

Boston University
Department of Astronomy
Boston, Massachusetts, 02215

[S0002-7537(90)03101-8]

This report provides a snapshot of the department and its affiliated research groups as of October 1999; it includes major changes since the 1996 report. The publications listed are representative recent references only. A full list of 1999 publications runs to 169 entries.

1. INTRODUCTION

The Department of Astronomy offers BA degrees in three fields, astronomy, astronomy and physics, and planetary and space sciences; the department also offers a combined BA/MA degree and a PhD in astronomy. There are currently 80 undergraduates and 26 graduate students enrolled in these programs. W. Jeffrey Hughes was appointed department Chair in September 1998. Ms. Elin Grimes is the departmental administrative assistant.

Research programs in the Boston University Astronomy Department are carried out primarily through the Center for Space Physics (CSP - Director, Supriya Chakrabarti) and the Institute for Astrophysical Research (IAR - Director, Dan Clemens). Research interests of members of the department range from terrestrial ionospheric and magnetospheric physics to the large-scale structure of the universe. Research facilities available to Boston University include the Perkins 1.83-meter telescope at Lowell Observatory and the Antarctic Sub-millimeter Telescope and Remote Observatory (AST/RO) at the South Pole.

1.1 Faculty

Jules Aarons, Research Professor (PhD, Paris) – *Magnetospheric physics, ionospheric physics*

Thomas Bania, Professor (PhD, Virginia) – *Galactic astronomy, interstellar medium*

Tereasa Brainerd, Assistant Professor (PhD, The Ohio State University) – *Theoretical astrophysics, cosmology, computational astrophysics, galaxy formation and evolution, gravitational lensing*

Kenneth Brecher, Professor (PhD, MIT) – *Theoretical high-energy astrophysics, relativity and cosmology*

Supriya Chakrabarti, Professor (PhD, Berkeley) – *Atmospheric and ionospheric physics, ISM, interplanetary medium*

Dan Clemens, Associate Professor (PhD, Massachusetts) – *Radio, infrared, and optical astronomy, interstellar medium, galactic structure, star formation*

Timothy Cook, Assistant Research Professor (PhD, Colorado) – *UV astrophysics*

Daniel Cotton, Assistant Research Professor (PhD, Berkeley) – *Space physics*

Nancy Crooker, Research Professor (PhD, UCLA) – *Experimental space physics*

Lynne Deutsch, Assistant Professor (PhD, Harvard) – *Star formation, interstellar medium, infrared astronomy and instrumentation*

Gary Erickson, Assistant Research Professor (PhD, Rice) – *Space plasma physics*

Eileen Friel, Adjunct Associate Professor (PhD, California) – *Star clusters and galactic astronomy, optical observational astronomy, photometry and spectroscopy*

Theodore Fritz, Professor (PhD, Iowa) – *Space plasma physics, magnetospheric physics, solar wind*

W. Jeffrey Hughes, Professor and Chairman (PhD, London) – *Magnetospheric physics*

James Jackson, Associate Professor (PhD, MIT) – *radio, infrared, and gamma-ray astronomy, interstellar medium, starburst galaxies, star formation*

Kenneth Janes, Professor (PhD, Yale) – *Galactic structure, photometry and spectroscopy*

Adair Lane, Adjunct Associate Professor (PhD, Massachusetts) – *Radio, infrared astronomy, star formation, astrophysical masers*

Alan Marscher, Professor (PhD, Virginia) – *Extragalactic astrophysics, quasars and active galaxies*

John Mattox, Associate Research Professor (PhD, Stanford) – *High energy astrophysics*

Michael Mendillo, Professor (PhD, Boston) – *Space physics, solar system astronomy*

Meers Oppenheim, Assistant Professor (PhD, Cornell) – *Computational and theoretical space plasma physics*

George Siscoe, Research Professor (PhD, MIT) – *Space physics*

Harlan Spence, Associate Professor (PhD, UCLA) – *Space physics, planetary magnetospheres and ionospheres*

1.2 Faculty Service and Awards

Aarons received the 1996 Appleton Lecturer award, and continues his affiliation with the IEEE as a senior fellow.

Bania is currently serving as Chairman of the Visiting Committee of the National Radio Astronomy Observatory. He is a Trustee of the Northeast Radio Observatory Corporation (NEROC) which operates Haystack Observatory and continues as one of the Harlow Shapley Lecturers of the American Astronomical Society.

Brecher continues as Director of the Boston University Science and Mathematics Education Center which focuses on the development of K - 12 and university level educational materials and software in science, mathematics, and technology. In 1999 he continued to serve a five-year term on the Editorial Committee of the Annual Reviews of Astronomy and Astrophysics.

Chakrabarti is the Director of CSP which focuses on space physics and planetary studies. This interdisciplinary unit spans the College of Arts and Sciences and the College of Engineering.

Crooker is a member of the Steering Committee for the SHINE (Solar and Heliospheric INterplanetary Environment) organization and convened their first stand-alone summer workshop in 1999. She currently is on the organizing committee of a series of three related international workshops.

Janes serves as a member of the Observatories Council (OC) of AURA. The OC acts as an oversight committee for the NOAO. Janes also serves on the AURA membership committee and as a member of the board of the Fund for Astrophysical Research.

Marscher served on the Radio and Submillimeter-wave Astronomy panel of the National Academy of Sciences Astronomy and Astrophysics Survey Committee. He serves as the secretary-treasurer of the High Energy Astrophysics Division of the American Astronomical Society, is on the editorial board of the *Blazar Data Journal*, and chairs the ad hoc Scientific Advisory Committee of the proposed ARISE space-VLBI mission. He also sat on the *Compton Gamma Ray Observatory Users Committee*.

Mendillo was selected to give the 1998 University Lecture, an annual award to honor members of the faculty engaged in outstanding research. The lecture, entitled ‘‘Through a Glass, Darkly – Searching for Extended Atmospheres of Planets, Moons and Comets,’’ was presented on 5 October 1998. He is currently serving as a member of the Committee on Planetary and Lunar Exploration (COMPLEX), the National Academy of Science advisory body for NASA’s program in solar system exploration.

Siscoe chairs the National Research Council’s Committee on Solar and Space Physics and the Steering Committee that oversees the construction of a Geospace General Circulation Model as part of the NSF-led Geospace Environment Modeling project (GEM). He is a member of the NOAA committee that advises and reviews the National Centers for Environmental Predictions.

Spence is currently a member of the NASA Magnetospheric Multiscale Mission Definition Team and the NASA Office of Space Science 1999 Roadmap Committee. Spence is chairing NASA’s Magnetospheric Constellation Science and Technology Definition Team.

1.3 Research Staff and Students

The CSP and IAR are well supported by many Research Associates: Jeffrey Baumgardner, Jiasheng Chen, Matthew Fox, Svetlana Marchenko, David Matthews, Ingo Mueller-Wodarg, John Noble, Harry Petschek, Duggirala Pallam Raju, Sheela Shodan-Shah, Robert Simon, Steven Smith, James Sullivan, James Vickers, Axel vom Endt, Georgios Vetoulis, Jody Wilson, and Hubble Fellow Simon Portegies Zwart.

Graduate students currently in the astronomy program include Mohamed Al-Othman, Yan Betremieux, Jyotirmoyee Bhattacharjya, Alberto Bolatto, Athanasios Boudouridis, Lars Dyrud, Dan Eldredge, Jessica Golub, Jeremy Hallum, Melissa Hayes-Gehrke, Maohai Huang, Marc Kassis, Michal Kolpak, Casey Law, Valerie Maher, Carlos Martinis, David Murr, William Pakula, Andrei Sokolov, Andrew Stephan, Sherri Stephan, Stephen Stonebraker, Lara Waldrop, Ann Walker, Kristen Wingfield, and Candace Wright.

Students receiving the PhD degree since 1996 include: Markos Georganopoulos, (Max Planck Institut fur Kernphysik, Heidelberg, Germany)

Karen Hirsch, (Postdoc, Los Alamos National Laboratory)

James G. Ingalls, (Postdoc, CalTech)

Anders Jorgensen, (Postdoc, Los Alamos National Laboratory)

Brian Kane

Redgie S. Lancaster, (Michigan)

Matthew L. Lister, (Jet Propulsion Laboratory)

John Noto, (Scientific Solutions, Inc.)

Eftyhia Zesta, (Postdoc, UCLA)

2. FACILITIES AND INSTRUMENTATION

2.1 AST/RO (Antarctic Submillimeter Telescope and Remote Observatory)

The exceptionally cold and dry atmosphere over the geographic South Pole make it the best observing site on Earth at submillimeter wavelengths. In collaboration with the Harvard-Smithsonian Center for Astrophysics, Boston University operates a 1.7 meter aperture submm-wave telescope at the NSF Amundsen-Scott South Pole Station. The AST/RO instrument was fabricated at the Scientific Instrument Facility at Boston University and tested extensively during the Winter of 1993-94 at an on-campus Test Site. AST/RO was installed during the 1994-95 Austral summer and is now beginning its seventh season of operation.

The AST/RO project is part of the Center for Astrophysical Research in Antarctica (CARA) NSF sponsored Science and Technology Center. Direct monitoring of the atmospheric opacity at the South Pole for over a seven year period has now proved without question that the South Pole is unique in offering a nearly transparent sky at wavelengths greater than 300 μm essentially all the time, allowing extensive low-noise observations which are unobtainable elsewhere from the ground.

AST/RO is a general purpose submm-wave telescope, ideal for large-scale studies of galactic structure. It has a 100 arcsec resolution at 600 microns with high beam efficiency and is highly automated. The AST/RO group is making CI and CO surveys of selected regions such as the galactic center, the Magellanic Clouds, portions of the fourth quadrant of the Galaxy, and particular high latitude regions.

