REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
11-01-2005

2. REPORT TYPE
REPRINT

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
The Surface Properties of Asteroids

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
62601F

6. AUTHOR(S)
Stephan D. Price

5d. PROJECT NUMBER
1010

5e. TASK NUMBER
BD

5f. WORK UNIT NUMBER
A1

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory
29 Randolph Road
Hanscom AFB MA 01731-3010

8. PERFORMING ORGANIZATION REPORT NUMBER

AFRL-VS-HA-TR-2005-1103

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

AFRL/VSBYB

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for Public Release; Distribution Unlimited

13. SUPPLEMENTARY NOTES
REPRINTED FROM: Advances in Space Research, Vol 33, pp 1548-1557, 2004.

14. ABST

The physical characteristics of asteroid surfaces are best defined by direct measurements, few of which currently exist. Thus, inferences from indirect observations must be made. From the limited visible and radar imagery heavy cratering marks the asteroid surfaces and the surfaces are rough at all scales. For those asteroids with both a size and mass determination, only the largest bodies have bulk densities close to those expected from their meteoritic analogs. The smaller asteroids have large-scale porosities of 20% and greater; the objects with highest macroporosity are likely to be rubble piles while the denser ones may be heavily fractured coherent objects. The regoliths on the larger asteroids appear to be at least centimeters deep, while infrared measurements on the smaller objects argue for either a much thinner regolith or a bare surface; although direct imagery on the modest sized near-Earth asteroid 433 Eros indicates a regolith that is meters deep. Visual and infrared spectra clearly show that the silicates olivine and pyroxene are present on many asteroids and indicate the spectral signature of hydrated minerals in several low Albedo asteroids. Disk integrated photometry and radiometry provide clues as to the surface porosity and roughness and the fraction of surface covered by craters. Microwave, radio and radar measurements can penetrate the surface regolith, yielding information on the particle size distribution, and the nature of the underlying material. Modeling of the radiative transfer within the surface and deeper layers of an asteroid is required to accurately interpret these disk integrated measurements in terms of realistic physical parameters. Although the modeling has become sophisticated, additional components as well as more extensive and accurate measurements are required to derive an unambiguous picture of the asteroid surface layers from the indirect observations.

15. SUBJECT TERMS
Asteroids Regolith Mineralogy

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					Stephan D. Price
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER (include area code)
UNCLAS	UNCLAS	UNCLAS	SAR	10	781-377-4552

AFRL-VS-HA-TR-2005-1103

Available online at www.sciencedirect.com

SCIENCE DIRECT®

ELSEVIER

Advances in Space Research 33 (2004) 1548–1557

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

www.elsevier.com/locate/asr

The surface properties of asteroids

Stephan D. Price *

Air Force Research Laboratory (VSBC), Space Vehicles Directorate, 29 Randolph Road, Hanscom AFB, Bedford, MA 01731, USA

Received 15 October 2002; received in revised form 1 April 2003; accepted 15 April 2003

Abstract

The physical characteristics of asteroid surfaces are best defined by direct measurements, few of which currently exist. Thus, inferences from indirect observations must be made. From the limited visible and radar imagery heavy cratering marks the asteroid surfaces and the surfaces are rough at all scales. For those asteroids with both a size and mass determination, only the largest bodies have bulk densities close to those expected from their meteoritic analogs. The smaller asteroids have large-scale porosities of 20% and greater; the objects with highest macroporosity are likely to be rubble piles while the denser ones may be heavily fractured coherent objects. The regoliths on the larger asteroids appear to be at least centimeters deep, while infrared measurements on the smaller objects argue for either a much thinner regolith or a bare surface; although direct imagery on the modest sized near-Earth asteroid 433 Eros indicates a regolith that is meters deep. Visual and infrared spectra clearly show that the silicates olivine and pyroxene are present on many asteroids and indicate the spectral signature of hydrated minerals in several low Albedo asteroids. Disk integrated photometry and radiometry provide clues as to the surface porosity and roughness and the fraction of surface covered by craters. Microwave, radio and radar measurements can penetrate the surface regolith, yielding information on the particle size distribution, and the nature of the underlying material. Modeling of the radiative transfer within the surface and deeper layers of an asteroid is required to accurately interpret these disk integrated measurements in terms of realistic physical parameters. Although the modeling has become sophisticated, additional components as well as more extensive and accurate measurements are required to derive an unambiguous picture of the asteroid surface layers from the indirect observations.
Published by Elsevier Ltd on behalf of COSPAR.

Keywords: Asteroids; Regolith; Mineralogy

1. Introduction

The surface properties of an asteroid consist of its geometric structure and the physical and mineralogical characteristics of the surface layer. The overall shape, the degree of cratering and other large-scale features such as grooves and ridges characterize the surface geometry. The surface layer or regolith is defined in the glossary of *Asteroids II* as "the layer of fragmentary incoherent rocky debris that nearly everywhere forms the surface terrain". This definition can be expanded to include the chemical/mineral composition of the surface material and the physical characteristics of the surface layer itself.

The classical scenario of the generation of asteroid morphology is one in which the asteroid is fractured or disrupted by collisions with other asteroids during the lifetime of the solar system. The result is a core of fractured rock or, if the impact is energetic enough, the body is disrupted and the large pieces are reassembled into a rubble pile. The debris from such an event, and subsequent impacts with smaller objects that crater the surface, is segregated by size (mass) according to whether or not the particles' speed exceed the escape velocity. The coarser material, with ejection speeds less than the escape velocity, will settle back onto the surface while the smaller debris escapes the weak gravity of the asteroid. The result is a regolith that is nominally composed of coarser material on the larger asteroids. The smaller asteroids, those with the weakest gravity, will have little or no regolith from such impacts. Further impacts by small meteorites will create small holes and

* Tel.: +1-781-377-5688; fax: +1-781-377-4552.
E-mail address: sreve.price@hanscom.af.mil (S.D. Price).

0273-1177/$30. Published by Elsevier Ltd on behalf of COSPAR.
doi:10.1016/S0273-1177(03)00453-8

20050118 044

turn over the surface material in a process called "gardening". Interaction with the solar wind and energetic radiation from the sun darkens and reddens the surface material.

Obviously, resolved images contain the most information on surface properties but, unfortunately, such observations have been obtained for only a small number of small solar system objects. Very coarse, disk resolved images were taken by the Hubble telescope of 4 Vesta (Zellner et al., 1997) and 1 Ceres (Parker et al., 2002); the Galileo spacecraft obtained moderate resolution images of Gaspra (Veverka et al., 1994), Ida and Dactyl (Belton et al., 1995); the near Earth asteroid rendezvous (NEAR)/Shoemaker spacecraft imaged Mathilde and extensively mapped the surface of Eros at high resolution; recently, Stardust coarsely imaged Annefrank. Comet Halley was imaged by Giotto (Keller et al., 1986) and Borrelly by deep space I (Soderblom et al., 2002).

