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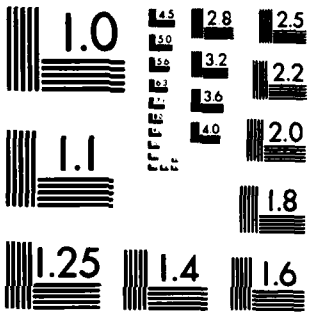

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TITLE OF RESEARCH:

A Program of Ground-Based Astronomy
to Complement *Einstein* Observations

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PREPARED BY:

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CONTENTS

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A total of eight ground-based astronomical observing programs were carried out in pursuit of a multiwavelength approach to a number of astrophysical problems. Synthesis of these results with existing X-ray data led to considerable progress on problems of the emission mechanisms and evolution of active galactic nuclei, the interaction of supernova remnants with the interstellar medium and the effects of coeval pulsars on the development of these remnants, and the coronal activity in main sequence stars. Four papers have either been published or submitted to technical journals detailing these

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20. Abstract (cont'd)

results and seven more are in preparation. Proposals for future observations were prepared and six presentations of the research were given at various scientific meetings.

B. RESEARCH OBJECTIVES

The objective of the funded research is to formulate and carry out a program of ground-based astronomical observations to complement X-ray data accumulated with the Einstein Observatory, and to use the results of these multiwavelength studies in addressing a number of significant astrophysical problems of current interest. The work focuses on three main topics: quasar emission mechanisms and their evolution; the structure and evolution of supernova remnants and the neutron stars which they may contain; and, the processes leading to high energy emission in the outer atmospheres (winds, coronae, etc) of main sequence stars. The physics to be addressed ranges from the generation and energetics of neutron star particle beams and their interaction with the surrounding medium to the details of supernova shock waves and their role in cosmic ray acceleration; from the basic structure of matter at supernuclear densities in neutron star interiors to the basic structure of the Universe as revealed in the evolution of quasars; and, from the study of the radiation processes in distant active galactic nuclei to the identification of the critical parameters which determine the level of coronal activity in nearby late-type stars. A detailed progress report is contained in section C below; sections D and F list the tangible products of the research; papers published in the technical literature and presented at scientific conferences.

C. STATUS OF THE RESEARCH

C.1 Introduction

A total of seven proposals to use the National Radio Astronomy Observatory's (NRAO) Very Large Array (VLA) were submitted and all seven were scheduled (despite a significant oversubscription rate at this facility). All of these observations have now been carried out, and the results are in various stages of analysis and presentation. In addition, we conducted observations at the National Astronomy and Ionosphere Center at Arecibo, Puerto Rico (as the first outside observers to use the Center's new two-element interferometer) and data from a prior run at the NRAO Green Bank 300-foot telescope were analysed. Work on our program to optically identify serendipitous X-ray sources continued apace although no new observing sessions were conducted during the first year of the grant. We outline below the results of these various programs and the current status of the work on each.

C.2 Radio Survey of X-ray Selected Active Galactic Nuclei (AGN)

We have observed an X-ray selected sample of 50 new quasars, 10 BL Lac candidates and a number of as yet unidentified high latitude sources with the VLA at 6 cm. The data reduction and analysis are complete. A presentation on the BL Lac results was given at the 1982 January meeting of the American Astronomical Society (AAS) and a paper has been published in the Astrophysical Journal (Letters). The results of the quasar survey were presented at the 1982 June AAS meeting and a paper is in preparation.