2.2 Boston University – Lowell Observatory Partnership

Boston University and Lowell Observatory joined in a partnership in August 1998 to operate the 1.83-meter Perkins Telescope on Anderson Mesa, 15 miles south of Flagstaff, AZ. Each institution has one-half the nights for the use of their respective staffs. The telescope, now owned by Lowell, has been well-maintained and thoroughly modernized. It is currently being re-instrumented with state-of-the-art infrared and optical instrumentation (see the following section on Instrumentation). BU and Lowell Observatory have embarked on an image-improvement program, with a goal of reaching a median seeing below one arcsecond; testing on the Anderson Mesa site indicates that this is an achievable goal.

Boston University Research Associate John Noble resides in Flagstaff and acts as a “friend of the telescope,” helping observers as they come to the telescope, supervising the image improvement program, and conducting his own blazar research.

2.3 AIRO

Jackson leads the effort to build a new infrared observatory, the Antarctic Infrared Observatory (AIRO), at the South Pole. Due to the extreme cold at the South Pole (-50 C), the thermal background is extremely low, and even a small telescope there will have excellent sensitivity. AIRO is a proposed 1.8 meter telescope combined with a three-color (K,L, and M) InSb camera that will perform wide-field imaging in the thermal infrared. AIRO will be automated, thoroughly field-tested, and available to the user community. Team members include Boston University, Rochester Institute of Technology, Lowell Observatory, National Optical Astronomy Observatories, and University of New South Wales.

2.4 Ground-based Instrumentation Programs

2.4.1 SPIFI

Along with PI Gordon Stacey of Cornell, Jackson and graduate student Bolatto have worked on a new instrument called SPIFI, the South Pole Imaging Fabry-Perot Interferometer. SPIFI is a 25 element submillimeter bolometer array coupled with a Fabry-Perot interferometer for imaging spectral lines in the 370 micron window. SPIFI saw first light in April 1999 at the JCMT, and will eventually be deployed to the AST/RO telescope at the South Pole.

2.4.2 MIRABU

Deutsch is PI of MIRABU (Mid-InfraRed Array for Boston University), currently under construction at Boston University. MIRABU is a mid-infrared camera system with both spectroscopic and imaging capabilities that will penetrate the dusty environments around very young and very old stars to study the process of stellar evolution.

The system is based on a new 320 x 240 Si:As IBC array that will be liquid-helium cooled during operation. The camera will offer a large field of view (1.6 arcmin x 1.2 arcmin), diffraction-limited spatial resolution (subarcsecond resolution in the 10 micron window), complete spectral coverage over the 8-14 micron and 17-26 micron atmospheric windows for both imaging and spectroscopy, and high sensitivity.

The camera development effort is also supported by co-PI J.L. Hora (SAO) and Boston University graduate student M. Kassis. First light for MIRABU is anticipated for the summer of 2000.

2.4.3 MIMIR

Clemens, Janes, Deutsch, and graduate student Dan Eldredge have begun design work on Mimir, an infrared imaging spectrograph, being jointly developed with Lowell Observatory and destined for use on the Perkins telescope. This instrument will operate across the 1-5 micron band with direct imaging, low- and moderate-resolution spectroscopy,

and polarimetry. It features a large-format InSb infrared detector array and a modern grism-based spectrograph design.

2.4.4 PRISM

Planning has begun for the Perkins ReImaging System (PRISM), to enable wide-field imaging, polarimetry and multi-object spectroscopy at the Perkins telescope. PRISM will reimage the f/17.5 focus of the telescope down to an f/6.6 beam, yielding a 13.65 arc-minute square field of view on an existing SITe 2048² CCD detector. PRISM will have a modular construction for maximum flexibility of operation. Removable units will permit insertion of focal plane masks of arbitrary configuration at the first (cassagrain) focus and multiple units for filters, grism, and polarimetry units near the pupil plane, in the collimated beam. All optics will be uv-transmitting.

2.5 Satellite Missions

2.5.1 TERRIERS

The Boston University satellite TERRIERS, part of the Student Explorer Demonstration Initiative (STEDI), was launched aboard a Pegasus booster. Unfortunately, because of an error in the attitude control system, its solar panel was pointed away from the Sun. As a result, five years of instrument development effort by BU researchers (Cotton, Cook, Chakrabarti, Vickers, Stephan and Taylor) ended with a satellite having nominal performance in all area except for one critical subsystem.

2.5.2 M4

Clemens and an international team continue to develop their concept for a NASA Small Explorer Mission. The “Milky Way Magnetic Field Mapping Mission” or M4, would perform the first ever survey of magnetic fields in the star forming interstellar medium of the galaxy, nearby molecular clouds, infrared cirrus clouds, and nearby galaxies. The team looks forward to the SMEX selection in mid-2000.

2.5.3 Constellation Pathfinder

As a result of the foundation-building MMM paper study (see section 4.3.2), BU researchers are now moving forward from mission concept to full mission design and launch of a prototype nanosatellite. This is being accomplished through the Constellation Pathfinder component of the University Nanosatellite Program, jointly funded by the USAF, DARPA, NASA, and USRA. Spence and Petschek are co-PIs of Constellation Pathfinder (CP). CP was one of five missions selected under this program. The objective of the Constellation Pathfinder program is to demonstrate the feasibility of fabricating and launching one to three, 1 kg satellites that are capable of collecting and returning quality scientific and engineering data for one to four or more months. The hardware demonstration of building and flying such a satellite, or small suite of satellites, will provide a proof of principle for many scientific and strategic applications where a fleet of coordinated small satellites is required. A website devoted to this project can be found at <http://buspace.bu.edu/EPG/spence/MMM>.

2.6 Sounding Rocket Program

2.6.1 SPINR - UV spectral imaging

The SPINR (Spectrograph for Photometric Imaging w/ Numeric Reconstruction) sounding rocket (Cook, Taylor and Chakrabarti) is a simple and efficient instrument to record the spectrum of a wide field while imaging in the cross dispersion direction. The system uses a tomographic imaging method to record and measure a full three dimensional data cube (e.g. RA, Dec, and wavelength) which can be used to study the spectrum of multiple objects in the field as well as the spectral properties and morphology of the diffuse ISM.

Our SPINR observations are designed to measure the albedo and phase function of dust in reflection nebulae. Reflection nebulae are excellent laboratories for these measurements because the bright emission allows for high signal to noise measurements even in the relatively brief duration of a sounding rocket flight. Interpreting the data can be somewhat complicated by the details of the scattering geometry but this is more than compensated for by the higher signal to noise.

2.6.2 SCARI: UV Interferometric spectroscopy

An interferometric spectrometer for use at wavelengths as short as 121.6nm, the Self Compensating All Reflection Interferometer (SCARI) has been developed and flown. SCARI has been used for high spectral resolution measurements of Lyman Alpha emission. Like SPINR, this system has successfully flown aboard a sounding rocket and is ready for a follow up flight. SCARI is a high resolution interferometric spectrometer with limited imaging capability in the cross dispersion direction. It observes a 0.4×2 degree elliptical field of view with a theoretical resolution of $R=120,000$.

2.6.3 SPECTRE: Student Launch Program

The Student-run Project for Exo-atmospheric Collecting Technologies and Rocket Experiment (SPECTRE), is a low budget (\$35,000 total!), student built sounding rocket payload. The proposal was developed by five students as a "homework assignment" for a first year class (Astronomy from Space) taught by Chakrabarti. The primary goal of SPECTRE is education. The idea is to do a physics lab experiment from a rocket. The students chose to find the atmospheric composition variations, by measuring the absorption of X-ray, UV and visible emissions from the Sun. To date, the project has involved over 60 undergraduate students who were responsible for the electrical and mechanical systems of the rocket payload. They worked under supervision from Taylor, Chakrabarti and faculty from the College of engineering. The project has been completely built up and tested at Wallops Flight Facility. It was ready for launch in early September, 1999. After three failed launch attempts, due to range clearance problems, it was decided to wait for a better launch window in the late spring/early summer of 2000.

2.6.4 BRITE: Ionospheric UV tomography

The U. S. Air Force conducted a sounding rocket experiment from Kodiak Island in September, 1999. It carried an UV imaging spectrograph developed by Cotton, Cook, Maher, Vickers, Taylor and Chakrabarti. The instrument was

pointed in the plane of rocket trajectory and by spinning the rocket, the field of view covered 360 deg zenith angle. The data obtained from this rocket will be used to infer ionospheric density in altitude and rocket trajectory plane.

PUBLICATIONS

Chakrabarti, S., "Students design, build and operate satellite for space physics mission," 1998, *Earth in Space*, 10, 6.

Kamalabadi, F., Karl, W.C., Semeter, J.L., **Cotton, D.M.**, **Cook, T.A.**, and **Chakrabarti, S.**, "A statistical framework for space-based EUV ionospheric tomography," 1999, *Radio Science*, 34, 437.

3. INSTITUTE FOR ASTROPHYSICAL RESEARCH (IAR)

The IAR was chartered by the University in January 1999, to promote the development of astrophysical research enterprises at Boston University and our remote sites. The first director of the IAR is Dan Clemens. The IAR includes eight faculty (Bania, Brainerd, Clemens, Deutsch, Jackson, Marscher, and Mattox), four research associates, and graduate as well as many undergraduate students. Ms. Kimberly Paci provides administrative assistance. The IAR coordinates and facilitates astrophysics research at BU, oversees external observatories for BU, and promotes instrument development.