Bulk mineral composition of asteroid surfaces may be inferred by matching high quality reflection and emission spectra with laboratory analogs. The analogs are candidate minerals found on the Earth, such as olivine or pyroxene and agglomerates in meteoritic or lunar samples. Burbine et al. (2002) estimate that 100–150 distinct parent object have contributed to the meteorite collection on Earth. Various types of meteorites have been associated with asteroid taxonomic classes (see Lipschultz et al., 1989 for a review) and specific asteroids have been suggested as the parent bodies for certain types of meteorites based on spectral and dynamic considerations (Gaffey, 2000). Most associations are suggestive but few are more definitive. A plausible association has been made between 4 Vesta and the Howardites, Eucrites and Diogenites (HED) Basaltic Achondrite meteorites (Binzel and Xu, 1993). Reasonable associations have been made between 3103 Eger plus the Hungaria group and the Aubrite/Eststatite Achondrites (Gaffey et al., 1992) and 6 Hebe with H-chrondrites (Gaffey, 2000). Meteorites are good analogs if measured under conditions that mimic those on the surface of an asteroid such as a powder under a vacuum and at the appropriate temperature. Gaffey et al. (2002) review the current state of associating meteoroids with specific parent asteroids.

The physical parameters of the particles on the surface may be inferred from visual photometry and optical polarimetry as a function of solar phase angle. The enhancement in visual brightness at opposition is sensitive to the microporosity of the surface while the variation of the visual brightness at large phase angles is indicative of surface roughness (Helfenstein and Veverka, 1989). The particle size distribution may also be deduced from optical polarimetry (Dollfus et al., 1989) while polarization at cm wavelength adds information on the depth of the particles and the density of the underlying material (Webster and Johnston, 1989). Thermal modeling of the infrared emission provides clues to the roughness, degree of cratering and thermal inertia of the surface.

2. Resolved imagery

Optical images taken from spacecraft are available for six asteroids (Ida, Dactyl, Gaspra, Mathilde, Eros and Annefrank) and two comets (Halley and Borrelly) with sufficient resolution to reveal some of the surface details. Some aspects of comet Borrelly are commented upon as they may possibly relate to transition objects; Bottke et al. (2002) did estimate that $6 \pm 4\%$ of the near Earth objects are extinct comets. The imagery of comet Halley is dominated by the dust and gas emission and is not included in this discussion. At least one issue of a scientific journal has been devoted to the observations and analysis for four of these asteroids and the reader is referred to these journals for details. They are: Gaspra – Icarus, #1, **107**, 1994; Ida – Icarus #1, **120**, 1996; Mathilde – Icarus #1 **140**, 1999; Eros – Meteoritics & Planetary Science, # 12, **36**, 2001 and Icarus #1, **155**, 2002. In summary:

951 Gaspra: The Galileo spacecraft imaged the asteroid 951 Gaspra during a flyby on 29 October 1991. Gaspra is an S-type asteroid with triaxial dimensions of $18.2 \times 10.5 \times 8.9$ km and an average albedo of 0.23. The cratering density on the surface is relatively low (Chapman et al., 1993) with an absence of intermediate to large craters. The surface is grooved with linear depressions and aligned pits. Thomas et al. (1994) concluded that Gaspra is a single coherent object from the continuity of these features over the length of the asteroid. Thomas et al. (1994) further suggested that the grooves are fractures, which have been filled in by several 10s of meters of regolith, although Chapman et al. (1993) surmised that a much thinner regolith might exist or even that the asteroid surface is bare. The surface is variegated with the brighter spots tending to correspond to craters (Belton et al., 1992). Spectroscopy from the instruments on board Galileo reported by Kelly et al. (2000) indicate an olivine rich surface with a high olivine to pyroxene ratio over the entire asteroid.

243 Ida: The Galileo spacecraft imaged 243 Ida, an S-type Kronis family asteroid, during a flyby on 28 August 1993. Ida is an irregular elongated object with triaxial dimensions of $59.8 \times 25.4 \times 18.6$ km. Chapman (1996) attributed the color variations observed on Ida to the exposure of lighter fresh subsurface material contrasted with the older, space weathered surface material. Ida is the first asteroid to be positively identified as having a satellite moon, Dactyl, the motions of which were used to derive a bulk density of 2.5 g/cm^3 (Belton et al., 1996). Dactyl is $1.6 \times 1.4 \times 1.2$ km in size and has a reflection spectrum somewhat different than, but similar to Ida

(Belton et al., 1996). Linear features are evident on Ida's surface as well as subtle variations in color. The relief appears to be smooth, however, the surface is heavily cratered. Analysis by Granahan (2001) indicates that the mineralogy varies over Ida's surface but that, in general, olivine is about three times more abundant than orthopyroxene.

253 Mathilde: The NEAR/Shoemaker spacecraft imaged the asteroid 253 Mathilde during a flyby on 27 June 1997. Mathilde was found to be a heavily cratered C-type asteroid with an albedo of 0.045 and a low mean density of 1.3 gm/cm^3 (Ververka et al., 1994). The triaxial dimensions are $66 \times 48 \times 46$ km. Four of the craters are comparable to or greater than the 27 km mean radius of the asteroid and the density of smaller craters is close to saturation (Chapman et al., 1998). The lack of impact ejecta noted by Cheng and Barnouin-Jha (1999) can be explained by oblique impacts in which most of the ejecta escapes (Asphaug, 2000). The large craters, lack of ejecta debris and the low bulk density implies that Mathilde is highly porous, either it is a rubble pile with large internal voids or is composed of small sized material that has a high degree of porosity.

433 Eros: Eros was the rendezvous target for the NEAR/Shoemaker spacecraft and was extensively observed at high spatial resolution. Eros is an irregularly shaped S-type asteroid and, with physical dimensions of $34.4 \times 11.2 \times 11.2$ km, is one of the largest Near Earth Asteroids. It is a primitive, undifferentiated and consolidated body as indicated by the continuity of the ridges, grooves and other surface features. Eros has bulk density is 2.67 g/cm^3 and a bulk porosity of 25–29% (Britt et al., 2001). The regolith is complex and fragmented with a range of sizes from blocks, or boulders, as large as 100 m to small particles that form sedimentary deposits (Robinson et al., 2002). The depth of the Eros regolith varies from a meter to several tens of meters (Robinson et al., 2002; Küppers, 2001).

4 Vesta: The disk of asteroid 4 Vesta was resolved by the Wide Field/Planetary Camera (WF/PC) on the Hubble Space Telescope. Vesta is the prototype for the asteroid taxonomic class, V. Thomas et al. (1997) derive a size of $289 \times 280 \times 229$ km from unaberrated images with the WFPC2 camera and a mean density of 3.8 g/cm^3. Binzel et al. (1997) inferred the geological composition of the surface from the multi-filter images and determined that the surface is variegated, which they interpret as due to impact cratering. Thomas et al. (1997) proposed that the images are consistent with a very large crater at the south pole of rotation some 460 km in diameter with a large central peak and a rim that extends halfway to the equator. The albedo effects of the variegated surface and flattening of the biaxial ellipsoid owing to the polar crater were anticipated by Cellino et al. (1987) based on photometry from multiple apparitions.

19P/Borrelly: Comet 19/Borrelly is a short period Jupiter family comet that was imaged by the Deep Space 1 spacecraft during a flyby on 21 September 2001. It is shaped like a bowling pin some 8 km in length from the aspect that it was imaged during the flyby. The nucleus is very dark with a geometric albedo in the range of 0.01–0.035 and an average Bond albedo of 0.006 (Soderblom et al., 2002). The nucleus is variegated and loosely divided into rough and smooth terrains with no indications of fresh impact craters. The morphology also includes dark spots and mesas with ridges and fractures. Analysis of the DS-1 near infrared spectra by Soderblom et al. (2002) indicates a hot, dry surface with relatively little activity; $\leqslant 10\%$ of the surface is sublimating.

