University of Maryland
Department of Astronomy

College Park, Maryland 20742

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This report covers the period 1 September 2001 to 30 September 2002.

MS degrees were earned by Jian Chen, Curtis Frank, Jianyang Li, and Robert Piontek.

1. PEOPLE

The teaching and research staff consisted of Full Professors: Marvin Leventhal (chair to 30 June), Lee Mundy (chair from 1 July), Michael A'Hearn (Distinguished University Professor), J. Patrick Harrington, Mukul Kundu, Dennis Papadopoulos, William Rose, James Stone, John Trasco (associate director), Virginia Trimble (visiting), Stuart Vogel, and Andrew Wilson.

Associate professors: Douglas Hamilton, Andrew Harris, Eve Ostriker, and Sylvain Veilleux.

Assistant professors: Stacy McGaugh, Coleman Miller, Chris Reynolds, and Derek Richardson.

Instructors: Grace Deming and David Theison.

Professors Emeriti: Roger Bell, James Earl, William Erickson, and Donat Wentzel.

Senior Research Scientists: Roger Bell, Charles Goodrich (now at Boston University), David Leisawitz (visiting), Carey Lisse, and Surjaial Sharma.

Associate Research Scientists: Keith Arnaud, Suchitra Balachandran, Rosemary Killen, Lucy-Ann McFadden, Gennady Milihk, Edward Schmahl, and Stephen White.

Faculty Research Associate: Narsipur Amarnath.

Assistant Research Scientists: Thejappa Golla, Tilak Hewegama, John Hillman, Michael Loewenstein, Chee Ng, Marc Pound, Peter Teuben, and Mark Wolfire.

Research associates and assistants: Sudip Bhattacharya, Dennis Chornay, John Cordes, Dana Crider (now at Goddard Space Flight Center), Mousumi Das, Tony Farnham, Fred Finkbeiner, Vladimir Garaimov, Andrew Gibb, Edwin Grayzeck, Victor Gretchnev (now at Inst. of Solar-Terrestrial Physics, Siberian Division of Russian Academy of Sciences), Una Hwang, Sophia Khan, Stephen Kortenkamp (now at Univ. of Arizona), Virgil Kunde, Chin-Fei Lee (now at JPL), Periasamy Manoharan, Craig Markwardt, Stephanie McLaughlin, Conor Nixon, Kevin Rauch, Anne Raugh, Ian Richardson, Leslie Sage (shared with *Nature*), Robert Samuelson, Takayoshi Sano, Mikhail Sitnov, David Smith, Philip Sprangle, Yuichi Terashima, Neal Turner (now at UC Santa Barbara), Gretchen Walker (now at the Museum of Natural History, NY), Elizabeth Warner, Dennis Wellnitz, Friedrich Wyrowski (now at Max Planck Institute, Bonn), and Andrew Young. Many of the research staff are headquartered at GSFC.

Visiting and Adjunct faculty: Neil Gehrels (GSFC), Stephen Holt (Olin College of Engineering), John Lyon, Richard Mushotzky (GSFC), David Neufeld (Johns Hopkins) and Nicholas White (GSFC).

Recipients of PhD degrees and their current affiliations are Rachel Gibbons (Lawrence Livermore Lab), Woong Tae Kim (Harvard), Donald Horner (Space Telescope Science Institute), Xi Shao (GSFC), and Chin-Fei Lee (JPL).

2. SERVICE AND RECOGNITION

Maryland's cohort of asteroids nearly doubled this year with the naming of Careylisse, Grayzeck, Anne-raugh, and Derichardson, plus asteroids named for alumni Marla Moore and Nalin Samarasinha. Student David Rupke received a Doctoral Dissertation Fellowship from the University. Other major new grants during the year came from NSF (Miller - Dense matter, strong gravity, and accretion onto compact objects; Ostriker - Dynamical studies of molecular cloud formation; McGaugh - Low surface brightness galaxies) and NASA (Richardson - Origins and PG&G programs; McFadden, part of the team for a new Discovery Mission called Dawn, scheduled to take off in 2006 and orbit Vesta and Ceres until 2015).

Prof. Vogel served as chair of the Visiting Committee for NRAO, operated by Associated Universities Incorporated. Prof. A'Hearn chaired the Observatories Council for AURA, the operator of NOAO, and served on their board of directors as well as on the visiting committee for Arecibo. Other observing facilities that benefitted from Maryland expertise on their boards or time assignment committees included HST, Subaru, and the Telescope Nazionale Galileo (Veilleux), Lowell (A'Hearn), and the Infrared Telescope Facility (John Hillman, as program scientist).

Editorial boards with Maryland input include *Icarus* (Prof. Hamilton), *Reviews of Modern Physics* (Trimble), *Nature* (research associate Sage), and several others of lesser prestige.