3.1 Interstellar Medium Studies

3.1.1 Helium 3

Bania, D. Balser (NRAO), and R. Rood (UVa) continued their studies of the abundance of 3-Helium in the interstellar medium. They have now made spectral line and continuum observations of a sample of 60 Galactic HII regions and planetary nebulae at 3.46 cm wavelength during the past 17 years as part of a program to measure the abundance of ^3He in the Milky Way interstellar medium. Determining the ^3He abundance requires not only accurate measurements but also realistic models for the ionization and density structure of the sources. The observations needed to model their sources are made with the NRAO 140 Foot, NRAO VLA, and MPIfR 100 m telescopes. When combined with other light element abundances these measurements of the ^3He abundance begin to either challenge Standard Big Bang Nucleosynthesis (BBNS) models or call into question some of the standard assumptions concerning the chemical evolution of ^3He .

3.1.2 High Galactic Latitude Clouds

Using the AST/RO South Pole telescope, Ingalls and Bania studied the atomic/molecular interfaces in high latitude galactic clouds (HLCs) using the CO molecule and the 492 GHz [C I] fine-structure transition of atomic carbon. A study of the lowest four rotational transitions of CO made toward HLCs shows that the emission from all observed CO transitions is linearly correlated. This implies that the excitation conditions which lead to emission in these transitions are uniform throughout the clouds. They have developed a statistical method to compare the observed line ratios with models of CO excitation and radiative transfer. They find that the

most probable models are those with the CO gas in a high density ($10^{4.5}$ cm⁻³) and low temperature (8 K) state with the CO in small, 0.01pc, cells. These cells are thus tiny fragments within the 100 times larger CO-emitting extent of a typical high-latitude cloud.

3.1.3 CI in HII regions

Graduate student Huang and Bania have studied CI emission from a sample of 49 southern hemisphere HII regions using AST/RO. The sources are compact, isolated HII regions whose LSR velocities are known from hydrogen radio recombination line measurements. CI emission was detected toward all of the HII regions, with multiple CI emission components found toward most sources. Analysis shows that all HII regions have associated CI emission and that CI emission from HII regions is brighter than CI emission not associated with HII regions. This suggests that the CI intensity is dominated by local heating.

PUBLICATIONS

- Balser, D.S., Rood, R.T., & **Bania, T.M.** “The 3-He Abundance in the Planetary Nebula NGC 3242,” 1999, *ApJ*, 522, L73.
- Bolatto, A.D.**, Balm, S., **Bania, T.M.**, Chamberlin, R.A., **Huang, M.**, Ingalls, J.G., **Jackson, J.M.**, **Lane, A.P.** & Stark, A.A. “Neutral Carbon in the Magellanic Clouds: Probing the Metal-Poor Interstellar Medium,” 1998, in “Astrophysics from Antarctica,” A.S.P. Conf. Ser., ed. G. Novak & R. Landsberg (San Francisco: A.S.P.), 141, 196.
- Bolatto, A.D.**, **Jackson, J.M.**, and Ingalls, J.G., “A Semi-analytical Model for the Observational Properties of the Dominant Carbon Species at Different Metallicities,” 1999, *ApJ*, 513, 275.
- Clemens, D.**, **Jackson, J.**, **Bania, T.**, & Heyer, H. “Galactic Star Formation and Galactic Structure: The BU-FCRAO Milky Way Galactic Ring Survey (GRS),” 1999, in “Infrared Astrophysics with Surveys: A Prelude to SIRTf,” ASP Conference Series, ed. M. Bica, C.A. Beichman, R.M. Cutri, & B.F. Madore (San Francisco: ASP), 177, 340.
- Huang, M.**, Baum, S.P., **Bania, T.M.**, **Bolatto, A.**, Chamberlin, R.A., Ingalls, J.G., **Jackson, J.M.**, **Lane, A.P.**, Rumitz, M.R., Stark, A.A., & Wilson, R.W. “Atomic Carbon in Galactic H II Regions,” 1998, in “Astrophysics from Antarctica,” A.S.P. Conf. Ser., ed. G. Novak & R.H. Landsberg (San Francisco: A.S.P.), 141, 192.
- Ingalls, J.G., **Bania, T.M.**, Chamberlin, R.A., **Jackson, J.M.**, **Lane, A.P.**, Rumitz, M.R. & Stark, A.A. “AST/RO Observations of Southern Hemisphere High-Latitude Clouds,” 1998, in “Astrophysics from Antarctica,” A.S.P. Conf. Ser., ed. G. Novak & R. Landsberg (San Francisco: A.S.P.), 141, 200.
- Jackson, J.M.**, and **Kraemer, K.E.**, “Photodissociation Regions and H II Regions in NGC 6334,” 1999, *ApJ*, 512, 260.
- Jackson, J.M.**, **Lane, A.P.**, Stark, A.A., & **Bania, T.M.**, “AST/RO Observations of Neutral Atomic Carbon,”

1998, in “Astrophysics from Antarctica,” A.S.P. Conf. Ser., ed. G. Novak & R. Landsberg (San Francisco: A.S.P.), 141, 146.

- Kraemer, K.E.**, **Deutsch, L.K.**, **Jackson, J.M.**, Hora, J.L., Fazio, G.G., Hoffman, W.F., Dayal, A., “The Mid-Infrared Properties of Three Star-forming Sites in NGC 6334,” 1999, *ApJ*, 513, 275.
- Kraemer, K.E.**, **Jackson, J.M.**, and **Lane, A.P.**, “[O I] 63 μ m Absorption in NGC 6334,” 1998, *ApJ*, 503, 785.
- Paglione, T.A.D., **Jackson, J.M.**, **Bolatto, A.D.**, & Heyer, M.H., “Interpreting the HCN/CO Intensity Ratio in the Galactic Center,” 1998, *ApJ*, 493, 680.
- Rood, R. T., **Bania, T. M.**, Balser, D. S., & Wilson, T. L. “3-Helium: Status and Prospects,” 1998, in “Primordial Nuclei and Their Galactic Evolution,” Space Science Series of ISSI, eds. N. Prantzos, M. Tosi, & R. von Steiger (Kluwer: Dordrecht), 4, 185–198.
- Wilson, T.L., Rood, R.T., **Bania, T.M.**, & Balser, D. “Isotope Ratios in the Interstellar Medium,” 1999, in “Nuclei in the Cosmos V,” eds. N. Prantzos & S. Harissopulos (Editions Frontieres: Gif-sur-Yvette) 10–16.

3.2 Star Formation and Stellar Evolution

3.2.1 Star-forming Sites

Clemens and Professor J. Yun (University of Lisbon) are completing a large catalog of infrared selected star forming sites in the Milky Way. They performed HIRES calculations on IRAS data to develop the best far-infrared images for over 4,000 regions. Evaluation of these images to establish which are bona fide star formation sites will be completed this year.

3.2.2 Bok Globules

Clemens is using the Perkins telescope to measure distances to star forming and starless small Bok globules, refining the photometric technique developed by Peterson & Clemens (1998). The globules under study include many of those already examined using ISO and those studied polarimetrically by Kane for his BU PhD. Clemens and former graduate student Andrew Byrne have completed a deep search for low-mass stars in small Bok globules using the Infrared Space Observatory (ISO). This study aimed to probe for star formation far below the sensitivity level of IRAS. Many globules were thus certified to be star-free to nearly the hydrogen burning limit. A few globules were found to contain stars, and at least one globule may harbor a cluster of low-mass young stars.

3.2.3 Mid-Infrared Studies

Deutsch, graduate student M. Kassis, former graduate student N. Smith, and the University of Arizona/Smithsonian Astrophysical Observatory Mid-Infrared Array Camera (MIRAC) team obtained multiwavelength (8-20 micron) images of the star-forming OMC-1 cloud core in Orion. They detected a subset of previously identified proplyds in the Trapezium region along with two new infrared sources. The Ney-Allen nebula was found to exhibit a ring or toroidal structure at the longest wavelengths as an extension to its familiar crescent shape. The BN/KL complex appeared as an

extended, butterfly-shaped structure with significant bipolar symmetry which is bifurcated by a dust lane at the longer wavelengths. IRC3, 4, and 5 gave the appearance of a ring-like structure with a possible jet-like protrusion from its center along a line from IRC2. Derived color temperature and dust opacity maps suggest that IRC3, 4, and 5 may not be self-luminous objects as previously thought. Deutsch, M.F. Campbell (Colby College), C.A. Garland (Colby College), and the MIRAC team have imaged and modelled the infrared emission from the star-forming HII complex G34.26+0.15. Several ultracompact (UC) and extended HII regions were detected, and two new sources were discovered at 20.6 microns. Deep silicate absorption is seen at 9.7 microns but no hydrocarbon emission features were detected. Their color temperature and dust opacity maps show that the source G34C is a centrally-heated dust cloud in the ultracompact HII region. Deutsch, M. Kassis, undergraduate L. Williams, and the MIRAC team have undertaken a study of temporal variability of Herbig Ae/Be stars in the mid-infrared. The current study looks specifically for changes in hydrocarbon emission features which are only seen in the near- and mid-infrared. Results so far indicate that not only may this emission vary on short (one year) timescales, but the location of the emission may also change with time. Understanding the processes which can produce substantial changes in the output of young stars on relatively short timescales is an important step toward understanding this stage of pre-main-sequence evolution and the overall star formation process.

3.2.4 Galactic Ring Survey

Jackson leads the Galactic Ring Survey (GRS), a new molecular line survey of the inner Milky Way Galaxy, using the FCRAO 14.7 meter radio telescope and its new 16-element SEQUOIA array receiver. This survey uses the ^{13}CO 1-0 line, a more optically thin tracer of molecular gas than ^{12}CO . To date 6 square degrees of the Galactic plane have been mapped between 40.5 and 46.5 degrees of Galactic longitude and -0.5 and 0.5 degrees of Galactic latitude. The GRS will compile a catalog of molecular clouds, map the structure of the Milky Way, and associate star-forming infrared sources with molecular clouds. The plan is to map 50 degrees along the Galactic plane to study the 5 kpc ring, the dominant star-forming structure in the Galaxy.