The Goldstone and Arecibo radars were used to obtain somewhat less direct, that is model dependent, asteroid imagery; the review by Ostro et al. (2002) describes the measurement techniques, how the observations are converted into images and results for some of the interesting objects. To date radar observations on 76 Main-belt asteroids and 109 near-Earth asteroids have been made, with enough information on about 10 or so to produce disk resolved images. A current tally of asteroids that have been measured by radar, and references to the imaging procedures and results may be found on the NASA/JPL web site: http://echo.jpl.nasa.gov/asteroids/index.html.

In summary, optical and radar images show that, asteroids have suffered large impacts, as evidenced by their highly irregular shape and/or extensive cratering. The S-type asteroids appear to be coherent objects with continuity in surface features such as grooves, ridges and alignment of pits. All the asteroids seem to have retained an appreciable amount of regolith, the thickness of which varies over the surface. Britt and Consolmagno (2001) compared the bulk densities estimated for the above asteroids with those of about a half dozen more that were derived from the motion of satellites or planetary/asteroid gravitational interactions. A fair amount of bulk porosity for all but the largest of the asteroids is indicated. Finally, the visual and infrared instruments on board the various spacecraft have unambiguously detected the signatures of pyroxenes and olivine on some asteroids.

3. Characteristics inferred from reflected light

Theoretically, the texture of the surface may be inferred from the manner in which the visual brightness and polarization change with solar phase angle. The mineral composition of the surface may be deduced from the reflected spectra, The general shape of the reflected spectral energy distributions has been used to sort the asteroid population into a taxonomic classification from which inferences have been made about their surface mineralogy.

3.1. Photometry and phase function

This section summarizes information in the chapters by Bowell et al. (1989), Helfenstein and Veverka (1989) and Dollfus et al. (1989) in the *Asteroids II* book (see Muinonen et al., 2002 for an updated review). The observed change in disk integrated brightness as a function of angle between the Sun – asteroid – Earth (the solar phase function) can be modeled in terms of the optical properties of the particles on the surface, by the manner in which the individual particles scatter light (particle phase function) and how the light is scattered between the particles on the surface. These are the principal analytic components of the models, which include the parametric representations of the roughness and porosity of the surface. Theoretically, observing over large enough angles provides the requisite information on the phase function to infer the surface properties of the asteroid. Disk integrated phase curves exist for a number of asteroids and some general inferences can be made such as a porous surface produces a large opposition enhancement, or opposition surge. Also, it is generally the case that the model parameters derived from the phase curves are similar for asteroids in a given taxonomic class, which implies that asteroids in a given taxonomic class have similar surface characteristics. However, the physical characteristics of the surfaces are not well constrained by the observations for several reasons. One is that the maximum phase angle of Main-belt asteroids is limited to <30° and observations over a large phase angle is required to infer something about the surface roughness. Another is that photometry over several apparitions, which is generally not available, is required to obtain the detailed knowledge of the non-spherical shape of the asteroid that is necessary to derive an accurate phase curve (Kaasalainen et al., 2002; Muinonen et al., 2002). Finally, the models are not unique and the model parameters are coupled. The IAU standard phase function (Bowell et al., 1989), $\varphi(\alpha) = (1 - G)\Phi_1(\alpha) + G\Phi_2(\alpha)$, well reproduces the observed phase curves for most asteroids but has only one free parameter, G, the slope parameter. Φ_1 and Φ_2 are analytic representations of the single particle scattering, scattering among particles and surface roughness. A non-linear least square solution is used to determine the physical surface parameters such as the asymmetric constant for the individual particle scattering and the volume density. All the parameters in these expressions are thus fixed and, to first order, the contributions from the various surface properties to the reflected disk integrated brightness as a function phase of an asteroid are combined into a single slope parameter. It is the second order departures from this expression that contain additional information. Muinonen et al. (2002) pointed out that this simple function also fails to fit the narrow opposition enhancement of E-class asteroids and is a poor fit to specific dark asteroids.

Measuring the disk integrated polarization of the reflected sunlight as a function of phase angle provides information on the surface texture of the asteroid. The particle size distributions may be inferred from polarization curves. For example, such curves indicate that the smaller asteroids are covered with coarse particles while the regolith of the larger ones such as Vesta contains a mix of particle sizes, some of which may be as small as 10 μm (Dollfus et al., 1989). Multiple scattering within the surface is necessary for the reflected light to be polarized (Dollfus et al., 1989; Muinonen et al., 2002). Since a darker surface will absorb more multiply scattered photons than a lighter surface, the details of the polarization vs. phase angle curve has been empirically related to the albedo of the asteroid. Indeed, the empirical polarization vs. phase – albedo relationship is a principal indirect technique to derive asteroid albedos and, subsequently, diameters (Cellino et al., 1999). Unfortunately, the necessary measurements require observations with a relatively large telescope over a fairly long time (phase angle).

3.2. Reflected spectral energy distributions

Inferences about surface composition may be drawn from taxonomic classification in which the different classes have different low-resolution energy distributions. Tholen (1984) and Zellner et al. (1985) conducted one of the first large-scale spectral surveys of asteroids, the Eight-Color Asteroid Survey, which obtained spectrophotometry on 589 asteroids. Shortly thereafter, Bell et al. (1988) measured ~120 asteroids in 52 narrow spectral band colors in the near infrared. Tholan and Barucci (1989) review these and other taxonomies in early use. The Sloan Digital Sky survey (Ivezić et al., 2002) has considerable potential for classifying tens of thousands of small Main-belt asteroids with a taxonomic scheme similar to that of Tedesco et al. (1989).

Matching moderate and high-resolution spectral shapes to those from material measured in the laboratory or detailed matching of the spectral absorption features is more definitive. Xu et al. (1995) and Bus and Binzel (2002a,b) recently extended and refined the previous classifications by creating a feature-based taxonomy based on 0.435–0.925 μm CCD spectra taken at moderate spectral resolution ($R \sim 100$) on about 1450 asteroids. More than half the asteroids in this small Main-belt asteroid spectral survey (SMASS) have diameters <20 km; the database also contains spectra on 106 Near-Earth asteroids and >100 Mars crossers (Binzel et al., 1998). Most of the SMASS asteroids are broadly classified as S and C but the small asteroids have more diverse shapes and depths to their absorption features than large ones. Lazzaro et al. (2001) obtained similar spectra on ~8000 asteroids, of which Angeli and Lazzaro (2002) examined the spectra on 22 Mars crossing asteroids and 12 near Earth asteroids and classified them using the SMASS taxonomic scheme.

