have caused an impact in Japanese territory. Either a saboteur or technical fault would have had to initiate an early de-orbit burn or *Mir* would have had to collide at just the right time with an object of significant mass heading in the opposite direction. In any event, it is doubtful whether the chairman's advisory would have survived the scrutiny of cost-benefit analysis.

⁷ Another purpose recently voiced in the NEO community is to "retire the risk" so as to reduce social dread. The author would guess, though, that the costs incurred by those who are kept awake at night due to the NEO threat are balanced by the benefits accruing to thrill-seekers.

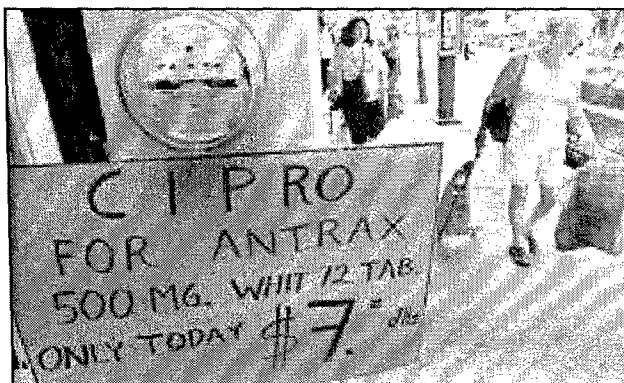
⁸ This presumption was painfully apparent in the NEO community's "open letter" to the Australian Minister of Science and the ensuing debacle, described in Chapter Four.

⁹ <http://news.bbc.co.uk/1/hi/world/asia-pacific/1225482.stm>

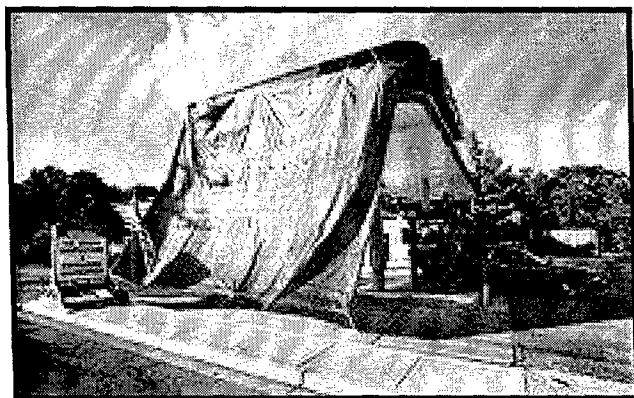
Figure 5.3
Costs of warning in many flavors



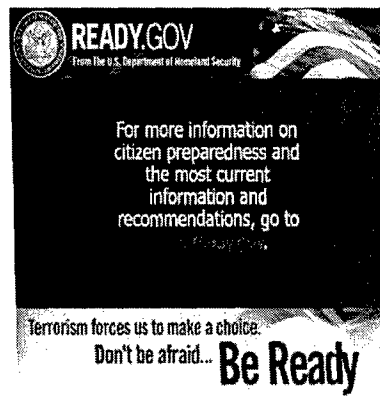
a. *Mir* warning



b. Anthrax alarm



c. Sniper alarm



d. Endless terror warning

Figure 5.3b shows the antibiotic Ciprofloxacin on sale during the U.S. anthrax scare of late 2001. Only seven people had contracted the disease by 18 October of that year, but panic was gripping the nation. The Director of the U.S. Department of Homeland Security (DHS) gave a press conference that day, trying to calm public nerves.¹⁰ Two observations are relevant to the current discussion. One is that, in any scare, some stakeholders profit—in this example it is the Cipro merchant who would no doubt have preferred the DHS Director to remain silent. The other is that the anthrax scare, coming as it did in the wake of the September 11th terror attacks, almost certainly was magnified by social reaction to those attacks. The same will be true of serious NEO impact alarms, which may well happen at an inconvenient time or involve an unfortunate location. It is exceedingly unlikely that an NEO will impact on September 11th of any given year, and it is even less likely that one will hit New

¹⁰ www.time.com/time/nation/article/0,8599,179760,00.html

York City—but there are many significant days and many sensitive locations that could magnify warning costs.¹¹

Figure 5.3c depicts an anti-sniper tarpaulin raised by a gasoline station owner in the Washington, D.C. area during the sniper rampage of 2002. Ten people were killed and millions were terrorized; but an individual's chance of taking a sniper bullet was miniscule. Nevertheless, this gasoline station owner went to extraordinary lengths to reassure his customers. The cost of doing so was no doubt borne privately, and would not appear in any loss statistics. The lesson when considering costs of impact hazard warning is that many (if not most) such costs will appear "off the books."¹² On the other hand, the gas station owner's action no doubt gave him an advantage relative to his competitors who did nothing to reassure their customers. The lesson of *this* is that what first appear to be costs may actually result in a net benefit.

Finally, Figure 5.3d shows an advertisement for the somewhat-Orwellian DHS web site READY.GOV.¹³ This web site is a monument to the practice of ignoring the social effects of false positives (noted in Chapter Three with respect to the disaster management community). There is even a linked web site for children, "FEMA for kids," with the note "Kids Go Here."¹⁴ One wonders whether any child psychologists were in the approval chain for this effort to reach the smallest of potential terror victims. The following two paragraphs are found on the "FEMA for kids" web pages:

What are biological weapons? They are organisms or toxins that can kill or injure people, livestock and crops. The three basic groups of biological agents that might be used as weapons are bacteria, viruses and toxins. These biological agents may be put out in the air or water or food.¹⁵

Nuclear explosions can cause blinding light, intense heat, fires and radiation fallout. You may have heard the term "dirty bomb," as a terrorist weapon. A "dirty bomb" is an explosive device that scatters radioactive material. You may have also heard the term "suitcase bomb," which is a very small nuclear device about the size of a suitcase.¹⁶

It is hard to believe that a child with limited experience and vocabulary could read the above descriptions of death and destruction without serious misconceptions of the risk or nature of terrorist threats. A profoundly disturbing element of these web pages is the jarring choice of accompanying artwork, examples of which are shown in Figure 5.4.

On the bright side, death-by-asteroid does not feature in "FEMA for kids."

¹¹ An example from Chapter Two is relevant here: "...if (the detonation) had occurred at the same latitude a few hours earlier, the result could have been much worse. Had the explosion occurred over India or Pakistan, the resulting panic could have sparked a nuclear war." <http://news.bbc.co.uk/1/hi/sci/tech/2246449.stm>

¹² The related problem of quantifying uninsured losses was noted in the NRC report *The Impacts of Natural Disasters—A Framework for Loss Estimation*, reviewed in Chapter Three.

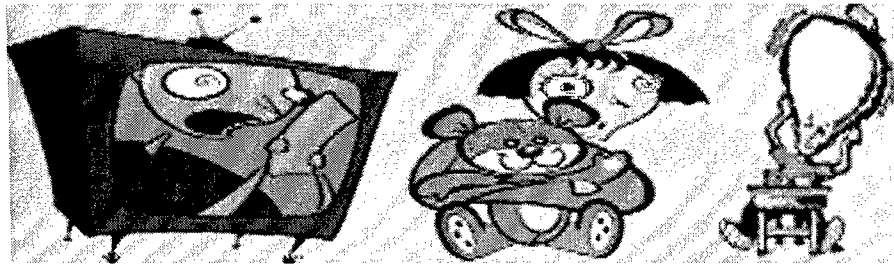
¹³ Unsurprisingly, www.ready.gov

¹⁴ www.fema.gov/kids/ The part of this web site named "National Security Emergencies" can be accessed by children who self-certify that they have an adult's "OK."

¹⁵ www.fema.gov/kids/nse/biological.htm

¹⁶ www.fema.gov/kids/nse/radiological.htm

Figure 5.4
No child left unharmed?



SOURCE: Artwork from www.fema.gov/kids/

Figure 5.5 shows a warning scale generated by the Electronic Privacy Information Center (EPIC), a U.S. non-governmental organization (NGO).¹⁷ This scale graphically demonstrates *one* of the social costs of terror warnings by turning the DHS terror threat advisory scale on its head. The EPIC scale warns of U.S. government threats to civil liberties, correlated in some measure with its eagerness to prosecute the “war” on terror.

Figure 5.5
Endless war, endless warning costs



To complete this review of analogous cases, we turn from the generation of alarm and warning costs to the question of how these costs evolve over time. It can be expected that total costs will depend on warning frequency, but how so is a matter of conjecture. There is no particular reason to believe that costs will be simply additive: warnings feed on other warnings, and sometimes on warnings issued regarding a different threat (as noted above with reference to the anthrax scare). Alarms can build into frenzies, in a crescendo of social angst. After enough false warnings, though, familiarization can be expected to set in (the “cry wolf” effect), and associated costs will then increase at a diminishing rate. The problem is

¹⁷ www.epic.org

determining the shape of this warning cost function *ex ante*. Chapter Six will propose a hypothetical form for such a function.

The story of the boy who cried "wolf" ends with a real wolf making an appearance. The moral of the story in policy-speak is that the familiarization resulting from frequent false positives causes increased costs following a true positive, an *ex post* argument. If wolves are sufficiently rare, familiarization carries a social benefit, and so it may well be with the impact hazard, *ex ante*.

Finally, warning costs do not accumulate in a social vacuum. Policymakers can intervene, and three model frameworks showing a "pulling of the policy levers" are examined later in this chapter. The role of the news media and other organs of public communication (such as movie studios, documentary producers, and so forth) is crucial in amplifying or attenuating public alarm. There is some evidence that initially, news media tend to fan the flames of an alarm, but once it is realized that social reaction is spinning out of control, the media reverse course and switch to a strategy of social reassurance.¹⁸

Moving beyond the dependency of social costs on warning frequency, we must recognize that the mechanisms by which those costs are incurred will depend critically on the warning horizon (the time from detection of a threatening object until its possible impact). Short warnings can be expected to incur "acute" social costs that are within the scope of human experience. These would not necessarily be the result of panic, but various manifestations of social disruption could occur, including distortions in financial markets. Nevertheless, the effects would be similar to those resulting from more familiar hazards or human conflicts and the literature of social psychology is germane. Perhaps short warnings would cause riots or other civil disturbances, but perhaps not. People have a tendency to pull together *in extremis*, at least in situations in which there is not an immediate threat to one's own life and limb and the resources that enable individual survival are not scarce.¹⁹

A more difficult question is the nature of society's reaction to a long-term warning of potential doom. Because of the possibility that threatening NEOs could be detected and then lost (that is, for various reasons, follow-up observations might not be conducted in time), a state of impact warning occasionally could endure for years. The more serious the warning, of course, the more social pressure would exist to recover the object and end the alert state—but that could take time, during which social costs of warning would accumulate.

This is the "Sword of Damocles" extended from the individual to the societal level. Unfortunately, because there have been no cases of similar extended social angst in recent memory, one searches in vain for a literature that is germane. The closest parallel might be the indefinite if not permanent "war" on terror, with its pernicious social effects, but that phenomenon is too recent to have generated much in the way of analysis.²⁰ *The Economic Costs of Terrorism* (reviewed in Chapter Three) addressed the effects of uncertainty on consumer and investor behavior, with only a nod to the "catch-all" long-run costs of added anxi-

¹⁸ These phases are termed "mutation-contagion" and "containment." Ungar, S., "Hot Crises and Media Reassurance: A Comparison of Emerging Diseases and Ebola Zaire," *The British Journal of Sociology*, Volume 49, Number 1, March 1998, pp. 36-56.

¹⁹ Dynes, R., et al., *A Perspective on Disaster Planning*, Third Edition, University of Delaware Disaster Research Center, Report Series Number 11, May 1981, pp. 15-20.

²⁰ Another analogous case might be the Palestinian resistance to occupation (the Intifada) and its effect on the Israeli economy.

ety, stress, and mental disorders.²¹ In the short run, September 11th imposed a negative supply-side shock to the economy that raised costs and inefficiencies, but the effects were not long-lasting because of an “adept and rapid offsetting policy response, early success in the war against terrorism, and [the absence of] another terrorist attack.”²² The policy response was for the Federal Reserve to provide immediate liquidity to the market and to lower interest rates, and for the government to put a “rescue package” in place. Consumer confidence, gross domestic product (GDP), orders, and later production and employment all rebounded.²³

However, notwithstanding certain similarities, there are major differences between long-term terror fears and a long-term impact warning. Terror fears dampen investment by raising the risk premium. In other words, projects with lower rates of return cannot attract investors so overall investment decreases. In the case of an impact warning *there is no risk* before the time of possible impact. Although the impact itself is uncertain (as is the location of the impact zone), the time of the possible impact is known very precisely. Hence the nature of the economic costs associated with an impact warning will be inherently different. Any economic activities that cross the “temporal divide” of the impact will possibly be affected—and that divide could be decades in the future.²⁴ Still, the bottom line is that in the impact case, the economic behavior of consumers and investors is unpredictable; there are simply no good precedents for such long-term warnings.

There is a possible solution to this difficulty, however. If it can be shown that for a reasonable range of parameters even a ridiculously low cost per warning is enough to overwhelm the direct benefits of an NEO survey program, then the issue of the mechanism by which social cost is incurred becomes almost moot.²⁵ If the cost per warning *per capita* at the crossover point is a fraction of a U.S. cent, for example, then it is not hard to see that just reading a news article about the impact warning could generate that level of opportunity cost. Alternatively, recall Table 2.3, and the global suicides resulting from the 1910 appearance of Comet Halley. If warnings occur frequently enough, and one suicide results from each warning (and the cost per life of a suicide is not devalued per Kenkel’s suggested monetized-QALY approach), then it is easy to see that no other sources of warning costs are required to make the whole effort socially damaging.²⁶

Perceptions

Society perceives the impact hazard only through the actions of the scientists who gather the source data and their interlocutors, such as the news media. Certainly, policymakers have the option to hold news conferences or otherwise attempt to manage or control information, and

²¹ Saxton, J., Chairman, *The Economic Costs of Terrorism*, Joint Economic Committee, U.S. Congress, May 2002.

²² *Ibid.*, p.5.

²³ A former Undersecretary of Commerce in the Clinton administration, Robert Shapiro, provides an alternative analysis at <http://slate.msn.com/id/2079298/>, with generally similar conclusions.

²⁴ This applies not only to the duration of the economic activities, but also to the time required for those projects to recover their costs of capital.

²⁵ These parameters would include but not be limited to survey effectiveness, life valuation, discount rate, and warning rate.

²⁶ Kenkel, D., *op. cit.*, p.10.

options along those lines will be discussed below.²⁷ However, for now we will consider the ways that the medium chosen for public communication of the hazard can distort reality and thus warp society's perception of risk. This in turn will affect the costs of alarm and warning.

The literature reviewed in Chapter Three is unequivocal: human beings generally perform poorly in conceptualizing probabilities, particularly low probabilities. In dealing with low probability, high consequence events, it might thus be expected that people would be better able to visualize the consequence than the probability. This failing extends to the community of experts who are entrusted in dealing with the particular hazard in question. The review of the NEO community's literature in Chapter Three plus the personal observations of the author over several years confirm that the impact hazard is no different. "Low probability, high consequence" is given lip service at the start of a paper or presentation, and the analysis proceeds to gloss over the rarity while luxuriating in images of death and destruction.²⁸

Today, images rule over words and numbers in shaping public perceptions, and this is particularly true for the impact hazard. In Chapter Two, we saw how constraints of graphic presentation can result in misleading messages about the magnitude of risk.²⁹ We now analyze several images using E. Tufte's "Lie Factor" introduced in Chapter Three (Equation 3.1). It is impossible to determine whether the results are due to the desire of the graphic artist to create an exciting image, or the editor to sell newspapers or advertising, or the scientist to gain attention, respect and hopefully funding. What counts is that the interests of the public are not being served.

Figure 5.6 shows six images where Earth impactors appear grotesquely large relative to the Earth. Lie Factors (LF) are shown beneath each panel (recall that Tufte considers a Lie Factor of fifteen to be extreme—here we have truly astronomical Lie Factors).³⁰ Figure 5.6a shows the Moon in the foreground, rendering the Earth even smaller and more defenseless in appearance. Figure 5.6d has an almost subliminal skull and crossbones painted on the asteroid, in a clear effort to inspire terror. Figures 5.6e and 5.6f show asteroids glowing hot and trailing gas in the emptiness of space, well outside the Earth's atmosphere, fire and brimstone imagery completely at odds with reality. The same two figures have ghoulish faces hidden on the surfaces of the asteroids.

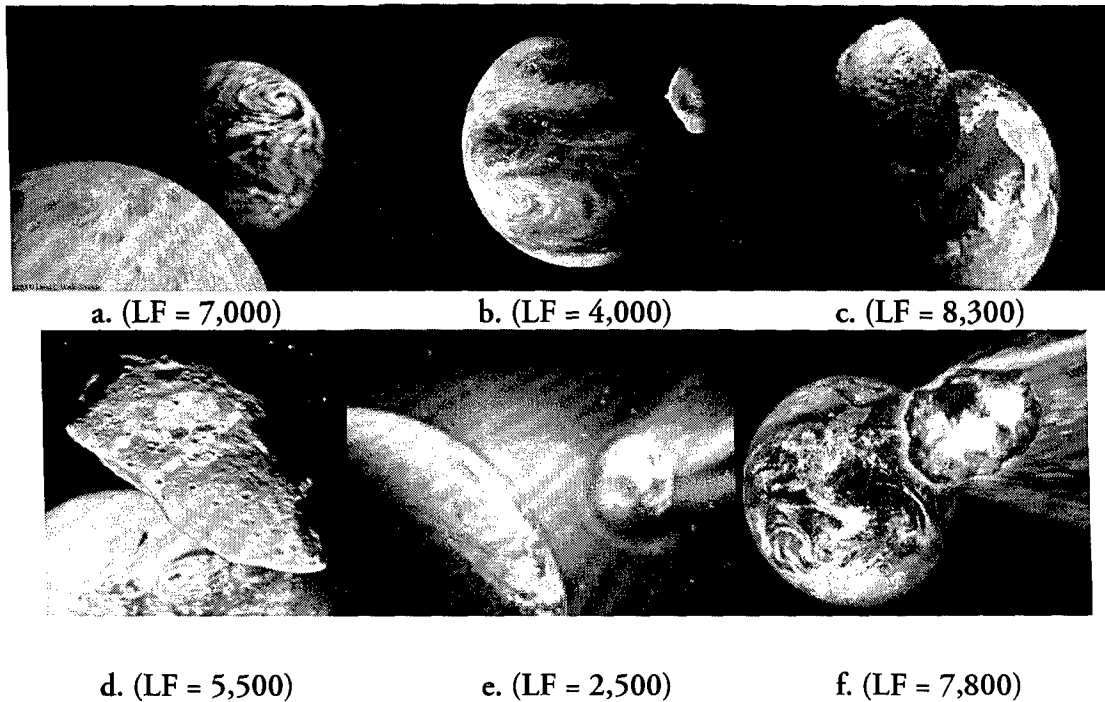
²⁷ This assumes that the policymakers themselves have an accurate perception of the impact hazard. Not long ago, the President of India A. P. J. Abdul Kalam (the "father" of India's missile program) publicly stated "Asteroid 1950DA's rendezvous with earth is predicted to be on Mar 16, 2880. Presently it is about 7.8 million kilometers away. The impact probability calculations indicate a serious condition of 1 in 300. In such a crucial condition, we should aim to deflect or destroy this asteroid with technology available with mankind (*sic*). His presentation material included the note "Extensive damage expected." Abdul Kalam, A., "Vision for the Global Space Community: Prosperous, Happy and Secure Planet Earth," speech to the 90th Indian Science Congress, Bangalore, India, 4 January 2003. The case of 1950 DA is described in Giorgini, J., *et al.*, "Asteroid 1950 DA's Encounter with Earth in 2880: Physical Limits of Collision Probability Prediction," *Science*, Volume 296, 5 April 2002, pp. 132-136. This paper gives an *initial* impact probability range of zero to 0.33 percent.

²⁸ This is of course a flaw in common with society's reaction to terrorism—images of suicide bomb attacks and other atrocities on the nightly news are easy to understand, but the statistics and probabilities of terrorism are not. The misperception applies only up to a point—when every strip mall in middle America is battening down for an Al Qaeda attack, even the probability-challenged begin to sense the ridiculousness of it all.

²⁹ See the footnoted discussions of Figures 2.6 and 2.8.

³⁰ These Lie Factors assume that in each case the depicted asteroid has a major axis of one kilometer in length.

Figure 5.6
Flaming death from the skies



In contrast with the exciting but socially irresponsible artwork of Figure 5.6, the image shown in Figure 5.7 has a Lie Factor of unity (that is, no graphic distortion whatsoever). It shows a 100-meter asteroid at rest in a football field, an excellent way to give the reader a good understanding of the NEO's size. Unfortunately, the odds of finding such a good graphic presentation seem to be as low as the chance of an asteroid making a soft landing in the middle of a sports stadium.

Figure 5.7
"M" is for megalith

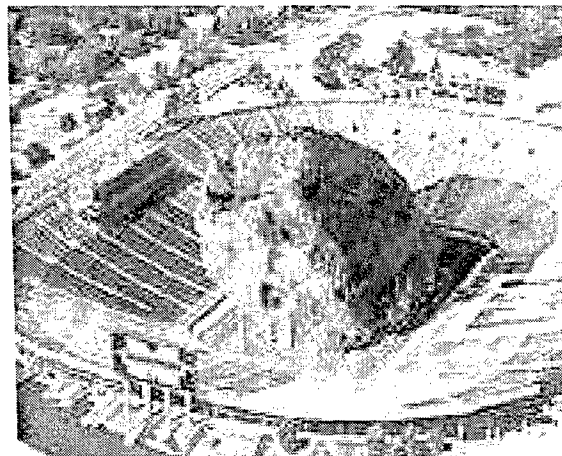


Figure 5.8 shows several more examples of graphic distortion. Figures 5.8a and 5.8b show the relative distances of the Moon and the asteroid in correct proportion, but the inflation of the asteroid size results in an extraordinarily high Lie Factor in both cases.³¹ Each figure has a “not to scale” caveat, but the damage is done—the graphic imagery is powerful, the fine print is not. Additionally, Figure 5.8b has a Lie Factor of fifty associated with the depicted distance of the Moon relative to the Sun, and distances seem to be measured from somewhere deep within the Earth’s mantle.

Figure 5.8c is notable for the use of a drop-shadow paralleling the asteroid’s track past the Earth. While the shadow might make the graphic pleasing to the eye, it also has the illusory effect of making the passage appear closer to the Earth than otherwise. Whether that effect was intentional or not is impossible to determine.

Figure 5.8d gives the impression of an inevitable collision with an asteroid little smaller than the Earth. Needless to say, the reality of the projected encounter was much less dramatic.

Finally, the reader should return to Chapter Two and the depiction of the Earth “hemmed in by a sea of asteroids” (Figure 2.8). The thickness of the lines representing asteroid orbits (relative to the actual sizes of asteroids) results in a Lie Factor of approximately one million.³²

Misunderstandings at Many Levels

We now address the next problem in the “chain of valuation.” Even presupposing a correct assessment of low probabilities and high uncertainty, people are very likely to misunderstand the *workings* of probability and the *meaning* of uncertainty.

This subject is addressed in the literature reviewed in Chapter Three, most notably in “Judgment under Uncertainty: Heuristics and Biases” by Tversky and Kahneman. Very often, laymen and experts alike draw the wrong lessons from their experiences.

In the case of the impact hazard, a very common error stems from a fundamental misunderstanding of the workings of a Poisson process in which events occur at random during a particular time span. From time to time, it is expressed that the Earth is “due” for another major NEO impact because it has been so long since the last one.³³ This is patently false. In a Poisson process, “the probability that a particular number of [events] occurs in a particular time interval [does] not depend on the number of these events that occurred prior to the beginning of this time interval.”³⁴

It might be expected that the general public would have difficulty with probabilistic reasoning. However, the insurance industry owes its existence to actuarial logic (and stands

³¹ The asteroid shown in Figure 5.8a is 2001 YB5, estimated to be about 300 meters across. The asteroid shown in Figure 5.8b is 2002 MN, with an estimated diameter of only 50-120 meters.

³² In the interest of full disclosure, the “nabla of fear” of Figures 5.1 and 5.2 above embodies a Lie Factor with respect to the ratio of warnings to discoveries. In the author’s defense, the nabla is intended to illustrate a process rather than to leave the reader with a quantitative impression. Lie Factors of unity are not necessarily easy to achieve.

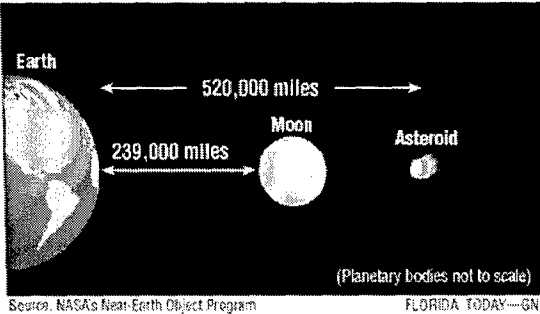
³³ It is distressing how often professionals and academics fall into this trap. For example, see www.historyoftheuniverse.com/massexti.html: “There was another one, the last of these mass extinctions, about sixty million years ago when the dinosaurs died out. So if the sixty million year theory is correct we might be due for another impact any day now!”

³⁴ Mansfield, E., *Statistics for Business and Economics*, Fifth Edition, W. W. Norton and Company, New York, 1980, p.177.

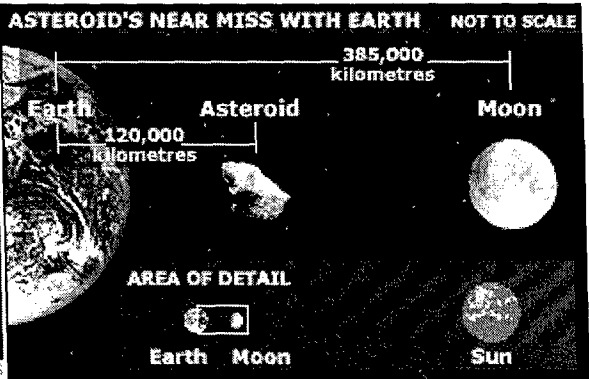
Figure 5.8
Pictures worse than a thousand words

A miss is as good as a mile

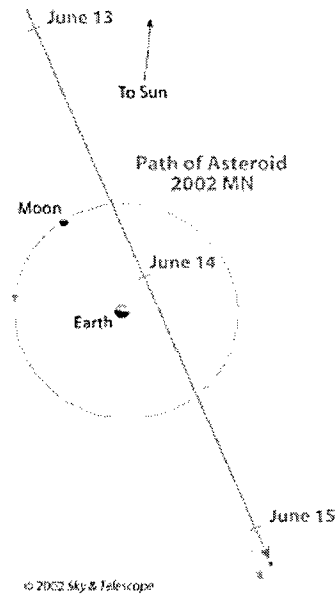
The relative distances between the Earth, the moon and the asteroid 2001YB5 with an estimated diameter of 230 yards to 503 yards:



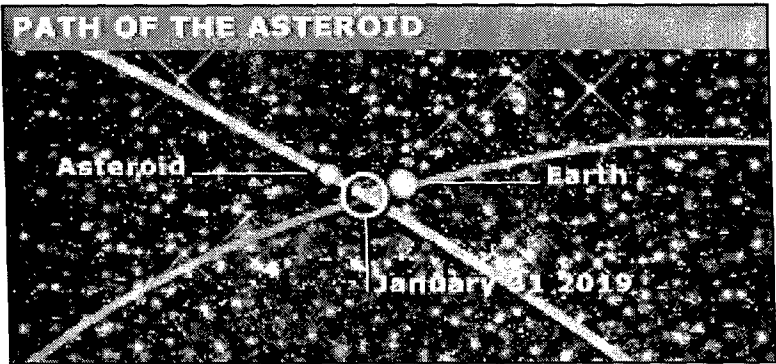
a. 2001 YB5 (LF = 3,400)



b. 2002 MN (LF = 41,000)



c. 2002 MN



d. 2002 NT7

to profit from policyholder misperceptions of risk). Here we might reasonably expect a higher standard. However, the following is an example of flawed probabilistic thinking at the world's largest reinsurance company, Munich Re:

"Too improbable," "too catastrophic," "probably not insured," "irrelevant to the insurance industry"; all these are answers the majority of risk managers in the insurance industry might have given if they had been asked about the risk of accumulation from meteorite impact—at least before the terrorists [*sic*] attack of 11th September 2001, which generally resulted in a radical reconsideration of loss potentials.³⁵

The insurance industry must consider whether, in the light of this substantial threat, it is equipped to deal with such a scenario—which is to be doubted. Simply pointing to the presumable rarity of such events should no longer suffice in the light of recent experience.³⁶

Terrorism is most assuredly not a Poisson process, and there are many reasons why insurance companies might have wanted to reexamine their exposure following the September 11th attacks. However, it would have been a serious fallacy to conclude that the occurrence of September 11th *necessarily* indicated that estimates of the probability of a serious terrorist attack were incorrect. Even rare events happen at some point. Furthermore, it is a fundamental error to transfer this logic to the impact hazard. The occurrence of an NEO impact would *never* indicate that estimates of the probability of such an impact were incorrect. Simply pointing to the rarity of such events *should* suffice, recent experience or not.

Incorporating System Effects

Next to be added to the policy framework are system effects.³⁷ Figure 5.9 shows two positive feedback loops (depicted on the left). By feeding a social response back into social WTP, that variable is made endogenous to the model.

The gains associated with social response are dependent on the amplifying effects of several social actors, identified by triangles.³⁸ The outside circuit represents the "Hollywood loop." The movie industry is attracted to the topic by the perennial public interest that is a feature of the impact hazard. This loop exists irrespective of the progress of survey efforts, although there is an obvious interdependency. The dog-legged arrow leading to the news media represents "media buzz" surrounding a given movie. The system gain in this loop is a result of rent-seeking behavior on the part of industry and media stakeholders.