3.2.5 Star Clusters

Janes, working with graduate student M. Hayes-Gehrke, is conducting a comprehensive study of a selection of the oldest open clusters in the galaxy, using the 1.83-meter Perkins telescope and the 1-meter Illinois telescope at the Mt. Laguna Observatory. The primary goals of the project are to derive definitive color-magnitude diagrams for the selection of clusters, tied precisely to the same photometric system so that reliable (relative) cluster ages can be determined, and to monitor the cluster members for microvariability. The monitoring program should uncover a variety of phenomena – low amplitude fluctuations from close, but not quite eclipsing binaries; stellar activity cycles and possibly even transits by brown-dwarf or planetary companions. Some 50 nights of data now exist and are being processed. Janes is working

with J. Heasley (University of Hawaii) and R. Zinn (Yale University) to determine the relative ages of globular clusters near the galactic center. Hubble Space Telescope images were acquired with the WFPC camera, covering the central area of several metal-rich and metal-poor clusters. The group finds that the color-magnitude diagrams of two of the metal-rich clusters, NGC 6637 and NGC 6624, are indistinguishable from one another. The two clusters also appear to be virtually identical to 47 Tuc and M71. These data support the idea that a short burst of star formation in the early days of the galaxy produced many, if not most of the globular clusters.

PUBLICATIONS

- Afonso, J. M., Yun, J.L., & **Clemens, D.P.**, “HCN in Bok Globules: A Good Tracer of Collapsing Cores,” 1998, *AJ*, 115, 1111.
- Ciardi, D. R., Woodward, C. E., **Clemens, D. P.**, Harker, D. E., & Rudy, R. J. “Understanding the Star Formation Process in the Filamentary Dark Cloud GF-9: Near-Infrared Observations,” 1998, *AJ*, 116, 349.
- Clemens, D.**, Byrne, A., Yun, J. L., & Kane, B. D., “ISO Observations of Starless Bok Globules: Usually No Embedded Stars,” 1998, in *Star Formation with the Infrared Space Observatory*, ASP Conference Series Vol. 132, ed. J.L. Yun and R. Liseau (San Francisco: ASP), p. 334.
- Clemens, D., Jackson, J., Bania, T., & Heyer, H.**, “Galactic Star Formation and Galactic Structure: The BUFCRAO Milky Way Galactic Ring Survey (GRS),” 1998, in *Infrared Astrophysics with Surveys: A Prelude to SIRTIF*, ASP Conference Series Vol. 177, ed. M. D. Bica, C. A. Beichman, R. M. Cutri, and B. F. Madore (San Francisco: ASP), p. 340.
- Dayal, A., Hoffmann, W.F., Biegging, J.H., Hora, J.L., **Deutsch, L.K.**, and Fazio, G.G. “Mid-Infrared (8-21 micron) Imaging of Proto-Planetary Nebulae,” 1998, *ApJ*, 492, 603.
- Fernandez, Y.R., A’Hearn, M.F., Lisse, C.M., Ressler, M.J., Dayal, A., Hanner, M.S., Meech, K.J., Bauer, J.M., Hoffmann, W.F., **Deutsch, L.K.**, Fazio, G.G., Hora, J.L. “Survey of the Physical Properties of Cometary Nuclei: Recent Progress,” 1998, *Comet Nuclei*, ed. M.F. A’Hearn, IAU Colloquium No. 168, ASP Conference Series, 145.
- Fernley, J., Skillen, I., Carney, B.W., Cacciari, C. and **Janes, K.**, “The slope of the RR Lyrae M_V -(Fe/H) relation,” 1998, *MNRAS*, 293, L61.
- Hoffmann, W.F., Hora, J.L., Fazio, G.G., **Deutsch, L.K.**, and Dayal, A. “MIRAC2, A Mid-Infrared Array Camera for Astronomy,” 1998, in *Infrared Astronomical Instrumentation*, ed. A. M. Fowler, Proc. SPIE 3354, 647.
- Hora, J.L., Latter, W.B., and **Deutsch, L.K.** “Investigating the Near-Infrared Properties of Planetary Nebulae: II. Medium Resolution Spectra,” 1999, *ApJS*, 124, 195.
- Keto, E., Hora, J.L., Fazio, G.G., Hoffmann, W.F., and **Deutsch, L.K.** “A Super Star Cluster in NGC253: Mid-IR Properties,” 1999, *ApJ*, 518, 183.
- Kraemer, K.E., Deutsch, L.K., Jackson, J.M.,** Hora, J.L., Fazio, G.G., Hoffmann, W.F., and Dayal, A. “The Mid-

- Infrared Properties of Three Star Forming Sites in NGC 6334,” 1999, ApJ, 516, 817.
- Lunhardt, R., Evans, N. J. II, Wang, Y., **Clemens, D. P.**, Henning, Th., & Yun, J. L., “Survey of CS Emission in Bok Globules,” 1998, ApJS, 119, 59.
- Lisse, C.M., Fernandez, Y.R., Kundu, A., A’Hearn, M.F., Dayal, A., **Deutsch, L.K.**, Fazio, G.G., Hora, J.L., and Hoffmann, W.F. “The Nucleus of Comet Hyakutake,” 1999, Icarus, 140, 189.
- Meixner, M., Ueta, T., Dayal, A., Hora, J.L., Fazio, G.G., Bobrowsky, M., Hrivnak, B.J., Skinner, C.J., Hoffmann, W.F., and **Deutsch, L.K.** “The Morphology of Proto-Planetary Nebulae Dustshells,” 1998, Asymptotic Giant Branch Stars, IAU Symposium 191, 515.
- Meixner, M., Ueta, T., Dayal, A., Hora, J.L., Fazio, G.G., Hrivnak, B.J., Skinner, C.J., Hoffmann, W.F., and **Deutsch, L.K.** “A Mid-Infrared Imaging Survey of Proto-Planetary Nebulae,” 1999, ApJS, 122, 221.
- Peterson, D.E., & **Clemens, D. P.**, “Photometric Distances to Dark Clouds: CB24,” 1998, AJ, 116, 881.
- Yun, J. L., Moreira, M. C., Afonso, J. M., & **Clemens, D. P.** “HCN in cloud cores: a good tracer of collapse and Class 0 Young Stellar Objects,” 1999, AJ, 118, 990.

3.3 Extragalactic Astronomy

3.3.1 Lensing, Large-scale Structure

Brainerd continued her research in the fields of weak gravitational lensing, cosmological N-body simulations, and the intrinsic clustering of faint galaxies. Together with her collaborators D. M. Goldberg (Princeton Univ.) and J. V. Villumsen, she investigated the formation history of rich clusters of galaxies using extremely high resolution N-body simulations. These simulations were also used by Brainerd and her collaborators C. O. Wright (BU), D. M. Goldberg, and J. V. Villumsen, to assess the accuracy of a number of simple cluster mass estimators, including weak lensing and virial mass estimates. Additionally, Brainerd and I. Smail (Univ. of Durham) measured the angular clustering of faint galaxies and used the measurement to constrain the redshift distribution of the galaxies in samples with limiting magnitudes of $I \sim 25$. From July 25 to July 30, 1999, Boston University hosted “Gravitational Lensing: Recent Progress & Future Goals,” an international conference which was attended by nearly 200 astronomers. The format consisted of invited reviews, “targeted talks,” contributed talks, and contributed posters; virtually all aspects of current gravitational lensing research were represented at the conference. Proceedings of the conference will be edited by Brainerd and C. S. Kochanek (SAO) and will be published by the Astronomical Society of the Pacific in spring 2000.

3.3.2 Astrophysical Jets

Marscher continues to collaborate with J.L. Gómez (Inst. de Astrofísica de Andalucía) and J.M. Martí and J.M. Ibáñez (U. Valencia) on a project that simulates time-variable relativistic jets using relativistic hydrodynamics. They find that a single perturbation in the flow (a higher Lorentz factor over a short time) causes the appearance of several knots moving at different superluminal speeds, as well as stationary com-

ponents. This agrees very well with high-frequency VLBI observations of 3C 120 [in collaboration with Gómez, Marchenko, and A. Alberdi (IAA)]. Georganopoulos and Marscher explained the range of properties of BL Lac objects through a combination of the effects of viewing angle and a distribution of magnetic fields among different objects. Lister and Marscher investigated the statistics of relativistically beamed flat-spectrum radio sources. When one takes into account the luminosity function and other effects, the observed distributions of redshift, apparent velocity, and other observed parameters, are reproduced for models in which low bulk Lorentz factors are more prevalent than high ones. The Lorentz factor can be either independent of or correlated with the luminosity, but cannot be anti-correlated.