The reflected spectral energy distributions of asteroids are matched to laboratory spectra of known minerals to deduce the asteroids' surface composition. The presence of silicates is revealed in asteroid reflection spectra by the broad orthophyoxene electronic absorptions near 1 and 2 μm and the broad asymmetric absorption at ~1 μm due to three overlapping bands of olivine (Clark et al., 2002). The 1 μm absorption is a component of the taxonomic classification of the SMASS spectra (Bus and Binzel, 2002b). The depth of this feature appears to depend on the surface characteristics as Binzel et al. (1998) noted an increase of depth of the feature as a function of diameter of the asteroid. Binzel et al. (2002) suggested that this trend might be due to space weathering of the older surfaces of the larger asteroids as compared to the smaller objects that have younger surfaces. Subtle silicate mineralogy can be inferred from the detailed modeling of high resolution near infrared spectra. For example, Sunshine et al. (2002) were able to deduce the presence and relative proportions of high and low calcium pyroxene on the surface of two asteroids from modeling the relative shapes of the near infrared features under the assumption that the electronic transition combine in a linear fashion. Recently Burbine and Binzel (2002) improved upon the statistics of the observations covering the 1 μm feature with 0.09 to 1.65 moderate resolution spectra on 151 Main-belt asteroids, a 10% subset of the SMASS database. Bus and Binzel (2002a) also detected a shallow band at 0.7 μm in a minority (10%) of the asteroids the measured that is attributed to absorption in oxidized iron, which is formed through aqueous alteration (Vilas et al., 1993). If such is indeed the case, the mineral hydration absorption at 3 μm is a diagnostic feature (Jones et al. 1990). Rivkin et al. (2002) review the evidence for hydrated minerals on asteroids.

4. Characteristics inferred from thermal emission

Theoretically, the texture of the surface may be inferred from the manner in which the spectral energy distribution of the passive thermal emission and polarization change with solar phase angle and the mineral composition of the surface may be deduced from the emission spectra. Simplified thermal models have been used to derive reasonably accurate asteroid sizes and albedos. The parameters of these models are empirically determined but the values say something about the physical characteristics of the surface. Sub-millimeter and radio observations provide information of the particle size and depth of the regolith.

4.1. Disk integrated broad spectral band radiometry

Lebofsky and Spencer (1989) provide an excellent review of thermal modeling of asteroids, which Harris and Lagerros (2002) recently updated. Passive thermal radiation provides clues to the thermal inertia of the asteroid, the particle size distribution in the regolith, and the temperature distribution with depth. Hapke and Hale (2000) note that the passive thermal emission from an asteroid is described by the simultaneous solution to three wavelength dependent partial differential equations that describe:

(1) the radiation transfer of how sunlight is absorbed and scattered in the upper layers of the regolith;
(2) the radiative transfer that accounts for thermal emission, absorption and scattering in the upper layers and;
(3) the temperature distribution describing how heat is absorbed, transferred and scattered in the upper layers.

It was realized early on that simple first principle models failed to account for the observed radiometry of asteroids. Lebofky et al. (1986) created a semi-empirical Standard Thermal Model (STM) that assumes that the asteroid surface is in instantaneous thermal equilibrium with the sunlight it receives. The radiometry is scaled to 0° phase angle by an empirical phase factor and the subsolar temperature, and the consequent temperature distribution, is adjusted by a beaming factor to bring the radiometry into agreement with that from asteroids with well determined diameters that were obtained by direct measurements. This model was developed for the N band radiometry near 10 μm and empirical corrections to measurements at other wavelengths have to be applied. Tedesco et al. (2002a,b) used this model to derive the mean diameters of nearly 2300 asteroids with space-based infrared radiometry and updated albedos for many of them. The beaming factor has been related to the thermal inertia of the body, its surface roughness and cratering (Spencer et al., 1989).

Most asteroids are dark, absorbing much more sunlight than they reflect and, consequently, efficiently reradiate this energy in the infrared. The emissivity of the relatively small-grained material anticipated to be on the surface is close to unity and an average wavelength independent emissivity of 0.9 is usually adopted. The (model dependent) predicted flux from an asteroid is a function of the temperature profile across the projected surface area at the time of observation. The projected area depends on phase angle of the asteroid and its size, shape, period and pole of rotation. The temperature profile is a function of the distance from the Sun, emissivity, and total fraction of sunlight absorbed, the thermal inertia, pole position and rotation rate, surface roughness and degree of cratering. A complex model, such as the one developed by Lagerros (1996, 1997a,b) and Müller and Lagerros (1998) takes all these parameters into account. However, an extensive set of measurements over a large wavelength range, over several rotation periods and over large phase angle is needed to sufficiently separate the effects of the various parameters employed in the models. Müller and Lagerros (1998) applied this thermo-physical model to 10 asteroids; three of these asteroids (1 Ceres, 2 Pallas and 4 Vesta) had sufficient ground-based radiometry and visual measurements, which defined the geometric parameters, to derive the thermal inertia, percent of cratering and degree of surface roughness. Model default parameters were derived from these results and applied to the remaining asteroids. The resulting thermal inertial derived for the 10 asteroids ranged from 20% to 50% that of the Moon, all objects (except 532 Heculina) were found to be saturated with craters with quite high values for the rms surface roughness. Subsequently, Müller et al. (1999) added the full spectral range ISO spectroscopy and photometry of 1 Ceres to the prior information from ground based measurements given in Müller and Lagerros (1998) and rederived the model. The updated result reduced the fraction of the surface covered by craters to 60% rather than 100%, and the rms surface roughness is less by a factor of two. This indicates that either the wavelength range ISO data is a significant factor in the modeling, that different starting points in the non-linear solution of the model in matching the observations produce different results, or both.

Microwaves can penetrate the surface layers to a few tens of centimeters. A relatively simple radiative transfer model is used to deduce the porosity, roughness and the real and imaginary parts of the dielectric constant. Eight asteroids have been observed in the radio region from 1.3 mm to 20 cm: the four largest asteroids (Vesta, Ceres, Pallas, Hygiea) and four smaller asteroids (Interamnia, Eunomia, Euphrosyne and Bamberga); Webster and Johnston (1989) describe these observations and summarize the results. All the asteroids showed an abrupt change in the brightness temperature at ~6 mm, which implies a change in bulk physical properties of surface at a depth of a few centimeters since as the longer wavelengths can penetrate more deeply into the surface. The brightness temperature observed at shorter wavelengths was consistent with that predicted by a rapidly rotating asteroid thermal model, while the centimeter values were much cooler (Johnston et al., 1988). The observations can be fitted by a simple two component model with a finely divided surface layer several cm thick overlying a more compacted or solid layer. However, the sub-millimeter observations on several asteroids by Redman et al. (1990, 1992) indicate a rather cool brightness temperature between 0.35 and 2 mm. The higher quality Redman et al. (1992) sub-millimeter measurements on Vesta are discordant with the Johnston et al. (1988) value at 2 mm but entirely consistent with the latter's results at centimeter wavelengths. Redman et al. (1992) suggest that the consistently low brightness temperature from the far infrared to centimeter wavelengths is due to scattering by 100 μm and larger particles in the regolith. The Lagerros thermophysical model does not include the radiative transfer in the regolith. Instead, Müller and Lagerros (1998) and Müller et al. (1999) derived a wavelength dependent emissivity that declined from the mid-infrared to millimeter wavelengths for 1 Ceres and 4 Vesta.

