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Final Technical Report

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**Long-Term Space Astrophysics Research
Program**

Multiwavelength and Statistical Research in Space Astrophysics

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This report summarizes the accomplishments funded by NASA Long-Term Space Astrophysics grant NAGW-2120 over a 7 year period in three research areas: multiwavelength study of active galactic nuclei; magnetic activity of young stellar objects; and statistical methodology for astronomical data analysis. The research is largely based on observations of the ROSAT and ASCA X-ray observatories, complemented by ground-based optical and radio studies. Major findings include: discovery of inverse Compton X-ray emission from radio galaxy lobes; creation of the largest and least biased available sample of BL Lac objects; characterization of X-ray and nonthermal radio emission from T Tauri stars; obtaining an improved census of young stars in a star forming region and modeling the star formation history and kinematics; discovery of X-ray emission from protostars; development of linear regression methods and codes for interpreting astronomical data; organization of the first cross-disciplinary conferences for astronomers and statisticians; coauthorship of the first contemporary monograph in astrostatistics. The grant supported the preparation of 43 articles in refereed journals, 38 articles in unrefereed journals (15 of which are invited reviews), 3 books, a Ph.D. dissertation, an undergraduate Honors thesis, and three software products. A full bibliography is included.

Multiwavelength study of active galactic nuclei

The focus here is to understand the astrophysics of AGN whose emission is dominated by nonthermal synchrotron and Compton processes. These include radio galaxies and BL Lac objects, which are thought to be intrinsically similar objects viewed from different orientations with respect to a relativistically beamed jet. This research was led by Dr. Ronald Kollgaard and was largely based on the unique ROSAT All-Sky Survey (RASS) which produced a flux-limited catalog of 60,000 X-ray sources. To obtain new and unbiased samples of nonthermal AGN, radio emission was sought from large numbers of RASS sources using the Very Large Array radio telescope. Our first attempt was to study a 30 square degree region around the North Ecliptic Pole [9, 64, and forthcoming]. A heterogeneous mixture of quasars and radio galaxies were discovered, but few if any BL Lac objects. A more ambitious and successful effort was to isolate a well-defined sample of >100 BL Lacs from a study of 2,000+ RASS sources with 5 GHz fluxes above 20 mJy [31, 33, 39, 40, 47, 69, 84]. This sample includes many objects with properties intermediate between those of traditional radio-selected and X-ray selected BL Lacs, demonstrating that these are probably not distinct classes of AGN. We also conducted the first extensive studies of the large-scale radio emission from X-ray selected BL Lacs and demonstrated that they appear to be AGN viewed at orientations intermediate between radio galaxies and radio-selected BL Lacs [6, 18, 24, 43, 49, 60].

In addition to these projects, we conducted an unsuccessful search for extreme nonthermal with suppressed optical emission [16, 62], discovered the first (and only) convincing example of inverse Compton X-ray emission from a diffuse radio lobe [17, 61], participated in a number of multiwavelength campaigns to study BL Lac variability [14, 15, 27, 34, 35, 65] and in studies of X-ray properties of BL Lacs initiated by other researchers [7, 20,

25, 26, 28, 63, 70]. Dr. Kollgaard authored a major review on BL Lacs and unified AGN models [12].

Magnetic activity in young stellar objects

While star formation is generally viewed as a cold hydrodynamic phenomenon, we have been accumulating evidence that hot magnetohydrodynamical processes are present and may play important roles in star formation and early stellar evolution. Furthermore, surveys of nonthermal young stars reveals significant populations not noticed in optical and infrared surveys. Our biggest effort was devoted to characterizing the X-ray emitting population associated with the nearby Chamaeleon I star forming cloud. From about 80 ROSAT X-ray sources, we discovered over 40 new young stars and produced one of the most complete censuses of stars from a cloud [8, 11, 21, 56, 57]. Among the findings are: circumstellar disk lifetimes range over $10^5 - 10^7$ yrs; star formation efficiency of small clouds can exceed 20%; star formation can be continuous for about 20 Myr; and stellar censuses are still incomplete due to kinematic dispersal of young stars [8, 29, 78].

ROSAT and ASCA studies of other nearby star forming clouds revealed for the first time X-ray emission from some protostars with ages $\sim 10^5$ yr, compared to $10^6 - 10^7$ yrs for previously studied T Tauri stars [13, 22, 30, 32, 41]. The resulting photoionization of the circumstellar material may be important for accelerating bipolar outflows. Circularly polarized radio continuum emission associated with the X-ray flares is also detected in both older [1, 23, 38] and younger [5, 42, 79] young stellar objects. The energetic particles associated with this nonthermal emission may explain several mysteries found in the meteoritic record of the solar nebula [85]. We also conducted a multiwavelength campaign of a particularly active star [10, 59], discovered X-ray emitting young stars in distant star forming regions [36], and clarified the nature of several young stars near the Coalsack [37]. Dr. Feigelson and his colleagues presented several invited reviews on the subject [48, 55, 66, 68, 76] including a forthcoming *Annual Reviews* article.

Statistical methodology for astronomy

Observational astronomers face a vast range of difficult problems in data analysis and interpretation that sometimes require sophisticated statistical methods. A cross-disciplinary group at Penn State has specialized in bringing the expertise of leading statisticians to bear on astronomical problems. We organized two international conferences 'Statistical Challenges in Modern Astronomy' to discuss issues at the research level, and authored a monograph 'Astrostatistics' to introduce students and researchers to the issues [44, 45, 46]. We developed methods and codes for linear regression problems in astronomy, particularly important for cosmic distance scale applications [2, 3, 87]. We operate a statistical consulting center for astronomers [67], created a Web metasite linking astronomers to statistical computer codes [52, 88], and continue to develop and distribute our code for treatment of nondetections in astronomical surveys [50, 51, 86]. Dr. Feigelson was invited

to give reviews or remarks for a number of journals and conferences [4, 19, 53, 54, 71, 72, 73, 75, 77, 80, 81, 82, 83].

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Papers to be submitted in 1997:

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40. S. A. Laurent-Muehleisen, R. I. Kollgaard, E. D. Feigelson and W. Brinkmann, "A unified population of BL Lacertae objects",
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42. E. D. Feigelson, L. Carkner and B. Wilking, "Circularized polarized radio emission from a protostar"
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Invited or contributed conference proceedings & parts of books:

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Software Products:

86. "ASURV", 15,000 line Fortran code providing a suite of statistical methods for censored astronomical data (.e. with upper limits). Requested by 200 astronomers since 1990.
87. "SLOPES", 300-line Fortran code calculating six least-squares bivariate linear regressions. Requested by 100 astronomers since 1992.
88. "StatCodes", World Wide Web metasite with links to >200 on-line statistical codes for use by astronomers (1997).