3.3.3 Blazar Variability

Marscher, Marchenko, and collaborators Gómez, I. McHardy (U. Southampton), and M. Aller (U. Michigan) are carrying out a long-term project to monitor the X-ray (with the *Rossi* X-ray Timing Explorer), optical (with the Perkins Telescope at Lowell Observatory), and radio emission of several blazars. The quasar PKS 1510 – 089 shows coincident radio and X-ray flares, with the radio leading the X-ray. In 3C 120, a few-week X-ray dip occurred shortly before a major radio outburst that created a complex of superluminal components. Further observations will determine whether this was merely a coincidence or a major clue on how changes in accretion onto the supermassive black hole relate to energetic events in the relativistic jets. Marscher and Marchenko are collaborating with J. Stevens (Mullard Space Science Laboratory), W. Gear (U. Cardiff), T. Cawthorne and A. Stirling (U. Central Lancashire), Lister, Gómez, and others to monitor the polarization of 15 blazars and blazar-like radio galaxies with the James Clerk Maxwell Telescope at 230 GHz and the VLBA at 43 GHz. Thus far, they find a surprisingly close connection between the 230 GHz polarization and that of either the core or the strongest superluminal component in the majority of sources. The 230 GHz polarization is in some cases much stronger than at 43 GHz, suggesting that the higher frequency emission comes from the same general region, but only in localized sites, relative to that at 43 GHz. Marchenko and her collaborators at the Astronomical Institute of St.Petersburg State University continue their investigation of the timescales and physical mechanisms of optical and IR variability of blazars. Comparison of the 1994 outburst of the BL Lac object OJ 287 with those of 1971 and 1983 shows that there is a clear correlation between the power of an outburst and the spectral energy distribution of the variable component in each event. The higher the amplitude of the outburst, the bluer is the variable component, i.e. in more powerful outbursts the energy spectrum of relativistic electrons is flatter. Mattox continues his study of the blazar class of AGN, augmenting gamma-ray studies with optical studies of variability using the Perkins Telescope at Lowell Observatory. In addition, he is developing plans for a network of automatic telescopes to study blazars and gamma-ray bursts, and to execute other scientific and educational programs; see <http://gamma.bu.edu/atn/>.

PUBLICATIONS

- Alberdi, A., Gómez, J.L., Marcaide, J.M., **Marscher, A.P.**, and Pérez-Torres, M.A. “The Parsec Scale Radio Jet of 4C 39.25: Witnessing the Interaction between a Superluminal and a Stationary Component,” 1999, in *The BL Lac Phenomenon*, ed. L. Takalo and A. Sillanpää, ASP Conf. Ser., 159, 452
- Aller, M.F., **Marscher, A.P.**, *et al.* “Radio to γ -Ray Observations of 3C 454.3: 1993–1995,” 1998, in *Proceedings of the Fourth Compton Symposium*, ed. C.D. Dermer, M.S. Strickman, and J.D. Kurfess, AIP Conf. Proc., 410, 1423.
- Bloom, S.D., **Marscher, A.P.**, Gear, W.K., Moore, E.M., Teräsanta, H., Valtaoja, E., Aller, H.D., and Aller, M.F. “Multiwaveband Observations of Quasars with Flat Radio Spectra and Strong Millimeter-Wave Emission,” 1999, *ApJ Supp*, 122, 1.
- Brainerd, T. G., Wright, C. O.**, Goldberg, D. M., & Villumsen, J. V., “A Comparison of Simple Mass Estimators for Galaxy Clusters,” 1999, *ApJ*, 524, 9.
- Brainerd, T. G.**, Goldberg, D. M., & Villumsen, J. V., “High-Resolution Simulations of Cluster Formation,” 1999, *ApJ*, 502, 505.
- Brainerd, T. G.** & Smail, I., “A Constant Clustering Amplitude for Faint Galaxies?,” 1998, *ApJ*, 494, L137.
- Georganopoulos, M., and **Marscher, A.P.** “A Viewing Angle–Kinetic Luminosity Unification Scheme for BL Lacertae Objects,” 1998, *ApJ*, 506, 621.
- Gómez, J.L., **Marscher, A.P.**, and Alberdi, A. “86, 43 and 22 GHz VLBI Observations of 3C 120,” 1999, *ApJL*, 521, L29.
- Gómez, J.L., **Marscher, A.P.**, Alberdi, A., and Gabuzda, D. C. “The Twisted Parsec-Scale Structure of 0735+178,” 1999, *ApJ*, 519, 642.
- Gómez, J.L., **Marscher, A.P.**, Alberdi, A., Martí, J.M., and Ibáñez, J.M. “Subparsec Polarimetric Radio Observations of 3C 120: A Close-Up Look at Superluminal Motion,” 1998, *ApJ*, 499, 221.
- Gómez, J.L., **Marscher, A.P.**, Alberdi, A., Martí, J.M., Ibáñez, J.M., and **Marchenko, S.G.** “A Close-Up Look at Superluminal Motion: Subparsec Radio Observations of 3C 120 and its Comparison with Numerical Simulations,” 1999, in *The BL Lac Phenomenon*, ed. L. Takalo and A. Sillanpää, ASP Conf. Ser. 159, 435.
- Gómez, J.L., **Marscher, A.P.**, and Alberdi, A. “Polarized Structural Outburst in 3C 454.3,” 1999, *ApJ*, 522, 74.
- Gómez, J.L., Martí, J.M., **Marscher, A.P.**, Ibáñez, J.M., and Alberdi, A. “Hydrodynamical Models of Superluminal Sources,” 1998, in *Astrophysical Jets: Open Problems*, ed. S. Massaglia and G. Bodo (Amsterdam: Gordon and Breach), 95.
- Hagen-Thorn, V.A., **Marchenko, S.G.**, Takalo, L.O., Sillanpää, and Pursimo, T. “Analysis of the Colour Variations of 3C 66A in the Optical Region during 1993–1997,” 1999, in *The BL Lac Phenomenon*, ed. L. Takalo and A. Sillanpää, ASP Conf. Ser., 159, 111.
- Hagen-Thorn V.A., **Marchenko, S.G.**, Takalo L.O., Sillanpää A., Pursimo T., Kidger M., and Gonzalez-Perez J.N. “Analysis of the colour variations of 3C 66A in Optical-IR region during 1993-1995,” 1998, in *Multifrequency Monitoring of Blazars*, Publ. Osservatorio Astronomico Università di Perugia, ed. G. Tosti and L. Takalo, 3, 17.
- Hagen-Thorn, V.A., **Marchenko, S.G.**, Takalo L.O., Sillanpää, A., Pursimo, T., Boltwood, P., Kidger, M., and Gonzalez-Perez, J.N. 1998, “The Variable Sources Responsible for the Photometric Behavior of OJ 287 in the IR–Optical–UV Region during 1993–1996,” *Astronomy and Astrophysics Suppl.*, 133, 353.
- Kataoka, J., **Mattox, J.R.**, Quinn, J., *et al.*, “A Study of High Energy Emission from the TeV blazar Mrk 501 during Multiwavelength Observations in 1996,” 1999, *ApJ*, 514, 138.
- Lister, M.L., **Marscher, A.P.**, and Gear, W.K. “Submilliarsecond Polarimetric Imaging of Blazar Jets at 43 GHz,” 1998, *ApJ*, 504, 702.
- Lister, M.L., and **Marscher, A.P.** “Predictions of ECS and SSC Models for Flux-Limited Samples of γ -Ray Blazars,” 1999, *Astroparticle Physics*, 11, 65.
- Marchenko, S.G., Marscher, A.P., Mattox, J.R.**, Wehrle, A.E., and Xu, W. “Multi-Epoch VLBA Observations of γ -Ray Bright Blazars,” 1998, in *IAU Colloquium 164, Radio Emission from Galactic and Extragalactic Compact Sources*, ed. J.A. Zensus, J.M. Wrobel, and G.B. Taylor, ASP Conf. Ser., 144, 67.
- Marchenko, S.G., Marscher, A.P.**, and Tosti, G. “Analysis of the Photometric Behaviour of OJ 287 in the Near-IR–Optical Region in February 1997,” 1998, in *Multifrequency Monitoring of Blazars*, Publ. Osservatorio Astronomico Università di Perugia, ed. G. Tosti and L. Takalo, 3, 36.
- Marscher, A.P.** “Some Theoretical Thoughts about OJ 287,” 1998, in *Multifrequency Monitoring of Blazars*, Publ. Osservatorio Astronomico Università di Perugia, ed. G. Tosti and L. Takalo, 3, 81.
- Marscher, A.P.** “The Compact Jets of TeV Blazars,” 1999, *Astroparticle Physics*, 11, 19.
- Marscher, A.P.**, and **Marchenko, S.G.** “The Compact Jets of BL Lac Objects,” 1999, in *The BL Lac Phenomenon*, ed. L. Takalo and A. Sillanpää, ASP Conf. Ser., 159, 417.
- Mattox, J.R.**, Halpern, J.P., Caraveo, P.A., “Timing the Geminga Pulsar with Gamma-Ray Observations,” 1998, *ApJ*, 493, 891.
- Mukherjee, R., . . . , **Marscher, A.P.**, *et al.* “EGRET Observations of PKS 0528+134 from 1991 to 1997,” 1998, in *Proceedings of the Fourth Compton Symposium*, ed. C.D. Dermer, M.S. Strickman, and J.D. Kurfess, AIP Conf. Proc., 410, 1346.
- Yurchenko, A.V., **Marchenko, S.G.**, and **Marscher, A.P.** “Parsec-Scale Behavior of NRAO 190 after γ -ray Outburst in August 1994,” 1999, in *The BL Lac Phenomenon*, ed. L. Takalo and A. Sillanpää, ASP Conf. Ser., 159, 454

4. CENTER FOR SPACE PHYSICS

The Center for Space Physics (CSP), founded in 1987 coordinates research in magnetospheric and ionospheric

physics for members of the Astronomy Department and the School of Engineering. The current director is Supriya Chakrabarti. The CSP staff include 13 faculty plus research associates and students. Administrative support is provided by Mrs. Kathy Nottingham.