The visual albedo and diameter are coupled in these models and values for both quantities are derived from visual and infrared observations. Tedesco (1994) noted that the well established bright – dark bifurcation of albedos disappears for the smaller asteroids ($D < 40$ km); Tedesco et al. (2002a) confirm this finding using a larger IRAS database of derived albedos and diameters. Lebofsky et al. (1979) speculated that the discrepancies they found between the radiometrically derived and the taxonomic albedos for several small near Earth asteroids that they observed were due to the objects being small and, consequently, either had a very thin or no regolith. We know that this is not the case for Eros. From the rotation period of asteroids as a function of diameter, Pravec et al. (2002) deduce that the smaller asteroids are collisionally derived fragments, mostly either rubble piles or with shattered interiors. Binzel et al. (1998) suggested that space weathering can change the surface reflectivity of an asteroid and that the smaller bodies have generally younger surfaces and higher albedos. Thermal models can only account for these discrepancies on a case-by-case basis (Harris and Lagerros, 2002).

4.2. Infrared spectroscopy

The infrared emission spectra from an asteroid surface contain features indicative of the mineral composition, density, particle size and packing. The features include the reststrahlen bands, the fundamental stretching and bending modes of minerals that for silicates lie in the 8–25 μm region. These bands combine linearly in a coarse mixture of various minerals, as do electronic bands (Thomson and Salisbury, 1993). The Christiansen features arise from the principle molecular vibration bands. Classically, the Christiansen frequency is defined as the frequency at which the real component of the index of refraction equals one. But, as pointed out by Hapke and Hale (2000), the maximum emission occurs at a nearby wavelength defined by where the dominant particle scattering changes from volume to surface scattering. Christiansen frequencies for typical rock material occur in the 8–20 μm region but grain size affects the exact wavelength of the peak and the shape and breadth of the feature. VanTassel and Short (1964) found that finely powdered material shows weak infrared spectral signature compared to coarser material, becoming barely discernible when the particles are the size of sand. This suggest that the contrast in the Christiansen bands might be greater for the smaller asteroids, if their surfaces do, indeed, have little or no regolith. The volume scattering function for fine particle on the surface exhibits a "transparency" or emission trough between the fundamental stretching and vibrational modes of silicates. The volume scattering features that arise from the smaller particles combine non-linearly (Salisbury and Wald, 1992).

Sprague (2000) gives a comprehensive review of mid-IR spectroscopy in the literature as of the summer of 1999. Spectra from the Infrared Space Observatory (ISO) have recently been published. ISO PHOT-S 2.4–11.6 μm spectra were obtained on 21 asteroids at a resolution ($R = \lambda/\Delta\lambda$) of 85 to 95. By comparing the PHT-S spectra of five bright Main-belt asteroids with those of laboratory samples, Dotto et al. (2000) deduced that silicate minerals are present on the surfaces of all five asteroids and more tenuous mineralogical associations made with five fainter objects (Dotto et al., 2002). However, as Hapke and Hale (2000) point out, the low contrast of the reststrahlen bands in the disk integrated, low-resolution infrared spectrum makes it difficult to determine the composition. On the other hand, the high resolution ($R \sim 1100$) Short Wavelength Spectrometer (SWS) spectra of 4 Vesta obtained by Heras et al. (2000) was able to be resolved rotational lines of olivine and pyroxene silicates on the surface. Heras et al. (2000) determined that these minerals are segregated on its surface.

The Low Resolution Spectrometer (LRS) on the Infrared Satellite (IRAS) obtained the largest collection of asteroid spectra (Walker and Cohen, 2002). Walker (private communication) found indications that the LRS spectral details depended on taxonomic class but could not make a definitive assessment owing to the lack of an adequate thermal (physical) model that would simultaneously fit all the IRAS mid to far infrared photometry. Unfortunately, the exact location and shape of the features in both the LRS and PHT-S asteroid spectra are dependent on the model used to ratio out the asteroid's continuum emission.

5. Conclusions

Asteroids and their surfaces are shaped by their history of impact with other asteroids and meteorites. These bodies are heavily cratered and, frequently, the smaller bodies are quite irregular. Grooves, ridges and lines of pits on the few asteroids on which resolved imagery has been obtained testify as to the coherence of these bodies. On the other hand, although the bulk densities, where known, indicate that the largest objects are reasonable solid, the macro-porosity of smaller asteroids ranges from about 20% to 70%. Certainly objects with the higher macro-porosities are candidates for being rubble piles. A small number of asteroids can be logically linked through dynamic and spectral evidence to specific classes of meteorites while general associations between asteroid taxonomic classes and types of meteorites have been made. Thus, pieces of specific asteroids or analogs are available for detailed analyses. The regolith of loose material on the surface ranges from depths of centimeter in scale for the smaller objects for which reasonable inferences can be made to meters for the large bodies.

The silicates olivine and pyroxene have been unambiguously identified on the surfaces of many asteroids by their characteristic visual and infrared spectral signatures. A strong case has been made for the presence of hydrated silicates on low albedo objects. The hydration signature also shows up in the spectra of the M class asteroids, where it is unexpected (Rivkin et al., 2002). Detailed visual and infrared spectral and photometric observations of 4 Vesta show that the surface is variegated with the ratio of pyroxene and olivine dependent of position. The NEAR/Shoemaker mission obtained detailed mapping of the surface composition of Eros by optical, near infrared and gamma spectroscopy.

Surface resolved imagery is available on only about half a dozen small bodies in the solar system. Radar images have been derived for about a dozen objects, mostly near-Earth asteroids; however, the radar images are model dependent. Inference as to the surface properties for most of the asteroids has to come from disk integrated remote sensing. The observed surface brightness of asteroids depends on the optical properties of the particles on the surface, by the manner in which the individual particles scatter the radiation and how radiation is scattered between the particles on the surface. Visible and infrared observations over a large phase angle and, for the thermal emission, over a large span of wavelengths provide information on the mean particle size and depth of the regolith, its roughness, thermal inertia and degree of cratering. To back these quantities out of the measurements, a model is required that takes into detailed account the radiative transfer of how sunlight is absorbed and scattered in the upper layers of the regolith, of the thermal emission, absorption and scattering in the upper layers and the temperature distribution that results from heat being absorbed, transferred and scattered in the upper layers. Errors or uncertainties in the pole and period of rotation and specific (triaxial) shape of the asteroid render the modeled surface properties uncertain.

The most accurate assessment of what an asteroid surface looks like is by direct imaging, preferably by a rendezvous mission such as NEAR. The only experiment currently manifested to perform such a detailed study is MUSES-C, which was launched in 2003. This Japanese engineering mission is designed to demonstrate enabling space technologies such as autonomous navigation and electric propulsion. It will also rendezvous with the near-Earth asteroid 1998 SF36 and after an extensive mapping program, obtain a few grams of surface material and return them to Earth in 2006 (Fujiwara et al., 1999). Future NASA sponsored sample return missions are outlined in the NRC Solar System Exploration Survey (*The Future of Solar System Exploration 2003–2013, Astron. Soc. Pac. Conf. Ser.* **272**). More advanced concepts are in situ assay/geology missions such as described by Heubner and Greenberg (2001). However, such missions are expensive and, consequently, rare. The disk resolved images that we now have, and the in situ data gathered from future missions provide the truth information with which to constrain and improve models used to interpret remote sensing observations. Observations over a number of rotation periods are needed to fix the pole and period of rotation and constrain the shape of the asteroid, quantities that are needed to accurately obtain the variation of brightness with phase angle that characterizes the surface. Measuring the visual and infrared variation over as large a phase angle as possible is needed to separate contributions of the surface conditions in the model. Thus, a healthy remote sensing program could expand our knowledge of the surface conditions on asteroids. Infrared spectrometry and photometry by the Space Infrared Telescope Facility would be highly productive.