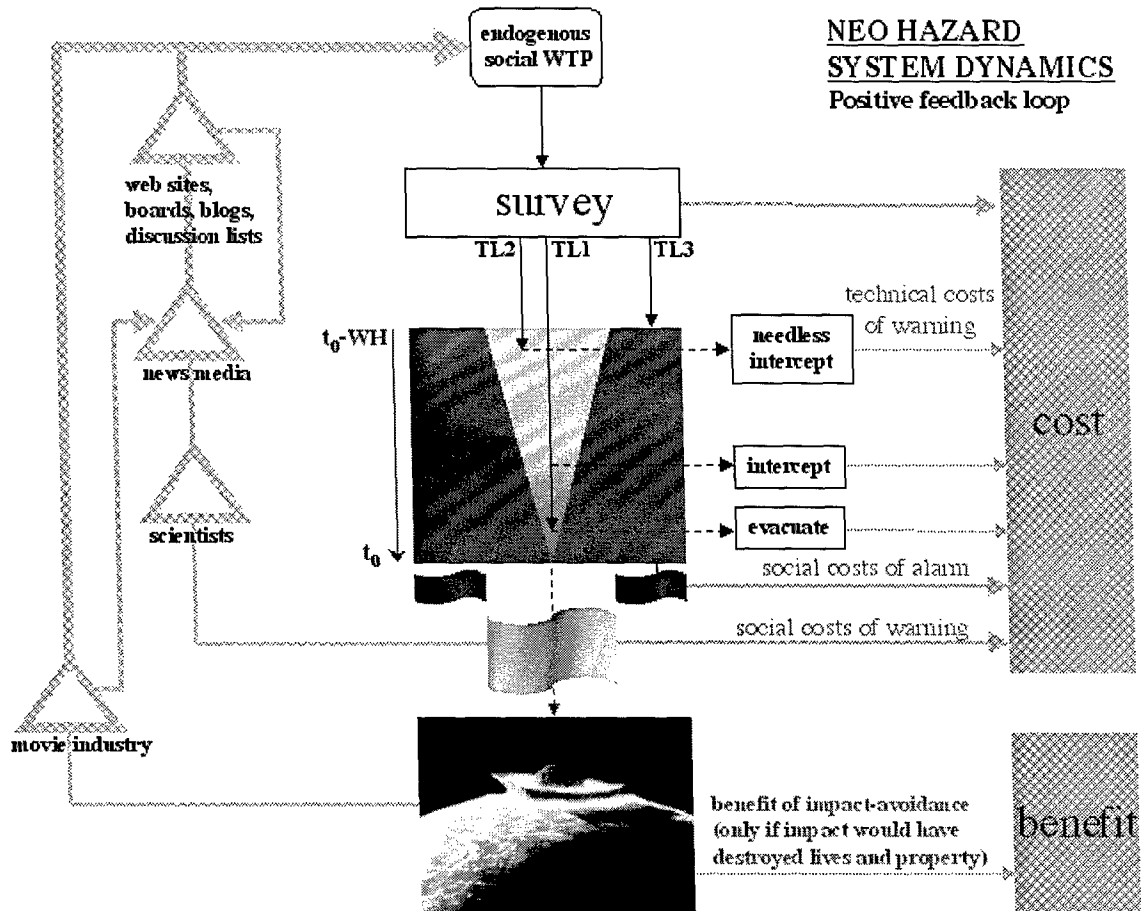
³⁵ *Topics—Annual Review: Natural Catastrophes 2001*, Munich Re Group, 9th Year, 2002, p.37.

³⁶ *Ibid*, p.41.

³⁷ This discussion draws on: Jervis, R., *System Effects—Complexity in Political and Social Life*, Princeton University Press, Princeton, New Jersey, 1997; a summer course given at RAND in September 1998 by Professor Y. Dror of the Hebrew University in Jerusalem titled "Capacity to Govern, Weaving the Future, Policy Planning"; and the author's own background in the applied sciences. The language of system dynamics is explained in the classic text by Cannon, R., *Dynamics of Physical Systems*, McGraw-Hill, New York, 1967.

³⁸ This is standard symbology: triangles represent amplifiers.

Figure 5.9
Including social dynamics



The inside loop represents the dynamics of the warning function. Scientists in the NEO community use warnings for their own or altruistic purposes. Rent-seeking behavior can be masked by assertion of social benefit. System gain will depend on the tension between the scientists' desire to gain social attention (and thus respect, elevated status, and perhaps grants) and their fear of inflicting social harm or appearing incompetent if an "asteroid scare" results.³⁹

A similar tension exists in the news media, as supported by sociological evidence.⁴⁰ These two tensions will have a time dependency, which introduces the possibility of phase differences between loops and consequent oscillatory system behavior that must be recognized by the proponents of any policy interventions.⁴¹

³⁹ The fear of appearing foolish is exemplified by a sensitivity in the NEO community to using the terms “false alarm,” “false warning,” or “retracted warning,” all of which imply error if not professional incompetence. Strictly speaking, the scientists are correct: the process is not a simple matter of binary state, but one of continuously evolving probabilities (as made clear in Chapter Two).

⁴⁰ Ungar, S., *op. cit.*

⁴¹ A specific example of oscillatory behavior will be provided in a later system diagram.

An interior circuit is shown, in which news reports bounce back and forth between the established media and the “new media” of the Internet, comprised of advocacy web sites, electronic discussion lists, bulletin boards, and web logs (“blogs”). The new media uses the currency of gossip, innuendo, and buzz. Public demand for this excitement draws the established media into a “race for the bottom,” and the result is yet more system gain.⁴²

Thanks to these positive feedback loops, and because of the amplifying effects of numerous social actors, a general conclusion can be drawn. Without any policy intervention to reduce system gains, a survey that generates an increasing number of warnings will (in all likelihood) result in increasing social pressure for even more capable surveys, which in turn will generate yet more warnings.⁴³

We now examine three potential policy interventions, and attempt to predict their effectiveness in modifying the dynamic system illustrated in Figure 5.9 above.

Alternative Policy Interventions

Information Management and Uncertainty Reduction

This case actually presents a combination of two policy options: to “manage” the information that society receives about the impact hazard, and, at the same time, to invest in technical measures that reduce the number of warnings. The two actions are shown in one system diagram (Figure 5.10), and are treated together because they represent “easy” near-term options for policymakers.

“Information management” actually refers to a full spectrum of policy options, ranging from the simple “framing” of an issue, through “spin,” to absolute secrecy. The attempt here would be to reduce the social costs of warning by affecting society’s perception of the hazard.

As a policymaker progresses from framing to secrecy, the social costs of warning will decrease, but another source of social costs will arise. This is because the policy option of information management is inextricably linked to issues of political control, freedom of information, informed consent, and paternalism. The optimum location on the spectrum of information management is one where social costs are reduced by reassurance but not magnified by public distrust of government. An immediate analytical problem is that, hard as the social costs of warning are to quantify, the social costs of distrust are well-nigh ineducible.

Another problem with information management is that its efficacy is questionable in an environment where access to the source data is decentralized. In the case of the impact hazard, it was noted in Chapter Two that the NEO community includes professional and amateur astronomers spread across the globe, each a potential source to a multitude of potentially interested governments, INGOs, and NGOs. Furthermore, the loose hierarchy of science ensures that professional astronomers tend to have weak links of allegiance to institutions (and conversely, that those institutions exert little control over the scientists). This is

⁴² The most powerful example of this process is the BBC report of an asteroid (2002 NT7) being on a “collision course” (<http://news.bbc.co.uk/1/hi/sci/tech/2147879.stm>).

⁴³ It is important to note that the author has made no value judgments regarding the social benefit of this system behavior. If society as a whole is so risk averse to a real impact as to be willing to endure a storm of warnings, then the positive feedback is in fact beneficial, at least initially. The problem lies in the system’s divergent behavior.

due partly to the process of awarding grants to individual scientists rather than to their nominal employers.

Nevertheless, weak forms of information management have been attempted, ranging from the IAU's policy statements on public communication in the case of a threatening object being discovered, to the U.K. government's establishment of an NEO Information Centre.⁴⁴

Progressing to uncertainty reduction, the policy option of reducing the warning rate by technical means involves both institutional and technical issues. "Fame and fortune" in the astronomical community accrue to discoverers, not to those who perform the dreary task of following up someone else's observations, so institutional incentives for that task would need to be reinforced.⁴⁵ Technically, a survey system optimized for a balance of detection and follow-up efficiency might look different from a discovery-maximizing system, possibly making more use of non-optical means (such as planetary radar).⁴⁶

Figure 5.10 shows how system gain is reduced by the policy intervention of information management.⁴⁷ The diagram posits an information center along the lines of that established by the U.K., "framing" or putting a positive "spin" on the hazard. System input of warning rate is reduced by uncertainty reduction (as shown by the narrower orange-red glyph beneath the nabla of fear). Following an initial warning, the system "scrambles" to shrink the Earth-inclusive uncertainty ellipse so as to exclude the Earth. The effect on costs and benefits is shown on the right. Costs of alarm and warning are reduced by some degree (but probably not by that much, since here we are applying "light" information management to avoid the costs associated with public distrust). There is also a possible reduction in the probabilistic benefit of impact-avoidance, to the degree that the calmed society reduces its support for NEO survey activities, and to the degree that discovery rates are reduced by a reallocation of effort to follow-up tasks.

Information Control

Secrecy is at the far end of the spectrum of information management. Should they be approved and funded, future survey systems will have more centralized control than today, not depending on the assistance of amateur astronomers for follow-up. This opens up the policy *option*, at least, for information *control* rather than just management.

Information control is tolerated by democracies in cases in which it is clear that such control is exercised for social benefit. Certainly, in issues relating to national security, few would argue that the public's right to know is absolute rather than moderated by the imperative of state survival.

In matters relating to the NEO impact hazard, however, even the inclusion of information control as one of a number of policy options is highly controversial. Along those

⁴⁴ These were discussed at length in Chapter Two. For the IAU position, see www.iau.org/IAU/FAQ/neo.html. For the U.K. NEO Information Centre, see www.nearearthobjects.co.uk.

⁴⁵ Future enhanced survey systems would be likely to conduct their own follow-up observations, so the concerns regarding institutional incentives would then presumably abate. Morrison, D., *et al.*, "Dealing with the Impact Hazard," in *Asteroids III*, Bortke *et al.*, editors, University of Arizona Press, Tucson, 2002, p.749.

⁴⁶ The utility of planetary radar for reducing the size of uncertainty ellipses was discussed in Chapter Two.

⁴⁷ The thinner arrows on the left depict the gain reduction.

In Figure 5.11, information control has the effect of increasing those social costs that stem from distrust of government and institutions. While the social costs of warning are reduced, the social costs of alarm actually increase. This is because the government loses its status as a trusted source of warnings, and the field opens up for charlatans and freelancers. Finally, there is a possible reduction in the probabilistic benefit of impact-avoidance, to the degree that the “blinkered” society reduces its support for NEO survey activities.

Project CARDINAL

The third and last of the policy interventions to be examined is the demonstration of a capability to intercept and deflect an NEO. By so doing, the social costs of warning are reduced to the extent that society is “reassured” that an object entering the nabl of fear will never reach its apex, *whichever timeline it occupies*. For the purpose of analysis and easy reference, the demonstration is designated Project CARDINAL (Comet/Asteroid Research and Development Interceptor Negating Alarms).⁴⁸

The concept of developing a system whose *primary* purpose is to reassure the public is revolutionary. Yet this may be the correct strategy when considering the cosmic impact hazard from an *ex ante* perspective. Warnings are a necessary byproduct of an NEO survey, but detection of an actual impactor is not. Hence, when impact costs are probability-weighted they can be dominated by the cumulative social costs of alarm and warning. In such a case, the actual ability of an interceptor to deflect an NEO is less important from the perspective of social benefit than its *perceived* capability (that is, the perception that society has of its capability).

This is obviously a slippery slope. In theory, a system with *zero* actual capability can provide a social benefit, and thus be judged socially worthwhile. It is common in the military sphere to procure systems intended to induce a behavioral effect in an enemy—that is, to deter the opponent. It is less common to acquire or deploy a system where a significant desired effect is reassurance of one’s own population. In these cases, a good faith effort is made to achieve some actual operational capability—after all, a system that is in effect a technical Potemkin Village would risk a catastrophic collapse of trust in the government were the truth revealed.⁴⁹

A good example of a program that is being pushed into a “declared” operational capability in advance of successful testing is the U.S. National Missile Defense (NMD) system, intended to defend (in particular) against North Korean ballistic missiles aimed at the United States. Like all ballistic missile defense (BMD) systems, NMD has a threefold purpose:

- To intercept enemy missiles;
- To deter the enemy from launching an attack; and
- To reassure the “homeland.”

⁴⁸ The following analysis draws heavily from a presentation by the author to the AIAA Planetary Defense Conference held in Los Angeles, February 2004 (www.aero.org/conferences/planetdef/). Appendix C sets forth the rationale behind the author’s concept for a planetary defense demonstrator. The conference was structured around a set of *ex post* scenarios that were given the names Athos, Porthos, Aramis, and D’Artagnan. CARDINAL was thus a natural choice for the name of a proposed *ex ante* demonstration program.

⁴⁹ An immediate criticism might be that such a system would give the public a “false sense of security.” This phrase masks an unspoken assertion that the threat is probabilistically significant and the government wants to bias perceptions (for malignant reasons), rather than that the threat is probabilistically *insignificant* and the government wants to *de-bias* perceptions (for benign reasons).

Currently, the primary *capability* of NMD is the last of these three. Reassurance was never its primary *purpose*—it is being deployed early for political and institutional reasons.

The *Patriot* missiles rushed to Israel in the first Gulf War serve as a second example. Designed as anti-aircraft missiles, then upgraded for use against tactical ballistic missiles (TBMs) but never tested in combat, there was no particular reason to expect great success against the Iraqi *Scuds* and *Al-Husseins* they faced in 1991.⁵⁰ In fact, it is possible that the *Patriots* never successfully intercepted a TBM, and there is no evidence that any damage on the ground was reduced (in fact, damage appears to have increased, partly due to unsuccessful *Patriots* returning to the ground). Yet, it can be argued with some conviction that despite technical failure, the *Patriot* deployment was a raging strategic success. Their reassurance of the Israeli government and population served to keep that country out of the war, and the allied coalition was consequently able to remain intact. Nevertheless, there was a good faith effort made to maximize technical success—in the end, it just did not matter.⁵¹

The foregoing has shown that issues of social reassurance are not alien to interceptor programs. In the case of the NEO impact hazard, the probability of an actual intercept being required is vanishingly remote, so the requirement for social reassurance to reduce alarm and warning costs is relatively more important than in the BMD case.

Notwithstanding this fact, another feature of the impact hazard works in favor of a system that has an actual capability against the incredibly rare confirmed impactor; and an actual capability bolsters its powers of social reassurance. Warning horizons will be relatively long in most cases (extraordinarily long when compared with the short response times that are a feature of BMD interceptions). This means that the interceptor can respond to a threat NEO by means of production-scale rather than system-scale. In other words, there is generally time to build and launch many small interceptors, rather than to design and deploy a single large interceptor with the same energy delivered to the NEO.

Consequently, the most logical approach for an NEO interceptor optimized for *ex ante* cost efficiency is to design the smallest system possible that retains a social reassurance effect. By so doing, the *ex ante* fixed costs of design, construction, and testing of a demonstrator are kept as low as possible. The *ex post* costs of surge production (in the unlikely event of a “for-real” interception being required) may well be higher than the costs of building the single “blockbuster” interceptor that is the usual focus of impact hazard-mitigation design studies.⁵² Such is a consequence of the *ex ante* versus *ex post* design optimization. In any event, *ex post*, it is safe to assume that close to an actual impact, a good chunk of Earth’s total global product would be made available to the planetary defense budget line if necessary.

The reliance on surge production drives system design and architectures in other ways. Simplicity of design is favored, and the avoidance of exotic materials and fuels is beneficial. It helps to avoid launch pad constraints by launching from large carrier aircraft.

⁵⁰ Upgrades since the first Gulf War have added a more robust anti-TBM capability to *Patriot*.

⁵¹ “The results of these studies are disturbing. They suggest that the *Patriot’s* intercept rate during the Gulf War was very low. The evidence from these preliminary studies indicates that *Patriot’s* intercept rate could be much lower than ten percent, possibly even zero.” (Statement of Theodore A. Postol before the U.S. House Of Representatives Committee on Government Operations, April 7, 1992). See www.cdi.org/issues/bmd/Patriot.html. Also, Postol, T., “Lessons of the Gulf War Experience With *Patriot*,” *International Security*, Volume 16, Number 3, Winter 1991/92, pp. 119-171.

⁵² An early example of an *ex post* approach to NEO interceptor design is Project Icarus, a study effort that recommended a *Saturn-V* class system. *Project Icarus*, MIT Student Project in Systems Engineering, MIT Press, Cambridge, Massachusetts, 1968.

Smaller interception systems can be based on launchers and payloads used for space science missions, with only the deflection-effectuators representing new development. The idea is to defer mitigation system investment for as long as possible, but to hedge by reducing structural constraints to action in the extremely unlikely event such action is necessary.

The resulting CARDINAL demonstrator thus takes shape as an adaptive program, a hedging strategy against the extremely unlikely event of a confirmed impactor being detected.⁵³ At the same time, it provides a continuing benefit via the reduction in the social costs of alarm and warning that will accompany any enhanced NEO survey. This social benefit is certain in terms of likelihood, but is of uncertain magnitude.

From an institutional perspective, it is worth addressing issues of program implementation. A primary determinant of the success of any major acquisition program is the stakeholder consensus accompanying the prospect of large amounts of funding. In the case of CARDINAL, we have a demonstrator that is designed to incur the least fixed costs possible while still retaining the effect of social reassurance. It will be launched, probably just once, and then "put on the shelf" against the extremely unlikely event that it will ever be needed to deflect an actual threatening NEO. Surge production is probability-weighted, but so are the industrial profits associated with production, and therein lies the problem (from the point of view of industrial stakeholders).

The closest parallel to this type of program structure is provided by an acquisition innovation of the U.S. DoD that originated in 1994. "Advanced Concept Technology Demonstrators" (ACTDs) are intended to demonstrate an operational capability at low cost (at least, low by Pentagon standards). Following their demonstration, they either transition to production, are put on the shelf as a "residual capability" for possible later acquisition (as a hedging strategy) or terminated. Most of the problems that DoD has experienced with ACTDs have revolved around issues associated with transition to production. The uncertainty of industrial profits in production (and the effect of that uncertainty on consensus-building) is balanced by high-level DoD management attention.⁵⁴

ACTDs originated in the immediate aftermath of the Cold War. When the Soviet military threat evanesced, the absolute risk aversion embodied in typical Pentagon worst-case planning scenarios no longer seemed appropriate. The U.S. military had entered a threat environment that was highly uncertain.

In many respects, the ACTD concept provides a good acquisition model for an NEO interception demonstration program such as CARDINAL. The improbability of surge production ever being required means that issues of production transition are themselves probability-weighted. *Ex post*, the production-inefficient breadboard or brassboard demonstrator can be duplicated as-is, because *ex post*, the cost is effectively irrelevant.⁵⁵

⁵³ For more discussion on the application of hedging strategies in the face of uncertainty, see Dewar, J., *et al.*, "Assumption-Based Planning," The RAND Corporation, Santa Monica, California, MR-114-A, 1993.

⁵⁴ Three informative reports from the early days of ACTDs are: Sommer, G., *et al.*, "The Global Hawk Unmanned Aerial Vehicle Acquisition Process—A Summary of Phase I Experience," The RAND Corporation, Santa Monica, California, MR-809-DARPA, 1997; Drezner, J., *et al.*, "Innovative Management in the DARPA High Altitude Endurance Unmanned Aerial Vehicle Program," The RAND Corporation, Santa Monica, California, MR-1054-DARPA, 1999; and Thirtle, M., *et al.*, "The Predator ACTD—A Case Study for Transition Planning to the Formal Acquisition Process," The RAND Corporation, Santa Monica, California, MR-899-OSD, 1997.

⁵⁵ Breadboard and brassboard refer to early, immature stages of prototype hardware.

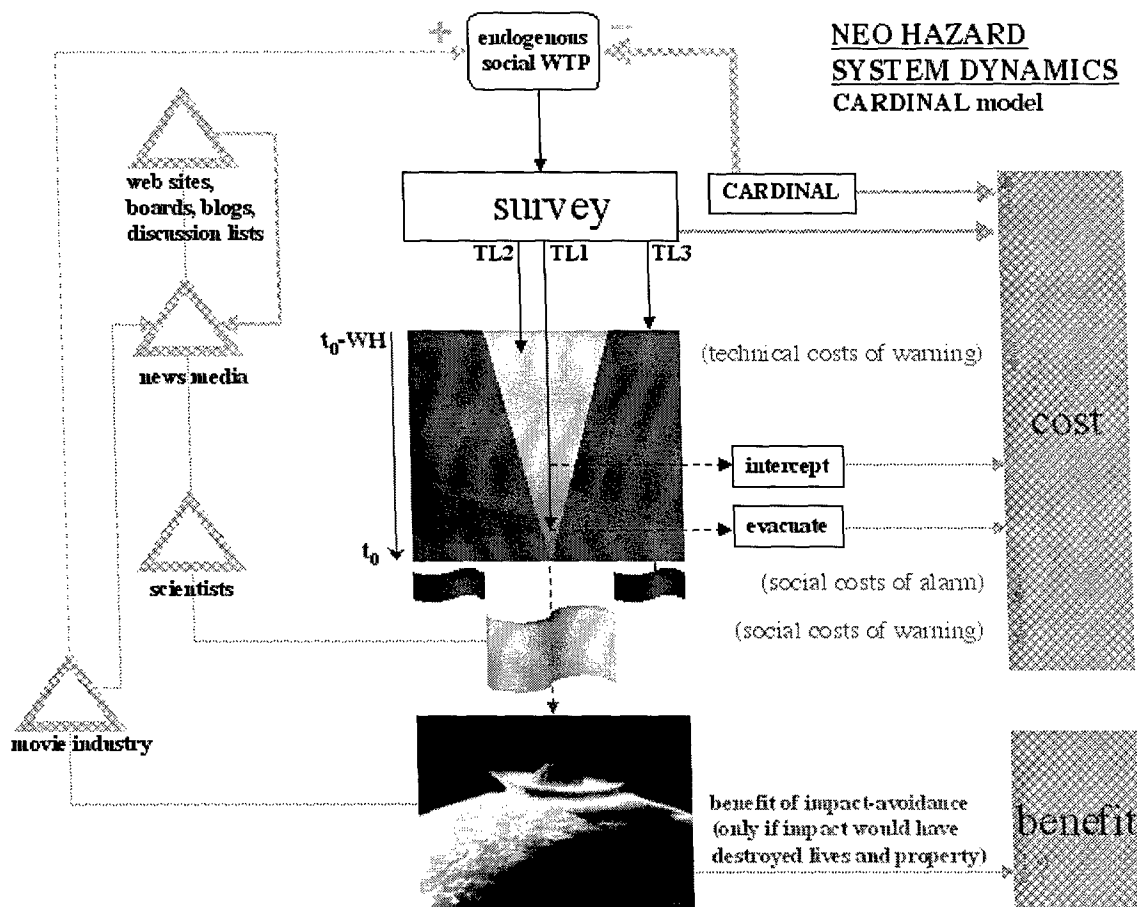
After this exposition of the purpose and likely structure of a CARDINAL demonstrator program, we turn to Figure 5.12 to examine the potential effect of such a program on the system dynamics of the NEO impact hazard.

A process box is added for the CARDINAL policy intervention. A direct cost is incurred as a result of the up-front demonstration program that provides social reassurance. That reassurance has the effect of eliminating the inner feedback loop's input to endogenous social WTP. The outer "Hollywood loop" is generated by movies, not warnings, and so still exists, although at a reduced strength since movie "buzz" feeds off real-world warnings.

CARDINAL sends a negative signal to endogenous social WTP. This is because of a hypothesized satiation effect. Previously, social pressure to "do something" was manifested by increased social WTP for the NEO survey. With CARDINAL, "something" has already been done: the CARDINAL demonstration.

Finally, note that CARDINAL reduces the social costs of alarm and warning, that being its primary purpose. It also reduces the technical costs of warning, since there is less social pressure to launch an interceptor at low estimated impact probabilities. This is because

Figure 5.12
Project CARDINAL



the prior CARDINAL demonstration enables a responsiveness to shorter warning horizons that a new start interception program cannot match. CARDINAL can be taken off the shelf and rushed into surge production almost at the last moment. CARDINAL may also reduce the probability-weighted benefit of impact-avoidance through the mechanism of its effect on endogenous social WTP—an unavoidable dilemma shared with the other alternative policy interventions.

This chapter has developed a conceptual framework for a comprehensive impact hazard policy, examining three alternative policy interventions designed to provide robustness to very uncertain social costs. The next chapter builds on this framework by constructing a quantitative model using:

- The latest available data on the physical aspects of the impact hazard;
- The latest available data on the projected costs and effectiveness of future NEO survey systems; and
- Estimates for reasonable ranges of several parameters of social response to the impact hazard.

Modeling the Policy Framework

Purpose of the Model

This chapter presents a model of a comprehensive impact hazard policy. The model illustrates the mechanism by which an increase in survey effectiveness can actually impose a net cost on society. It also shows how a net social benefit becomes easier to achieve if steps are taken to attenuate social response (such as the proposed CARDINAL adaptive policy implementation introduced at the end of Chapter Five). The calculation of benefit is naturally dependent on the interaction of chosen discount rate and several other uncertain parameters and functional forms. The model is not nor can it be prescriptive given the large uncertainties involved in so many dimensions. It can, however, identify regions of the policy space where the proposed policy implementation might be favored.

Foundation of the Model

The model is constructed on the foundation of the NEO Science Definition Team (SDT) study first discussed in Chapter Two.¹ The cost-benefit model at the core of that study is significantly modified in the present work. It is expanded to include predicted warning rates and uncertainty in several parameters of social response, including probability-weighted expenditures on mitigation programs. Two variations of the new model are presented. One is a baseline case, while the other explicitly models the proposed adaptive policy implementation.²

SDT Model

The NEO SDT released its study report on 22 August 2003. This report represents the most comprehensive *technical* assessment of expanded NEO survey objectives yet published. It

¹ Stokes, G., *et al.*, "Study to Determine the Feasibility of Extending the Search for Near-Earth Objects to Smaller Limiting Diameters," report of the NEO Science Definition Team, prepared at the request of the NASA Office of Space Science, Solar System Exploration Division, 22 August 2003. The SDT study report is available at <http://neo.jpl.nasa.gov/neo/neoreport030825.pdf>. The SDT model and a selection of supporting data were graciously provided to this author by Grant Stokes and Jenifer Evans, MIT Lincoln Laboratories, for the purpose of the present study.

² Note that this new model is static, not dynamic: neither variation includes the positive loop of social feedback described in Chapter Five. This is due to the limitations of the model tools that are used, but also because a static model is sufficient for the purpose of illustration.

recommends a new goal of surveying the population of 140-meter or larger PHOs to a completeness of 90 percent.

The SDT model takes the latest available data from the scientific community on the physical aspects of the impact hazard, along with the costs and effectiveness of proposed telescopic survey programs. Twenty-seven different notional survey systems and the baseline LINEAR system are exercised against a simulated population of PHOs. Construction and operational costs are estimated for each of these systems—five years of construction and ten years of survey operation are assumed. Survey completeness (percentage of the PHO population discovered) is assessed by year, across the range of PHO sizes. Two types of benefits are considered. A “cataloging” benefit is accrued, proportional to survey completeness and the expected annual loss in lives and infrastructure in each PHO size bin. A “warning” benefit is accrued, proportional to the efficiency of a given survey in detecting an object days to months before impact, the *incompleteness* of the survey, and the expected annual lives lost, again for each PHO size bin.³ These benefits are summed together, and then the costs are subtracted for each survey system by year. A return on investment (ROI) is calculated, that being the cumulative-by-year sum of benefits less costs, divided by costs.

The model looks ahead one century. “Warning” benefits naturally cease when the survey ends (after ten years of operation), whereas cataloging benefits accrue for a further 90 years and then go to zero.

All costs and benefits are monetized in FY03 dollars, and parallel current dollar values are tabulated using an inflation rate of 2.9 percent, taken from the NASA 2002 new start inflation indices.⁴ The original FY03 base-year values are represented to reflect net present value (NPV)—although this is the case only if a zero discount rate is assumed.⁵ As a result of the lack of discounting, the conclusion of the SDT cost-benefit study is that “based solely upon cost considerations, all the explored options are viable.” This is because in almost every case, the survey program achieves break-even (cumulative benefit less cost) in its first year of operation.⁶

The SDT model attempts to capture uncertainty in the physical hazard by examining minimum, nominal, and maximum death rates due to the residual (post-2003) PHO hazard. These equate to 81, 293, and 1,105 deaths per year. Global and U.S.-only values of life are

³ The complement of survey completeness is used because the study reasons that there will not be any warnings from cataloged PHOs. Note that the SDT definition of warning is different from that used throughout the present work, and is perhaps better reflected as “short-term warning of *definite* impact.” Note also that there is no infrastructure benefit assumed for “warning,” as it is reasoned that insufficient time would be available for moving capital stock and other fixed assets. SDT study report, p.107.

⁴ “Current” amounts reflect the dollar value in the year of expenditure. They have budgetary relevance but do not inform policy.

⁵ The use of a zero discount rate, although unintentional in this case, is not *necessarily* inappropriate for an environmental cost-benefit analysis. “...it has been argued that if the current population has an ethical responsibility for future generations, then the costs of environmental degradation should not be discounted. Under this scenario, discount rates would effectively be zero. However, in recent years, these arguments for reducing or removing high discount rates have largely been refuted.” (Barbier, E., *et al.*, *Paradise Lost? The Ecological Economics of Biological Diversity*, Earthscan Publications, London, 1994, p.84, cited by Lumley, S., “Cost-Benefit Analysis, Ethics and the Natural Environment,” *Cost-Benefit Analysis*, Puttaswamaiah, K., editor, Transaction Publishers, New Brunswick, U.S., 2002, p.108).

⁶ SDT study report, p.110.

monetized at \$1.6 and \$6.96 million (FY03\$), respectively.⁷ Global and U.S.-only infrastructure values are assessed at \$98,000 and \$734,000 per person (FY03\$) respectively.⁸

The methodology of the SDT model credits each survey with an annual cataloging and “warning” benefit in terms of expected lives and infrastructure saved. A credit is taken for each discovery in the year of that discovery. However, there is no accounting for the costs and duration of the mitigation effort that would be necessary to actually save the lives and infrastructure.⁹

Warning Rates

The SDT model does not address the highly uncertain social costs of warning. Uncertainties in PHO location in the Earth target plane were not considered, since the methodology used in the benefit calculation weighted PHO discovery rates according to expected annual fatalities and the orbital uncertainty was thus subsumed.

Nevertheless, in the course of the PHO survey simulation, some warning rate information was generated (though the SDT did not make use of it). Cumulative number of warnings at the completion of the Spaceguard and SDT surveys are shown in Table 6.1, for both the Palermo and Torino scales.¹⁰ Note the paucity of Palermo warnings but the large number of Torino scale “TS=1” warnings as well as the high warning rate of the SDT survey relative to the Spaceguard survey—not an unexpected result given the sheer number of objects detected by the former.