Prior to these observations, radio emission was a defining characteristic of a BL Lac, and many theoretical models have been based on the apparent universality of strong radio synchrotron radiation in these objects. However,

we detected only one of the ten observed candidates which were selected as sources of strong X-ray emission associated with optical objects with featureless, neutral continua. The one detection confirmed the optical identification of the X-ray source on positional grounds, although the flux of 0.8 mJy gives this source a smaller radio-to-optical flux ratio than any previously known BL Lac. Coupled with the stringent upper limit to any radio emission from one of the other optical candidates whose identification with the X-ray source was secured with the high resolution imager (HRI) on board Einstein, these data strongly support our claim to have discovered the first radio-quiet BL Lacs. If the optical identifications of the remaining eight candidates are confirmed, it will be clear that, in fact, the vast majority of BL Lacs are radio quiet and that the surface density of these objects to $m_v \sim$ 18.5 approaches 20% of the quasar surface density at the same limiting magnitude. These results have profound implications for emission models, space densities, and evolution of this particularly active subclass of AGN.

The results of the quasar radio survey are equally interesting. Only four of the fifty objects have 6 cm radio fluxes greater than 1 mJy, a fraction comparable to that found in optically-selected QSO samples. However, the distribution of the detections yields an important clue to the emission mechanisms operating in the X-ray regime: three of the five sources with X-ray luminosities above 2×10^{45} ergs s^{-1} were found to have radio fluxes >5 mJy, while only a single object ($f_R \sim 1$ mJy) was seen among the remaining 45 lower luminosity members of the sample. No such correlation was present between radio flux and the X-ray-to-optical flux ratios. Coupled with previous work on radio and optically selected QSO samples (Ku, Helfand, and Lucy 1980; Nature, 288, 323; Zamorani et al. 1981 Ap. J. 245, 357; Owen, Helfand, and Spangler 1981, Ap. J. (Letters), 250, L55), these results suggest that the

soft X-ray emission from AGN is a composite of the tail of the optical/UV synchrotron power law and inverse Compton scattered photons from the radio continuum. Future work, including our program to correlate radio and X-ray intensity fluctuations, will help to quantify these contributions, providing important new constraints on models of the central engine which drives these various emission processes.

We have also conducted a new survey of primarily optically selected AGN using the new interferometer at the Arecibo Observatory. A few X-ray selected objects discovered by other workers were included. These data are currently being analyzed. An important result already apparent, however, is the utility of this new instrument in resolving the source confusion problem of the 1,000 foot dish and allowing rapid, routine observation of sources with fluxes down to 5 mJy. This capability may well be useful in some of the stellar observations we hope to make in the coming year.

C.3 Supernova Remnants (SNR) and Neutron Stars

C.3.1 M33

In a search for supernova remnants and other possible correspondences between radio emission and the X-ray sources discovered in our Einstein observations of this nearby spiral galaxy (Long et al. 1981, Ap. J. (Letters), 246, L61), we conducted a survey with the VLA at 6 cm and 20 cm. More than 60 sources were detected. Many of these appear to be extended and have spectral indices characteristic of the nonthermal emission from SNR. The analysis of these data is nearly complete and a publication is planned.

C.3.2 Galactic Source Survey

As a result of our ability (supported by this grant) to analyze VLA data at Columbia, we were granted what would otherwise have been idle telescope time to observe a sample of strong, small diameter, flat spectrum radio

sources in the galactic plane in a search for new examples of Crab-like SNR. Eighteen such sources were observed at 6 cm wavelength. Nearly half the sample is probably extragalactic: five unresolved sources, which may prove useful as calibrators for the VLA, and two double sources were observed. Several of the remaining objects are extended, but are probably compact HII regions. None of them, however, exhibits the strong (>5%) polarization characteristic of supernova remnants. These results were presented at the June meeting of the AAS and a paper discussing the implications of these observations for the number and evolution of Crab-like remnants in the Galaxy is essentially complete.

C.3.3 Mapping Small-Diameter SNR

A large number of shell-type galactic SNR were surveyed with the Einstein Observatory. In a few cases, the result was that a higher resolution, more detailed map existed in X-rays than was available in the radio regime. To rectify this unusual situation and to allow detailed comparison of radio and X-ray images taken with similar spatial resolution, we observed three such remnants with the D (most compact) configuration of the VLA. The radio data analysis is complete with both total intensity and polarization maps at one or two frequencies for each remnant. The X-ray data are being reduced by collaborators at other institutions and joint publications are planned. One of the objects is particularly interesting in that the X-rays are not limb-brightened to match the radio shell. This has been seen in a few other remnants and the origin of this morphology is unclear. Detailed comparison of the radio and X-ray images may provide insight into the mechanism responsible.