Acknowledgements

This research has made extensive use of NASA's Astrophysics Data System.

References

Angeli, C.A., Lazzaro, D. Spectral properties of mars-crossers and near-Earth objects. Astron. Astrophys. 391, 757–765, 2002.

Asphaug, E. The large, undisturbed craters of Mithilde: evidence for structural porosity. Lun. Planet. Sci. Conf. XXXI, 2000, abstract 1864.

Bell, J.F., Owensby, P.D., Hawke, B.R., Gaffey, M.J. The 52-color asteroid survey: final results and interpretation. Lun. Planet. Sci. Conf. XIX, 57–58, 1988.

Belton, M.J.S., Veverka, J., Thomas, P., Helfenstein, P., Simonelli, D., Chapman, C., Davies, M.E., Greeley, R., Greenberg, R., Head, J. Galileo encounter with 951 Gaspra – first pictures of an asteroid. Science 257, 1647–1652, 1992.

Belton, M.J.S., Chapman, C.R., Clark, R., Klaasen, K.P., Harch, A.P., Thomas, P.C., Veverka, J., McEwen, A.S., Pappalardo, R.T. Galileo's encounter with 243 Ida: an overview of the imaging experiment. Icarus 120, 1–19, 1996.

Belton, M.J.S., Chapman, C., Thomas, P., Davies, M., Greenberg, R., Laasen, K., Byrnes, D., D'Amario, L., Synnott, S., Merline, W., Petit, J.-M., Storrs, A., Zellner, B. Bulk density of asteroid 243 Ida from the orbit of its satellite Dactyl. Nature 374, 785–788, 1995.

Binzel, R.P., Bus, S.J., Burbine, T.H. Size dependence of asteroids spectral properties: SMASS results for near-Earth and Main-belt asteroids. Lun. Planet. Sci. Conf. XXIX, 1998, abstract 1222.

Binzel, R.P., Bus, S.J., Burbine, T.H., Malcom, I.E. Size dependence of near-Earth asteroid spectral properties: a comparison with space weathering models. Bull. Am. Ast. Soc. DPS 33, 2002, abstract #590.

Binzel, R.P., Xu, S. Chips off of asteroid 4 Vesta: evidence for the parent body of Basaltic Achondrite meteorites. Science 260, 165–191, 1993.

Binzel, R.P., Gaffey, M.J., Thomas, P.C., Zellner, B.H., Storrs, A.D., Wells, E.N. Geologic mapping of Vesta from 1994 Hubble space telescope images. Icarus 128, 95–103, 1997.

Bottke, W.F., Morbidelli, A., Jedicke, R., Petit, J.-M., Levison, H., Michel, P., Metcalf, T.S. Debiased orbital and absolute magnitude distributions of near-Earth objects. Icarus 156, 399–433, 2002.

Britt, D.T., Consolmagno, G.J. Asteroid bulk density: implications for the structure of asteroids. Lun. Planet. Sci. Conf. XXXII, 1611, 2001.

Britt, D.T., Yeomans, D.K., Consolmagno, G.J. The porosity of 433 Eros. Lun. Planet. Sci. Conf. XXXII, 2001, abstract 32.1212B.

Burbine, T.H., Binzel, R.P. Small Main-belt asteroid spectroscopic survey in the near-infrared. Icarus 159, 468–499, 2002.

Burbine, T.H., McCoy, T.J., Meibom, A., Gladman, B., Keil, K. Meteoritic parent bodies: their number and identification, in: Bottke, W., Cellino, A., Paolicchi, P., Binzel, R.P. (Eds.), Asteroids III. University of Arizona Press, Tucson, pp. 653–667, 2002.

Bus, S., Binzel, R.P. Phase II of the small Mail-belt asteroid spectroscopic survey – the observations. Icarus 258, 106–145, 2002a.

Bus, S.J., Binzel, R.P. Phase II of the small Mail-belt asteroid spectroscopic survey – a feature-based taxonomy. Icarus 258, 126–173, 2002b.

Bowell, E., Hapke, B., Domingue, D., Lumme, K., Peloniemi, J., Harris, A.W. Application of photometric models, in: Binzel, R.P., Gehrels, T., Shapley, M.S. (Eds.), Asteroids II. University of Arizona Press, Tucson, pp. 524–556, 1989.

Chapman, C. S-type asteroids, ordinary Chondrites and space weathering. Meteor. Planet. Sci. 31, 699–725, 1996.

Chapman, C., Merline, W., Thomas, P. the NEAR MSI-NIS team, cratering of the C-type asteroid Mathilde. Meteor. Planet. Sci. Suppl. 33, 30, 1998.

Chapman, C.R., Neukum, G., Veverka, J., Belton, M. Cratering on Gaspra. Lun. Planet. Sci. Conf. XXIV, 1993, abstract 269C.

Cellino, A., Hutton, R.G., Tedesco, E.F., DiMartino, M., Burnini, A. Polarimetric observations of small asteroids: preliminary results. Icarus 138, 129–140, 1999.

Cellino, A., Zappalá, V., DiMartino, M., Farinella, P., Paolicchi, P. Flattening, pole and Albedo features of 4 Vesta from photometric data. Icarus 70, 546–565, 1987.

Cheng, A.F., Barnouin-Jha, O.S. Giant craters on Mathilde. Icarus 140, 34–48, 1999.

Clark, B.E., Hapke, B., Peters, C., Britt, D. Asteroid space weathering and regolith evolution, in: Bottke, W., Cellino, A., Paolicchi, P., Binzel, R.P. (Eds.), Asteroids III. University of Arizona Press, Tucson, pp. 585–599, 2002.

Dollfus, A., Woolf, M., Geake, J.E., Lupishko, D.F., Dougherty, L.M. Photopolarimetry of asteroids, in: Binzel, R.P., Gehrels, T., Shapley, M.S. (Eds.), Asteroids II. University of Arizona Press, Tucson, pp. 594–642, 1989.

Dotto, E., Müller, T.G., Barucci, M.A., Encrenas, Th., Knacke, R.F., Lellouch, E., Doressoundiram, A., Crovisier, J., Brucato, J.R., Colangeli, I., Mennella, V. ISO results on bright Main-belt asteroids: PHT-S observations. Astron. Astrophys. 358, 1133–1141, 2000.

Dotto, E., Barucci, M.A., Müller, T.G., Brucato, J.R., Fulchignoni, M., Mennella, I., Colangeli, V. ISO observations of low and moderate Albedo asteroids PHT-P and PHT-S results. Astron. Astrophys. 393, 1065–1072, 2002.

Fujiwara, A., Mukai, T., Kawaguchi, J., Uesugi, K.T. Sample return mission to NEA: Muses-C. Adv. Space Sci. 25, 231–238, 1999.

Granahan, J.C. Galileo 243 Ida system spectral observations revisited. Bull. Am. Ast. Soc. DPS, 2001, abstract #33 41.06.