Table 6.1
Expected warnings by survey, Palermo and Torino scales

	Spaceguard 90% > 1 km NEOs	SDT 90% > 140 m PHOs
PS=0	5.0	16.6
PS=1	0.6	1.5
TS=1	134.9	1,583.7
TS=2	7.4	27.0
TS=3	1.0	80.5
TS=4	1.2	8.6
TS=5	0.08	0.21
TS=6	0.019	0.023
TS=7	0.012	0.014

⁷ There are three problems with these values. 1) They are derived from Kenkel (*op. cit.*), but only reflect the conclusion of one U.S. government agency (EPA). The SDT study implies that Kenkel endorses the EPA estimate. In fact, the thrust of Kenkel is that there is a very wide range of life valuations. 2) The confidence interval recounted in Kenkel (plus or minus \$3.2 million in FY90\$) is repeated in the text of the SDT study report, but not reflected in the model itself. In any event, Kenkel's failure to associate a confidence level with the confidence interval renders the value meaningless. 3) The adjustment of the U.S. value to a global value is based on a willingness to pay (WTP) derived from a ratio of per capita incomes from World Bank data. This method embodies an implicit valuation, that the value of a human life is proportional to income.

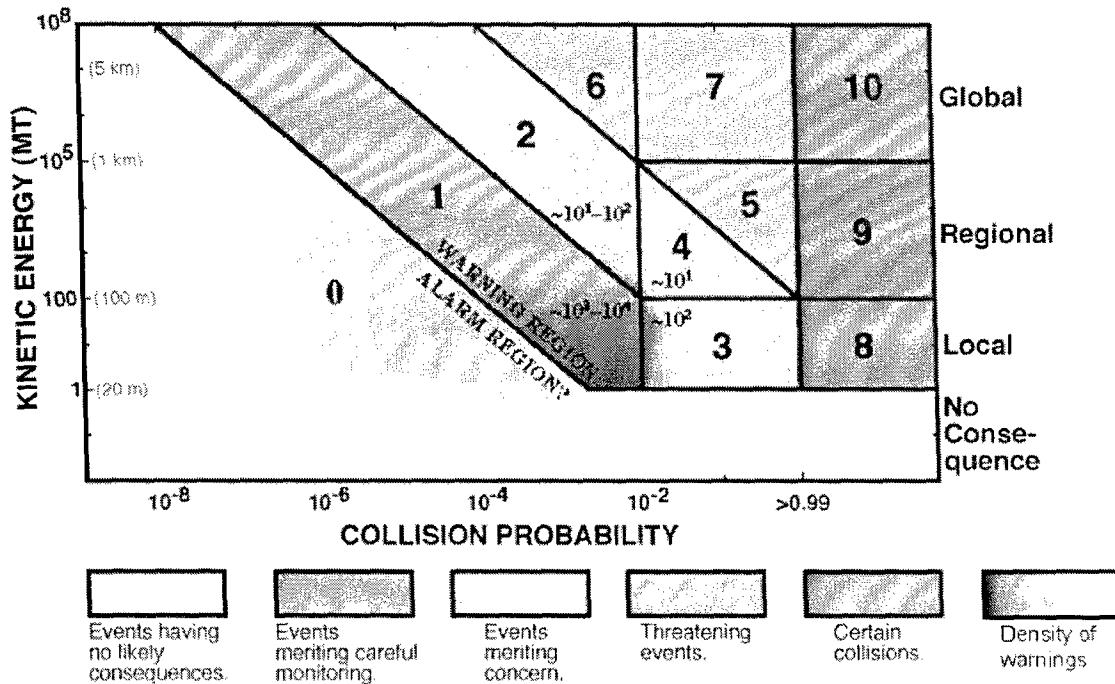
⁸ These values are based on the methodology of Canavan (*op. cit.*), the failings of which were discussed in Chapter Three. The conversion to a global value embodies the same implicit valuation as above.

⁹ In the terminology of Table 2.6, the cataloging benefit should be accompanied by the cost of an active mitigation (interception) program, spread out through time between year of discovery and year of impact. The “warning” benefit should be accompanied by the cost of a passive mitigation (civil defense) program, incurred in the same year as discovery.

¹⁰ This unpublished data was graciously provided by Steve Chesley of the NEO Program Office, NASA JPL, 16 March 2004. It is used here for illustrative purposes only, as a departure point for parametric variation of warning rate. As should be clear from the extensive discussion of warnings in Chapter Two, actual warning rates are determined by a complex interplay of survey characteristics, and the validity of Table 6.1 for other than the modeled surveys is uncertain.

Figure 6.1 shows the Torino scale warnings associated with the SDT survey mapped onto the Torino scale itself.¹¹ Naturally, the highest density of warnings is associated with small objects with low collision probabilities, yet still within the “Torino Level 1” region. An “alarm region” in Torino Level 0 is shown to make the point that social costs can be incurred even in the absence of “official” warnings.

Figure 6.1
Estimated Torino warnings during SDT survey



A New Model

We now construct a new model on the foundation of the SDT cost-benefit model. That previous model is expanded to allow variation of some of its parameters: discount rate; cost per life; and cost of infrastructure. New parameters are added to reflect society's response to survey outcome and a structural form for the variation of these parameters is modeled. Specifically, a social response to short-term warning of definite impact (or just “warning” in the SDT terminology) is modeled by adding an evacuation factor and an evacuation cost per person. A social response to long-term warnings is accommodated in two ways: by modeling two varieties of interceptor acquisition programs (baseline and CARDINAL) and by modeling warning rates and variations of associated social costs. Finally, the influence of the CARDINAL approach on social costs of warning is allowed to vary.

¹¹ The threshold for Torino scale warnings in Table 6.1 is determined by kinetic energy in megatons (MT) and collision probability. The object diameters shown in Figure 6.1 reflect an average velocity somewhat different from that assumed by Figure 2.11.

For the purpose of argument, it is sufficient that only four of the twenty-eight SDT study survey cases are considered: the baseline LINEAR survey, four and eight-meter aperture ground-based telescopes, and a one-meter space telescope in Low Earth Orbit (LEO).¹² Likewise, only the nominal hazard case is considered (293 deaths), since variation of the death rate is mathematically equivalent to variation of the cost per life. The cometary component of the impact hazard is neglected, as it is in the SDT study, although here for different reasons.¹³

The measure of effectiveness chosen for all cases is net present value (NPV) in FY03 U.S. dollars.

The following addresses the features of the new model in more detail.

Discount Rate

Chapter Five addressed the enormous difficulties associated with choice of discount rate, especially discount rates for the far future. This model accommodates a uniform variation in discount rate, "uniform" in the sense that the discount rate is not a function of either time or object size. Furthermore, costs and benefits are discounted at the same rate. One source in the literature (Pearce) states that this is in fact a requirement imposed by the methodology of cost-benefit analysis.¹⁴ On the other hand, a second source (Schelling) states that the discount rate "...is usually uniform over time, but sometime allowed to diminish in the far future. (For the near future, something akin to arbitrage keeps the rate constant)."¹⁵ A third source (Weitzman) says "Society should be using effective discount rates that decline from a mean value of, say, around 4 percent per annum for the immediate future down to around zero for the far-distant future."¹⁶

The blue curve in Figure 6.2 demonstrates the effect of a discount rate that diminishes with time, using the schedule specified by Weitzman.¹⁷ In this figure, annual benefits before discounting are assumed to remain constant and are normalized to unity. The vertical scale represents discounted benefits, and hence the area under each curve is equal to NPV. The variation in discount rate serves to increase the relative contribution of far-future benefits (or costs, considering the general case) to NPV.

¹² These are listed in order of survey effectiveness (as measured by SDT survey completeness from year to year), although there is not much difference seen between the two new ground-based telescope systems (GB 4m and GB 8m). Cost estimates for the acquisition and operation of these systems are taken from the SDT model. These costs include a 25 percent management reserve, which should be adequate given the recent history of NASA SSE and NSF programmatic cost growth (11 percent for SSE, and 8 percent for NSF: *Budget of the United States Government*, Fiscal Year 2003, p.325 and p.343.)

¹³ Increased death rates and reduced interceptor effectiveness would reflect an increased cometary hazard component by proxy, although the exact correspondence is difficult to model. The uncertainty of the cometary contribution to the impact hazard is discussed in Chapter Two.

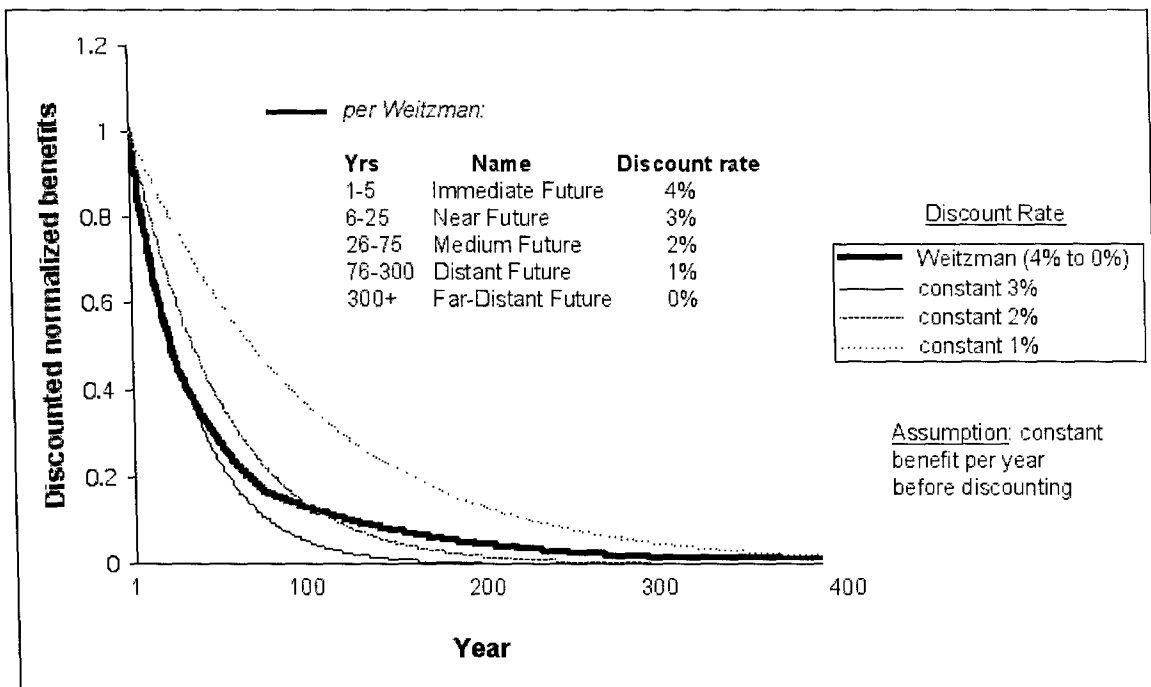
¹⁴ "There is a presumption that all benefits and costs, regardless of their nature, are to be discounted at the same rate, and that this rate is constant over time"; Pearce, D.W., *Cost-Benefit Analysis*, Macmillan Studies in Economics, Macmillan, London, 1971, p.40 (cited in Lumley, S., "Cost-Benefit Analysis, Ethics and the Natural Environment," *Cost-Benefit Analysis*, Puttaswamaiah, K., editor, Transaction Publishers, New Brunswick, U.S., 2002, p. 109).

¹⁵ Schelling, T., "Intergenerational Time Discounting—Preliminary synthesis, with questions," unpublished manuscript, received by facsimile from that author on 10 May 2001, p.1.

¹⁶ Weitzman, M., "Gamma Discounting," *The American Economic Review*, Volume 91, Number 1, March 2001, p. 270. Note that Schelling's definitions of "near future" and "far future" do not necessarily correspond with the classifications of Weitzman.

¹⁷ *Ibid*, Table 2—"Approximate Recommended" Sliding-Scale Discount Rates.

Figure 6.2
Diminishing discount rate vs. constant rates



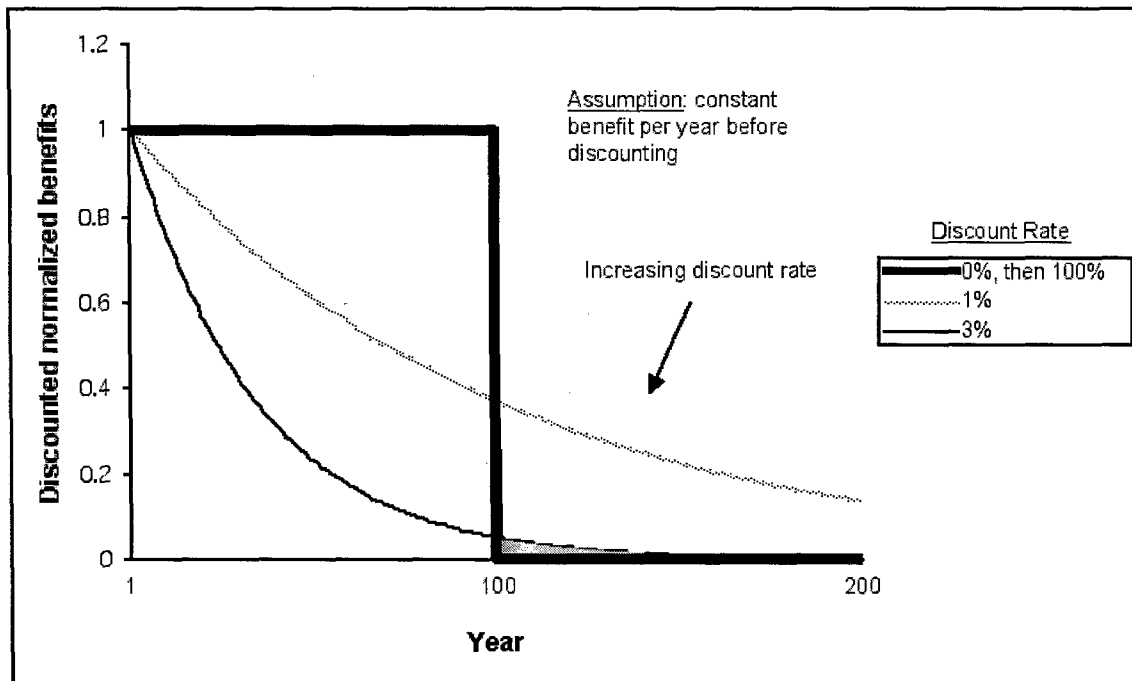
While Weitzman's approach is methodologically attractive, his specified discount schedule relies on the results of a survey of expert economists who were asked "...what real interest rate do you think should be used to discount over time [projects] to mitigate the possible effects of global climate change?"¹⁸ It is not clear whether the resulting discount schedule is appropriate for application to the costs and benefits associated with the impact hazard.

Lacking the basis for choice of an appropriate schedule of diminishing discount rates, we fall back on orthodoxy. We choose to accommodate uncertainty with a single discount rate that is independent of time but varied across a "reasonable" range of values.

In the present work, all costs and benefits are modeled for a period of one century, as with the underlying SDT model. The neglect of longer-term costs and benefits embodies an implicit assumption of 100 percent discounting (following a century of zero discounting in the original SDT model, and a century of not-necessarily-zero discounting in this revised model). Naturally, the lower the *actual* long-term discount rate, the more the validity of the model suffers. This is demonstrated by Figure 6.3. The heavy black line represents the discounting of the SDT model. The gray zone under the three percent discount curve shows the NPV lost to the new model by its truncation at the century mark, for that discount rate. If a one percent discount rate prevails, then the truncation error (in terms of NPV) corresponds to the area under the light gray curve from 100 years onward. In any event, the illustrative value of the model is not harmed by the somewhat arbitrary truncation of costs and benefits: the main effect will be an underestimation of NPV at very low discount rates (say, under 1–3 percent).

¹⁸ *Ibid*, p.271.

Figure 6.3
Truncation of discounted net benefits



Cost per Life

As noted above, the SDT model assesses global and U.S.-only lives at \$1.6 and \$6.96 million in FY03 dollars. The present model allows this parameter to vary. Cost per life is used in the calculation of both cataloging and “warning” benefit (the latter being the benefit of *definite* near-term impact warning, as in the SDT model).

Cost of Infrastructure (per Person)

The SDT model assesses global and U.S.-only infrastructure at \$98,000 and \$734,000 per person in FY03 dollars. Again, this parameter is now allowed to vary. Cost of infrastructure is used only in the calculation of cataloging benefit, as in the SDT study.

Evacuation Factor

Evacuation factor is defined as the ratio of people evacuated to the expected number of fatalities; it is assumed constant across the range of possible NEA impactor sizes. Together with evacuation cost per person, evacuation factor is used in calculating a cost necessarily associated with “warning” benefit that is not accounted for in the SDT model. Note that in the real NEA impact case, there will be a wide variation in the size and evolution of the uncertainty ellipse’s footprint on the Earth and thus the timing and extent of any evacuations. Still, for the purpose of this model the simplification is acceptable. A nominal factor of one hundred is chosen: for example, if ten thousand people are likely to die from the event, one million people are evacuated.

Evacuation Cost per Person

Evacuation cost per person is multiplied by the evacuation factor to calculate the cost associated with near-term warnings. A nominal value of \$1,000 is chosen. This is significantly higher than costs found in the literature of hurricane evacuation, which was reviewed as an analogous case. One study estimated *private* evacuation costs of between \$42 and \$68 per person for three hurricanes that hit the mid-Atlantic coast of the United States.¹⁹ However, total evacuation costs should include public safety expenditures, so a larger sum is used as a starting point in this model.

Active Mitigation Program (Interceptor) Costs

The cataloging benefits of the SDT model can be realized only if a survey is accompanied by a mitigation program, whether active or passive. Here it is assumed that in the event of a long-term warning of definite impact, society's response will take the form of active mitigation (that is, interception of the threatening NEA). The model examines two potential mitigation program structures. A baseline case considers that an interceptor development and production program is initiated only upon a long-term warning of definite impact. A case denoted CARDINAL entails the demonstration of an NEA interception capability in advance of any warnings; thereafter, a production program awaits a warning of definite impact, as in the baseline case. For both cases, the model assumes that no interceptor production costs are associated with false warnings.²⁰

Warning Horizon

In the real case, the warning horizon (that is, time from impactor detection until projected impact) will vary from a year out to perhaps several decades.²¹ For simplicity this variation is here collapsed to a uniform fifteen-year horizon.²² Accordingly, cataloging benefits lag discovery by the same period, rather than being credited in the year of discovery as in the SDT model.

Program Structure (Baseline Case)

In the baseline case, program initiation awaits detection of a specific impactor. A single interceptor sized for that impactor is then designed, built, and launched. An initial one-year delay in program start is assumed (for observational follow-up and political or bureaucratic reasons). Development and production occurs over six years, following a typical end-loaded

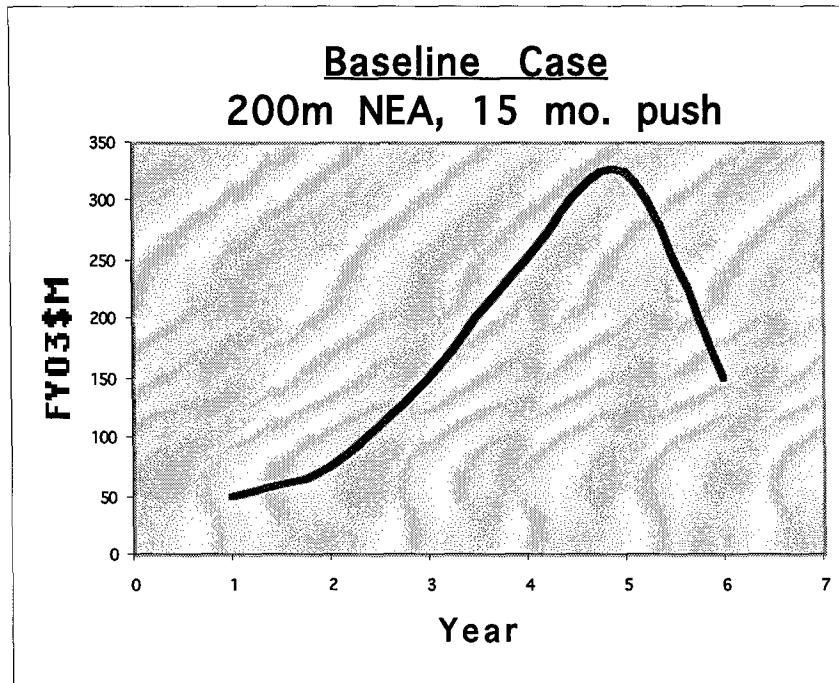
¹⁹ Wilson, K., *et al.*, "All People Are Not the Same: Incorporating Social, Economic and Cultural Factors Into Mitigation Planning," East Carolina University, Greenville, North Carolina, undated (www.dem.dcc.state.nc.us/mitigation/Library/Research/wilson.pdf). The authors studied evacuations associated with hurricanes Bonnie, Dennis and Floyd.

²⁰ In all likelihood, political pressures will impel such expenditures even in cases where probability of Earth impact is quite low. However, the exact probability threshold for action is a matter of conjecture. In this model, the only costs associated with uncertain predictions are the social costs of warning.

²¹ The lower end of the range represents transition to the near-term warning case, where only passive mitigation (evacuation) is possible.

²² The relatively short horizon is chosen because of the requirement for a *certain* prediction of impact. Uncertain predictions of impact could of course occur with a much longer horizon. The actual average warning horizon depends on the evolution of the uncertainty ellipse, as discussed in Chapter Two. However, for the purpose of this model, the fifteen-year assumption is sufficient.

Figure 6.4
Baseline acquisition profile



funding profile, depicted in Figure 6.4.²³ The length of an acquisition program can extend from two or three years to a matter of decades.²⁴ A six-year program is chosen as a reasonable intermediate value, especially given the assumed fifteen-year warning horizon.²⁵

Costs of the baseline case are scaled from Project B612 costs (a total of one billion dollars, sized for a 200-meter NEA) and assume a continuous 15-month non-nuclear push as means of deflection.²⁶ This scaling is by impactor mass, assuming constant density across NEA sizes, with mass varying by the cube of diameter. No economies of scale are assumed.

Expected program costs are integrated across object sizes using estimated impact frequencies and the same survey completeness values used in the calculation of cataloging benefit. Each year's total expected mitigation costs result from the likelihood of program initiation that year, plus the likelihood of up to five prior-year program initiations. This methodology is illustrated in Figure 6.5.

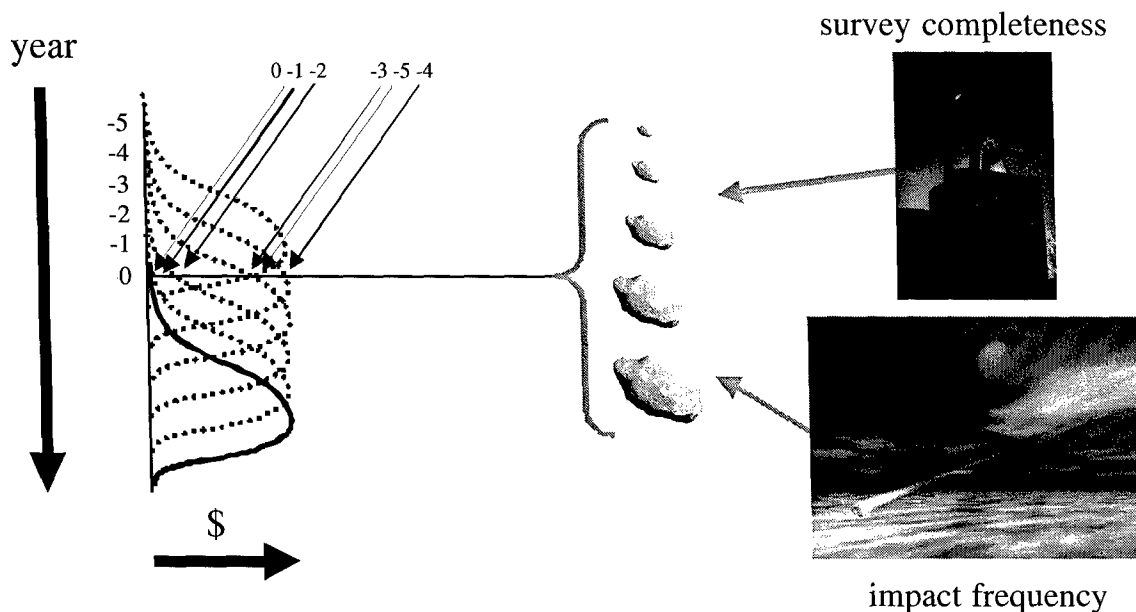
²³ For cost distributions of typical programs, see *Systems Engineering Management Guide*, Second Edition, Defense Systems Management College, October 1986, p.17-2.

²⁴ An example at the low end of the scale was the *Clementine* lunar/asteroidal probe (discussed in Chapter Two). One does not have to look far to find programs at the other end of the scale: *Galileo*, *Hubble*, *Cassini*, *Rosetta*, and many others.

²⁵ After the assumed ten-year survey period, the warning horizon begins to extend beyond fifteen years. That is, each six-year mitigation program (and its associated benefit) is anchored to the year of projected impact. The actual interception mission (launch, fly-out to the NEA, and deflection) is included in the six-year program span.

²⁶ Project B612 was first discussed in Chapter Two. That project envisions a three-month period of pushing the NEA using a type of ion drive known as the Variable Specific Impulse Magnetoplasma Rocket (VASIMR). For an operational system pushing a 200-meter NEA with a time to Earth impact (from start of deflection) of one decade, a fifteen-month push would be needed. This timeline is generally consistent with the fifteen-year average warning horizon assumed in the present model. Schweickart R., *et al.*, "The Asteroid Tugboat," *Scientific American*, November 2003, pp. 54-61, and Chang Diaz, F., "The VASIMR Rocket," *Scientific American*, November 2000.

Figure 6.5
Derivation of expected annual mitigation costs



Program Structure (CARDINAL)

The CARDINAL program consists of a demonstration phase and a conditional surge phase. Development of a single CARDINAL demonstration interceptor is initiated coincident with the start of expanded NEO survey efforts. The demonstration program extends over six years, without the one-year delay in program start experienced in the baseline case. The interceptor is sized for a 100-meter NEA, assuming a continuous 15-month non-nuclear push as in the baseline case.²⁷ CARDINAL's demonstration funding profile is shown in Figure 6.6, reflecting a total of \$250 million. This sum is derived from a mass-scaling of the 200-meter B612 target NEA, coupled with an assumed doubling of acquisition costs for the same velocity change (ΔV) imparted to the asteroid target.²⁸

In the conditional surge phase, CARDINAL interceptors are built and flown in bulk, matching production quantities to impactor size rather than tailoring the size of a single interceptor.²⁹ As in the baseline case, no economies of scale are assumed.³⁰ For simplicity, surge

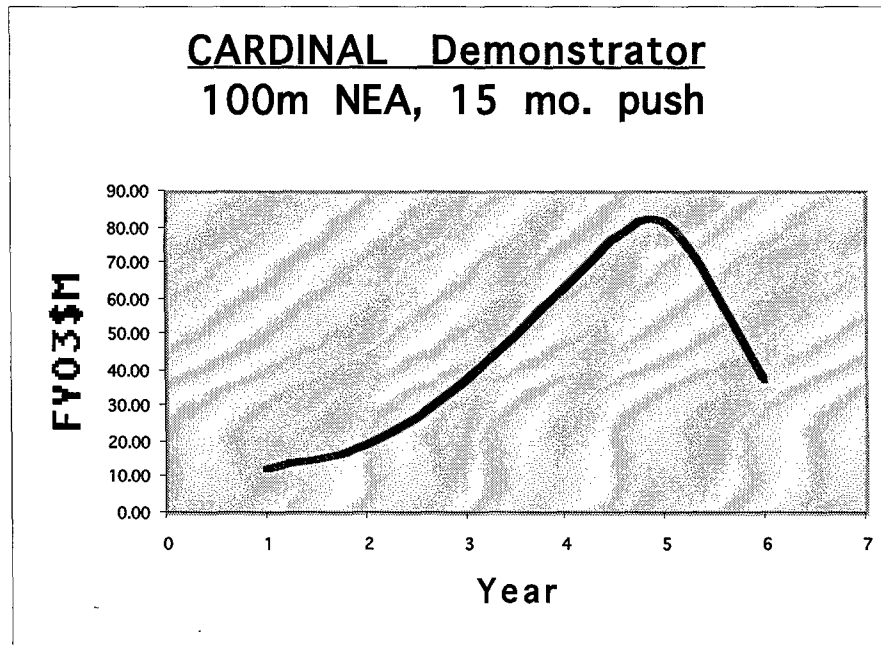
²⁷ Given the dual purpose of the CARDINAL demonstrator (to provide social reassurance and to serve as a foundation for surge production, however unlikely), a smaller interceptor than assumed by B612 is probably desirable, as discussed in Chapter Five.

²⁸ Mass-scaling reduces cost eightfold, since NEA mass is assumed to diminish by the cube of diameter reduction. Costs are then doubled, since the system is optimized for surge production (as discussed in Chapter Five), and this reduces system effectiveness for a given launch mass. Hence, demonstration cost is reduced by a factor of four. Note, however, that this is a *definite* cost, whereas costs in the baseline case are weighted by impact probability and survey completeness. Also note that the model assumes a successful demonstration.

²⁹ This scheme does not preclude cluster-launches of multiple CARDINAL interceptors on single boosters: in effect, Multiple Independently-targeted Interplanetary Vehicles (MIIVs). Whether the interceptors would "swarm" the NEA or be launched in a "shoot-look-shoot" sequence (to use military parlance) would depend largely on warning horizon.

³⁰ These are not economies of unit scale, which are considered nonexistent in the baseline case, but economies of production quantity scale.

Figure 6.6
CARDINAL demonstrator acquisition profile



production is conducted within the space of one year (since the interceptor design was proven in the demonstration phase).³¹ Unit costs in surge production are assumed to be double baseline acquisition costs for the same ΔV imparted to the NEA.³²

Expected surge production costs are integrated across object sizes using estimated impact frequencies and survey completeness values, again as in the baseline case.

Interceptor System Reliability

“Interceptor system reliability” refers to the ability of the interceptor to perform its intended mission without an *engineering* failure. Given this definition, it is logical to hold reliability constant across the full range of NEA sizes. This model assumes that reliability is known before launch, hence mitigation costs scale inversely with reliability (for example, a 50 percent reliability is accommodated by acquiring twice the number of interceptors).³³

³¹ Note that the ability of CARDINAL to respond to very short warnings is an advantage that is masked by the collapsed fifteen-year warning horizon used in this new model.

³² Optimizing the design for surge production reduces system effectiveness for a given launch mass, whether considering a demonstrator or a production article.

³³ This is a simplification of the real case. System acquisitions can experience stochastic failure due to inadequate quality control. They can also fail due to a design flaw. A system procured in quantity (such as CARDINAL) may be robust to stochastic failures while still susceptible to a common weakness of design. In the latter case, increasing the production buy does not improve matters. The solution would be to fund multiple, competing design approaches. Still, this is unnecessary complexity for the purpose of the model under discussion.