4.1 Ultraviolet Instrumentation Group

The ultraviolet instrumentation group is continuing a broad program involving laboratory development of new instrumentation, observations from sounding rockets, and the development of satellite systems. The SPINR (Spectrograph for Photometric Imaging w/ Numeric Reconstruction) sounding rocket (Cook, Taylor and Chakrabarti) has recently flown and produced excellent data which will allow the spectral properties, and thus the physical characteristics to be mapped, of dust in the Orion region. Data from recent observations of Orion are allowing us to measure the dust phase function and its spectral dependence. The package will be flown again in the summer of 2000 to make similar measurements of the Scorpio region.

4.1.1 SCARI: UV Interferometric spectroscopy

SCARI has been used by (Chakrabarti, Cook, Vickers, Stephan and Cotton) to study gas and dust in the immediate solar neighborhood, the Very Local Interstellar Medium (VLISM). The VLISM moves with respect to the sun, creating an interstellar wind. The solar wind shields the solar system from the VLISM, interacting with the VLISM and ultimately coming into pressure balance with the interstellar wind at the heliopause. The VLISM plasma component is excluded from the heliosphere as it is swept up by the interplanetary magnetic field. The neutral component of the VLISM enters the heliosphere and flows through the solar system; Lyman alpha emission from this inflowing neutral gas provides an excellent opportunity to measure VLISM and heliospheric interface region conditions using spacecraft near the Earth. The major thrust of the instrumentation effort will be the development of a high resolution (resolving power of about 250,000 at 120.0nm) spectrograph that will cover from 120.0 to 500.0nm with no scanning or other moving parts. The system delivers good signal to noise spectra of hot, bright stars when used with a 16 inch telescope over a 300 second observation. Its performance will be of wide utility for a variety of high resolution applications. The high resolution of the proposed instrument ($v \sim 1$ km/sec) will allow the next generation of ultraviolet instrumentation to separate interstellar structure and probe the physical properties of the ISM at a level not currently possible.

4.1.2 SADIE: 2-D photon counting using VLSI anode

With the support of NASA UV detector program Chakrabarti and Vickers have developed a 2-D photon counting detector that uses VLSI technology. Small chips (2 mm square and 4 mm X 6 mm) have been built with very good performance. We are now investigating its electrical characteristics for a large (> 25 mm square) anode implementation.

4.1.3 Sodium Interferometric spectrograph

Undergraduate student K. France with Professors Chakrabarti and Cook is developing a high resolution interferometer capable of detecting sodium absorption in the earth's atmosphere and in the interstellar medium. The instrument is a member of the Self Compensating All Reflective Interferometer (SCARI) family, and offers a theoretically spectral resolution of 30 milliAngstroms. One of its key features is its durability, ruggedity and tolerance to small misalignments due to vibration or thermal stresses. This feature allows it to be used on a telescope mount without destroying the interference pattern.

4.1.4 Hi-TIES: Groundbased auroral studies under fully sunlit conditions

While we see aurora extend at all local time from space based UV instruments, observation of aurora during day time remains one of the last challenges in ground based optical astronomy studies. Duggirala, Baumgardner and Chakrabarti have developed a high resolution echelle spectrograph that uses a mosaic of interference filters for order sorting. This instrument has been deployed in Sondrestromfjord, Greenland and observed visible aurora under sunlit sky. Its high spectral resolution and long-slit imaging properties make it attractive for many applications.

PUBLICATIONS

- Chakrabarti, S.**, "Ground based spectroscopic studies of sunlit airglow and aurora," 1998, J. Atmos. Solar-Terr. Phys., 60, 1403.
- Nakamura, M., Yamashita, K., Yoshikawa, I., Shiomi, K., Yamazaki, A., Sasaki, S., Takizawa, Y., Hirahara, M., Miyake, W., Saito, Y., and **Chakrabarti, S.**, "Helium observation in the martian ionosphere by the x-ray ultra violet scanner on the mars orbiter NOZOMI," 1999, Earth, Planets and Space, 51, 61.
- Vickers, J.S., and Chakrabarti, S.**, "Silicon-anode detector with integrated electronics for microchannel plate imaging detectors," 1999, Rev. Sci. Instrum., 70, 2912.

4.2 Ionospheric Research

To study the development of ionospheric irregularities at equatorial and auroral latitudes, Global Positioning System (GPS) data from regional network stations are being analyzed by Aarons, Mendillo, and graduate student B. Lin (College of Engineering). This study revealed the spread of irregularity development at auroral latitudes in one dramatic case only as a function of storm time; other storms show the importance of local magnetic time.

4.2.1 Hot Atomic Oxygen corona

Measurements of extreme ultraviolet atomic oxygen features at 98.9 and 130.4 nm from the BEARS sounding rocket and STP78-1 ECOM satellite spectrographs reveal an excess of emission compared to standard thermospheric model calculations at exospheric altitudes. Cotton along with colleagues from the University of Liege (Hubert and Gerard), have been investigating the possible cause for the discrepancy. A leading candidate is a Hot O geocorona that has been

hypothesized by a number of scientists. Models for the OI emission features are consistent with a hot O geocorona, but the density and temperature required to fit the data is not substantiated by Monte Carlo energy distribution function calculations.

4.2.2 UV ionospheric tomography

A tomographic reconstruction technique for the inversion of atomic oxygen volume production rates and consequently ionospheric electron densities from UV and optical emissions has been developed. The inversion algorithm uses a stochastic regularization approach to address the ill-conditioning of the nearly singular system of equations which map the measured brightness to the unknown ionosphere. The regularization is achieved by constraining the solution space statistically in order to obtain an optimal reconstructed ionosphere. This work has led to the first characterization of reconstruction uncertainties in ionospheric tomography. Further investigations include the exploration of methods of tomographic reconstruction from partial (limited angle) observations of UV and optical emissions. This is accomplished by minimization of an appropriately different set of functionals.

4.2.3 Tomographic spectral imaging

Investigations of tomographic spectral imaging techniques have revolved around the development of algorithms to reconstruct the three-dimensional data cube (e.g. RA, Dec, and wavelength) from spatially compressed two-dimensional recorded data by the SPINR system. The algorithms address difficulties experienced by conventional reconstruction methods in the inherent presence of noise by regularization through a total-variational approach. In addition, the performance of these techniques has been characterized in comparison with conventional methods of spectral imaging. Methods of increasing system throughput using multiplexing schemes are currently being explored.

PUBLICATIONS

- Aarons, J., Mendillo, M.,** and Lin, B., "The great magnetic storm of May 1998 and its effect on phase fluctuations in the auroral and equatorial regions," Symposium Record, Ionospheric Effects Symposium, Arlington, VA, May 1999.
- Aarons, J.** and Lin, B., "Development of High Latitude Phase Fluctuations During the January 10, April 10-11, and May 15, 1997 Magnetic Storms," 1999, *J. Atmos. Sol-Terr. Phys.* 61, 309.
- Aarons, J. et al.,** "Equatorial F Region Irregularity Morphology during an Equinoctial Month at Solar Minimum," 1999, *Space Science Reviews* 87, 357.
- Chakrabarti, S., Cook, T., Kamalabadi, F., Cotton, D., Taylor, V., Godlin, S., and Vickers, J.,** "Instrumentation and techniques for diffuse/multi-object spectroscopy," 1999, *Ultraviolet-Optical Space Astronomy Beyond HST*, J.A. Morse, J.M. Shull, and A.L. Kinney, eds, Astron. Soc. of the Pacific, 1644, 322.

Chakrabarti, S., Taylor, V., Cook, T.A., Stephan, A.W., Cotton, D.M., and Kamalabadi, F., "Spectral imagery in the far ultraviolet: results from a sounding rocket experiment," 1998, *Proc. SPIE*, 3356, 816.

Hubert, B., Gerard, J.C., **Cotton, D.M.,** Bisikalo, D.V., She-matovich, V.I., "Effect of hot oxygen on thermospheric O I UV airglow," 1999, *Journal of Geophysical Research*, 104 A8, 17 and 139.

4.3 Magnetospheric Physics

4.3.1 MACCS

The MACCS (Magnetometer Array for Cusp and Cleft Studies) Project (PI's, W.J. Hughes and M.J. Engbretson, Augsburg College) consists of 12 magnetometers located in arctic Canada at geomagnetic latitudes between 75 and 85 degrees and spanning about 5 hours in local time. Each magnetometer records the geomagnetic field vector continuously twice a second. The observed magnetic variations can be inverted to obtain the ionospheric current pattern over a large region above the array. Currently Hughes and graduate student D. Murr are working on understanding the mechanism by which transient field-aligned currents linking the magnetosphere and ionosphere are created by changes in the solar wind, and on measuring the time scale on which the ionospheric flows respond to interplanetary magnetic field changes, which is a few minutes. Hughes and graduate student A. Walker are comparing the signatures seen by MACCS with in situ plasma and field measurements made in the cusp by the POLAR spacecraft at an altitude of about 5 earth radii in order to better understand the magnetospheric response to changes in the solar wind.

4.3.2 Magnetospheric Mapping Mission

Over the past several years, Boston University has become a leader in the study of potential micro- (< 100 kg) and nano-satellites (< 10 kg) for use in scientific studies. This includes the class of missions known as "constellations," those consisting of many tens to even one thousand concurrently operating spacecraft. The first of these constellation studies at BU is a mission design project, the Magnetospheric Mapping Mission (MMM), funded through NASA's highly-competitive New Mission Concept program. Spence is the PI of this project, while Senior Fellow Petshek and Siscoe are co-Is. Their study demonstrates the feasibility of building and launching potentially hundreds of nanosatellites (1 kg, $1W$) into the distant magnetosphere to map the three-dimensional magnetic fields of the dynamic magnetotail, the region where processes leading to the aurora are thought to originate. The MMM proposes to deploy 100-200 nanosatellites carrying three-axis magnetometers onto highly elliptical orbits into this region. The resulting data will be revolutionary in revealing the instantaneous state and physical modes of magnetotail dynamics that have remained elusive using current satellite data.