C.3.4 Crab-like SNR and Neutron Stars

One of our primary interests has been the relationship between SNR and the origin and evolution of neutron stars. One of the two well-established associations of a young neutron star (i.e., short-period radio pulsar) and a SNR is Vela. The Einstein X-ray image of the pulsar reveals an unpulsed point source surrounded by a diffuse emission region with a power law energy spectrum - in essence, a miniature version of the prototypical Crab Nebula. In such synchrotron nebulae, particles accelerated to energies of $\gtrsim 10^4$ GeV by the pulsar diffuse out into the surrounding medium and radiate synchrotron photons in the weak ($\sim 10^{-4}$ G) nebular magnetic field. The ratio of the X-ray luminosity of the Vela nebula to that of the Crab is $\sim 10^{-5}$; if a similar ratio holds in the radio portion of the spectrum (i.e., if the input particle spectra are similar), then a corresponding diffuse radio source should be detectable with the VLA. We conducted an observation to search for such a source in 1981 December and failed to detect any extended emission at 6 cm wavelength, setting any important constraint on models of the particle generation and subsequent diffusion. A proposal to perform more detailed observations of this sort for Vela and several other older pulsars which also exhibit diffuse X-ray emission has been accepted by the VLA and will be carried out in 1982 December. A proposal for optical observations of these sources has been submitted and is currently pending.

Although no young radio pulsars are known to be associated with them, a number of galactic SNR exhibit Crab-like properties in the radio regime - centrally-peaked brightness distribution, a high degree of linear polarization and a flat synchrotron spectrum. Several of these sources have now been observed to emit X-rays as well, and in two cases, evidence for a central point source is seen (Becker, Helfand and Szymkowiak 1982, Ap. J., 255,

557). The most luminous such remnant, 3C58, was observed at the VLA in a search for a point source of radio emission coincident with the X-ray source. While no point-like object was detected, there are several bright knots of emission close to the X-ray source. These data are being combined with those taken at different frequencies and spatial resolution by other observers in an attempt to obtain a coherent picture of the central region of this nebula.

New VLA data were combined with X-ray observations of the galactic supernova remnant G29.7-0.3 to show that it is composed of two spectrally distinct components: a steep-spectrum, incomplete shell 3 arcmin in extent enclosing a flat-spectrum, X-ray emitting region 30 arcsec across. Thus, G29.7-0.3 joins the ranks of SNR which exhibit a combination of Crab-like and shell remnant attributes. The Crab-like core has the highest ratio of X-ray-to-radio luminosity of all the Crab-like remnants observed to date, suggesting that it is an extremely young object. A paper has been submitted to the Astrophysical Journal (Letters) describing these results and discussing their implications for neutron star formation and evolution.

Finally, the short-period pulsar PSR 1055-52 was detected as a soft X-ray source in the course of an Einstein Observatory survey of radio pulsars. Its X-ray to radio luminosity ratio is $\sim 10^4$, although the X-rays are not modulated at the neutron star's rotation frequency. High spatial resolution observations suggest that a significant fraction of the emission comes from an extended region surrounding the pulsar. Several possible scenarios for the origin of both point and extended X-ray emission from isolated neutron stars were investigated: radiation from the hot stellar surface, from hot polar caps, and from an optically thick atmosphere, as well as from a circumstellar nebula emitting thermal brehmsstrahlung or synchrotron radiation. We con-

cluded that the spatial, spectral, and temporal characteristics of this source are most consistent with a model in which relativistic particles generated by the pulsar are radiating synchrotron X-rays in the surrounding magnetic field; i.e., that PSR 1055 is embedded in a mini-Crab nebula. A paper describing this work has been submitted for publication in the Astrophysical Journal.