Gaffey, M.J. Identifying asteroidal parent bodies of the meteorites: the last lap. Lun. Planet. Sci. Conf. XXXI, 1092, 2000, abstract.

Gaffey, M.J., Coutis, F.A., Kelley, M.S., Reed, K.L. Mineralogy of asteroids, in: Bottke, W., Cellino, A., Paolicchi, P., Binzel, R.P. (Eds.), Asteroids III. University of Arizona Press, Tucson, pp. 183–204, 2002.

Gaffey, M.J., Reed, K.L., Kelley, M.S. Relationship of E-type Apollo asteroid 3103 (1982 BB) to the Enstatite Achodrite meteorites and the Hungaria asteroids. Icarus 100, 95–109, 1992.

Hapke, B., Hale, A.S. Theoretical modeling of radiation transfer in planetary regoliths, in: Sitko, M.L., Sprague, A.L., Lynch, D.K. (Eds.), Thermal Emission Spectroscopy and Analysis of Dust, Disks, and Regoliths. Astron. Soc. Pac. Conf. Ser., vol. 106, pp. 213–219, 2000.

Harris, A.W., Lagerros, J.S.V. Asteroids in the thermal infrared, in: Bottke, W., Cellino, A., Paolicchi, P., Binzel, R.P. (Eds.), Asteroids III. University of Arizona Press, Tucson, pp. 205–218, 2002.

Helfenstein, P., Veverka, J. Physical characterization of asteroid surfaces from photometric analysis, in: Binzel, R.P., Gehrels, T., Shapley, M.S. (Eds.), Asteroids II. University Arizona Press, Tucson, pp. 557–593, 1989.

Heras, A.M., Morris, P.W., Vandenbussche, B., Müller, T.G. Asteroid 4 Vesta as seen with the ISO short wavelength spectrometer, in: Sitko, M.L., Sprague, A.L., Lynch, O.K. (Eds.), Thermal Emission Spectroscopy and Analysis of Dust, Disks and Regoliths. Astron. Soc. Pac. Conf. Proc., vol. 196, pp. 205–213, 2000.

Heubner, W.F., Greenberg, J.M. Methods for determining material strengths and bulk properties of NEOs. Adv. Space Res. 28, 1129–1137, 2001.

Ivezić, Z., Lupton, R.H., Jurić, M., Quinn, T., Gunn, J.E., Knapp, G.R., Rockosi, C.M., Brinkmann, J. Color confirmation of asteroid families. Astron. J. 124, 2943–2948, 2002.

Johnston, K.J., Lamphear, E.J., Webster Jr., W.J., Lowman Jr., P.O., Seidelmann, P.K., Kaplan, G.H., Wade, C.M., Hobbs, R.W. The microwave spectra of the asteroids Pallas, Vesta and Hygiea. Astron. J. 98, 335–340, 1988.

Jones, T.D., Lebofsky, L.A., Lewis, J.S., Marley, M.S. The composition and origin of the C, P and D asteroids – water as a tracer of thermal evolution in the outer belt. Icarus 88, 173–192, 1990.

Kaasalainen, M., Mottola, S., Fulchignoni, M. Asteroid models from disk-integrated data, in: Bottke, W., Cellino, A., Paolicchi, P., Binzel, R.P. (Eds.), Asteroids III. University of Arizona Press, Tucson, pp. 139–150, 2002.

Keller, H.U., Arpigny, C., Barbieri, C., Bonnet, R.M., Cazes, S., Coradini, M., Cosmovici, C.B., Delamere, W.A., Huebner, W.F., Hughes, D.W., Jamar, C., Malaise, D., Reitsema, H.J., Schmidt, H.U., Schmidt, W.K.H., Seige, P., Whipple, F.L., Wilhelm, K. First Halley multicolour camera imaging results from Giotto. Nature 321, 320–326, 1986.

Kelly, M.S., Granahan, J.C., Abell, P.A., Gaffey, M.J., Prudente, A. Reanalysis of the Galileo SSI/NMS-derived spectra of asteroid 951 Gaspra. Lun. Planet. Sci. Conf. XXXI, 2000, abstract 1769.

Küppers M. A comprehensive model of regolith evolution: the case of asteroid 433 Eros. Bull Am. Ast. Soc. DPS, 33, 2001, abstract#41.04.

Lagerros, J.S.V. Thermal physics of asteroids I. Effects of shape, heat conduction and beaming. Astron. Astrophys. 310, 1011–1020, 1996.

Lagerros, J.S.V. Thermal physics of asteroids III. Irregular shapes and Albedo variegations. Astron. Astrophys. 325, 1226–1237, 1997a.

Lagerros, J.S.V. Thermal physics of asteroids IV. Thermal infrared beaming. Astron. Astrophys. 332, 1123–1132, 1997b.

Lazzaro, D., Carvano, J.M., Mothé-Diniz, T., Angeli, C., Florczak, M., Harris, A.W. A visible spectroscopic survey of around 800 asteroids, in: Asteroids III: From Piazzi to the 3rd Millinium, (abstract) Osservatorio di Palermo, Sicily, p. 174, 2001.

Lebofsky, L.A., Lebofsky, M.J., Riecke, G.H. Radiometry and surface properties of Apollo, Amor and Aten objects. Astron. J. 84, 885–888, 1979.

Lebofsky, L.A., Spencer, J.R. Radiometry and thermal modeling of asteroids, in: Binzel, R.P., Gehrels, T., Shapley, M.S. (Eds.), Asteroids II. University of Arizona Press, Tucson, pp. 297–308, 1989.

Lebofky, L.A., Sykes, M.V., Tedesco, E.F., Veeder, G.J., Matson, D.L., Brown, R.H., Gradie, J.C., Feierberg, M.A., Rudy, R.J. A refined "standard" thermal model for asteroids based on observations of 1 Ceres and 2 Pallas. Icarus 68, 239–251, 1986.

Lipschultz, M.E., Gaffey, M.J., Pellas, P. Meteoritic parent bodies: nature, number, size and relation to present-day asteroids, in: Binzel, R.P., Gehrels, T., Shapley, M.S. (Eds.), Asteroids II. University of Arizona Press, Tucson, pp. 740–777, 1989.

Muinonen, K., Piironen, J., Shkuratove, Y.G., Ovcharencko, A., Clark, B.E. Asteroid photometric and pholarmetric phase effect, in: Bottke, W., Cellino, A., Paolicchi, P., Binzel, R.P. (Eds.), Asteroids III. University of Arizona Press, Tucson, pp. 123–138, 2002.

Müller, T.G., Lagerros, J.S.V. Asteroids as far-infrared photometric standards for ISOPHOT. Astron. Astprophys. 338, 340–352, 1998.

Müller, T.G., Lagerros, J.S.V., Burgdorf, M., Lim, T., Morris, P.W., Salama, A. Schulz, B., Vandenbussche, B. Fundamental thermal emission parameters of Main-belt asteroids derived from ISO observations of (1) Ceres, in: Cox, P., Kessler, M.F. (Eds.), Proceedings of the Universe seen by ISO, ESA SP, vol. 427, pp. 141–144, 1999.