4.3.3 Magnetospheric Particle Populations from POLAR and Archival Data Sets

Over the course of the last year, analysis of energetic particle data from the NASA/POLAR spacecraft has continued to be a very high priority within the CSP. Two main science thrusts have emerged from this work. The first of these topics has involved Fritz, Spence, Chen, Sullivan, and Matthews and graduate students Alothman and Karra, as well as a large number of undergraduate researchers and involves observations of energetic particles in the cusp and the interpretation of the possible profound significance of these data. The second topic involves the ongoing global imaging of energetic neutral atoms (ENAs) during magnetic storms and substorms. Both of these topics (cusp and ENA studies) will remain high priority items in the coming years as the ISTP mission transforms to the SOLARMAX 2000 mission. A new project has started in the past year that will use TIROS and POLAR measurements to investigate possible solar cycle variations in ENA emissions. Other ongoing POLAR ENA studies include collaborations with JHU/APL scientists in the areas of modelling, joint analysis with the GEOTAIL satellite, and the search for heliospheric ENAs that are expected to be formed as the solar system moves through the interstellar medium. In addition to the POLAR-related studies, the CSP is actively researching magnetospheric particles through the systematic analysis of large archival data sets. Graduate student A. Boudouridis continues to analyze the unique dual-DMSP data set to assess the temporal stability and coherence of auroral particle precipitation. His work has revealed the unambiguous characteristic size and time scales of auroral precipitation structures and has also tested, for the first time with two nearly colocated spacecraft, a much-used magnetospheric region identification scheme. Results of these ongoing studies are also in preparation.

PUBLICATIONS

- Angelopoulos, V., and **Spence, H.E.**, "Magnetospheric constellation: past, present, and future," 1999, in The International Solar Terrestrial Physics Program: The Great Observatory for the Sun-Earth Connection, AGU Geophysical Monograph Volume 109, p. 247.
- Chang, S.-W., Scudder, J.D., Fuselier, S.A., Fennell, J.F., Trattner, K.J., Pickett, J.S., **Spence, H.E.**, Menietti, J.D., Peterson, W.K., Russell, C.T., Lepping, R.P., and Friedel, R., "Cusp energetic ions: a bow shock source," 1998, *Geophys. Res. Lett.*, 25, 3729.
- Engebretson, M.J., Glassmeier, K.-H., Stellmacher, M., **Hughes, W.J.**, and Luhr, H., "The dependence of high-latitude Pc5 wave power on solar wind velocity and on the phase of high-speed solar wind streams," 1998, *J. Geophys. Res.*, 103, 26271.
- Engebretson, M.J., **Murr, D.L.**, **Hughes, W.J.**, *et al.*, "A Multipoint determination of the propagation velocity of a sudden commencement across the polar ionosphere," 1999, *J. Geophys. Res.*, 104, 22,433.
- Fennell, J. F., Roeder, J.L., Friedel, R., Grande, M. and **Spence, H.E.**, "Dayside open field line region boundary at high altitudes," 1999, *Phys. and Chem. of the Earth*, 24, 129.
- Fritz, T. F.**, **Chen, J.**, Sheldon, R.B., **Spence, H.E.**, Fennell, J.F., Livi, S., Russell, C.T. and Pickett, J.S., "Cusp energetic particle events measured by POLAR spacecraft," 1999, *Phys. and Chem. of the Earth*, 24, 135.
- Henderson, M. G., Reeves, G.D., Moore, K.R., **Spence, H.E.**, Jorgensen, A.M., Fennell, J.F., Blake, J.B. and Roelof, E.C., "Energetic neutral atom imaging with the POLAR CEPPAD/IPS instrument: initial forward modeling results," 1999, *Phys. and Chem. of the Earth*, 24, 203.
- Huang, C.-S., Sofko, G.J., **Murr, D.**, **Hughes, W.J.** and Moretto, T., "High-latitude ionospheric convection during strong interplanetary magnetic field By," 1999, *Geophys. Res. Lett.*, 26, 405.
- Jorgensen, A. M., **Spence, H.E.**, Hughes, T.J. and McDiarmid, D., "A study of omega bands and Ps-6 pulsations on the ground, at low-altitude, and at geostationary orbit," 1999, *J. Geophys. Res.*, 104, 14705.
- Lyatsky, W.B., Sofko, G.J., Kustov, A.V., Andre, D., **Hughes, W.J.**, and **Murr, D.**, "Traveling convection vortices as seen by the SuperDARN HF radars," 1999, *J. Geophys. Res.*, 104, 2591.
- Ohtani, S., G. Rostoker, K. Takahashi, V. Angelopoulos, M. Nakamura, C. Waters, H.J. Singer, S. Kokubun, K. Tsuruda, **W.J. Hughes**, T.A. Potemra, L.J. Zanetti, J.B. Gary, A.T.Y. Lui, and D.J. Williams, "Coordinated ISTP satellite and ground observations of morningside Pc5 waves," 1999, *J. Geophys. Res.*, 104, 2381.
- Petschek, H. E.**, Rayburn, C. Sheldon, R., **Vickers J.**, Bellino, M., Bevis, G. and **Spence, H.E.**, "The Kilo-Satellite Constellation Concept, in Science Closure and Enabling Technologies for Constellation Class Missions," 1998, V. Angelopoulos and P. Panetta, eds., Univ. of California, Berkeley Press, p. 51.
- Pilipenko, V.A., Shalimov, S.L., Fedorov, E.N., Engebretson, M.J. and **Hughes, W.J.**, "Coupling between field-aligned current impulses and Pi1 noise bursts," 1999, *J. Geophys. Res.*, 104, 17419.
- Posch, J.L., Engebretson, M.J., Weatherwax, A.T., Detrick, D.L., **Hughes W.J.** and MacLennan, C.G., "Characteristics of broadband ULF magnetic pulsations at conjugate cusp latitude stations," 1999, *J. Geophys. Res.*, 104, 311.
- Reeves, G. D., Baker, D.N., Belian, R.D., Blake, J.B., Cayton, T.E., Fennell, J.F., Friedel, R.H.W., Meier, M.M., Selesnick, R.S. and **Spence H.E.**, "The global response of relativistic radiation belt electrons to the January 1997 magnetic cloud," 1998, *Geophys. Res. Lett.*, 25, 3265.
- Shiokawa, K., Anderson, R.R., Daglis, T.A., **Hughes, W.J.** and Wygant, J.R., "Simultaneous DMSP and CRRES observations of broadband electrons during a storm-time substorm on March 25, 1991." 1999, *Phys. Chem. Earth (C)*, 24 281.
- Szuberla, C.A.L., Olson, J.V., Engebretson, M.J., Fraser, B.J., Ables, S. and **Hughes, W.J.**, "Interstation Pc3 coherence at cusp latitudes," 1999, *Geophys. Res. Lett.*, 25, 2381.
- Takahashi, K., **Hughes, W.J.**, Anderson, R.R. and Solov'ev, S.I., "CRRES Satellite Observations associated with low

latitude Pi2 pulsations,' 1999, *J. Geophys. Res.*, 104, 17431.

4.4 Aeronomy and Planetary Atmospheres

4.4.1 Imaging Science Facilities for Aeronomic Research

Baumgardner has developed several state-of-the-art CCD-based imaging instruments for use in terrestrial and planetary applications conducted in conjunction with Mendillo, graduate students, and postdoctoral research associates. Under sponsorship from the NSF's program in Coupling, Energetics and Dynamics of Atmospheric Regions (CEDAR), Boston University operates the CEDAR Optical Tomographic Imaging Facility (COTIF) in the New England area. The network consists of three all-sky imaging spectrographs (two in Maine and one in Rhode Island) and an all-sky 2-dimensional all-sky imager at the Haystack Observatory in Westford, MA. These instruments comprise the first-ever optical tomographic facility to study the altitude vs. latitude emission profiles of atmospheric structures. As part of the CEDAR program in Equatorial Aeronomy, a CCD all-sky imager operates in Arequipa, Peru, to record sub-visual emission features related to dynamical processes in the ionosphere. A companion instruments is located at Argentina's national observatory in El Leoncito, under sponsorship by the Office of Naval Research, to study latitude effects in atmospheric dynamics.

4.4.2 Planetary Atmospheres Imaging Spectrograph and Monochromatic Imagers

In a collaborative arrangement with the McDonald Observatory in Fort Davis, Texas, operated by the University of Texas at Austin, the Center for Space Physics constructed "Boston University Station" to house instruments dedicated to the study of large-scale, low-light-level emissions associated with solar system bodies. An 18-foot dome, together with a separate control room, house a 0.5 meter Richey-Cretien telescope to conduct searches for extended planetary and cometary comas. Companion 0.1 meter imaging and spectrographic systems provide 6-degree fields of view to study truly extended atmospheres, primarily of Jupiter's moon Io and of our Moon. Sodium emission is the trace species used to map the extent of such transient atmospheres. Under sponsorship by the Office of Naval Research, a prototype imaging system is being developed to record bright structures in a very rapid data taking method (currently 60 pictures per second). This High Definition Imaging (HDI) method relies on subsequent image processing to select the few images taken under essentially perfect seeing conditions. These images are then combined to form time-exposures (selective integration) to improve signal to noise. The system will be used to record atmospheric structures in the Earth's ionosphere and in planetary environments.