Interceptor Effectiveness

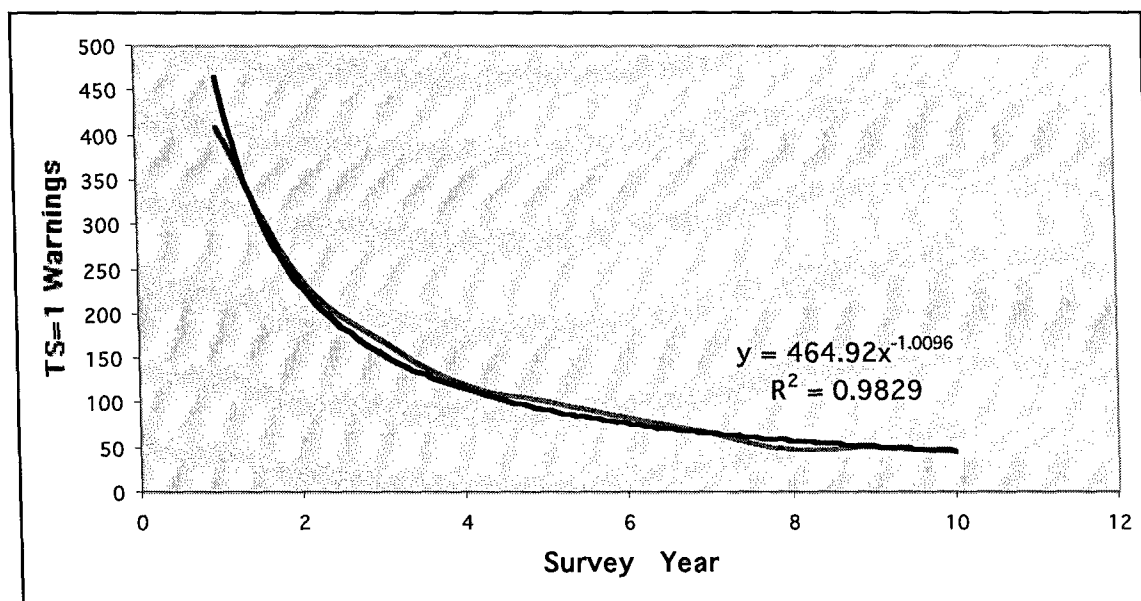
“Interceptor effectiveness” can be thought of as a measure of the ability of the interceptor to perform its intended mission without a *science* failure. In the model it is a factor between zero and one that is applied to the benefits of mitigation (hence, its complement reflects the lives and infrastructure lost due to a partial or complete interception failure). Effectiveness is assumed to remain constant across the full range of NEA sizes, and is not known before launch.³⁴

Warning Rate

Total warning costs will be a function of both warning rate and the costs associated with each warning. This model uses the predicted Torino warning rates associated with the SDT survey, shown in Table 6.1 and Figure 6.1.³⁵ Warnings are disaggregated into NEA size bins and scaled down in proportion to survey completeness by year.

The binning of object discoveries (and thus warnings) into years obscures an inverse power-law dependency of warnings on time. Significantly, the bulk of all warnings will occur within a very short time of initial activation of any enhanced survey system. As an example, Figure 6.7 depicts Torino Level 1 warnings for each year of a ten-year SDT survey for the space telescope case. Astronomers describe the activation of a new telescope as “first light”; in this case, “blinded by first light” might describe the experience. An initial cascade of warnings will occur, with associated scope and duration of warning costs that are very uncertain.

Figure 6.7
Torino Level 1 warnings, LEO 1-meter space telescope



³⁴ The model does not consider multiple interception attempts, evacuation following a failed interception, or heightened social costs after a failure. These would all depend on the warning horizon, which is collapsed in this simplified model.

³⁵ The model does not explicitly address the rate or cost of Palermo scale warnings. That scale is intended for the use of astronomers rather than the public, although it is the basis of the IAU procedure for reviewing impact warnings (Chapter Two). This model does allow parametric variation of the warning rate, however, so the issue of which warning scale to use is moot.

Beyond survey completeness, the particular characteristics of the survey system used have no effect on warning rates.³⁶

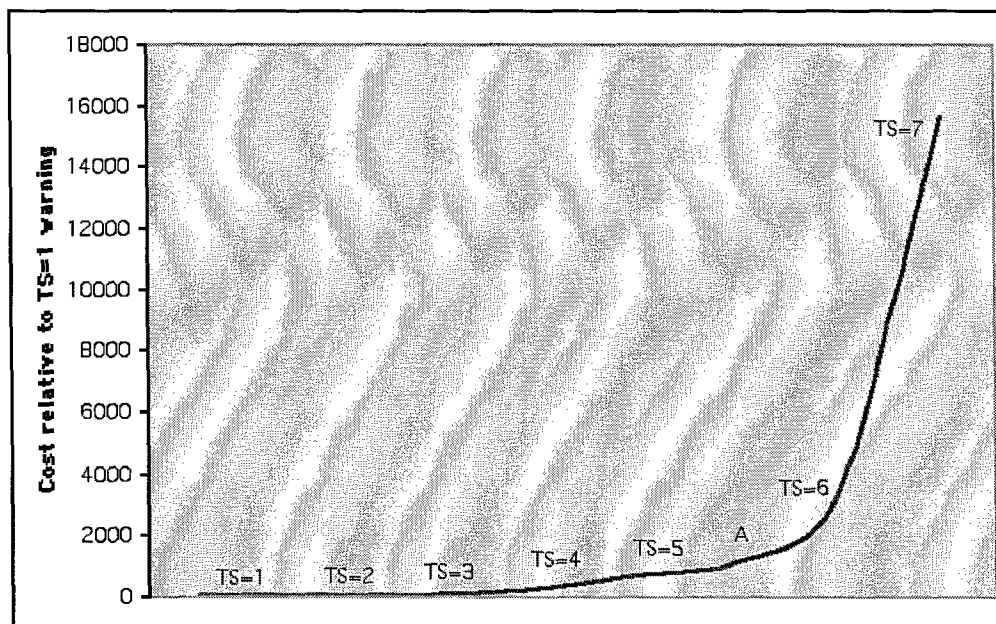
A special accounting is made for those Torino Level 1 warnings involving civilization-ending impactors of one-kilometer diameter or greater (the threshold of the original Spaceguard survey). These enter the Torino scale at a probability of one in a million. It is reasoned that “Armageddon” warnings are different in kind from those involving smaller impactors, so such warnings are scaled differently, with an effect between Torino Level 5 and 6. Ten percent of those PHOs detected by the survey in any given year are considered to generate an “Armageddon” warning, as defined here.³⁷

Warning Costs

As pointed out in Chapter Two, costs may be incurred as a result of alarms that are not associated with any official “warning.” For example, alarms are likely to be generated by “near misses” (close approaches to the Earth by an asteroid or comet), in which the public perception of risk will be higher than warranted by astrodynamical calculations. Alarm costs are not considered in this model.

Warning costs are assumed to scale geometrically by Torino scale level. Figure 6.8 depicts a five-fold increase in costs per warning per level, five being the nominal “warning rise factor” chosen for the model.³⁸

Figure 6.8
Cost per warning with rise factor equal to five



³⁶ This is because the survey simulation that is the basis of Table 6.1 did not show such a dependency. Steve Chesley, NEO Program Office, NASA JPL, personal communication, 16 March 2004.

³⁷ The simulation work in support of the SDT study resulted in the following “rules of thumb.” Ten percent of all detected PHOs in the simulation rise to an impact probability of one in a million. One percent rise to a probability of one in ten thousand. The chance of a PHO having an impact probability of one percent is between one in four thousand and one in three thousand. Steve Chesley, NEO Program Office, NASA JPL, personal communication, 26 February 2004.

³⁸ The vertical scale of Figure 6.8 represents a multiplier of the cost associated with a Torino Level 1 warning.

In this figure, “A” denotes the “Armageddon” warning level discussed above. The cost of each such warning is modeled by Equation 6.1, where “A” is the cost of an Armageddon warning, “T1” is the cost of a Torino Level 1 warning, and “wrf” is warning rise factor. “A” will always lie between Torino Levels 5 and 6 in this formulation, and is equal to one thousand times the T1 cost when “wrf” equals five as above.

$$A = T1 \left(\text{wrf}^{\left(\frac{3}{\log 5} \right)} \right) \quad (6.1)$$

In the model, warning costs increase in direct proportion to number of warnings per year. That is, no crescendo or familiarization (“cry wolf”) effects are assumed. An interesting possible representation of both effects is shown in Equation 6.2 and Figure 6.9, but implementation in the model is not attempted due to the lack of any theoretical basis for choosing a functional form. Establishing such a basis is left as a subject for further research.³⁹

$$y = (1 + \sin(x - 1))e^{(1-x)} \quad (6.2)$$

Finally, warning costs are assumed to be incurred entirely in the year of object discovery. This simplification neglects those cases in which an object is lost, or delays are experienced (for many possible reasons) in follow-up observations of threatening objects.

Warning Rise Factor

“Warning rise factor” is the parameter introduced in Equation 6.1 above. It determines the rapidity of the geometric progression of warning costs as a function of Torino level.

Cost per Warning

“Cost per warning” is the cost of a single Torino Level 1 warning. Variation of this parameter has a linear effect on total warning costs by construction. Consequently, uncertainty in cost per warning is mathematically equivalent to uncertainty in the total warning rate. Cost per warning is applied to the SDT Torino warning rates of Table 6.1.

Reassurance (CARDINAL Only)

“Reassurance” represents the warning cost reduction occasioned by the prior demonstration of a CARDINAL interceptor. It is a value between zero and one and is assumed to remain constant across the full range of NEA sizes.⁴⁰

Table 6.2 below summarizes the parametric variation exercised in the model, with reference to the preceding paragraphs.

³⁹ The three curves of Figure 6.8 follow the form of Equation 6.2, and use nominal costs per warning and warning rise factor as initial conditions. They illustrate the possible effect of a “drumbeat” of Torino Level 1 warnings (with reference to Figure 6.6 or its equivalent for other survey systems).

⁴⁰ In theory, a value greater than one could reflect a less-than-successful CARDINAL demonstration program, although in such a case it might be preferable to build and fly a second demonstrator.

Figure 6.9
Crescendo, then familiarization

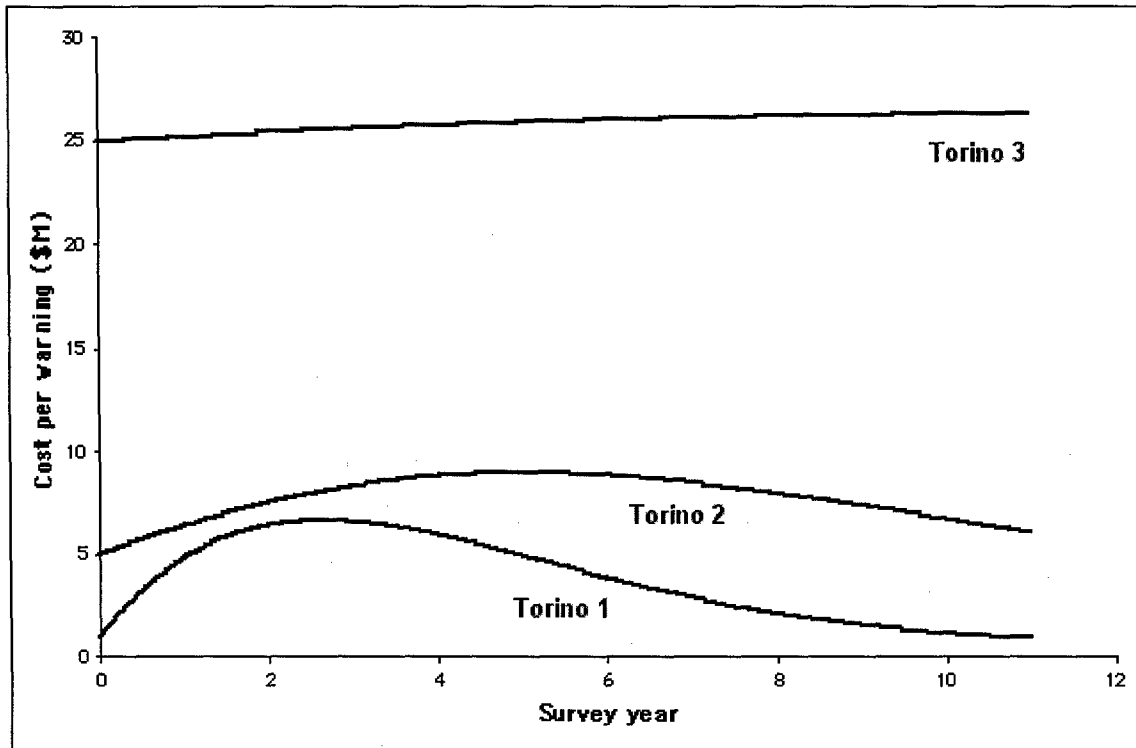


Table 6.2
Parametric variation

Parameter	Units	Start value	Nominal value	End value
Discount rate		0	0.03	0.15
Cost per life	\$M	0.01	1.6	12
Cost of infrastructure (per person)	\$M	0	0.098	0.2
Evacuation factor		0	100	1000
Evacuation cost per person	\$M	0	0.001	0.005
Interceptor system reliability		0.1	0.9	1
Interceptor effectiveness		0	1	1
Warning rise factor		2	5	50
Cost per warning	\$M	0	1	5
Reassurance		0	0.9	1

Model Results

The new model is implemented in Microsoft Excel, with baseline and CARDINAL cases for each of the four survey systems (continuation of the LINEAR survey, and three prospective surveys using new ground or space-based telescopes). These eight “sub-models” are then used as input data for the Computer Assisted Reasoning[®] system (CARs[™]) exploratory modeling software.⁴¹ This software facilitates multi-dimensional parametric variation, allowing the rapid exploration and mapping of a large uncertainty-space.⁴²

It quickly becomes apparent from exercising CARs that both baseline and CARDINAL model results are robust to uncertainty in several of the parameters of Table 6.2. Specifically, NPV is insensitive to variation in infrastructure cost, evacuation factor, evacuation cost, and interceptor system reliability. Accordingly, these parameters are left at nominal values in the analysis. In contrast, Figures 6.10 through 6.34 (below) show that variation of the other parameters has a large effect on NPV.

Nominal Cases

In Figures 6.10 and 6.11, the parameters of Table 6.2 are left at nominal with the exception of discount rate. In the baseline case, increasingly effective surveys have increasing NPV only up to a discount rate of about 2.3 percent.⁴³ At high discount rates, all the surveys have a negative NPV, with the most effective surveys faring the worst. Interestingly, just continuing the existing LINEAR survey results in an NPV on the order of minus \$400 million at higher discount rates. The most capable survey (LEO 1m) has an NPV on the order of minus \$5 billion at the same high discount rates.

For LINEAR, the internal rate of return (IRR) is 4.2 percent.⁴⁴ For the other three systems, IRR is between 2.6 and 2.7 percent.

NPV decreases with increasing discount rate because the warnings that incur social costs occur only during the ten-year period of survey operation, whereas survey benefits are spread out over a full century following survey initiation. In this nominal baseline case, with a nominal 3 percent discount rate, LINEAR takes 50 years to break even (that is, to achieve cumulative discounted benefits that balance cumulative discounted costs). The other surveys never break even. Even with a one percent discount rate, it takes LINEAR 36 years to break even, and the other three surveys 46 to 49 years.

In the CARDINAL case (Figure 6.11), the social costs of warning have been reduced by the reassurance of a demonstration program, and the more effective surveys are associated with higher NPV as one would hope. CARDINAL has a higher NPV than does the baseline case for all discount rates. LINEAR’s NPV is always positive. For the other surveys, IRR is 12.3 percent (GB 8m), 14.5 percent (GB 4m), and 10.8 percent (LEO 1m). NPVs of all four surveys become comparable above discount rates of 8 percent. At the nominal 3 percent

⁴¹ CARs[™] is a product of Evolving Logic, Inc. (www.evolvinglogic.com).

⁴² The parametric variation discussed below is, with one exception, conducted along the multi-dimensional coordinate axes (*i.e.*, only one parameter is varied at a time). It represents a reconnaissance, not a full mapping, of the uncertainty-space.

⁴³ LINEAR is the least effective survey, and the one-meter space telescope (LEO 1m) is the most effective. The two ground-based telescopes (GB 4m and GB 8m) are in between.

⁴⁴ IRR is the discount rate associated with zero NPV.

Figure 6.10
Baseline nominal

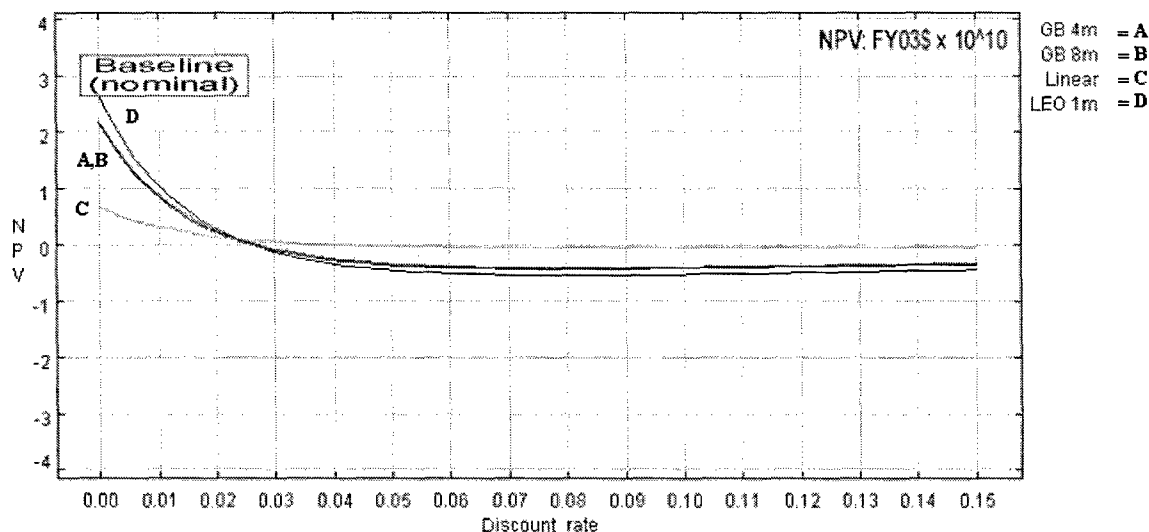
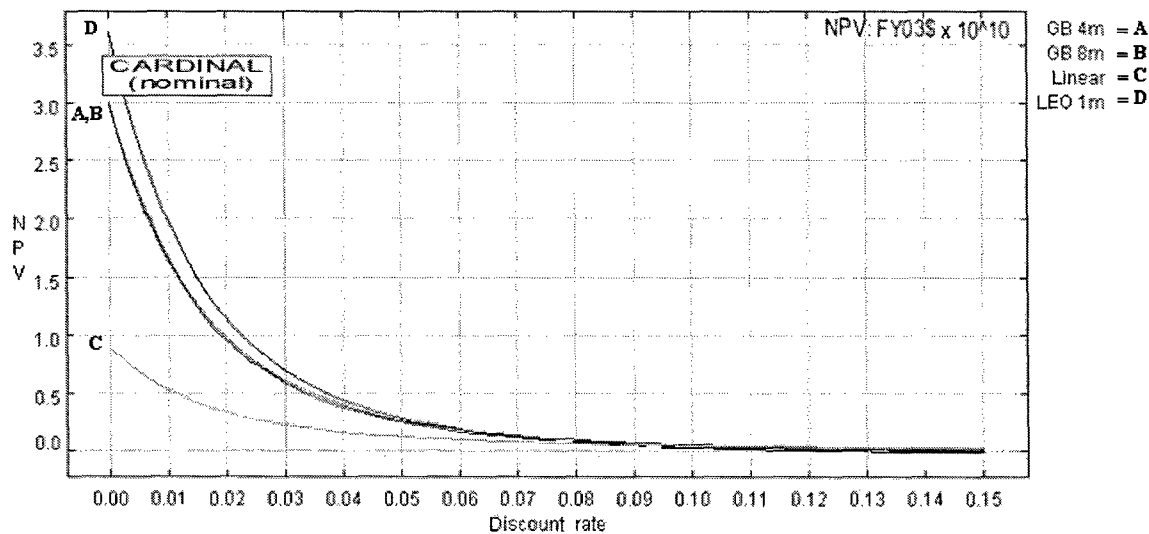


Figure 6.11
CARDINAL nominal

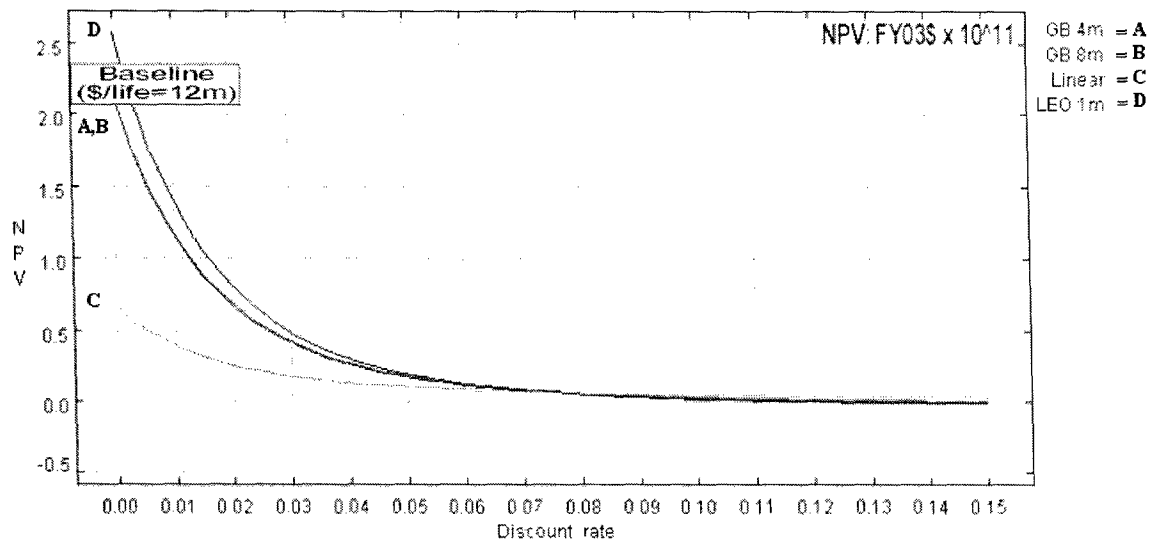
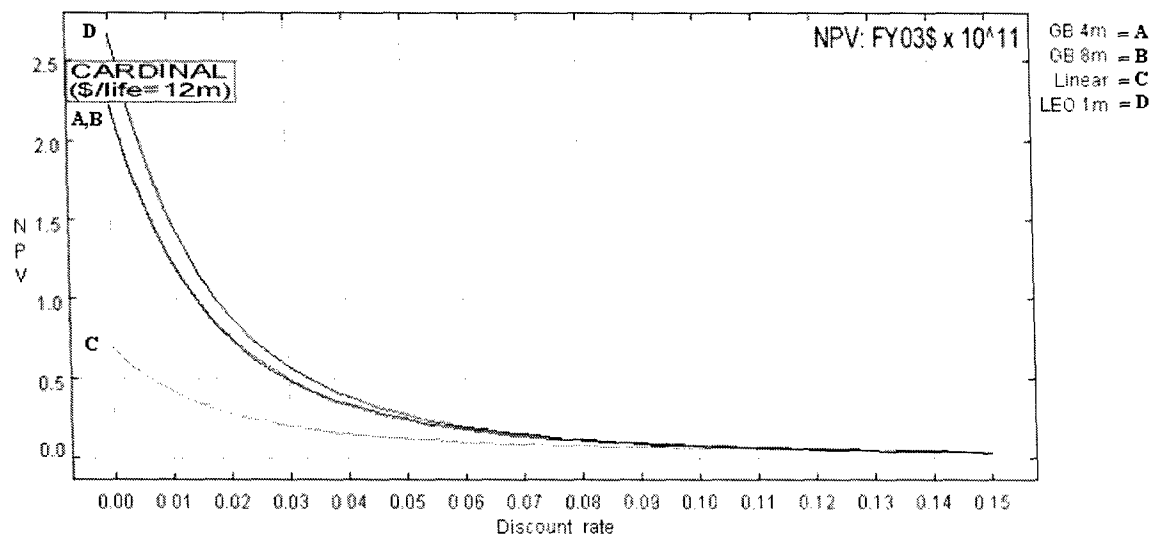


discount rate, LINEAR breaks even in the second year of operation, the other three surveys after sixteen to nineteen years.

These results show that under the chosen nominal conditions (and with the assumptions previously noted) the CARDINAL approach dominates the baseline case and is robust to uncertainty in discount rate. The analysis now proceeds to explore off-nominal conditions.

Maximum Cost per Life (\$12 million)

Figures 6.12 and 6.13 reproduce the nominal cases of Figures 6.10 and 6.11 with one exception: cost per life is increased from the nominal \$1.6 million to a relatively extreme \$12 million.⁴⁵

Figure 6.12**Baseline (\$/life = \$12m)****Figure 6.13****CARDINAL (\$/life = \$12m)**

⁴⁵ The highest cost per life referenced in Kenkel (*op. cit.*) is \$11.56 million (adjusted to FY03 dollars), and represents the higher bound of an EPA estimate for the U.S. population.

The primary effect of the increase in life valuation is to reduce the difference between the baseline and CARDINAL cases.⁴⁶ This is simply because the benefits accruing from saving lives swamp any reduction of warning costs that CARDINAL may achieve. In particular, both cases show increasing NPV associated with increasingly effective surveys.

Still, there are differences in IRR between the cases. CARDINAL NPV is always positive. GB 4m, GB 8m, and LEO 1m have IRRs of 18.4 percent, 15.2 percent, and 12.1 percent in the baseline case (LINEAR NPV is always positive). Hence, even with the extreme life valuation, CARDINAL is more robust to uncertainty in discount rate.

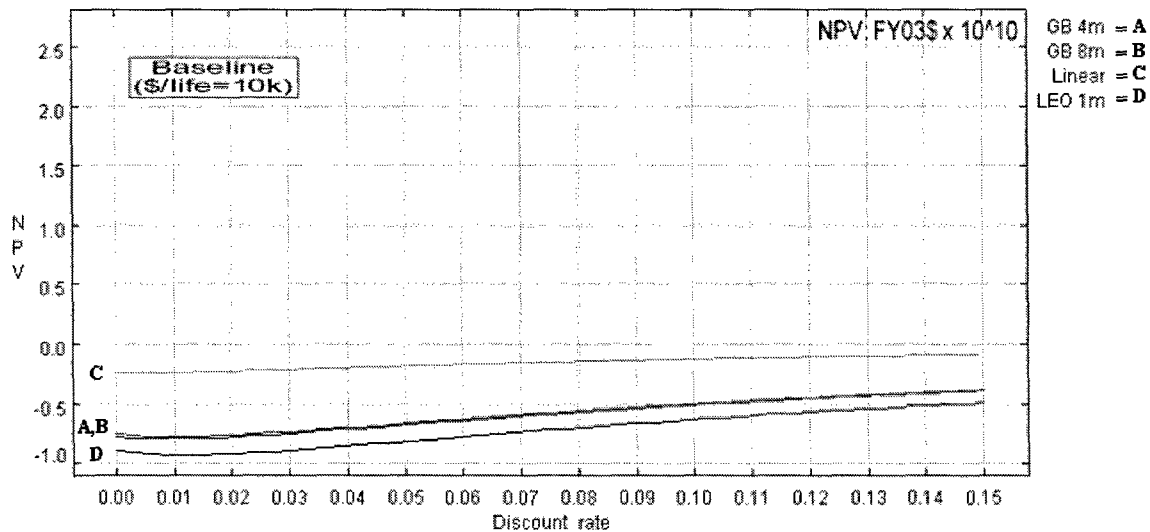
There are also differences in break-even points. At a nominal 3 percent discount rate, CARDINAL breaks even in the first year of operation for each of the four survey systems. In the baseline case, GB 4m, GB 8m, and LEO 1m break even after nine, seventeen, and eighteen years (LINEAR breaks even in the first year, as in the CARDINAL case).

The conclusion is that even with very high assumed costs per human life, the CARDINAL approach is still favored over the baseline case, although not so markedly as before.

Minimum Cost per Life (\$10,000)

Figures 6.14 and 6.15 reduce cost per life to a mere \$10,000.⁴⁷ Here we see a magnification of the differences between the baseline and CARDINAL cases. This is because with such a very small cost per life, the benefits accruing from saving lives are overshadowed by the reduction of warning costs as a result of the CARDINAL demonstration.

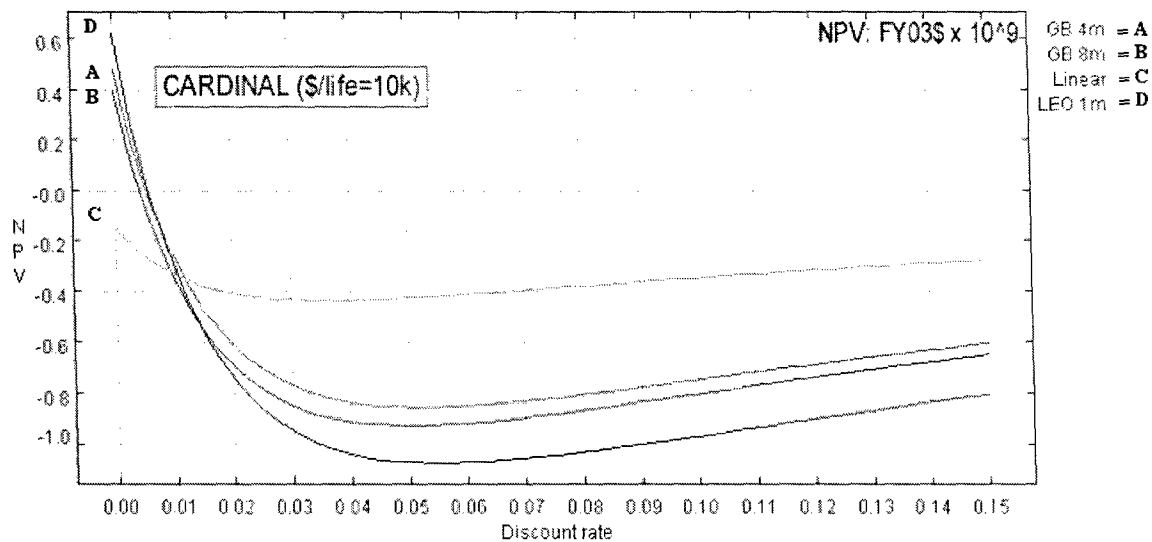
Figure 6.14
Baseline (\$/life = \$10k)



⁴⁶ Note that these two figures show NPV in hundreds of billions of dollars, rather than the tens of billions of Figures 6.10 and 6.11.

⁴⁷ The lowest cost per life referenced in Kenkel (*op. cit.*) is \$12,000 in 1993 dollars.