Ostro, S.J., Hudson, R.S., Benner, L.A.M., Giorgini, J.D., Magri, C., Margot, J.-L., Nolan, M.C. Asteroid radar astronomy, in: Bottke, W., Cellino, A., Paolicchi, P., Binzel, R.P. (Eds.), Asteroids III. University of Arizona Press, Tucson, pp. 151–168, 2002.

Pravec, P., Harris, A.W., Michalowski, T. Asteroid rotations, in: Bottke, W., Cellino, A., Paolicchi, P., Binzel, R.P. (Eds.), Asteroids III. University of Arizona Press, Tucson, pp. 113–121, 2002.

Parker, J.W., Stern, S.A., Thomas, P.C., Festou, M.C., Merline, W.J., Young, E.F., Binzel, R.P., Lebofsky, L.A. Analysis of the first disk-resolved images of Ceres from ultraviolet observations with the Hubble space telescope. Astron. J. 123, 549–557, 2002.

Redman, R.O., Feldman, P.A., Halliday, I., Matthews, H.E. Submillimetre spectra of asteroids with the JCMT, in: Lagerkvist, C.-I., Rickmand, H., Lindblad, B.A., Lindgren, M. (Eds.), Asteroids Comets and Meteroids III. Uppsala University Press, Uppsala, pp. 153–156, 1990.

Redman, R.O., Feldman, P.A., Halliday, I., Matthews, H.E., Creuzberg, F. Millimeter and submillimeter observations of the asteroid 4 Vesta. Astron. J. 104, 405–411, 1992.

Rivkin, A.S., Howell, E.S., Vilas, F., Lebofsky, L. Hydrated minerals on asteroids: the astronomical record, in: Bottke, W., Cellino, A., Paolicchi, P., Binzel, R.P. (Eds.), Asteroids III. University of Arizona Press, Tucson, pp. 235–253, 2002.

Robinson, M.S., Thomas, P.C., Veverka, J., Murchie, S. 433 Eros regolith: implications for global statigraphy, sedimentary processes and degradation rates. Meteoritical Soc. Mtg., 64, 2002, abstract #6444.

Salisbury, J.W., Wald, A. The role of volume scattering in reducing spectral contrast of reststrahlen bands in spectra of powdered minerals. Icarus 102, 121–128, 1992.

Soderblom, L.A., Becker, T.L., Bennett, C., Boice, D.C., Briit, D.T., Brown, R.H., Buratti, B.J., Isbell, C., Giese, B., Hare, T., Hicks, M.D., Howington-Kraus, E., Kirk, R.L., Lee, M., Nelson, R.M., Oberst, J., Owen, T.C., Rayman, M.D., Sandel, B.R., Stern, S.A., Thomas, N., Yelle, R.V. Observations of comet19P/Borrelly by the miniature integrated camera and spectrometer aboard deep space I. Science 296, 1087–1091, 2002.

Spencer, J.R., Lebofsky, L.A., Sykes, M.V. Systematic biases in radiometric diameter determinations. Icarus 78, 227–354, 1989.

Sprague, A.J. Thermal emission spectroscopy and data analysis of solar system regoliths, in: Sitko, M.L., Sprague, A.L., Lynch, D.K. (Eds.), Thermal Emission Spectroscopy and Analysis of Dust, Disks, and Regoliths. Astron. Soc. Pac. Conf. Ser., vol. 106, pp. 167–186, 2000.

Sunshine, J.M., Bus, S.J., Burbine, T.H., McCoy, T.J., Binzel, R.P. Unambiguous spectral evidence for high- (and low-) calcium pyroxenes in asteroids and meteorites Lun. Planet. Sci. XXXIII, 2002, abstract #1536.

Tedesco, E.F. Asteroids Albedos and diameters, in: Millani, A., Di Martino, M., Cellino, A. (Eds.), Asteroids Comets and Meteorites. Kluwer Academic Press, London, pp. 55–74, 1994.

Tedesco, E.F., Noah, P.V., Noah, M., Price, S.D. The supplemental IRAS minor planet survey (SIMPS). Astron J. 123, 1056–1085, 2002a.

Tedesco, E.F., Egan, M.P., Price, S.D. The MSX infrared minor planet survey (MIMPS). Astron. J. 124, 583–591, 2002b.

Tedesco, E.F., Williams, J.G., Matson, D.L., Veeder, G.J., Gradie, J.C., Lebofsky, L.A. A three-parameter asteroid taxonomy. Astron. J. 97, 580–606, 1989.

Tholen, K.J. Asteroid taxonomy from cluster analysis of photometry, Ph.D Thesis, University of Arizona, Tucson, Arizona, 1984.

Tholan, D.J., Barucci, M.A. Asteroid taxonomy, in: Binzel, R.P1., Gehrels, T., Shapley, M.S. (Eds.), Asteroids II. University of Arizona Press, Tucson, pp. 298–315, 1989.

Thomas, P.C., Veverka, J., Simonelli, D., Helfenstein, P., Carcich, B., Belton, M.J.S., Davies, M.E., Chapman, C. The shape of Gaspra. Icarus 107, 23–36, 1994.

Thomas, P.C., Binzel, R.P., Gaffey, M.J., Storrs, A.D., Wells, E.N., Zellner, B.H. Impact excavation on asteroid 4 Vesta: Hubble space telescope results. Science 227, 1492–1495, 1997.

Thomson, J.L., Salisbury, J.W. The mid-infrared reflectance of mineral mixtures (7–14 microns). Remote Sensing Environ. 45, 1–13, 1993.

VanTassel, R.A., Short, I. Thermal emission characteristics of mineral dusts, in: Salisbury, J.W., Glaser, P.E. (Eds.), The Lunar Surface Layer. Academic Press, New York, pp. 445–468, 1964.

Ververka, J., Belton, M., Klassen, K., Chapman, C. Galileo's encounter with 951 Gaspra: overview. Icarus 107, 2–17, 1994.

Veverka, J., Thomas, P., Simonelli, D., Belton, M.J.S., Carr, M., Chapman, C., Davies, M.E., Greeley, R., Greenberg, R., Head, J. Discovery of grooves on Gaspra. Icarus 107, 72–83, 1994.

Vilas, F.A., Larson, S.M., Hatch, E.C., Jarvis, K.S. CCD reflectance spectra of selected asteroids II. Low-Albedo asteroid spectra and data extraction techniques. Icarus 105, 67–78, 1993.

Walker, R.G., Cohen, M. The thermal beaming parameter according to IRAS. Bull. Am. Ast. Soc. DPS 34, 2002, abstract 14.16.

Webster Jr., W.J., Johnston, K.J. Passive microwave observations of asteroids, in: Binzel, R.P., Gehrels, T., Shapley, M.S. (Eds.), Asteroids II. University of Arizona Press, Tucson, pp. 213–227, 1989.

Xu, S.R., Binzel, R.P., Burbine, T.H., Bus, S.J. Small Main-belt asteroid spectroscopic survey: initial results. Icarus 115, 67–78, 1995.

Zellner, B.H., Albrecht, R., Binzel, R.P., Gaffey, M.J., Gaffey, P.C., Storrs, A.D., Wells, E.N. Hubble space telescope images of asteroid 4 Vesta. Icarus 128, 83–87, 1997.

Zellner, B.H., Tholen, D.J., Tedesco, E.F. The eight-color asteroid survey: results for 589 minor planets. Icarus 61, 335–416, 1985.