4.4.3 Planetary and Cometary Atmospheres

In conjunction with research associate J. Wilson, Mendillo and Baumgardner continue their NASA sponsored studies of Jupiter's sodium magneto-nebula, using their multiple FOV telescopes at the McDonald Observatory. Current em-

phasis is on modeling the different mechanisms that produce the nebula, and on identifying the relationship between volcanic activity on Io and the subsequent evolution of Jupiter's neutral clouds and plasma torus. Wilson, Mendillo and Baumgardner continue to study the sources of the lunar exosphere. Having demonstrated that solar wind sputtering is not the major mechanism for production of the Moon's extended atmosphere, their efforts have turned to examining the micro-meteor impact source mechanism. Working with CSP Research Associate S. Smith, they demonstrated that during the Leonids meteor storm of November 1998, a rather spectacular enhancement of the lunar atmosphere occurred, producing a tail of escaping gas that extended well past the Earth's orbit. The observational and modeling aspects of the lunar work are supported by NASA.

4.4.4 Atmospheric and Ionospheric Studies

Dr. S. Smith as awarded an NSF CEDAR Post-doctoral Fellowship to join Boston University to initiate a program of optical imaging of atmospheric gravity waves in the Earth's mesosphere (region near 90 km altitude). Using a new CCD detector, Smith, Baumgardner and Mendillo succeeded in obtaining the first multi-spectral images of gravity waves from the BU imaging site at Millstone Hill (Haystack Observatory). They will continue to study the properties of gravity waves at this sub-auroral site, and search for the blend of generation mechanisms (tropospheric storms, auroral events) during the upcoming solar maximum years. In areas of equatorial aeronomy, an active program exists in using the imagers in Peru and in Argentina to study a variety of plasma processes unique to the low latitude region. Graduate student C. Martinis is working on the neutral wind and plasma drift patterns that seem to govern the onset conditions of plasma instabilities in the post-sunset period. M. Colerico uses the imagers to study 6300 Å "brightness waves" that propagate from the midnight sector, perhaps generated by the so-called midnight temperature anomaly in the low latitude thermosphere (regions near 250 km altitude). Smith and Mendillo are continuing the tomographic studies of sub-auroral structures in the ionosphere and mesosphere, concentrating on stable auroral red (SAR) arcs produced near 400 km altitude and the altitude profiles of gravity waves in the mesospheric layers of OH, Na and O. Mendillo and graduate student B. Lin continue in their collaboration with J. Aarons in the application of global positioning system (GPS) satellite signals to studies of ionospheric structures at both high and low latitudes. During the solar maximum period centered on 2001, they will study the effects of geomagnetic storms on producing or hindering the ionospheric irregularities that occur at both auroral and equatorial latitudes, programs under sponsorship by ONR and NASA. CSP visitor Rishbeth, staff researcher J. Wroten, and Mendillo continue in their studies of the causes of ionospheric variability. Sponsored by the Space Weather initiative at NSF, their current emphasis is on comparisons of observed variability of the ionospheric F-region (near 300 km altitude) using archived ionosonde data and predictions from the new TIEGCM/CCM-3 model provided by collaborator Dr. Ray Roble at NCAR.

PUBLICATIONS

- Mendillo, M., Baumgardner, J. and Wilson, J.**, "Observational Test for the Solar Wind Sputtering Origin of the Moon's Extended Sodium Atmosphere," 1999, *Icarus*, 137, 13.
- Smith, S., Wilson, J., Baumgardner, J. and Mendillo, M.**, "Discovery of the Distant Lunar Sodium Tail and its Enhancement Following the Leonid Meteor Shower of 1998," 1999, *Geophys. Res. Lett.*, 26, 1645.
- Wilson, J.K., **Baumgardner, J. and Mendillo, M.**, "Three Tails of Comet Hale-Bopp," 1998, *Geophys. Res. Lett.*, 25, 225.

4.5 Space Plasma Theory

The space plasma simulation and theory group studies particle/wave interactions in the Earth's ionosphere and magnetosphere. To perform this research Oppenheim, vom Endt, Vetoulis, and Dyrud develop kinetic and fluid plasma simulation programs using modern computational techniques and run them on some of the world's largest and fastest supercomputers. Through a combination of simulations and theory, they have been able to further our understanding of the behavior of a number of nonlinear processes observed in space plasmas.

4.5.1 Research on the E-region ionosphere

Oppenheim and vom Endt continue research on the Earth's equatorial electrojet which he began at Cornell University. The equatorial electrojet is a stream of current that travels above the equator at an altitude of 90 - 120 km in the E-region ionosphere. Periodically, strong radar echoes reflect from the electrojet indicating the presence of coherent plasma density waves. Many of the observations cannot be explained by linear theory, because these are nonlinearly saturated waves. Using a two-dimensional hybrid computer code we were able to explain many of these features and, further, predict the generation of a nonlinear electron current which modifies the large-scale charge distribution of the electrojet. This research is currently being extended to meteor trails, the auroral region electrojet, and three dimensions. This research is funded by NASA through the ITM program.

4.5.2 Theory and Simulations of Space Plasmas in the Auroral Ionosphere and Magnetosphere

Oppenheim, Vetoulis, and Dyrud also study a range kinetic plasma processes in the upper ionosphere, magnetosphere and solar wind using simulations and theory. One of the topics currently under study is electron phase-space tornados. This research was stimulated by recent observations of streams of isolated electric field pulses made by four Earth orbiting satellites in four vastly different regions of near-Earth space; in the auroral ionosphere (FAST) and magnetosphere (POLAR), in front of the Earth's bow-shock (WIND), and in the magnetotail (GEOTAIL). These measurements result from nonlinearly stabilized electron density depletions and contain some of the highest electric field energy densities found in space plasmas. In 1D, these depletions result from "phase-space electron holes" where rotating trapped

electron vortices in (X-Vx) phase space are contained by a strong positive potential. In 2D, electron holes form tornadoes when viewed in (X-Y-VX) phase space. Using simulations we have observed the formation, evolution, and eventual decay of these tornadoes and have been able to discuss the magnetospheric conditions necessary for observing them.

4.5.3 Computational Tools

Oppenheim has recently completed development of a large-scale, massively parallel particle and field simulator to study space plasma phenomena in 3-D. Additionally, he has developed and continues to apply a number of 2-D simulators to investigate plasma phenomena. These simulators runs on parallel supercomputers such as the Cray Origin 2000 machines available through the Boston University Scientific Computing and Visualization Group and the Advanced Computing Laboratory at Los Alamos Nation Laboratories.

PUBLICATIONS

- Goldman, M., Newman, D. and **Oppenheim, M.**, "New Insights into how beam-excited instabilities saturate," 1998, *Physica Scripta*, Vol. T75, 52.
- Goldman, M.V., **Oppenheim, M.M.** and Newman, D.L., "Nonlinear two-stream instabilities as an explanation for auroral bipolar wave structures," 1999, *Geophys. Res. Lett.*, Vol. 26, No. 13, 1821.
- Oppenheim, M.**, Newman, D.L. and Goldman, M.V., "Evolution of Electron Phase-Space Holes in a 2-D Magnetized Plasma," 1999, *Phys Rev Lett*, Vol 23, Issue 11.
- Otani, N. and **Oppenheim, M.**, "A saturation mechanism for the Farley-Buneman Instability," 1998, *Geophys. Res. Lett.*, Vol. 25, No. 11, 1833.

5. OTHER PROGRAMS

5.0.1 High Energy Studies

Kenneth Brecher has continued to carry out theoretical studies concerned primarily with the physics of neutron stars. One recent project focused on models of asymmetric radiation from strongly magnetized neutron stars (magnetars) which could explain the origin of at least some runaway pulsars. Another study examined the effects of nearby gamma ray bursts on the terrestrial environment. Brecher continues to examine astrophysical implications of historical records of supernovae, most recently, the dynamical implications of the observed explosion date for Cas A for the recently discovered point x-ray source at its center.

5.0.2 Education Programs

Brecher has been actively involved in a variety of precollege and informal science education programs, including the projects "On Growth and Form," "Random Universe," and "Quantum Science Across Disciplines" at Boston University and the "MicroObservatory" and "MicroObservatory Net" projects at Harvard University, all with support from the National Science Foundation. He has just begun a new NSF-supported undergraduate level curriculum, materials, and software development program called "Project LITE: Light Inquiry Through Experiments." Development of the

“MicroObservatory” project has continued during the past several years. Five second generation automated telescopes, equipped with high resolution CCDs and pointed and image processed by computer have been completed. Software has been written which allows their control over the Web for remote use by students, amateurs astronomers and museums.

PUBLICATIONS

Garik, P., Abegg, G., **Brecher, K.**, Carr, P., Dill, D., Horowitz, P., Hurwitz, C., Robblee, K., “Multilevel Molecular Modeling Tools,” 1998, Chem. & Eng. News, 76, No.30, 99.

Brecher, K. and Sadler, P., “MicroObservatory Net,” 1998, in New Trends in Teaching Astronomy, IAU Colloquium 162, 37, (L. Gougenheim, D. McNally and J. R. Percy, eds.), Cambridge University Press.

Brecher, K. and Sadler, P., “The MicroObservatory Net,” 1998, in New Trends in Astronomy Teaching, IAU Colloquium 162 (L. Gougenheim et. al. eds., Cambridge U. Press), 37.

Deutsch, F., Antonucci, P., Sadler, P., Leiker, S., Gould, R. and **Brecher, K.**, “MicroObservatory Net,” 1998, Am. As. Phys. Teachers Announcer, 28, No. 4, 91.

Abegg, G. L., **Brecher, K.**, Carr, P., Dill, D., Garik, P., Horwitz, P., Hurwitz, C. & Robblee, K., “Descriptive Quantum Science: Visual Programs for Atomic and Molecular Physics Education,” 1999, Bull. Am. Phys. Soc., 44, No. 1, 1011.

K.A. Janes
E. Grimes