Figure 6.15
CARDINAL (\$/life = \$10k)



All baseline NPVs are severely negative, and increasingly capable surveys are increasingly detrimental to society for all discount rates.

Note that the lowest baseline NPVs are an order of magnitude greater (in the negative direction) than those of CARDINAL. Interestingly, CARDINAL fails to raise LINEAR NPVs to positive values at any discount rate. For the other three survey systems of the CARDINAL case, IRR ranges between 0.4 and 0.6 percent. Relative to the case with a nominal \$1.6 million cost per life, CARDINAL has become much less robust to uncertainty in discount rate. Nevertheless, CARDINAL dominates the baseline for all rates.

On the other hand, for the first time we have a situation in which for either baseline or CARDINAL (in most cases) it is better to do nothing than to pursue the SDT survey, whatever the choice of system.⁴⁸ The exception is if a new survey is conducted, a CARDINAL approach is taken, and discount rate is under about one half of one percent - a quite restrictive set of conditions.

Fifty Percent Interceptor Effectiveness

Figures 6.16 and 6.17 reduce interceptor effectiveness from the nominal 100 percent to 50 percent. Relative to the nominal cases (Figures 6.10 and 6.11), the main effect is to reduce NPVs across the board, but especially for low discount rates. IRRs are also reduced.

In the baseline case, IRR for LINEAR has gone to 2.3 percent (from 4.2 percent in the nominal case which assumes a completely effective interception). IRR for the new surveys now ranges between 1.0 and 1.2 percent (down from 2.6 to 2.7 percent).

With the CARDINAL approach, LINEAR still enjoys positive NPVs across the board—at least, to the maximum 15 percent discount rate exercised in the parametric varia-

⁴⁸ While “doing nothing” necessarily entails the loss of lives, such a condition represents the axis of zero benefit (and zero NPV). This is because “doing something” garners a benefit, rather than resetting a cost to zero. It is simply the bookkeeping chosen by the SDT study team, carried forward to this new model.

Figure 6.16
Baseline (interceptor effectiveness = 0.5)

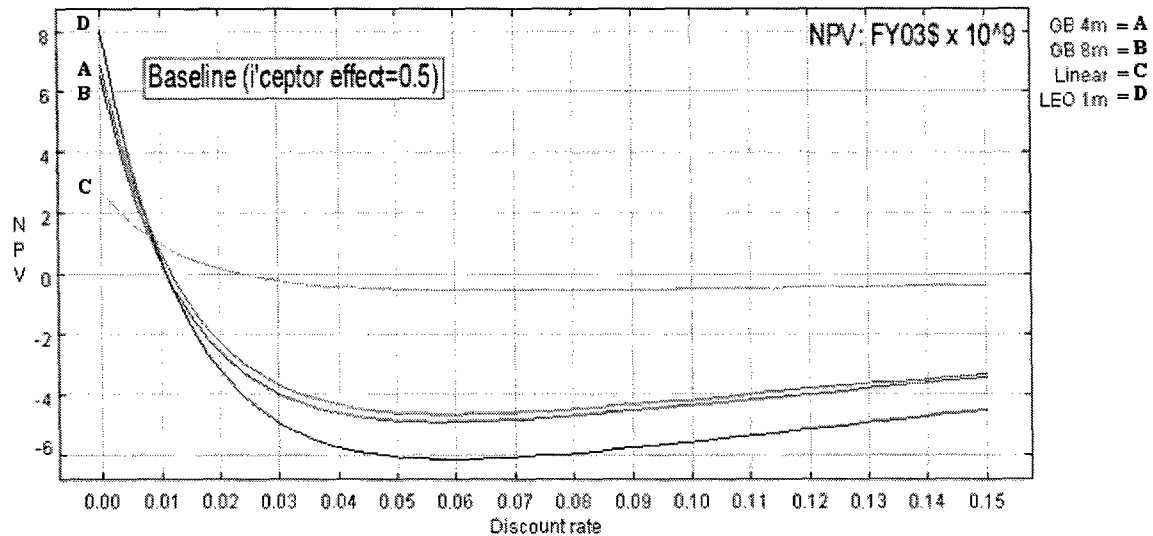
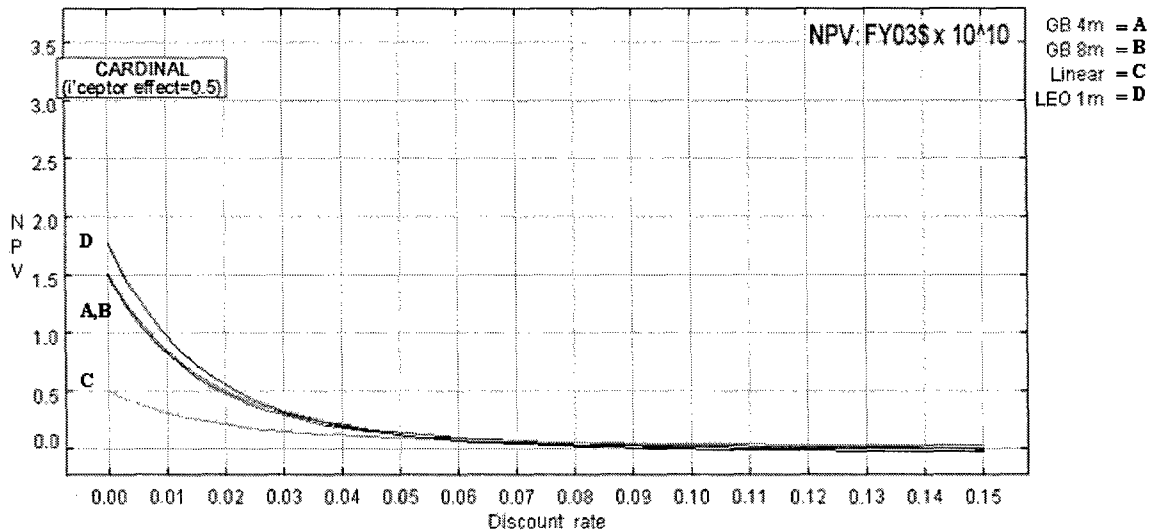


Figure 6.17
CARDINAL (interceptor effectiveness = 0.5)



tion. However, IRRs for the three new survey systems have all reduced. They are 12 percent (GB 4m), 9.7 percent (GB 8m), and 8.2 percent (LEO 1m). The values assuming 100 percent interceptor effectiveness were 14.5 percent, 12.3 percent, and 10.8 percent, so a slight reduction in robustness to uncertainty in discount rate has occurred.

Notwithstanding these details, a reduction in interceptor effectiveness to 50 percent does not alter CARDINAL's domination of the baseline case for all discount rates.

Zero Interceptor Effectiveness

Figures 6.18 and 6.19 further reduce interceptor effectiveness all the way to zero. In other words, interception efforts are completely unsuccessful, and lives and infrastructure are destroyed on the Earth in full measure. This excursion assumes that for one reason or another, a subsequent interception cannot be attempted and no evacuation of the target zone occurs. This may seem like an extreme assumption, but that is the point: it represents an extreme on the scale of efficacy, and so is of analytical interest.

Figure 6.18
Baseline (zero interceptor effectiveness)

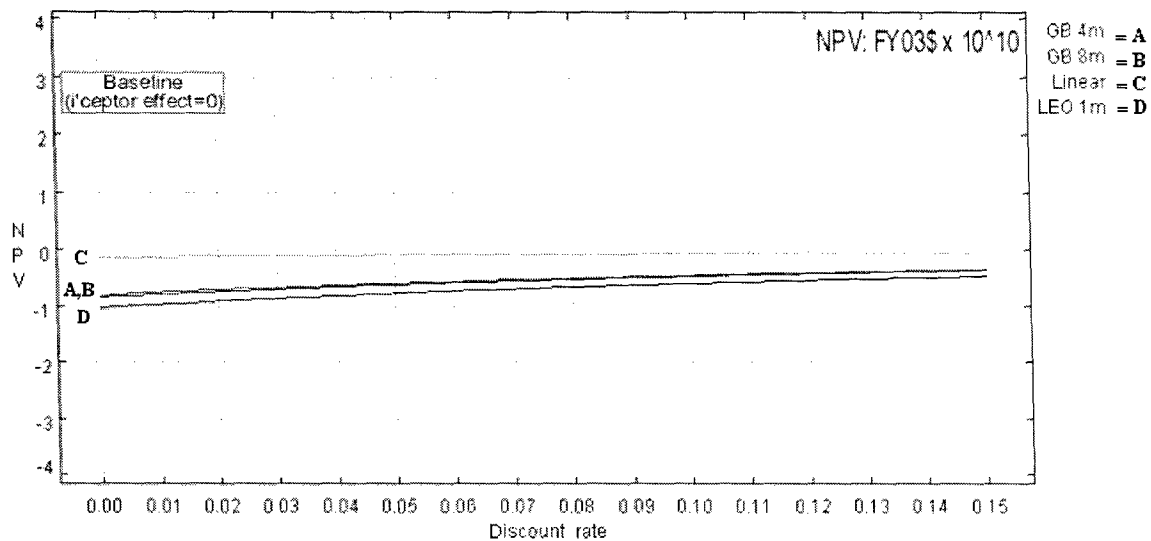
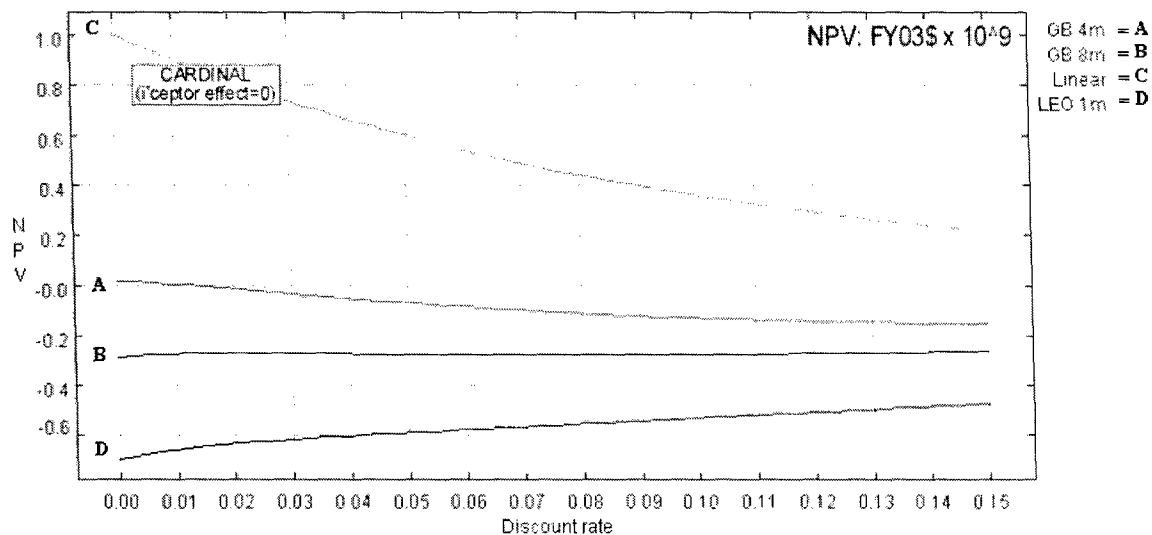


Figure 6.19
CARDINAL (zero interceptor effectiveness)



The baseline results are remarkably similar to those of the baseline excursion to a minimum cost per life (Figure 6.14), although the shape of the curves is slightly different and LINEAR NPVs are not quite as negative. As in that case, we have a situation in which inaction dominates action—NPVs are always negative. It is better to do nothing than to pursue the SDT survey, whatever the choice of system.

The CARDINAL results are very interesting. For the first time, we have a case in which CARDINAL is unable to prevent the most capable surveys from incurring the greatest social cost. LINEAR is the only survey that enjoys positive NPVs across the board. GB 4m has a positive NPV only below its IRR of 1.3 percent. NPV is negative for all other GB 4m discount rates, and for all discount rates in the case of GB 8m and LEO 1m.

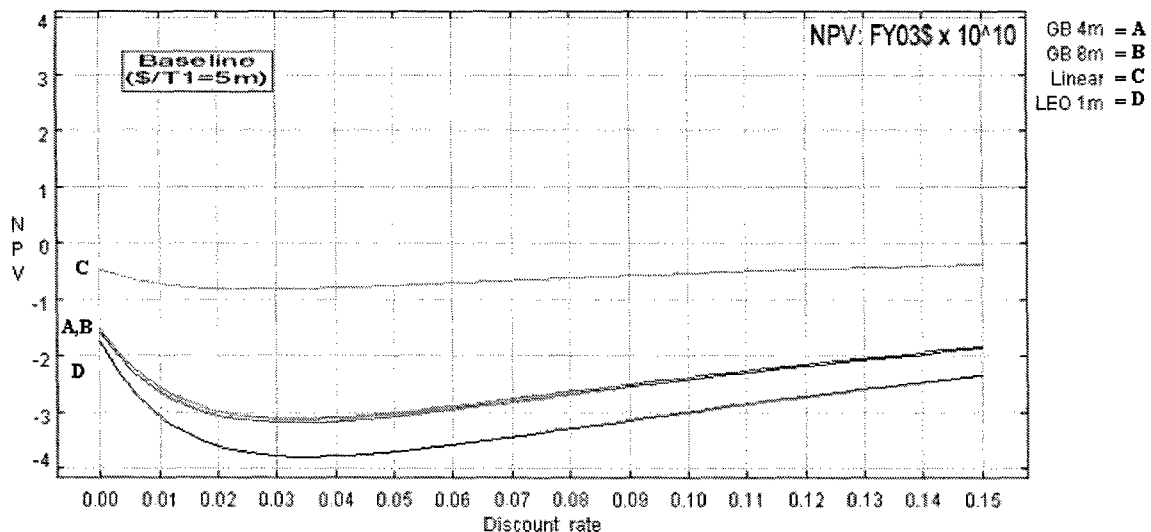
The central conclusion from this parametric variation of interceptor effectiveness (referring to the four prior figures plus those representing the two nominal cases) is that CARDINAL consistently dominates the baseline case for all discount rates.

Maximum Cost per Warning (\$5 million)

Figures 6.20 and 6.21 show the effect of increasing cost per Torino Level 1 warning from \$1 million to \$5 million.⁴⁹

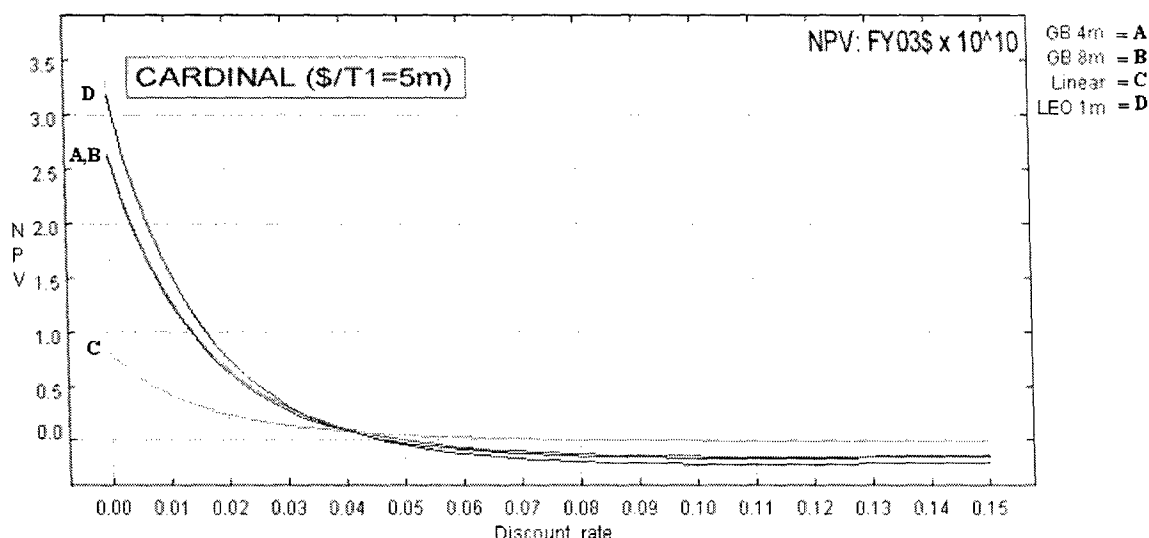
Relative to the nominal conditions shown in Figures 6.10 and 6.11, NPVs are drastically lower in the baseline case, and somewhat lower in the CARDINAL case. A distinct minimum has developed in the baseline NPV curves, especially for the new survey systems in which it is found between discount rates of 3 percent and 4 percent. Minimum baseline NPVs are as low as minus \$30–\$40 billion, much worse than the approximately minus \$2.5

Figure 6.20
Baseline (\$/T1 = \$5m)



⁴⁹ Recall that this is mathematically equivalent to a five-fold increase in total warning rate, so uncertainty in that parameter is subsumed in this case.

Figure 6.21
CARDINAL (\$/T1 = \$5m)



billion of CARDINAL. Baseline NPVs are always negative—as has been seen before in previous cases, it is better to do nothing than to pursue the SDT survey, whatever the choice of system. The LINEAR system's IRR is now 9.5 percent in the CARDINAL case (CARDINAL LINEAR NPV was always positive when a nominal cost per warning was assumed, as in Figure 6.11). CARDINAL cannot prevent negative NPVs for the new survey systems beyond a discount rate of about 4.5 percent.

This condition represents a reduction in robustness to uncertainty in discount rate, relative to a nominal Torino warning rate. Nevertheless, CARDINAL's advantage over the baseline case is extended across the board, as one might expect.

Every deviation from nominal conditions examined thus far has seen CARDINAL enjoying an advantage over the baseline case. The next excursion looks at a *reduction* in warning costs, and here is where one might expect the tables to be turned.

Zero Warning Costs

Figures 6.22 and 6.23 show the effect of a complete absence of warnings costs on NPV across a span of discount rates. This case represents either zero costs per warning or a warning rate of zero.

CARDINAL NPVs are slightly lower than those of the baseline case across the board. This is not surprising, since the absence of warning costs renders meaningless CARDINAL's ability to reduce the social costs of warning and the certain costs of the CARDINAL demonstrator program outweigh the probability-weighted costs of the baseline interceptor.

This begs an obvious question: at what cost per warning (or warning rate) is the policymaker indifferent to the baseline and CARDINAL approaches? This will vary according to discount rate, and is shown in Figure 6.24 below. For all survey systems examined, a very low cost per warning (or warning rate) is sufficient to justify the CARDINAL strategy—as low as about \$27,000 per warning in the case of the new survey systems.

Figure 6.22
Baseline (zero warning costs)

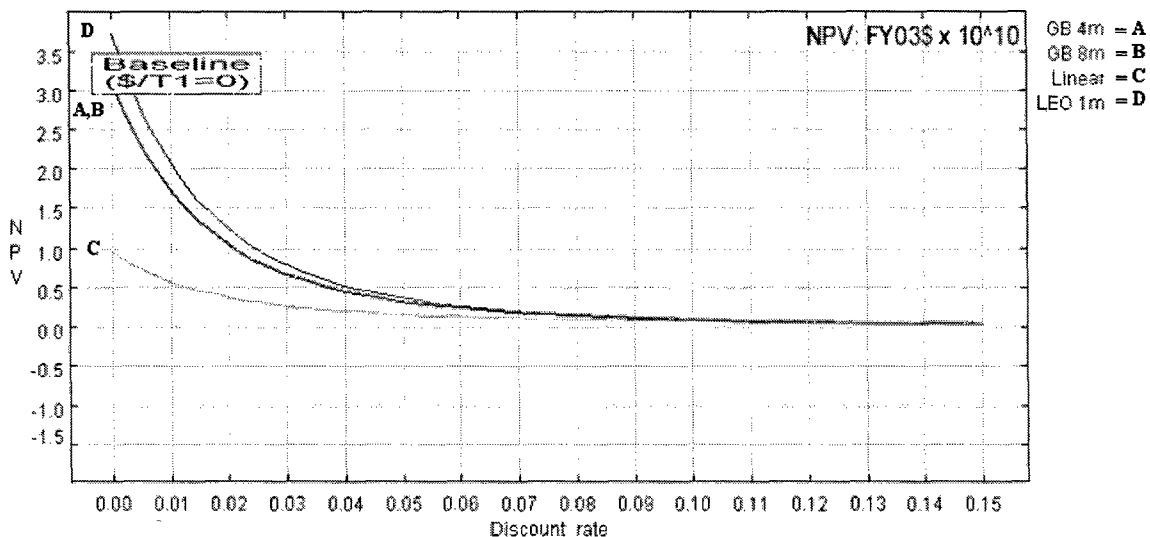


Figure 6.23
CARDINAL (zero warning costs)

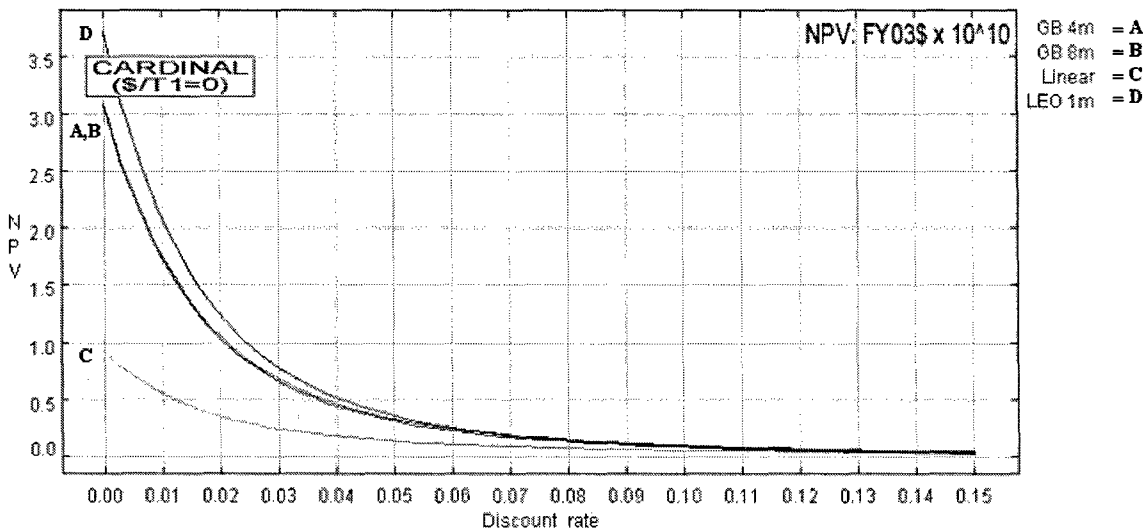
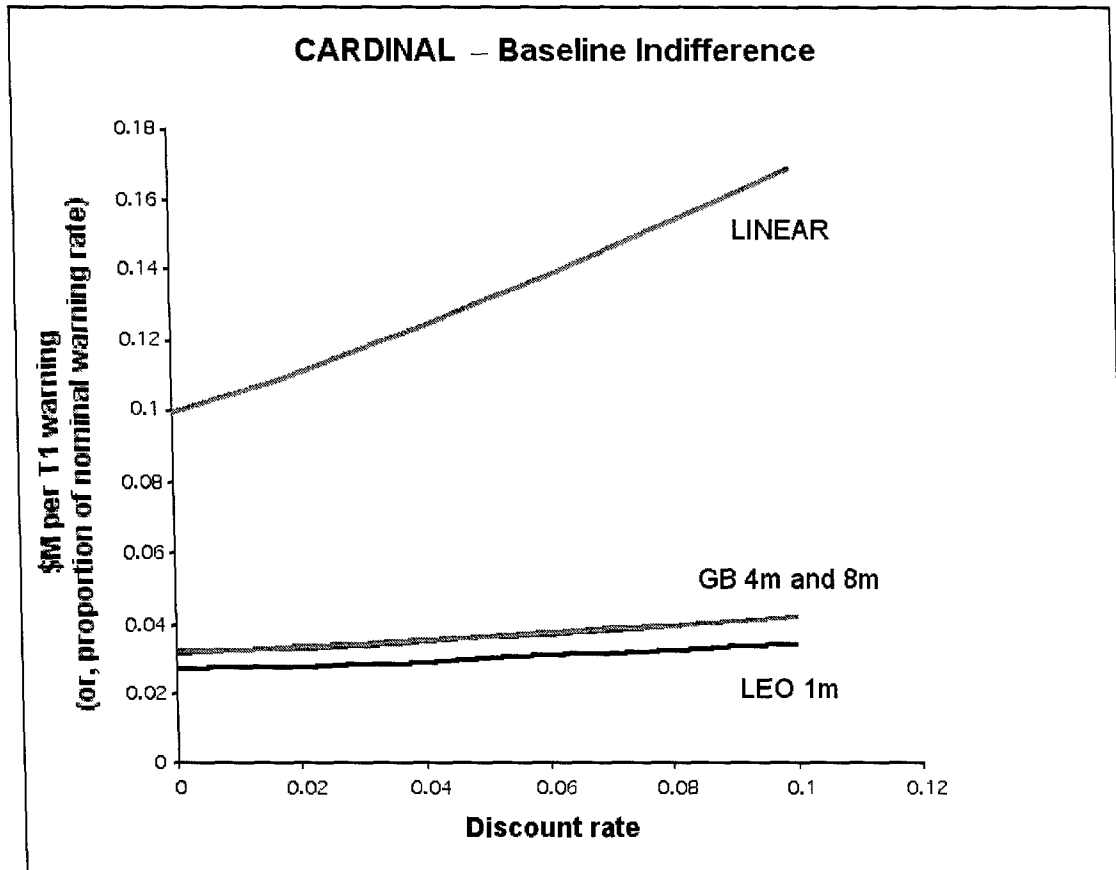


Figure 6.24
Indifference curves



Variation of Reassurance

Reassurance represents the warning cost reduction occasioned by the prior demonstration of a CARDINAL interceptor, and is here varied from a nominal 90 percent (Figure 6.11) through 60 percent down to 30 percent (Figures 6.25 and 6.26). It can be seen that NPVs are progressively reduced, but not drastically so unless discount rates are high. This is shown by the migration of IRR to lower values as reassurance is diminished. In other words, CARDINAL's robustness to uncertainty in discount rate is reduced the less effective it is in reassuring society of its putative capabilities.

In the nominal case, CARDINAL enjoyed an IRR of 10.8 percent or higher for the new survey systems—LINEAR was always positive. With a 60 percent reassurance, the new surveys have an IRR between 5.2 and 5.7 percent, and LINEAR's IRR is now 14 percent. With 30 percent reassurance, the new surveys' IRRs diminish to between 3.4 and 3.7 percent, and LINEAR's IRR is further reduced to 5.7 percent.

Nevertheless, if actual discount rates are below 3.4 percent (as may well be the case), any of the survey systems will add value to society even if reassurance levels are quite low. Furthermore, below a discount rate of about 3 percent, increasingly capable surveys result in increasing social benefit, as one would hope, as long as CARDINAL's reassurance is at least 30 percent.

Figure 6.25
CARDINAL (Reassurance = 0.6)

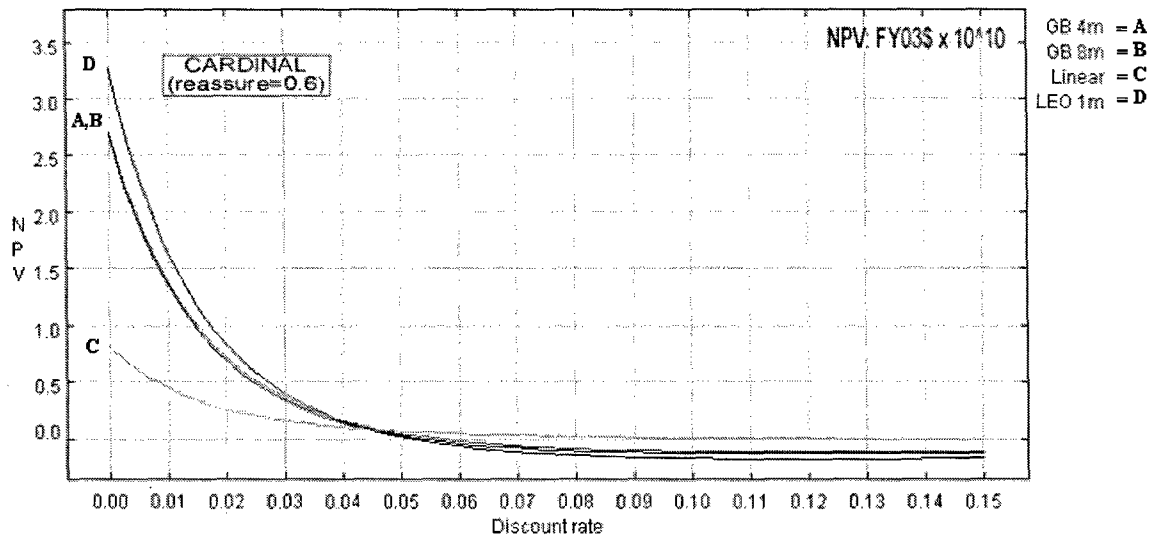
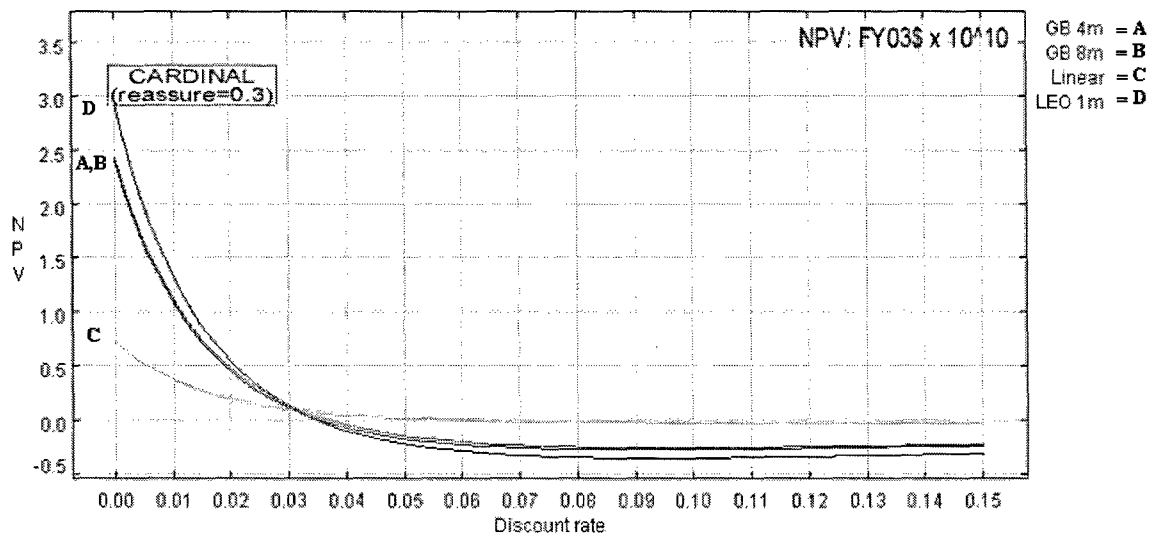


Figure 6.26
CARDINAL (Reassurance = 0.3)



Low Cost per Warning, High Warning Rise Factor

When the Torino scale was unveiled in 1999, its creator (Dr. Richard Binzel of MIT) opined that “nobody should lose sleep over an asteroid in the zero or one category.”⁵⁰ However, when the scale was first conceived nobody had reason to expect an over-tenfold increase in

⁵⁰ “Near Earth Objects Scale Helps Risk Communication,” NASA press release 99-83, 22 July 1999.

the number of Torino Level 1 warnings (such as predicted by Table 6.1 for an extended NEO survey). Consequently, in the future, social costs may be incurred by such warnings despite the best intentions of astronomers. The parametric variation exercised above consistently assumes that Torino Level 1 warnings carry a social cost (except for Figures 6.22 and 6.23, which reflect no costs for *any* warning). We now begin to relax that assumption.