Trimble continued a term as President of the Division of Galaxies and the Universe of the International Astronomical Union, and A'Hearn was part of the Committee on Small Body Nomenclature (Hm. Is that why Maryland did so well on asteroid names?). Other professional scientific societies that had our help included American Geophysical Union (Surja Sharma, vice-chair of focus group on non-linear geophysics), the American Astronomical Society (Sage, the panel on employment; A'Hearn, publications board; Hamilton, DPS prize committee; Deming, education committee; and a handful of other committees), the American Physical Society, the American Institute of Physics Center for the History of Physics, and Sigma Xi.

Associate Director Trasco served on the NSF career grants peer review panel. The NSF pre-doctoral fellowship program, the extragalactic review panel, and other groups handing out NSF dollars also had Maryland members.

Prof. Wilson was Chandra Interdisciplinary Scientist and a member of its science working group. Other NASA programs with departmental membership included planetary atmospheres proposal review (Lisse; Killen - chair of tenuous atmospheres panel), astrobiology, origins (Richardson), astrophysics data program (McFadden), the space sciences program proposal review panel (Schmahl), and the planetary astronomy and atmospheres program (Hillman as program scientist).

A baker's dozen department members who provided input for this report gave something like 60 invited colloquia, seminars, and talks at other institutions and at large national and international meetings. Some of the ones you might have wanted to come along to include SPIE in Hawaii (Reynolds), Galaxies, the Third Dimension in Cozumel, Mexico and Active Galactic Nuclei in Meudon, France (Veilleux), the AST-ROSAT workshop in Mumbai, India (Bhattacharyya), IAU Colloq. 186 in Tenerife, Spain (A'Hearn), Star Formation in Taiwan (Ostriker). We would understand if the local attractions had not drawn you to the RAS National Astronomy Meeting in Bristol, UK (Wilson), the APS in Albuquerque (Miller), the Delaware Instructional Technology Conference (McFadden), the Bartol Research Foundation (Richardson), the CEDAR meeting in Longmont, Colorado (Milikh), the Cambridge, MA workshop on cool stars (Balachandran), COSPAR in Houston (Killen), or colloquia at Southern Illinois University at Edwardsville and Willamette University Founders Day. Trimble was the 32nd J. Robert Oppenheimer Memorial Lecturer at Los Alamos, but unfortunately he was not there.

Staff member Barbara Scott was re-elected to the University Senate Executive Committee.

3. EDUCATION AND PUBLIC OUTREACH

About 1200 University of Maryland undergraduates passed through introductory astronomy courses during the year. As usual, the University Observatory was open to the public for observing and a lecture on the 5th and 20th of each month, hosted by departmental faculty, students, and researchers, generally for capacity crowds of 200 or more. In addition to the regular open nights, there were six ‘‘Learn the Sky Friday's'' for beginning amateur astronomers.

Many department members collaborated on a Maryland Day presentation called ‘‘Strange Lights in the Sky.'' No one reported seeing a flying saucer during the presentation.

Department members Hillman, Warner, and Cordes direct a program called Science, Discovery, and the Universe within the College Park Scholars, an enrichment program for freshmen and sophomores, also involving a local high school. One of the high school science fair projects produced as part of this program was the Optical Society of America national winner and an Intel honorable mention.

The Deep Impact group maintains an active E/PO program (in accordance with NASA regulations) which now provides free classroom modules for K-12 teachers and students on their web site. This year their activities included public talks and broadcasts at Wilhelm Tempel Schuele in Niedercunnersdorf, Germany (home town of the discoverer of Comet Tempel 1, where the Deep Impact will occur), by A'Hearn and McFadden. They and Warner also spoke with school and public groups in North and South Carolina and throughout Maryland.

On the international front Prof. Emeritus Donat Wentzel continued to coordinate the program of IAU Teaching for Astronomy Development, directing projects in Vietnam, Central America, and Morocco.

The department hosted a summer teacher workshop in which science teachers from a nearby high school spend their days on campus, developing curriculum modules on waves, light, and remote sensing in the context of earth sciences. Drs. Mundy and Wolfire worked with local high schools to get the NASA E/PO grant which is supporting this effort. Jason Vestuto, formerly a research assistant in astronomy and now a candidate for an M.Ed. is acting as coordinator. Curriculum modules will be tested during the 2002-03 school year, with the intention of distribution the final products to teachers at conferences and on the WWW.

Graduate students Kevin Walsh and Matthew Knight received distinguished teaching assistant awards from the University Center for Teaching Excellence. Other members of the department judged science fairs (including student Kelly Fast), spoke to senior citizen's groups, and tried hard to keep the science media honest. The Deep Impact groups provided input and interviews for WTOP, NPR, WBUR, the Reuters Service, NRK radio (Oslo), and Wednesday's Child (an adoption program). Other department members contributed to news items in Nature and Science (McGaugh, Richardson, Miller), Sky and Telescope (Das), the NY Times (Reynolds, A'Hearn), and at least a dozen others, perhaps less prestigious, venues (Turner, Trimble, McFadden).