C.4 Stars

Prior to the launch of Einstein, fewer than half a dozen normal stars and about 40 nondegenerate binary systems were known to emit X-rays. Of the nearly 10,000 new sources discovered by this satellite, however, more than half are main sequence or premain sequence stars. This explosion in our knowledge of the hot outer atmospheres, stellar winds, and coronae of stars throughout the H-R diagram, will allow us, for the first time, to place in context the Sun's high energy emission, helping to assess the importance of such factors as age, rotation rate, convection zone depth and global magnetic field strength in heating the corona and driving the solar wind. Although stellar work was not explicitly mentioned in our first proposal, we had been involved in the analysis of stellar X-ray emission, and have recently been pursuing and planning complementary ground-based work under the auspices of this grant to follow up on these important new discoveries.

Among the early-type stars (spectral types O through A5), the ratio of X-ray to bolometric luminosity is roughly constant at $\sim 10^{-7}$ (Long and White 1980, Ap. J. (Letters), 239, L65). The origin of this emission is as yet unclear, although our collaborators at Columbia have made a strong case for time-dependent shock heating of the outer regions of the wind as the source of the X-ray plasma (Lucy and White 1980, Ap. J., 241, 300). The model they have developed predicts that radio free-free emission will be also observable and, furthermore, that this radio emission should be spatially resolvable with the

VLA. To test this prediction, we undertook A-array VLA observations of one of the classic mass-losing stars, P Cygni. The source was, in fact, found to be extended, and important new constraints on the structure of the wind were derived. A paper has been published and a follow-up proposal to look at other similar sources was recently completed, resulting in the detection of yet another source with a resolvable wind.

While the winds of a few early-type stars have been detected in the radio regime, the majority of known stellar radio sources are coronally active late-type stars. The two main subclasses are the RS CVn systems, containing two solar type (G and K) stars in a close binary orbit (P ~ 1 to 14 days), and dwarf M flare stars. Both classes are now known to be strong X-ray sources. In addition, however, many other stars of the same spectral types are also strong X-ray emitters with luminosities spanning the entire range between the RS CVn and solar emission levels. It is unknown what fraction of these are also radio emitters. Since optical selection criteria have been notably unsuccessful in predicting stellar radio luminosities, we are proceeding to exploit the tentative correlation between radio and X-ray fluxes noted by Gibson and Ewald (1981, preprint) in an attempt to increase the sample of known radio stars and explore the interrelationship of high energy thermal and nonthermal emission from late-type stellar coronae.

A large sample of F-M stars selected for high X-ray-to-optical luminosity ratios had each been observed daily for two weeks by Gibson, Helfand, and Ewald at the NRAO 300-foot telescope in a search for flaring radio emission. Several stars were unambigiously detected and a larger number of candidate radio sources were culled from the initial sample. Based on this work, a proposal was submitted to the VLA to map the fields containing possible radio detections in an attempt to confirm the stellar identification. This program

was carried out and data reduction is nearly complete. We expect to submit follow-up proposals for the detected sources, and to extend this work to the larger sample of X-ray bright stars now available.

We have also begun assembling a large sample of X-ray serendipitous sources which, on the basis of existing optical plate material, are candidates for stellar X-ray sources (in particular, M dwarfs). Optical follow-up work is being planned to positively identify these sources, with a view toward better defining the high luminosity tail of the M-star X-ray luminosity function and thus establishing with more certainty the contribution of such stars to the diffuse galactic background radiation.

C.5 Summary

An active program of ground-based observations to complement the X-ray data accumulated by the Einstein Observatory has been planned and implemented. The numerous results in areas ranging from quasars to pulsars to nearby stars reemphasizes the importance of a multiwavelength approach in attacking the many problems of current astrophysical interest.

D. PUBLICATION LIST

D.1 Papers Published:

Gary A. Chanan, Bruce Margon, David J. Helfand, Ronald A. Downes, and Don R. Chance, "Two X-Ray Selected BL Lacertae-Type Objects," Astrophys. J. (Letters), 261, L31-L34 (1982).