Figure 6.27

Baseline (cost per warning = \$50k, warning rise factor = 20)

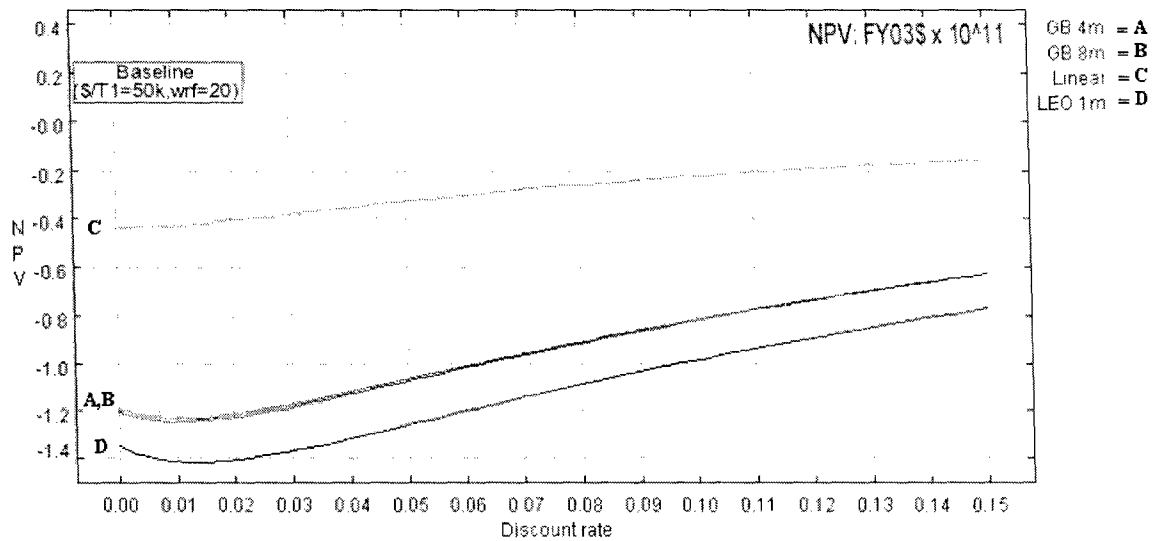
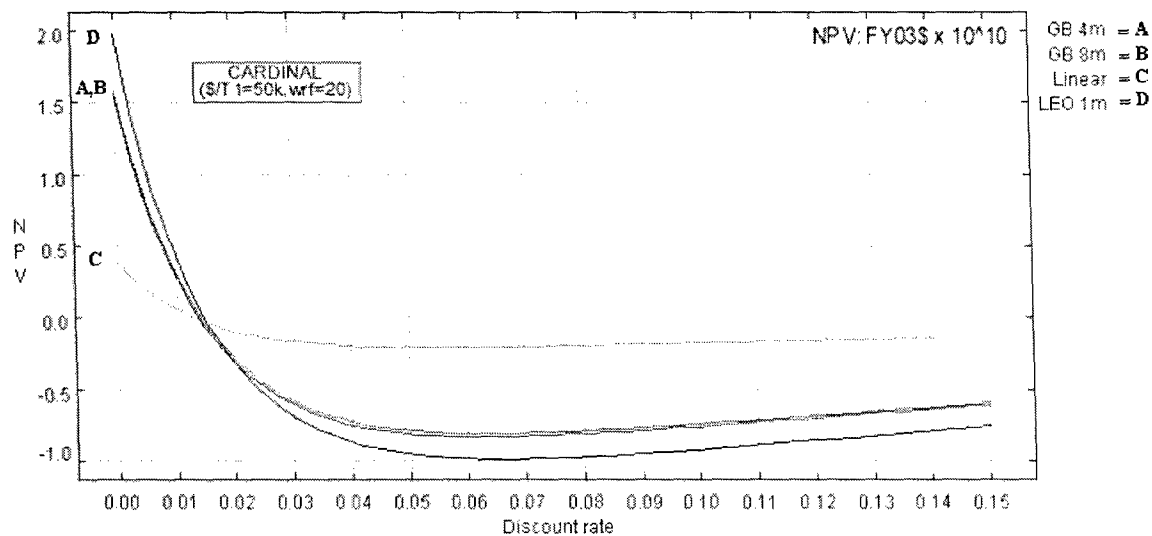


Figure 6.28

CARDINAL (cost per warning = \$50k, warning rise factor = 20)



Figures 6.27 and 6.28 scale back the social reaction to Torino Level 1 warnings, but higher Torino levels are taken much more seriously than in the nominal case (that is, the cost per Torino Level 1 warning is significantly reduced, while warning rise factor is increased).⁵¹

As in the excursion to a maximum cost per warning of \$5 million (Figure 6.20), baseline NPVs are negative for all discount rates. In this case, the geometric rise of warning costs with warning level has swamped the effect of the lower Torino Level 1 costs, notwithstanding the extreme rarity of the higher Torino level warnings. Again, we have a case in which inaction dominates action—it would be better to do nothing than to pursue the SDT survey, whatever the choice of system.

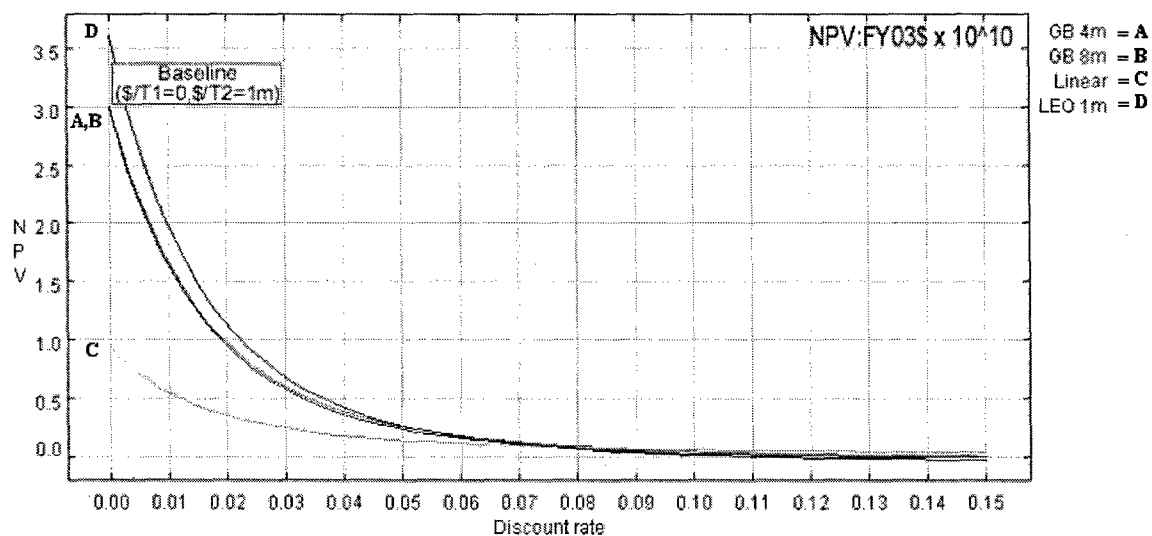
CARDINAL NPVs are just under 1.5 percent for all survey systems. Unless there is confidence that discount rates are very low, inaction again dominates action. CARDINAL is thus shown to be no panacea—at a sufficiently high level of warning costs, or a sufficiently rapid ramp-up of those costs as a function of warning level, mankind would be better off if the resources demanded by the new NEO survey were directed to other pursuits.

Shifted Warning Progression

We now examine two sets of cases in which, per the Torino scale's original intent, "no sleep is lost" over Torino Level 1 warnings. The first set (Figures 6.29 and 6.30) shows a shifted warning progression. That is, the nominal case is shifted on the Torino scale: Torino Level 2 has the effect of the previous Level 1, Level 3 has the effect of the previous Level 2, and so forth. The second set (Figures 6.31 and 6.32) shows a clipped warning progression. That is, Torino Level 1 warnings are simply excised from the nominal case.

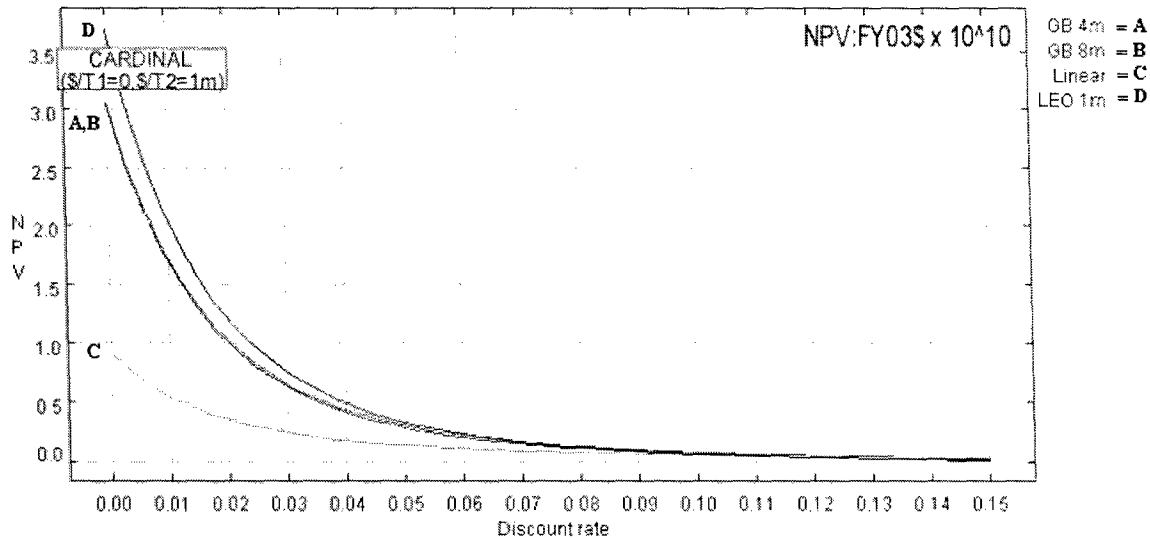
Figure 6.29

Baseline (no T1 warning costs, $\$/T2 = 1m$)



⁵¹ The two figures illustrate an off-axis parametric variation (that is, the simultaneous variation of more than one of the nominal parameters).

Figure 6.30
CARDINAL (no T1 warning costs, \$/T2 = 1m)



One exception is made to the “no sleep is lost” assumption. Armageddon warnings (those Torino Level 1 warnings involving potentially civilization-ending impactors, as discussed earlier in this chapter) are retained but modified to fall between Torino Level 4 and 5 instead of between Level 5 and 6. Equation 6.3 shows the new Armageddon warning formulation.

$$A = T2 \left(\text{wrf} \left(\frac{2}{\log 5} \right) \right) \quad (6.3)$$

At first impression, Figures 6.29 and 6.30 show very little difference from Figures 6.22 and 6.23, which reflect the zero warning cost case. A closer examination shows that for the baseline, there is up to a \$1 billion NPV reduction due to the addition of warning costs, even without Torino Level 1 costs included. With CARDINAL, the difference is less dramatic: up to about \$125 million. Differences are greatest at low discount rates.

Above a discount rate of about 8 percent in the baseline case alone (Figure 6.29), we see an inversion of NPV with system capability. This inversion was not present when there were no warning costs whatsoever (Figure 6.22).

Notably, whereas CARDINAL was dominated by the baseline when warning costs were zero, in this shifted warning progression case, CARDINAL seems to hold a slight advantage over the baseline across the board.

Clipped Warning Progression

Figures 6.31 and 6.32 illustrate a clipped warning progression, in which Torino Level 1 warnings are simply excised from the nominal case. CARDINAL’s dominance over the baseline is clearer than with a shifted warning progression.

Relative to the nominal cases shown in Figures 6.10 and 6.11, the main effect of excising the Torino Level 1 warnings (not to forget the reduction in Armageddon warning costs per Equation 6.3) is to increase NPVs and shift IRRs to higher discount rates. However, the patterns are similar. Even with the clipped progression, increasingly capable surveys incur increasing net social costs in the baseline case (beyond a low crossover discount rate). With CARDINAL, this inversion is avoided.

Figure 6.31
Baseline (no T1 warning costs, $\$/T2 = 5m$)

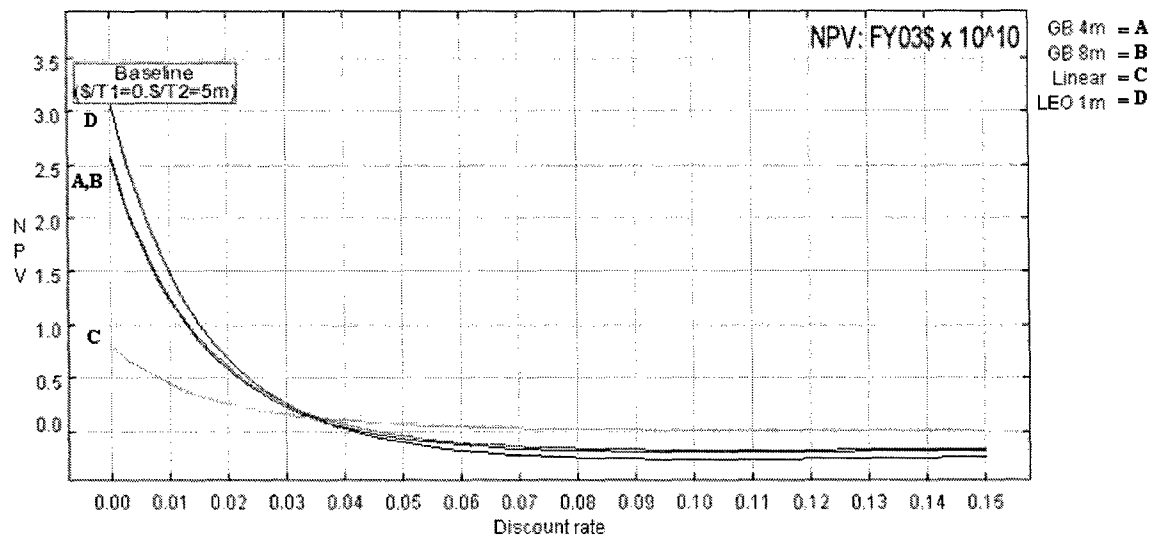
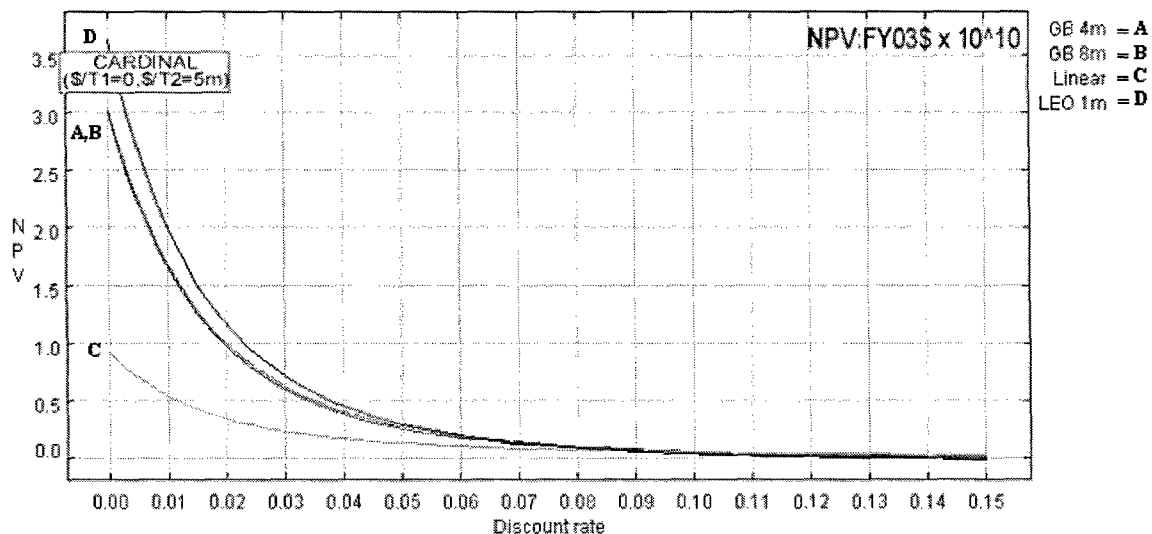


Figure 6.32
CARDINAL (no T1 warning costs, $\$/T2 = 5m$)



IRR vs. Warning Costs

It is interesting to consider the nominal and “no T1” cases from another perspective. Figures 6.33 and 6.34 show IRR as a function of cost per warning (cost per T1 in the case of Figure 6.33, and cost per T2 in the case of Figure 6.34—hence, Figure 6.34 includes the cases shown in Figures 6.29 through 6.32).

In these figures, high costs per warning and high IRRs are desirable from the standpoint of robustness to uncertainty. That is, uncertainty-weighted utility increases from the origin diagonally upward and to the right. “High costs per warning” means that positive NPVs extend over a wider possible range of warning costs. Likewise, “high IRRs” means that positive NPVs extend over a wider possible range of discount rates.

It quickly can be seen that CARDINAL provides significantly greater robustness to uncertainty in these two parameters than the baseline case. This is true under nominal conditions and also in a regime in which society generally ignores the multitudinous Torino Level 1 warnings.

Figure 6.33
IRR vs. cost per warning, nominal

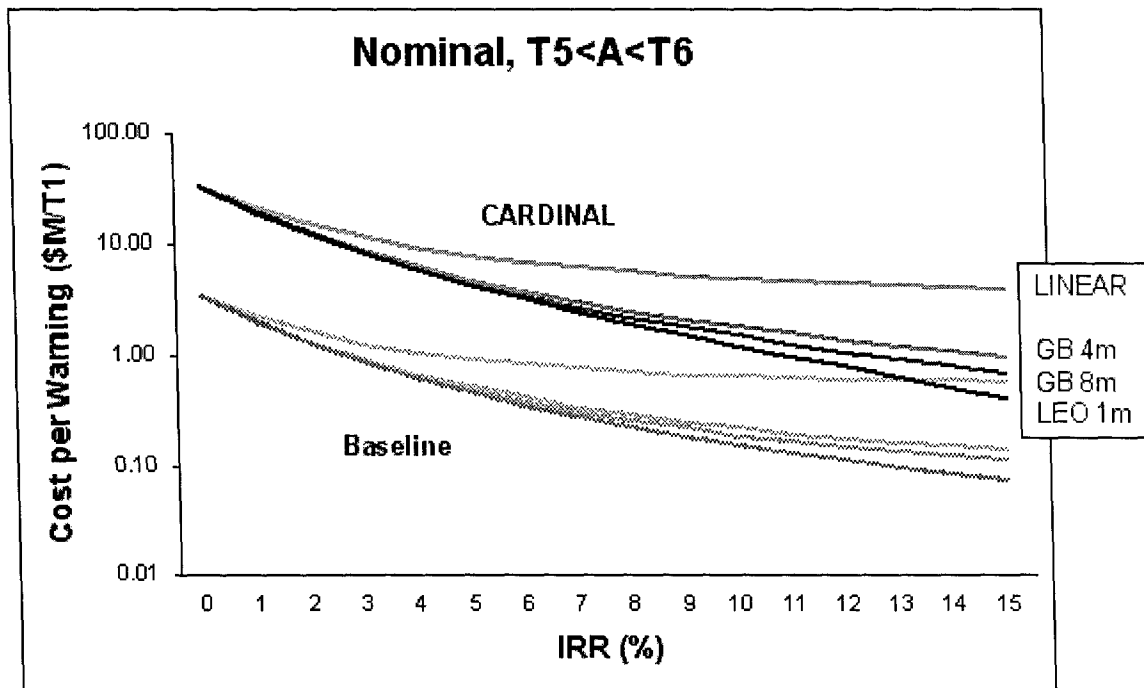
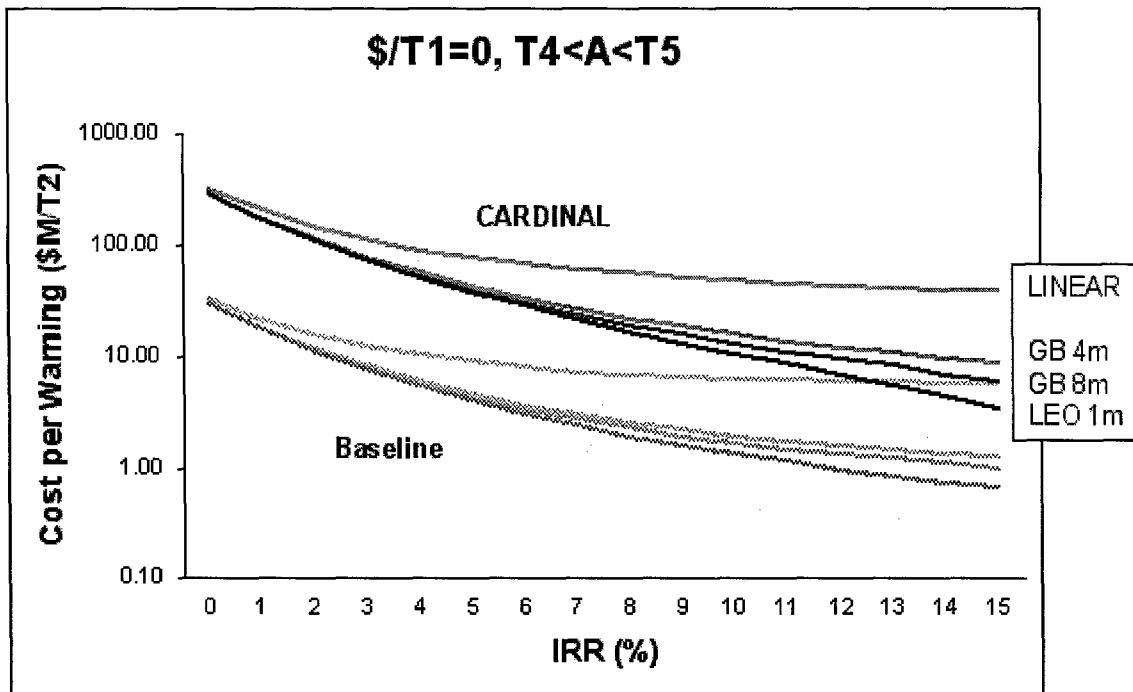


Figure 6.34
IRR vs. cost per warning, $\$/T1 = 0$



Summary of Model Results

This model showcases the structure of a comprehensive framework for considering the costs and benefits of an impact hazard policy. It has presented a comparative analysis of a baseline case in which mitigation expenditures await the discovery of an actual threatening object and a proposed alternative (designated CARDINAL) in which the social costs of warning are reduced by the prior demonstration of an interception capability. It has shown that the proposed alternative is relatively robust to uncertainty in many dimensions but particularly to uncertainty in discount rate. The proposed alternative is shown to dominate the baseline case down to exceedingly low costs per warning (or, equivalently, exceedingly low warning rates).⁵²

All this said, many assumptions were incorporated into the structure of this model that could change crossover points, indifference levels, and so forth. A superior model would employ Monte Carlo techniques in the same fashion as the underlying SDT study model. It would also incorporate the system effects discussed in Chapter Five. Nevertheless, this new model is sufficient for its purpose:

⁵² It must be remembered that costs per warning as used here represent global costs, not per capita costs. Consider the nominal cost per T1 warning of \$1 million. For each human on the face of the Earth, that equates to about 0.015 U.S. cents per T1 warning. Still, the bulk of mankind will never be exposed to a warning. If we assume that only the U.S. population receives the warning, we will still have a per capita cost of about 0.34 cents per T1 warning. Alternatively, as of 24 May 2004, there were 785.7 million internet users worldwide (www.internetworldstats.com/stats.htm). If we assume that one percent of those users access a web page and read about the warning for thirty seconds, then to accumulate \$1 million in total costs we calculate an average opportunity cost of \$15.27 per hour, a not unreasonable figure.

- To show that a full accounting of costs and benefits is necessary for methodological rigor, and that failure to make such an accounting can result in specious conclusions;
- To demonstrate an analytical process for dealing with multidimensional uncertainty in both technical and social parameters; and
- To provide an intellectual foundation for future modeling that can be prescriptive rather than illustrative in nature.

Conclusions

Summary of Analysis

Chapter Two presented the historical and physical context of the impact hazard. It described society's response to the NEO threat in great detail, focusing on the genesis of the NEO surveys (including the current Spaceguard Survey).

Chapter Three cast a wide net across the policy literature, examining works from many different disciplines with a bearing on this low probability, high consequence hazard. The chapter reviewed the high and low points of the NEO hazard literature, which runs the gamut from shallow advocacy to good faith efforts to get to the bottom of a very difficult problem.

Chapter Four methodically surveyed the wide variety of organizations with an interest in the impact hazard. The result was an appreciation of the global nature of the stakeholder base, and an understanding of how such a small community functions to garner institutional support for its aims.

Chapter Five took the first strides toward a framework for a comprehensive impact hazard policy. It presented flow diagrams of progressively increasing model sophistication, using an original graphical construction to represent pathways through uncertainty. First to be added to the model framework were the costs of alarm and warning. The chapter discussed the potential mechanisms by which society might incur such costs. In particular, the difficulties associated with perception and comprehension of a low probability threat were reviewed. The discussion then progressed to system effects, using analogies from the dynamics of physical systems. Finally, the chapter closely examined three different policy interventions: information management and investment in uncertainty reduction; information control; and social reassurance by means of a demonstrated mitigation capability.

Chapter Six built on the theoretical framework presented in Chapter Five by presenting a quantitative model of a comprehensive impact hazard policy. This model took the form of a static cost-benefit analysis, albeit with several added parameters of social response. Exploratory modeling showed that the demonstration concept proposed at the end of Chapter Five dominated a baseline case across almost all of the explored policy space, within the assumptions of the model.

Areas for Further Improvement

The analysis presented in these chapters is not prescriptive—it merely attempts to present a way of thinking about low probability, high consequence hazards. Naturally, there are areas for improvement associated with reducing the manifold uncertainties surrounding the problem. What are the likely costs of warning? How will they be incurred by society? How do warnings accumulate, and how does society acclimate to a long-run “Sword of Damocles?”

At least as important as uncertainty reduction, though, is improvement of the tools that can identify areas of the policy space that are *robust* to uncertainty. Chapter Six presented a static model because such was sufficient for its illustrative purpose—but a dynamic model including the system effects shown in Chapter Five would have an interesting story to tell.

Finally, it should be clear that a defining characteristic of the impact hazard is its ability to attract social attention disproportionate to its gravity, if such gravity is distilled to a metric such as expected annual deaths. This is a cautionary point: the costs and benefits of the most exquisitely-crafted impact hazard policy are moot if the hazard has a catalytic effect in a policy arena of greater import. Chapter Two mentioned space control and space resource exploitation; those are two possible such arenas.¹ If society’s response to the impact hazard pushes it down a pathway it would not otherwise choose to take, then any policy analysis within the “box” of the impact hazard will be specious. The catalytic effects can be thought of as “meta-effects”: those effects outside the policy space of the problem in question, but catalyzed by that problem, and with the potential for costs, benefits, and future-shaping effects dwarfing that problem.² Meta-effects may be difficult or impossible to quantify, but they should be considered within any analytical framework that purports to be prescriptive.

Implications for Other Policy Problems

The impact hazard is not the only low probability, high consequence threat to society. Although it is something of an outlier in this regard, there are clear lessons to be learned.

A very common behavior is to give lip service to the low probability, high consequence nature of the issue, but then proceed with the analysis, presentation, or discussion in a manner that ignores the probability and dwells on the effect. This tendency is *enabled* by scenario-based methods of analysis.

There is confusion between the *ex ante* and *ex post* perspectives (even in the minds of analysts who should know better). Again, a scenario-based analysis is inherently *ex post*, and can lead to grotesquely inappropriate policy responses in the case of a very-low probability threat.

Uncertain costs are often treated as nonexistent costs. In the case of the impact hazard, senior government officials and lawmakers approved an effort (the Spaceguard Survey) that ignored, and thus failed to predict, the social effect of false positives. Although that has

¹ Another example is China’s use of the impact hazard to explain its reluctance to sign the Comprehensive Test Ban Treaty. “No one can quite understand it, but China is arguing that mankind needs to keep developing ‘peaceful’ nuclear weapons in case a giant asteroid is discovered careering through space on a collision course with the earth.” Tyler, P., “Chinese Seek Atom Option to Fend Off Asteroids,” *New York Times*, 27 April 1996 (Late Edition – Final), p.4.

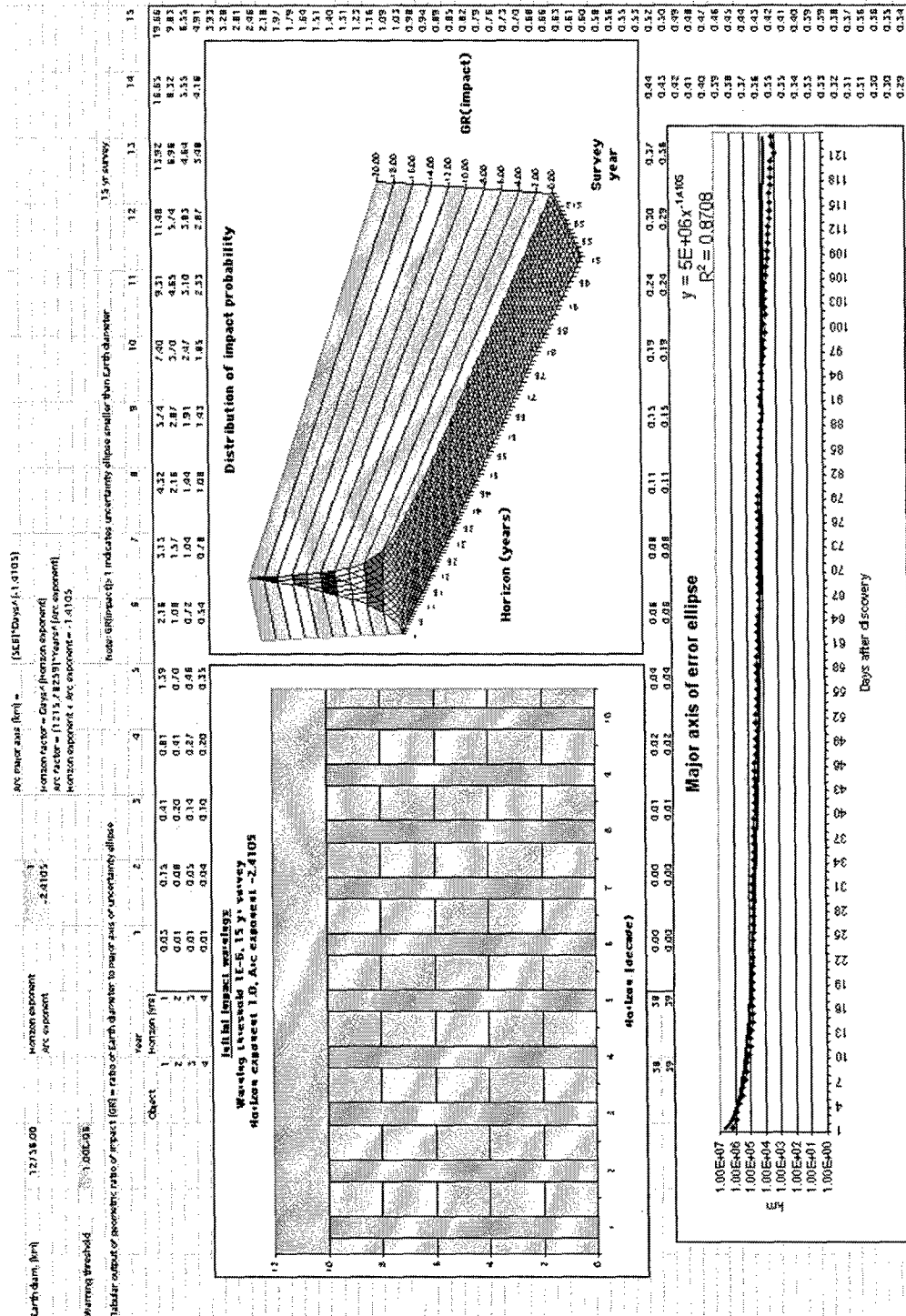
² In this construction, meta-effects can be meta-hazards or meta-benefits, depending on stakeholder valuations.

not caused major problems so far, the pursuit of more capable surveys may cause some significant social disturbance downstream.

Finally, it must be emphasized that warning is a social function, not a technical function. Society should not expect technical specialists to “learn on the job” by experimenting with social effects. Also, those who issue the warnings should not benefit from the warnings—this clear conflict of interest can have enormous social consequence, whether the subject is asteroids, aliens, or terrorists.

Initial Impact Warning Rate Estimation

Figure A.1
Uniform distribution of warning horizon



Armageddon in a Teapot

The author received the electronic mail included herein in February – March 2003, in response to press coverage associated with his presentation at the Annual Meeting of the American Association for the Advancement of Science (AAAS), February 2003.¹ An erroneous and unfortunate AAAS press release ascribed to the author the position of *advocating* “silence and secrecy in the event that a warning would come too late and not make a difference to the outcome.”

In addition to the electronic mail, RAND received one suspicious package from abroad, containing a letter demanding all of the author’s work on the subject at hand.

The pathway for the media storm started with wire service reporters at the AAAS press conference, who quoted from the press release. This was picked up from the wire first by online outlets of the British print media, with the flames fanned by internet discussion groups, and in particular, by a prominent placing in the Drudge Report (of Monica Lewinsky fame). Indeed, the link was largely inaccessible because of the volume of “hits,” while the adjacent topics of Osama bin Laden and thong bikinis being banned in Daytona Beach were relatively unexamined (Figure B.1).

Eventually, the hue and cry spread to respectable mainstream online outlets, including the BBC, CNN, MSNBC, CBS, and many others. Requests for live radio and television interviews poured in. A distinct second wave occurred, coinciding with the publication cycle of the print media. A full page in *USA Today* was devoted to the matter (with cartoon), and a quote from the AAAS press release appeared in *Newsweek* magazine.² A CNN “Quick Vote” poll was taken on the subject (Figure B.2).³

It appeared to come as a genuine surprise to both the media and the scientific community that as many as 30 percent of poll-respondents elected “blissful ignorance” (notwithstanding the unscientific nature of the poll).⁴ A reasonable hypothesis is that both scientists and reporters are professionally biased toward openness and against secrecy.

¹ Sommer, G., “Policy Frameworks for Impact Mitigation,” presentation to the AAAS Annual Meeting, Denver, Colorado, 14 February 2003.

² Lyman, E., “Much Ado About Asteroids,” *USA Today*, 11 March 2003 (First Edition), p.9D (also www.usatoday.com/news/science/2003-03-10-asteroids_x.htm) and “Perspectives,” *Newsweek*, 10 March 2003, p.21.

³ Totals shown are as of 8 February 2004. See <http://edition.cnn.com/2003/TECH/space/02/28/asteriod.alert/>

⁴ The fraction might have been significantly higher had the poll postulated a longer warning time, hence a longer opportunity for dread (through the mechanism of a negative discount rate).

Figure B.1
Drudge Report, 15 February 2003

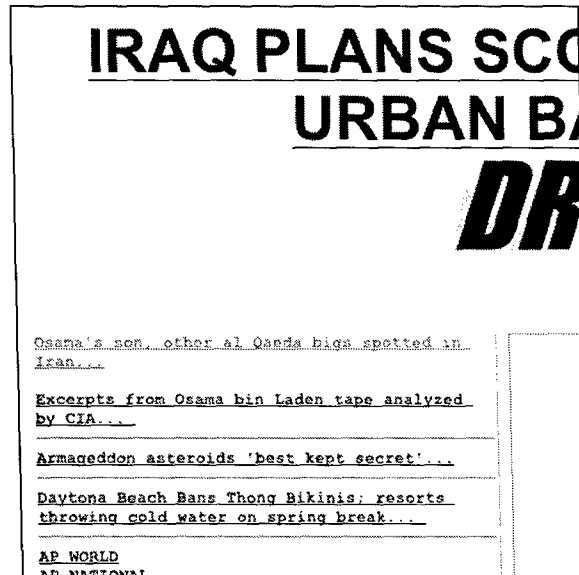
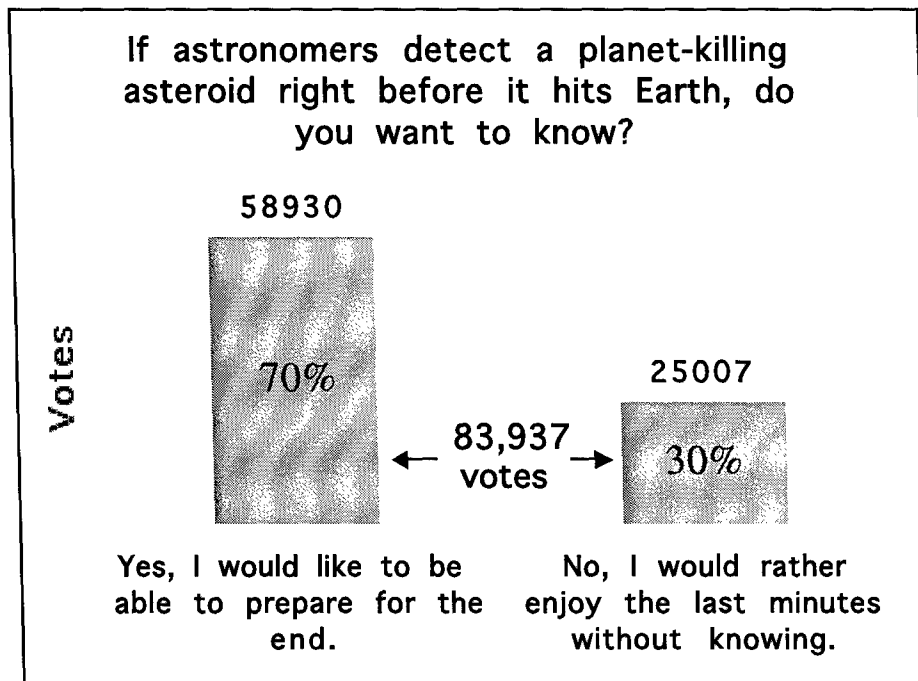


Figure B.2
CNN Quick Vote



The academic purpose behind this discussion of an asteroid “tempest in a teapot” is to show how the mere voicing of an asteroid impact warning scenario can result in an unexpectedly large social reaction. There were social costs incurred, as follows:

- The aggregated costs of worry, anger, and stress borne by those who wrote to this author, and the countless others who did not; including costs to their associates in proportion to their agitation; and
- The opportunity cost associated with the crowding-out of more socially germane news topics, including the pending war in Iraq and the manifold other areas of science discussed at the 2003 AAAS Annual Meeting—column-inches never to be recovered.

On the other hand, certain stakeholders did benefit. The AAAS Annual Meeting had an enormous amount of press attention as a result (and expectation of this no doubt influenced the inflammatory wording of the press release); newspapers and magazines sold, people visited web sites, and advertisers were happy.

As John Doe 12 points out below (Item B-13), the intense flurry of media attention in this case supports a major point of this work. When even warning of warnings causes a sharp social reaction, one must view the potential social effects of the warnings themselves with a degree of trepidation. Furthermore, the high leverage of the subject (in terms of disproportionate domination of the public agenda) can only give pause to the policymaker. This “leverage effect” and the “giggle factor,” taken together, tend to increase policymaker aversion to even mere consideration of the issue, whatever the socially optimum course of action might be.

The following communications are unedited, and give a variety of perspectives on the issue of impact warning. Religious themes are common, as is also a failure to comprehend the difference between the individual case (for example, warning of terminal illness as in Item B-7) and the social case at hand. There is generally an unspoken assumption that an individual’s right to information gives him or her the right to inflict that information on someone else. Of course, those who did not make that assumption would probably have been less inclined to write, so the messages are presented to illustrate patterns of thought rather than to make assertions of aggregated social valuation. Note also Item B-12, in which John Doe 11 states “I’d like to make the obvious observation that in a doomsday scenario, the total social cost rendered by the asteroid far outweighs any caused by anticipatory panic.” This is true, *ex post*, but most likely false, *ex ante*. It can be very misleading to use scenarios in the analysis of low probability events.

B-1

Subject: Armageddon asteroids 'best kept secret'

Dear Sir,

If the end of the world, as we know it, was at hand due to an imminent asteroid collision, not informing the public would be morally wrong and pointless. If everyone was going to die anyway, why not let them put their souls at ease by being able to set themselves right with the Gods of their choice and say goodbye to their friends? Humans have always performed best under pressure, whose to say that an un-thought of solution to imminent demise might come from the general populace? Might humanity have a better chance of survival if they were able to prepare, rather than not at all?

Sincerely,
John Doe 1

B-2

Apparently, you believe it would be better for us all to die happy. It's rather arrogant of you to presume that not a single human would survive after a large impact. Perhaps no one would. If people don't try, the odds are certainly worse. There are many intelligent people in the world, and I suspect there are a few who are more intelligent than a think-tank analyst. There are also lucky people, luckier than someone who works in Santa Monica, near the beach, in a greenish building. With the combination of intelligence and luck I wouldn't be so damned sure zero humans would survive an 'extinction' event. People should know what the danger is. We have a right to try to survive - that should be our free choice. If we are all going to die anyway, then no matter what the potential social upheaval, no one will be left to write the history. Knowing what is to come, you cannot predict what some people will do in an effort to survive. Some might pull it off. How dare you deprive the humans of the world that opportunity? Are we merely herd animals, and you are the keeper? I neither need nor want your patronizing meddling.

John Doe 2
Sonora, CA

B-3

Dear Mr. Sommer,

I can't begin to express how much I disagree with your notion that the public should not be told of an imminent asteroid threat. Your viewpoint that "extinction-type" events are "inevitable" give us a clue as to your lack of optimistic thinking, your lack of engineering knowledge, and maybe even your own self-worth. The human will to overcome would essentially be muted in your "ignorance is bliss" scenario. The general population, including the best minds on earth, would have no chance to caucus in order to at least make an attempt at coming up with a solution. In fact, I feel compelled to ask the rhetorical question, "how dare you" make the suggestion that you know what's best for mankind?

One doesn't have to be a RAND "expert" to realize that the world would rather go down fighting, than to be lulled into a false sense of security. Even in the event of immediate and irreversible doom, foreknowledge would allow the souls of this planet to make peace with their inner consciousness, their higher power. I hope for the sake of mankind itself that neither you, nor the minority of others who share your misguided views, are ever empowered with making these types of ultimate decisions.

Respectfully,
John Doe 3
MSE Nuclear Engineering, MIT

B-4

Suppose an extinction level asteroid was on an impact trajectory with Earth and something *could* be done about it. But the information was suppressed by the U.S. Government as you suggested until it was too late to take any action. [Reference to personal web page]

John Doe 4

B-5

Dear Mr. Sommer,

Regarding the CNN article I read online today about knowing if/when a killer asteroid might strike -- I have had a theory about this subject for a long time, and thought you'd be someone with whom to share it.

I've thought that the only way the world (people/countries) will unite is if we are globally threatened and we are all "in it together." So, maybe knowing a catastrophe is coming will create even a moment of terrified global unity -- and a possible (however remote) action toward our survival. For what it is worth.

Aloha,
Jane Doe 1

B-6

From: John Doe 5

Subject: armageddon asteroids, terrorism, no warnings

As a counterpoint:

Honesty and disclosure would allow:

- a. intense research on possible countermeasures (wouldn't hurt to try)
- b. people to say goodbye to loved ones and square things up with their God[s], deities, etc
- c. the opportunity to score with hot chicks using the time-honored "one last fling" strategy (see, e.g. "Spies Like Us" w/ Chevy Chase)

In interest of honest disclosure, I'm only writing because of (c).

B-7

Subject: Mr. Sommer, you should be fired immediately.

Cc: xxx@entercom.com, xxx@entercom.com, xxx@rand.org, xxx@mikeonline.com, xxx@eibnet.com, xxx@rand.org, xxx@rand.org, xxx@rand.org, xxx@rand.org, xxx@rand.org, xxx@rand.org

To: xxx@rand.org

From: xxx@earthlink.net

ARMAGEDDON ASTEROIDS 'BEST KEPT SECRET'

"...it would be best not to tell the public anything," said Geoffrey Sommer, of the Rand Corporation in Santa Monica, California. "If an extinction-type impact is inevitable, then ignorance for the populace is bliss."

If the above article is accurate, you should be fired immediately. You are not God, Mr. Sommer. But you obviously are suffering from a God complex. Your arrogance is pathetic. In the event of an imminent collision of an asteroid with the Earth, neither you nor any of your omniscient "buddies" have the right to withhold such information from the public. I suppose if you were diagnosed with a rapidly progressing terminal illness, you would prefer to be told, "All your tests came back OK, Mr. Sommer. There's nothing wrong with you at all."

Good day sir,
John Doe 6

B-8

Dr. Sommer,

My name is [John Doe 7], I found a link on the Drudge Report to an article for which you were quoted: "When a problem arises with high uncertainty, there is an opportunity to spin the problem to avoid global panic. If you can't do anything about a warning, then there is no point in issuing a warning at all" (The article I speak of can be viewed at http://news.independent.co.uk/world/science_medical/story.jsp?story=378392)

If I approached your quote from a worldly perspective, it is very logical and would make sense. However, I am a practicing Roman Catholic, and as such I often find myself thinking about the "other-worldly." I suppose you could say this is all about philosophy, but I look at this world as temporary and not as important as other things.

If the world were in the path of some Exintion Level asteriod, and some individual was aware of this, I would hope I would be informed as early as possible. I try to live my life everyday the best can, but if someone knew our days were seriously numbered I would want to know this. I am certain countless others would agree with me: this theoretical situation would provide the ideal opprotunity for change in ones' life. This would be that last chance to appologize or forgive before you would die. Or perhaps some person always ment to return to church, but was "too busy."

We put off and avoid many of the difficult things in our life, these things we know we really should take care of: promising ourselves we'll finish it tomorrow or don't tell someone how much we love them because we can say it tomorrow... but if we knew there was no tomorrow, could you do everything in one day?

You may not view things as I do, but at least I got a chance to voice my opinion. Thank you for your time!

Sincerely,
John Doe 7

B-9

Dr. Sommer-

I'd rather know. I have some people I would like to be with or say goodbye to. I am an adult and don't appreciate your patronizing conclusion.

Recently RAND fired Laurent Murawiec and now this.

I guess you guys aren't as deep thinkers as you think you are.

John Doe 8
Pittsburgh, PA USA

B-10

Dr. Sommer

I hope the reports are wrong and you do not advise the Bush administration on terror threats and responses. If so then I have one more thing to fear.

Perhaps it would have been more humane and cause less social strife if you had taken your own advice and kept silent on the matter.

No offence intended.
John Doe 9

B-11

Dr. Sommer,

I have to write you personally to tell you that I am appalled by your arrogance and irresponsible behavior. Given any warning whatsoever individuals may come forward with ground breaking ideas, countries around the world could pool resources, and results could occur. If any more than a years warning were available, the options would be practically endless, including massive evacuations of highly populated areas, and the building and deployment of landing vehicles which could be sent to the asteroid to attempt some sort of in place detonation. Have no fear that the human spirit is capable of dreaming up all sorts of possible solutions to problems it knows it has.

Consider also the damage you have done to those working in the field at this time. You are effectively reducing or removing their talent pool by restricting this information. I personally work to avert NEO collisions, with the sponsorship of an "Open" Space Initiative, which fosters collaboration by scientists, both amateur and professional. Groups like this having time to work for solutions, will be able to attempt to reduce, or even alleviate damage from an NEO by efforts of collaboration with any knowledge of an impending event.

No amount of "Social Damage Reduction" can overcome the sheer cost of species extinction which could be averted with any proper warning. Do not take for granted that others are willing to work to solutions, or at least die trying, rather than lying down and simply accepting a fate that can be averted.

I recommend that you rescind your recommendations, publicly. Stop causing harm for whatever selfish reasons you may have. Expect letters contradicting your recommendations to be sent to NASA administration from myself and my organization, as well as from other groups which I am closely affiliated with.

Sincerely,

John Doe 10

B-12

Hello Mr. Sommer,

I'm sure you're a busy man, but I'd like to offer a short reply to the advice you recently gave regarding doomsday asteroid scenarios.

Your contention, as reported in The Independant, is that "to a large extent you are better off not adding to your social costs," referring to the panic and scurrying that would occur if such news was made public.

I'd like to make the obvious observation that in a doomsday scenario, the total social cost rendered by the asteroid far outweighs any caused by anticipatory panic. While panic is certainly a negative outcome of making such information public, there are postive outcomes as well that need to be considered. For instance, many people have prepared for doomsday scenarios, having built shelters, stockpiled food, water, and protection, and advance notice gives them a much higher chance of surviving if they have time to get themselves and their families to safer ground.

Also, the people that wouldn't be consumed with panic (however small a group that is) would cherish the knowledge of impending death, to say final goodbyes and express love to friends and family. Religious and otherwise spiritual folks in this category would be grateful for the time to meditate and pray. My own worst fear would be not being able to be with my wife at the end.

If the world as we know it is going to end, I want to know about it as far in advance as possible.

John Doe 11

B-13

Recently read an article on space.com regarding your comments and the resulting outcry. I would like to let you know that I feel I understand your position and applaud you for your openness on the issue.

My take on this: The words of Chapman: 'Chapman said individual flames of controversy tend to be small, but they get fanned "by those who prefer to see conflict rather than convergence and consensus." ' I feel this illustrates your point perfectly even within the issue being debated; that it is in mans nature to look to chaos rather than consensus.

cf: '(think looting, profiteering, and economic collapse, he says)'

Regards,
John Doe 12

B-14

From: Jane Doe 2
Subject: Asteroids and Ignorance

Thanks a heap for deciding that I don't need to know if my life is going to end by being squashed, drowned, fried, starved, or whatEVER.

If I am going to expire prematurely I'd like the opportunity to quit my job and do all the things I wouldn't ordinarily have the time or cash to do.

Those of us who live outside of your intellectual bubble are not all hysterical morons who do nothing but watch wrestling on television, attend monster truck rallies, and eat McDonald's three times a day.

Give us some credit.

B-15

Dear Mr. Sommer,

I just read the article on CNN.com and am a bit disturbed by your recommendation. "If you can't do anything about a warning, then there is no point in issuing a warning at all." I strongly disagree. I've discussed this with several peers and a majority of us would like to have some sort of warning. Ignorance isn't always bliss, especially when it comes to the last moments of a person's life. I, for one, would like to know when the global end is near. I would like to call my family, make love to my lover, and stand outside and step outside to watch the extraordinary sight of a giant asteroid burn in our atmosphere. Trying to warn people that the end is near so they can do something may be futile, but warning them so they can do the things most important to them before they disintegrate is not. Please keep that in mind in case the event does occur.

Regards,
John Doe 13

B-16

You, sir, are an extreme nut-case.

Of course, you're probably assuming that you are an IMPORTANT person, and therefore you would KNOW about such an approach anyway, so YOU would have enough time to (a) say a proper good-bye to your loved ones, and/or (b) dig a hole, so... why should YOU care about the "little people," eh...?

John Doe 14
Enterprise Technology Corp.

B-17

Mr. Sommer,

I find your reported conclusion, "If you can't do anything about a warning, then there is no point in issuing a warning at all," extremely shortsighted and, in a way, belittling. Although I have neither seen the entire report, nor hear all of your conclusions, the portions that were reported in the press cause concern.

Granted, there would most assuredly be extreme panic and chaos by a large portion of the various populations around the globe, but following your prescription would deprive hundreds of millions, if not billions, of people from both seeking final amends with friends and family, and making their peace as they deem appropriate under the tenants of their religion. I can appreciate your position if you subscribe to an atheistic view, after all, if there is no God and everyone is eliminated there "would be no point" in making an alert. We would be oblivious, irrelevant creatures, similar to an ant being crushed under one's shoe during a walk.

However I submit that a large majority of humans do not subscribe to that theory. Allowing those, so inclined, to take their final rites before they perish from the Earth is the proper response. In fact, I would submit that in the United States, the government has an obligation in the 1st Amendment to ensure the free exercise of religion is not prohibited. Issuing a warning would neither establish nor promote religion, but failing to do so would most assuredly would prevent people from fully exercising it.

Sincerely,
John Doe 15

B-18

From: John Doe 16

I've read an article...

<<http://www.cnn.com/2003/TECH/space/02/28/asteriod.alert/>><http://www.cnn.com/2003/TECH/space/02/28/asteriod.alert/>

Where one of your quote (you know those kind where you are absolutely not thinking at all...sliped your mind...slipery whent wet)

If an extinction-type impact is inevitable, then ignorance for the populace is bliss.

-- *Geoffrey Sommer of the Rand Institute*

Well if ignorance is bliss...then your whole life has never been dedicated to bliss !

And you should therefore flee your job and retire in total ignorance to satisfy your personal pursuit in Holy Bliss ! Like Monk's do !

Bliss is not about ignorance...You have to understand that true bliss can be experienced by anyone at any time and such experience, wich is the core of human life, lead every human being out of ignorance... !

You should be ashamed of that quote of yours...specially comming from a knowledgeable man like you

There you go ! Now Think in your Tank...Think well & wise

but don't spoil your inner skull and ravage your inner soul !

Think more about bliss learn from it...May your life be influence by it !

And remember carefully that

Innocence has nothing to do with ignorance

And high intelligence has sometimes more to do with various aspects of Ignorance than Bliss

One that has been touched by bliss every day of his entire life

Project CARDINAL

It has become traditional in the field of NEO impact hazard studies to analyze mitigation systems and strategies in the context of defined scenarios. These are usually structured by warning time: long, medium, short, or very short. Scenario-based analysis might be appropriate for military threats, where relatively high probabilities are made even higher by a reactive opponent. However, the use of such analysis in the case of a low probability, high consequence event is precarious. The reason is straightforward—the use of a scenario, by definition, eliminates consideration of the most interesting (and problematic, from a policy standpoint) aspect of the event: its low probability.

An *ex ante* policy analysis of the cosmic impact threat must consider that the benefits of any mitigation system investments are heavily probability-weighted. Any investments in mitigation prior to the detection of an object worth mitigating have a very high likelihood of being a net loss to society. This fundamental, policy-driven consideration can lead to a very different design for a mitigation system than one resulting from the imposition of a scenario: we are in the world of hedge strategies and adaptive planning.

In a hazard regime characterized by extremely rare events and somewhat more frequent warning of such events, a mitigation system imparts social benefit in two distinct ways. Very infrequently, it will prevent loss of lives and wealth as the result of actual impacts. More frequently, it will serve to reduce the social costs that are an unavoidable, if uncertain, aspect of the search for hazardous comets and asteroids. To the degree that objects are discovered that are even temporarily projected to threaten the Earth, social effects ranging from short-term dislocation and disruption (“panic”) to long-term macroeconomic effects are possible. These effects are reduced by the reassurance provided by a mitigation capability.

A key observation is that the value of an interception system in reducing impact costs is a function of its *actual* capability and the impact rate. The value of an interception system in reducing social costs of warning is a function of its *perceived* capability (that is, its capability as perceived by society) and the warning rate.

The probability-weighting of a mitigation system, and the consideration of perceived capability, both tend to drive architectures toward smaller, more numerous interceptors. A premium is placed on reduction of research and development costs, at the expense of greater acquisition and operation and support costs (since these last are all probability-weighted). *Ex ante*, the costs are lower; *ex post*, the costs are higher. *Ex post*, though, all uncertainty has been driven out of the problem, and the benefits (avoiding calamity on the Earth) are also much higher.

Although like the social costs of warning, hard to quantify, the social perception of mitigation system effectiveness can be expected to be nonlinear. The details of a mitigation system's effectiveness may well be secondary to the mere fact of its existence.

The *ex ante* perspective, and the consequent focus on adaptive planning, influences other aspects of mitigation system design and technology selection. Surge production and surge operations are favored, and it is advisable to subsume mitigation goals within space science objectives. Simplicity of design and the avoidance of exotic materials and fuels all tend to enable surge production. Surge operations are enabled by options that avoid launch pad constraints. Smaller interception systems can be based on launchers and payloads used for space science missions, with only the warheads representing new development. The idea is to defer mitigation system investment for as long as possible, but to hedge by reducing structural constraints to action in the extremely unlikely event such action is necessary. It can be assumed that there will be no economic constraints to action once a future impact is confirmed.

The emphasis on probability-weighting also affects the consideration of ground based deflection alternatives such as beamed energy systems. To the degree that such systems have high development costs and little if any scientific value, they are contraindicated by an *ex ante* analysis.

The considerations of probability-weighting and social costs of warning thus result in a smaller-than-otherwise system that could reasonably be labeled a "Comet/Asteroid Research and Development Interceptor Negating Alarms"—Project CARDINAL.

Baseline GB 4m

171

CARDINAL LINEAR

CARDINAL GB 4m

[illegible]

CARDINAL GB 8m

CARDINAL LEO 1m

[illegible]

Bibliography

- "Concept of Operations for Natural Impact Warning Clearinghouse," SAIC report EADDII-21-10152, 14 June 2002.
- "Cranberry Picking," *Inside the Pentagon*, 15 June 2000.
- "Dealing with the Threat of an Asteroid Striking the Earth," AIAA Position Paper, April 1990.
- "Economic and Societal Benefits," Background Paper 11, Third United Nations Conference on the Exploration and Peaceful Uses of Outer Space, 2 June 1998.
- "Fact Sheet—National Space Policy" (PDD/NSTC-8, PDD/NSC-49), White House, 19 September 1996.
- "Killer Asteroid Headed for Earth!," *Weekly World News*, 22 March 2004, p.1.
- "Near Earth Objects Scale Helps Risk Communication," NASA press release 99-83, 22 July 1999.
- "Planetary Defense," NSIA Government Affairs Issue Brief 104-53, November 1996.
- "Policy Statement on Near-Earth Object Research," IAU Executive Committee, 4 July 1998.
- "Report of the Committee on the Peaceful Uses of Outer Space," U.N. General Assembly, Official Records—Fiftieth Session, Supplement Number 20, A/50/20, 15 September 1995.
- "Report on Space Surveillance, Asteroids and Comets, and Space Debris—Volume 2: Asteroids and Comets," USAF Scientific Advisory Board SAB-TR-96-04, June 1997.
- "Responding to the Potential Threat of a Near-Earth-Object Impact," AIAA Position Paper, September 1995.
- "The Berlin Declaration on the Cosmic Impact Hazard," *Astronomy & Geophysics*, Volume 43, Number 6, December 2002, p.8.
- "Workshop on Near Earth Objects: Risks, Policies and Actions," Final Report, OECD Global Science Forum, Frascati, Italy, 20-22 January 2003.
- 6th *International Space Cooperation Workshop Report*, AIAA International Activities Committee, Seville, Spain, March 2001.
- Abdul Kalam, A., "Vision for the Global Space Community: Prosperous, Happy and Secure Planet Earth," speech to the 90th Indian Science Congress, Bangalore, India, 4 January 2003.
- Alvarez, L., *et al.*, "Extraterrestrial cause for the Cretaceous-Tertiary extinction," *Science*, Volume 208, 1980, pp. 1095-1108.
- Anselmo, L., *et al.*, "International Surveillance of Outer Space for Security Purposes," *Space Policy*, August 1991, pp. 184-198.
- Arvai, J., "Evaluating NASA's role in risk communication process surrounding space policy decisions," *Space Policy*, Volume 16, Number 1, 29 February 2000, pp. 61-69.