Richard L. White and R. H. Becker, "The Resolution of P Cygnus' Stellar Wind," Astrophys. J., in press.

D.2 Papers Submitted for Publication:

Andrew F. Cheng and David J. Helfand, "X-Rays from Radio Pulsars: The Detection of PSR 1055-52," Astrophys. J.

R. H. Becker, David J. Helfand, and A. E. Szymkowiak, "G29.7-0.3: Another Supernova Remnant with an Identity Crisis," Astrophys. J. (Letters).

D.3 Papers in Preparation:

"An X-Ray Survey of the Pleiades Cluster," J.-P. Caillault, D. J. Helfand, and W. H.-M. Ku, to be submitted to Astrophys. J.

"X-Ray Emission from Radio Pulsars: The Portable SNR," D. J. Helfand, to be submitted for publication in Proc. of IAU Symposium 101

"A Radio Survey of X-Ray Selected Active Galactic Nuclei," D. J. Helfand, G. A. Chanan, B. Margon, and R. A. Downes, to be submitted to Astrophys. J. (Letters)

"Point Sources of Radiation in Supernova Remnants," D. J. Helfand and R. H. Becker to be submitted to Nature.

"A Search for Crab-like Supernova Remnants in the Galactic Plane," D. Chance, R. H. Becker, R. L. White, to be submitted to Astron. J.

"A Radio Survey of M33," R. H. Becker and K. S. Long, to be submitted to Astrophys. J.

"A Radio Survey of X-Ray Selected Late-Type Stars," D. Gibson, Ewald, and D. J. Helfand to be submitted to Astron. J.

E. PROFESSIONAL PERSONNEL

Principal Investigator:

- David J. Helfand, Associate Professor of Physics, Columbia University

Co-Investigators:

- Gary A. Chanan, Assistant Professor of Physics, Columbia University

- Robert H. Becker, Assistant Professor of Physics, Virginia Polytechnic Institute and State University (formerly Research Associate, Columbia Astrophysics Laboratory, Columbia University).

Graduate Research Assistants:

John Hughes
Jean-Pierre Caillault
Don Chance
Saeqa D. Vrtilek

F. INTERACTIONS

F.1 Papers Presented at Scientific Conferences:

"An X-Ray Survey of the Pleiades," J.-P. Caillault, D. J. Helfand, and W. H.-M. Ku, contributed paper presented at the 159th Meeting of the American Astronomical Society held in Boulder, Colorado, 10-13 January 1982.

"X-Ray Synchrotron Nebulae and the Origin of Neutron Stars," D. J. Helfand, invited talk presented at the 159th Meeting of the American Astronomical Society held in Boulder, Colorado, 10-13 January 1982.

"An X-Ray Survey of the Pleiades," J.-P. Caillault, D. J. Helfand, and W. H.-M. Ku, contributed paper presented at the Spring Meeting of the Astronomical society of the New York held at the University of Rochester, Rochester, New York, 16-17 April 1982.

"Radio Emission from X-Ray Selected AGN," D. J. Helfand, G. A. Chanan, B. Margon, and R. Downes, contributed paper presented at the 160th Meeting of the American Astronomical Society held in Troy, New York, 6-9 June 1982.

"Radio Images of Eighteen Small Diameter Galactic Radio Sources," D. Chance, R. Becker, and R. White, contributed paper presented at the 160th Meeting of the American Astronomical Society held in Troy, New York, 6-9 June 1982.

"X-Ray Emission from Radio Pulsars: The Portable SNR," David J. Helfand, invited paper presented at the IAU Symposium No. 101, "Supernova Remnants and Their X-Ray Emissions," held in Venice, Italy, 30 August-2 September 1982.

F.2 Consultative and Advisory Functions

None

F.3. Patent Disclosure

Not applicable; Form 22-R160 submitted.