- Astronomy and Astrophysics in the New Millennium*, Astronomy and Astrophysics Survey Committee, Board on Physics and Astronomy, Space Studies Board, Commission on Physical Sciences, Mathematics, and Applications, National Research Council, 2001.
- Atkinson, H., *et al.*, *Report of the Task Force on potentially hazardous Near Earth Objects*, September 2000.
- Barbier, E., *et al.*, *Paradise Lost? The Ecological Economics of Biological Diversity*, Earthscan Publications, London, 1994.
- Belton, M., *et al.*, *Final Report, NASA Workshop on Scientific Requirements for Mitigation Of Hazardous Comets and Asteroids*, Arlington, Virginia, 2-6 September 2002.
- Belton, M., *et al.*, letter to Mr. Gary L. Martin, NASA Space Architect, NASA Headquarters, Washington, D.C., 4 April 2003.
- Binzel, R., "A Near-Earth Object Hazard Index," *Annals of the New York Academy of Sciences*, Volume 822, 1997, pp. 545-551.
- Binzel, R., *et al.*, "Origins for the Near-Earth Asteroids," *Science*, Volume 257, 7 August 1992, pp. 779-782.
- Binzel, R., *et al.*, "Physical Properties of Near-Earth Objects," in *Asteroids III*, Bottke *et al.*, editors, University of Arizona Press, Tucson, 2002.
- Boattini, A., *et al.*, "The Arcetri NEO Precovery Program," *Astronomy & Astrophysics*, Volume 375, Number 1, August 2001, pp. 293-307.
- Bottke, W., *et al.*, "Understanding the Distribution of Near-Earth Asteroids," *Science*, 23 June 2000, pp. 2190-2194.
- Bottke, W., *et al.*, "An Overview of the Asteroids: The Asteroids III Perspective," in *Asteroids III*, Bottke *et al.*, editors, University of Arizona Press, Tucson, 2002.
- Bowell, E., and Muinonen, K., "Earth-Crossing Asteroids and Comets: Groundbased Search Strategies," in *Hazards Due to Comets and Asteroids*, Gehrels, T., editor, University of Arizona Press, Tucson, 1994.
- Brandt, J., and Chapman, R., *Rendezvous in Space—The Science of Comets*, W. H. Freeman and Company, New York, 1992.
- Brown, P., *et al.*, "The Flux of Small Near-Earth Objects Colliding With the Earth," *Nature*, Volume 420, 21 November 2002, pp. 294-296.
- Brumfiel, G., "The Heavens At Your Fingertips," *Nature*, Volume 420, 21 November 2002, pp. 262-264.
- Budget of the United States Government*, Fiscal Year 2003.
- Byrant, E., *Tsunami: The Underrated Hazard*, Cambridge University Press, 2001.
- Camerer, C., and Kunreuther, H., "Decision Processes for Low Probability Events: Policy Implications," *Journal of Policy Analysis and Management*, 1989, Volume 8, Number 4, pp. 565-592.
- Canavan, G., "Cost and Benefit of Near-Earth Object Detection and Interception," *Hazards Due To Comets And Asteroids*, Gehrels, T., editor, University of Arizona Press, Tucson, Arizona, 1994, pp. 1157-1189.
- Canavan, G., *et al.*, editors, *Proceedings of the Near-Earth-Object Interception Workshop*, Los Alamos National Laboratories, Los Alamos, New Mexico, LA-12476-C, February 1993.
- Cannon, R., *Dynamics of Physical Systems*, McGraw-Hill, New York, 1967.

- Cantor, R., and Rayner, S., "Thinking the Unthinkable: Preparing for Global Disaster," *New Risks*, Plenum Press, New York, 1990, pp. 153-158.
- Chang Diaz, F., "The VASIMR Rocket," *Scientific American*, November 2000.
- Chapman, C., "The Threat of Impact by Near-Earth Asteroids," Statement before the Subcommittee on Space and Aeronautics of the Committee on Science of the U.S. House of Representatives, 21 May 1998.
- Chapman, C., "Impact Lethality and Risks in Today's World: Lessons for Interpreting Earth History," Geological Society of America Special Paper, proceedings of the Conference on Catastrophic Events and Mass Extinctions: Impacts and Beyond (Vienna Snowbird IV Conference), July 2000.
- Chapman, C., "The Asteroid/Comet Impact Hazard: Homo Sapiens as Dinosaur?," in *Prediction: Science, Decision Making, and the Future of Nature*, Sarewitz, D., et al., editors, Island Press, Washington, D.C., 2000.
- Chapman, C., et al., "The Comet/Asteroid Impact Hazard: A Systems Approach," 24 February 2001.
- Chesley, S., et al., "Quantifying the risk posed by potential Earth impacts," *Icarus*, Volume 159, Number 2, October 2002, pp. 423-432.
- Chodas, P., and Yeomans, D., "Predicting Close Approaches and Estimating Impact Probabilities for Near-Earth Objects," AAS/AIAA Astrodynamics Specialist Conference, AAS 99-462, Girdwood, Alaska, 16-19 August 1999.
- Clarke, A., *Rendezvous With Rama*, Harcourt Brace Jovanovich, New York, 1973.
- Cox, D., and Chestek, J., *Doomsday Asteroid—Can We Survive?*, Prometheus Books, Amherst, New York, 1996.
- Desonie, D., *Cosmic Collisions*, Henry Holt and Company, New York, 1996.
- Dewar, J., et al., "Assumption-Based Planning," The RAND Corporation, Santa Monica, California, MR-114-A, 1993.
- Drabek, T., *Emergency Management: The Human Factor*, FEMA National Emergency Training Center Monograph Series, Volume 2, Number 3, 1985.
- Drabek, T., *Some Emerging Issues in Emergency Management*, FEMA National Emergency Training Center Monograph Series, Volume 1, Number 3, 1984.
- Drezner, J., et al., "Innovative Management in the DARPA High Altitude Endurance Unmanned Aerial Vehicle Program," The RAND Corporation, Santa Monica, California, MR-1054-DARPA, 1999.
- Dynes, R., et al., *A Perspective on Disaster Planning*, Third Edition, University of Delaware Disaster Research Center, Report Series Number 11, May 1981.
- Tufte, E., *The Visual Display of Quantitative Information*, Graphics Press, Cheshire, Connecticut, 1983.
- Edberg, S., and Levy, D., *Observing Comets, Asteroids, Meteors, and the Zodiacal Light*, Cambridge University Press, 1994.
- Farinella, P., "Evolution of Earth-Crossing Binary Asteroids Due to Gravitational Encounters with the Earth," *Icarus*, Volume 96, 1992, pp. 284-285.
- Federal Reinsurance for Disasters*, Congressional Budget Office study, September 2002.
- Fischhoff, B., Carnegie Mellon University, cited in *RAND Review*, The RAND Corporation, Santa Monica, California, Spring 2003, p.10.
- Fischhoff, B., et al., *Acceptable Risk*, Cambridge University Press, Cambridge, 1981.

- Flammarion, C., *Omega: The Last Days of the World*, University of Nebraska Press, Lincoln, Nebraska (reprint), 1999.
- Fogg, M., "The Ethical Dimensions of Space Settlement," *Space Policy*, 16 July 2000, Volume 16, Number 3, pp. 205-211.
- Frankel, C., "Avoiding Cosmic Catastrophe," *The Futurist*, July-August 2000, pp. 23-28.
- Froeschle, C., *et al.*, "Secular Resonances and the Dynamics of Mars-Crossing and Near-Earth Asteroids," *Icarus*, Volume 117, 1995, pp. 45-61.
- Gaggero, E., "Quo Vadis COPUOS," *Space Policy*, August 1986, pp. 196-199.
- Garshnek, V. *et al.*, "The mitigation, management, and survivability of asteroid/comet impact with Earth," *Space Policy*, 16 July 2000, Volume 16, Number 3, pp. 213-222.
- Gehrels, T., "A Review of Comet and Asteroid Statistics," *Earth, Planets, and Space*, Volume 51, Number 11, 1999, pp. 1155-1161.
- Gehrels, T., editor, *Hazards Due To Comets And Asteroids*, University of Arizona Press, Tucson, Arizona, 1994.
- Gerrard, M., "Risks of Hazardous Waste Sites versus Asteroid and Comet Impacts: Accounting for the Discrepancies in U.S. Resource Allocation," *Risk Analysis*, Volume 20, Number 6, December 2000, pp. 895-904.
- Gerrard, M., and Barber, A., "Asteroids and Comets: US and International Law and the Lowest-Probability, Highest Consequence Risk," *New York University Environmental Law Journal*, Volume 6, Number 1, 1997.
- Gerrard, M., and Remo, J., "Response to Sub-Critical Cosmic Impacts," *Journal of the British Interplanetary Society*, Volume 52, 1999, pp. 115-120.
- Giorgini, J., *et al.*, "Asteroid 1950 DA's Encounter with Earth in 2880: Physical Limits of Collision Probability Prediction," *Science*, Volume 296, 5 April 2002, pp. 132-136.
- Gold, R. E., "SHIELD—A Comprehensive Earth Protection System," Phase I Report to the NASA Institute for Advanced Concepts, 28 May 1999.
- Gonzales, D., *The Changing Role of the U.S. Military in Space*, The RAND Corporation, Santa Monica, California, MR-895, 2000.
- Greenberg, D., *Science, Money, and Politics—Political Triumph and Ethical Erosion*, University of Chicago Press, Chicago, 2001.
- Greenberg, M., "The Physical Properties of Potential Earth Impactors: Know Your Enemy," workshop in Erice, Sicily, 17-21 June 2001.
- Haas, P., "International Institutions and Social Learning in the Management of Global Environmental Risks," *Policy Studies Journal*, Volume 28, Number 3, 2000, pp. 558-575.
- Harris, A., "The Population of Near-Earth Asteroids," *Bulletin of American Astronomy*, 2000, Volume 32.
- Harris, A., *et al.*, "The Deflection Dilemma: Use Versus Misuse of Technologies for Avoiding Interplanetary Collision Hazards," in *Hazards Due to Comets and Asteroids*, Gehrels, T., editor, University of Arizona Press, Tucson, 1994, pp. 1145-1155.
- Harris, E., and Sollinger, J., *Linking Space Exploration Programs to National Goals*, Issue Paper, The RAND Corporation, Santa Monica, California, March 1994.
- Hills, J., and Goda, M., "Damage From Comet-Asteroid Impacts with Earth," *Physica*, Volume 133, Number 1-4, 1999, pp. 189-198.

- Hills, J., and Goda, M., "The Asteroid Tsunami Project at Los Alamos," *Science of Tsunami Hazards*, Vol. 19, No.1, 2001, pp. 55-65.
- Hirshleifer, J., *Economic Behavior in Adversity*, University of Chicago Press, Chicago, 1987.
- Hotz, R., "NASA Orders 72-Hour Secrecy On Asteroid Threats," *Los Angeles Times*, 14 May 1998, p.1.
- Ingolfsson, A., *Estimating the Probability of Rare Events*, Cooperative JR East/MIT Research Program on Risk Assessment, Report 13, September 1994.
- Jaroff, L., "Dreadful Sorry, Clementine: Washington brushes off the asteroid threat," *Time Magazine*, 27 October 1997.
- Jervis, R., *System Effects—Complexity in Political and Social Life*, Princeton University Press, Princeton, New Jersey, 1997.
- Johnson, D., et al., *Space—Emerging Options for National Power*, The RAND Corporation, Santa Monica, California, MR-517, 1998.
- Johnson, L., Program Manager, NASA NEO Observation Program, statement before the Senate Subcommittee on Science, Technology and Space, Commerce Committee, U.S. Senate, 7 April 2004.
- Johnson, R., and Scicchitano, M., "Uncertainty, Risk, Trust, and Information: Public Perceptions of Environmental Issues and Willingness to Take Action," *Policy Studies Journal*, Volume 28, Number 3, 2000, pp. 633-647.
- Johnson-Freese, J., "Transitioning to a Space and Air Force: Moving Beyond Rhetoric?," *Space Policy*, Volume 16, Number 4, November 2000, pp. 249-259.
- Kenkel, D., "Using Estimates of the Value of a Statistical Life in Evaluating Regulatory Effects," Session 1, "Valuing Statistical Lives," *Valuing the Health Benefits of Food Safety: A Proceedings*, Kuchler, F., editor, U.S. Department of Agriculture Economic Research Service, MP1570, April 2001.
- Knox, J., "Preparing for Planetary Defense: Detection and Interception of Asteroids on Collision Course with Earth," USAF Air University, 1998.
- Larsen, J., et al., "The Spacewatch Wide-Area Survey for Bright Centaurs and Trans-Neptunian Objects," *Astronomical Journal*, Volume 121, Number 1, January 2001, pp. 562-579.
- Launius, R., "The Historical Dimension of Space Exploration: Reflections and Possibilities," *Space Policy*, Volume 16, Number 1, 29 February 2000, pp. 23-38.
- Lawrence, J., NASA Associate Administrator for Legislative Affairs, letter to Robert Walker, Chair of the House Science Committee, 9 August 1995.
- Leslie, J., *The End of the World—The Science and Ethics of Human Extinction*, Routledge, London, 1996.
- Levy, D. et al., *Conceptual and Statistical Issues in Contingent Valuation—Estimating the Value of Altered Visibility in the Grand Canyon*, The RAND Corporation, Santa Monica, California, MR-344-RC, 1995.
- Lewis, J., *Comet and Asteroid Impact Hazards on a Populated Earth*, Academic Press, San Diego, California, 1999.
- Lewis, J., *Mining the Sky*, Addison-Wesley Publishing Company, New York, 1996.
- Lewis, J., *Physics and Chemistry of the Solar System*, Academic Press, San Diego, California, 1997.

- Lewis, J., *Rain of Iron and Ice—The Very Real Threat of Comet and Asteroid Bombardment*, Addison-Wesley Publishing Company, New York, 1995.
- Lumley, S., "Cost-Benefit Analysis, Ethics and the Natural Environment," in *Cost-Benefit Analysis*, Puttaswamaiah, K., editor, Transaction Publishers, New Brunswick, U.S., 2002, pp. 95-114.
- Lyman, E., "Much Ado About Asteroids," *USA Today*, 11 March 2003 (First Edition), p.9D.
- Maccone, C., "Planetary Defense From The Nearest 4 Lagrangian Points Plus RFI-Free Radioastronomy From The Farside Of The Moon: A Unified Vision," *Acta Astronautica*, Volume 50, Issue 3, February 2002, pp. 185-199.
- Mansfield, E., *Statistics for Business and Economics*, Fifth Edition, W. W. Norton and Company, New York, 1980.
- Mark, K., *Meteorite Craters*, University of Arizona Press, Tucson, Arizona, 1987.
- Mazanek, D., "Comet/Asteroid Protection System" (CAPS), Concept Summary Briefing to NASA Headquarters, 2 October 2001.
- McLean, A., "A New Era? Military Space Policy Enters the Mainstream," *Space Policy*, Volume 16, Number 4, November 2000, pp. 243-247.
- Milani, A., "Emerging Stability and Chaos," *Nature*, Volume 338, 16 March 1989, pp. 207-208.
- Milani, A., and Valsecchi, G., "The Asteroid Identification Problem—II. Target Plane Confidence Boundaries," *Icarus*, Volume 140, Number 2, 1999, pp. 408-423.
- Milani, A., *et al.*, "Statistics of Close Approaches Between Asteroids and Planets: Project SPACEGUARD," *Icarus*, Volume 88, 1990, pp. 292-335.
- Milani, A., *et al.*, "Virtual Impactors: Search and Destroy," *Icarus*, Volume 145, May 2000, pp. 12-24.
- Milani, A., *et al.*, "Asteroid Close Approaches: Analysis and Potential Impact Detection," in *Asteroids III*, Bottke *et al.*, editors, University of Arizona Press, Tucson, 2002.
- Milani, A., "Extraterrestrial Material—Virtual or Real Hazards?," *Science*, Volume 300, 20 June 2003, pp. 1882-1883.
- Mileti, D. *et al.*, "Fostering Public Preparations for Natural Hazards—Lessons from the Parkfield Earthquake Prediction," Volume 34, Number 3, *Environment*, 1 April 1992, pp.16-20 and 36-39.
- Millis, R., *et al.*, "The Deep Ecliptic Survey," *Astronomical Journal*, Volume 123, Number 4, April 2002, pp. 2083-2109.
- Mitchell, D., *Summary of Proposed Studies On The Implications Of Peaceful Space Activities For Human Affairs*, Brookings Institution, December 1960.
- Mitchell, R., and Carson, R., *Using Surveys to Value Public Goods: The Contingent Valuation Method*, Johns Hopkins University Press, 1989.
- Morrison, D., "The Contemporary Hazard of Cometary Impacts," in *Comets and the Origin and Evolution of Life*, Thomas, P., *et al.*, editors, Springer-Verlag, New York, 1997.
- Morrison, D., Chairman, "The Spaceguard Survey—Report of the NASA International Near-Earth-Object Detection Workshop," 25 January 1992.
- Morrison, D., *et al.*, "Dealing with the Impact Hazard," in *Asteroids III*, Bottke *et al.*, editors, University of Arizona Press, Tucson, 2002.
- Morrison, D., *et al.*, "The Impact Hazard," in *Hazards Due To Comets and Asteroids*, Gehrels, T., editor, University of Arizona Press, 1994.

- Mottola, S., *et al.*, "The Near-Earth Objects Follow-Up Program: First Results," *Icarus*, Volume 117, 1995, pp. 62-70.
- Nadis, S., "Planetary Protection—X-Ray Tests Show How To Deflect An Incoming Asteroid," *Scientific American*, October 2002.
- NASA 2003 Strategic Plan.
- NASA FY2004 Budget Request.
- Near Earth Objects—NEOs*, Parliamentary Office of Science and Technology, POST Report 126, April 1999.
- Near-Earth Objects Survey Workgroup Report*, NASA, Solar System Exploration Division, Office of Space Science, June 1995.
- New Frontiers in the Solar System—An Integrated Exploration Strategy*, Solar System Exploration Survey, Space Studies Board, National Research Council, 9 July 2002.
- Nozette, S., *et al.*, "The Clementine Mission to the Moon: Scientific Overview," *Science*, 16 December 1994, pp. 1835-1843.
- Ostro, S., "The Role of Groundbased Radar in Near-Earth Object Hazard Identification and Mitigation," in *Hazards Due to Comets and Asteroids*, Gehrels, T., editor, University of Arizona Press, Tucson, 1994.
- Park, R., Garver, L., and Dawson, T., "The Lesson of Grand Forks: Can a Defense Against Asteroids Be Sustained?," *Hazards Due To Comets and Asteroids*, University of Arizona Press, 1994, pp. 1225-1230.
- Pearce, D.W., *Cost-Benefit Analysis*, Macmillan Studies in Economics, Macmillan, London, 1971.
- Petty, R., and Cacioppo, J., *Attitudes and Persuasion: Classic and Contemporary Approaches*, Westview Press, Boulder, Colorado, 1996.
- Pilcher, C., Science Director, Solar System Exploration, Office of Space Science, NASA, statement before the Subcommittee on Space and Aeronautics, Committee on Science, Space and Technology, U.S. House of Representatives, 21 May 1998.
- Postol, T., "Lessons of the Gulf War Experience With *Patriot*," *International Security*, Volume 16, Number 3, Winter 1991/92, pp. 119-171.
- Postol, T., statement before the U.S. House Of Representatives Committee on Government Operations, April 7, 1992.
- Pratt, J. and Zeckhauser, R., "Inferences From Alarming Events," *Journal of Policy Analysis and Management*, 1982, Volume 1, Number 3, pp. 371-385.
- Preston, R., *et al.*, *Space Weapons—Earth Wars*, The RAND Corporation, Santa Monica, California, MR-1209-AF, 2002.
- Project Icarus*, MIT Student Project in Systems Engineering, MIT Press, Cambridge, Massachusetts, 1968.
- Qizhi, H., "On Strengthening the Role of COPUOS—Maintaining Outer Space for Peaceful Uses," *Space Policy*, February 1986, pp. 3-6.
- Quarantelli, E., *Organizational Behavior in Disasters and Implications for Disaster Planning*, FEMA National Emergency Training Center Monograph Series, Volume 1, Number 2, 1984.
- Rabinowitz, D., *et al.*, "A Reduced Estimate of the Number of Kilometer-Sized Near-Earth Asteroids," *Nature*, 13 January 2000, pp. 165-166.
- Raines, F., OMB Director, White House press briefing on the line-item veto, 14 October 1997.

- Rather, J., Assistant Director for Space Technology (Program Development), NASA, statement before the Subcommittee on Space, Committee on Science, Space and Technology, U.S. House of Representatives, 24 March 1993.
- Remo, J., "Policy perspectives from the U.N. international conference on near-Earth objects," *Space Policy*, February 1996, pp.13-17.
- Resolution 1080 on the Detection of Asteroids and Comets Potentially Dangerous to Humankind*, Council of Europe Parliamentary Assembly, Strasbourg, 20 March 1996.
- Roques, F., and Moncuquet, M., "A Detection Method for Small Kuiper Belt Objects," *Icarus*, Volume 147, October 2000.
- Rustan, P., "Clementine; Measuring the results," *Aerospace America*, February 1995, pp. 34-38.
- Sagan, C., and Druyan, A., *Comet*, Random House, New York, 1997.
- Salem, S., et al., *Issues and Problems in Inferring a Level of Acceptable Risk*, The RAND Corporation, Santa Monica, California, R-2561-DOE, August 1980.
- Samuel, E., "Incoming: To Deflect An Asteroid, Choose Your Shot Carefully," *New Scientist*, 16 February 2002.
- Sarewitz, D., et al., editors, *Prediction—Science, Decision Making, and the Future of Nature*, Island Press, Washington, D.C., 2000.
- Sarsfield, L., *The Cosmos on a Shoestring*, The RAND Corporation, Santa Monica, California, MR-864-OSTP, 1998.
- Sawai, S., et al., "Development of a Target Marker for Landing on Asteroids," *Journal of Spacecraft and Rockets*, Volume 38, Number 4, July-August 2001, pp. 601-608.
- Saxton, J., Chairman, *The Economic Costs of Terrorism*, Joint Economic Committee, U.S. Congress, May 2002.
- Schelling, T., "Intergenerational Discounting," *Energy Policy*, Volume 23, Number 4/5, 1995, pp. 395-401.
- Schelling, T., "Intergenerational Time Discounting—Preliminary synthesis, with questions," unpublished manuscript, received by facsimile from the author on 10 May 2001.
- Schmitt, H., et al., "An Open Letter to Congress on Near Earth Objects," 8 July 2003.
- Schweickart, R., et al., "The Asteroid Tugboat," *Scientific American*, November 2003, pp. 54-61.
- Scotti, J., et al., "Near Miss of the Earth by a Small Asteroid," *Nature*, Volume 354, 28 November 1991, pp. 287-289.
- Seamone, E., "The Duty to 'Expect the Unexpected': Mitigating Extreme Natural Threats to the Global Commons Such as Asteroid and Comet Impacts with the Earth," *Columbia Journal of Transnational Law*, Volume 41, 2003, pp. 735-794.
- Seamone, E., "When Wishing on a Star Just Won't Do: The Legal Basis for International Cooperation in the Mitigation of Asteroid Impacts and Similar Transboundary Disasters," *Iowa Law Review*, Volume 87, Number 3, March 2002, pp. 1091-1139.
- Seneca, *Quaestiones Naturales*, "de Cometis," Book VII.
- Serio, G., "Giuseppe Piazzi and the Discovery of Ceres," in *Asteroids III*, Bottke et al., editors, University of Arizona Press, Tucson, 2002.
- Shoemaker, E., Chairman, "Report of the Near-Earth Objects Survey Working Group," June 1995.
- Shoemaker, E., et al., "First natural occurrence of coesite from the Meteor Crater, Arizona," *Science*, Volume 132, 1960, pp. 220-222.

- Simonenko, V., "Space Protection of the Earth: Concepts and Approaches to the Development," Institute of Technical Physics, Snezhinsk, Chelyabinsk Region, Russia, 1995.
- Simonov, I. V., "The Feasibility of Using Large Impact To Destroy a Dangerous Asteroid," *International Journal of Impact Engineering*, Volume 27, Number 3, March 2002, pp. 293-315.
- Solomon, K., *Comparing Risk Management Practices at the Local Levels of Government With Those at the State and Federal Levels*, The RAND Corporation, Santa Monica, California, P-7263, December 1986.
- Solomon, K., *et al.*, *Dealing with Uncertainty Arising Out of Probabilistic Risk Assessment*, The RAND Corporation, Santa Monica, California, R-3045-ORNL, September 1983.
- Sommer, G., "Policy Frameworks for Impact Mitigation," presentation to the AAAS Annual Meeting, Denver, Colorado, 14 February 2003.
- Sommer, G., "Project CARDINAL: A Policy-Relevant NEO Hazard Mitigation System," AIAA Planetary Defense Conference, Garden Grove, California, 25 February 2004.
- Sommer, G., *et al.*, "The Global Hawk Unmanned Aerial Vehicle Acquisition Process—A Summary of Phase I Experience," The RAND Corporation, Santa Monica, California, MR-809-DARPA, 1997.
- Spitale, J., "Asteroid Hazard Mitigation Using the Yarkovsky Effect," *Science*, Volume 296, 5 April 2002, p.77.
- Staehle, R., "Finding 'Paydirt' on the Moon and Asteroids," *Astronautics & Aeronautics*, November 1983, pp. 44-49.
- Steel, D., "Our Asteroid-Pelted Planet," *Nature*, Volume 354, 28 November 1991, pp. 265-267.
- Steel, D., "The Search for Earth-Threatening Asteroids: What We Are Doing, and What You Could Do Too," *Proceedings of the XVth National Australian Convention of Amateur Astronomers*, Grida, J., editor, Adelaide, South Australia, April 1992.
- Steel, D., "Cometary impacts on the biosphere," in *Comets and the Origin and Evolution of Life*, Thomas, P., *et al.*, editors, Springer-Verlag, New York, 1997.
- Steel, D., *Rogue Asteroids and Doomsday Comets*, John Wiley & sons, New York, 1995.
- Steel, D., *Target Earth*, Reader's Digest Association, Pleasantville, New York, 2000.
- Stewart, T., "Uncertainty, Judgment, and Error in Prediction," in *Prediction: Science, Decision Making, and the Future of Nature*, Sarewitz, D., *et al.*, editors, Island Press, Washington, D.C., 2000.
- Stokes, G., *et al.*, "Lincoln Near-Earth Asteroid Program (LINEAR)," *Icarus*, Volume 148, Number 1, November 2000, pp. 21-28.
- Stokes, G., *et al.*, "Study to Determine the Feasibility of Extending the Search for Near-Earth Objects to Smaller Limiting Diameters," report of the NEO Science Definition Team, prepared at the request of the NASA Office of Space Science, Solar System Exploration Division, 22 August 2003.
- Stokes, G., *et al.*, "Near-Earth Asteroid Search Programs," in *Asteroids III*, Bottke *et al.*, editors, University of Arizona Press, Tucson, 2002.
- Stokey, E., and Zeckhauser, R., *A Primer For Policy Analysis*, W.W. Norton and Company, New York, 1978.
- Sweet, K., "Planetary preservation: the need for legal provision," *Space Policy*, Volume 15, 1999, pp. 223-231.
- Systems Engineering Management Guide*, Second Edition, Defense Systems Management College, October 1986.

- Tate, J., "Avoiding Collisions: the Spaceguard Foundation," *Space Policy*, Volume 16, Number 4, November 2000, pp. 261-265.
- Tate, J., *et al.*, "An Open Letter to the Australian Federal Government from International Scientists—Australia's Contribution to Spaceguard," 29 January 2002.
- Tedeschi, W., and Teller, E., "A Plan for Worldwide Protection Against Asteroid Impacts," *Space Policy*, August 1994, pp.183-184.
- Teller, E., "The Need For Experiments on Comets and Asteroids," in *Proceedings of the Planetary Defense Workshop*, Lawrence Livermore National Laboratory, Livermore, California, 22-26 May 1995.
- The 1966 Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies*
- The 1971 Convention on International Liability for Damage Caused by Space Objects*, entered into force on 1 September 1972.
- The 1979 Agreement Governing the Activities of States on the Moon and Other Celestial Bodies*, entered into force on 18 December 1979.
- The Exploration of Near-Earth Objects*, Committee on Planetary and Lunar Exploration, Space Studies Board, Commission on Physical Sciences, Mathematics, and Applications, National Research Council, 1998.
- The Impacts of Natural Disasters—A Framework for Loss Estimation*, National Research Council, National Academy Press, 1999.
- Thiele, L., "Limiting Risks: Environmental Ethics as a Policy Primer," *Policy Studies Journal*, Volume 28, Number 3, 2000, pp. 540-557.
- Thirtle, M., *et al.*, "The Predator ACTD—A Case Study for Transition Planning to the Formal Acquisition Process," The RAND Corporation, Santa Monica, California, MR-899-OSD, 1997.
- Ticha, J., *et al.*, "Klet Observatory NEO Follow-up Programme," *Planetary and Space Science*, Volume 48, Number 9, August 2000, pp. 787-792.
- Topics—Annual Review: Natural Catastrophes 2001*, Munich Re Group, 9th Year, 2002, p.37.
- Tversky, A., and Kahneman, D., "Choices, Values, and Frames," *American Psychologist*, April 1984, Volume 39, Number 4, pp. 341-350.
- Tversky, A., and Kahneman, D., "Judgment under Uncertainty: Heuristics and Biases," *Science*, Volume 185, Number 4157, 27 September 1974, pp. 1124-1131.
- Twigg, J., "Physician, Heal Thyself?—The Politics of Disaster Mitigation," Benfield Greig Hazard Research Centre Working Paper 1/2001, University College, London, January 2001.
- Tyler, P., "Chinese Seek Atom Option to Fend Off Asteroids," *New York Times*, 27 April 1996 (Late Edition – Final), p.4.
- Ungar, S., "Hot Crises and Media Reassurance: A Comparison of Emerging Diseases and Ebola Zaire," *The British Journal of Sociology*, Volume 49, Number 1, March 1998, pp. 36-56.
- Urias, J., *et al.*, "Planetary Defense: Catastrophic Health Insurance for Planet Earth," paper presented to Air Force 2025, October 1996.
- Van der Straaten, J., "Challenges and Pitfalls of Cost-Benefit Analysis in Environmental Issues," in *Cost-Benefit Analysis*, Puttaswamaiah, K., editor, Transaction Publishers, New Brunswick, U.S., 2002, pp. 323-346.
- Verschuur, G., *Impact!—The Threat of Comets and Asteroids*, Oxford University Press, 1996.

- Vokrouhlicky, D., *et al.*, "Direct Solar Radiation Pressure on the Orbits of Small Near-Earth Asteroids: Observable Effects?," *Astronomy and Astrophysics*, Volume 362, Number 2, October 2000, pp. 746-755.
- Wall, R., "New Military Space Telescope To Exploit Curved Electro-optics," *Aviation Week & Space Technology*, 26 August 2002, p.65.
- Ward, S., and Asphaug, E., "Asteroid Impact Tsunami: A Probabilistic Hazard Assessment," *Icarus*, Volume 145, Number 1, May 2000.
- Weissman, P., "The Comet and Asteroid Impact Hazard in Perspective," *Hazards Due To Comets and Asteroids*, Gehrels, T., editor, University of Arizona Press, 1994, pp. 1191-1212.
- Weitzman, M., "Gamma Discounting," *The American Economic Review*, Volume 91, Number 1, March 2001, pp. 260-271.
- Weitzman, M., "Why the Far-Distant Future Should Be Discounted at Its Lowest Possible Rate," *Journal of Environmental Economics and Management*, Volume 36, Number 3, November 1998, pp. 201-208.
- Wilson, K., *et al.*, "All People Are Not the Same: Incorporating Social, Economic and Cultural Factors Into Mitigation Planning," East Carolina University, Greenville, North Carolina, undated.
- Woo, G., *The Mathematics of Natural Catastrophes*, Imperial College Press, London, 1999.
- Yeomans, D., "Small Bodies of the Solar System," *Nature*, Volume 404, 20 April 2000, pp. 829-832.