4. STUDENT RESEARCH

Wayne Baumgartner continues work on the Infocus hard X-ray telescope at NASA Goddard Space Flight Center under the direction of Drs. Jack Tueller and Marvin Leventhal. A recent balloon flight of Infocus obtained the first astronomical image with a CZT detector, and proved the efficacy of multi-layer foil grazing incidence mirrors for hard X-ray astronomy. Mr. Baumgartner also is working on the intermediate element abundances of galaxy clusters with Drs. Richard Mushotzky and Mike Loewenstein at Goddard, and former Maryland graduate student Dr. Donald Horner at STScI. Their work shows that the abundance pattern in clusters does not easily conform to a mix of type Ia and type II supernovae products.

Laura Brenneman will be working with Prof. Chris Reynolds. Before coming to Maryland, she worked on topics such as asteroid astrometry, emission line galaxy distribution, globular clusters and their relation to spiral galaxy bulges, x-ray properties of the galactic cluster NGC 3603, x-ray grating spectroscopy of the stars Algol and UX Ari, and x-ray timing evolution of the Eta Carinae system. The latter three projects were all pursued from 2000-2002 during Laura's visiting fellowship held in the Lab for High Energy Astrophysics at NASA Goddard Space Flight Center in Greenbelt, MD. Her other interests include dynamics of accretion disks around black holes and other compact bodies, the formation and evolution of large scale structure in the universe, and astrobiology: specifically, the search for exoplanets.

Nicholas Chapman has completed his second year research project working with Lee Mundy to study the Jet- and

Wind-driven models in the molecular outflow HH 212, using data taken with the BIMA interferometer.

Kelly Fast has begun her thesis project on the study of the Martian CO_2 stability problem using infrared heterodyne spectra of ozone. She is working under the guidance of Dr. Michael A'Hearn at the University of Maryland and Dr. Theodor Kostiuk at NASA/GSFC through NASA's Cooperative Education Program. She also continues her work on spectroscopy of planetary atmospheres with Kostiuk's infrared heterodyne group.

Rachel Gibbons, working with Sylvain Veilleux, completed and successfully defended her thesis ''Deviations from the Fundamental Plane of Early-Type Galaxies and Large-Scale Cluster Motions.''

Kayhan Gultekin has been working with Dr. M. Coleman Miller on the dynamics of three- body systems in globular clusters. He is doing numerical simulations of encounters between black-hole-binaries and single black holes. Gultekin is examining how these encounters affect the rate of mergers of black hole binaries. Such mergers are sources of gravitational waves, which may be detectable by LIGO II and LISA. These mergers have been proposed as a mechanism for creating larger black holes, perhaps as large as 10^2 to 10^4 solar masses so called intermeidate-mass-black-holes, which may have been observed in recent X-ray observations.

Gultekin has also been working with **Zoe Leinhardt** and **Kevin Walsh** to create a new Beowulf cluster at the department. This cluster is made up of independently operated desktops as well as department PCs that are primarily used for teaching purposes during the day. At night they become VAMPIRE (Very Awesome Multiple Processor Interconnected Research Environment), a serial distributed computing network. VAMPIRE is currently operational and will soon be available for all of the department to use.

Ji Hoon Kim is working on several aspects of low surface brightness galaxy (LSBG) with Dr. McGaugh. He is analyzing various observational data to find correlations among various galaxy parameters such as gas mass fraction, mass-to-light ratio, luminosity and surface brightness. He is also using various stellar population synthesis models to test the results they found. In addition, he is studying globular clusters in LSBGs involving number counting and chemical abundance. This study will provide a clue to how differently LSBGs evolve compared to high surface brightness galaxies.

Woong-Tae Kim, in collaboration with Eve Ostriker (thesis advisor) and James Stone, performed three-dimensional MHD simulations to investigate nonlinear development of the Parker, magneto-Jeans (MJI), swing mechanisms, and combinations of them in galactic disk models. They showed that the Parker instability, even combined with self-gravity and galactic shear, is not the primary formation mechanism for giant molecular clouds at least in galactic disks at large. By producing in the saturated state mild velocity fluctuations at only 10% of sound speed, the Parker instability is insufficient to generate the observed level of interstellar turbulence, as well. The most powerful cloud-condensing mechanism, requiring low-shear conditions as occur in spiral arms or galactic centers, appears to be the MJI, forming bound clumps within one orbital time of galaxy rotation. They argued that MJI is at least partly responsible for the giant cloud formation in disk galaxies.

Matthew Knight is currently working with Prof. Mike A'Hearn studying the Kreutz family of sungrazing comets, using observations made by the Solar and Heliospheric Observatory (SOHO).

Rachel Kuzio de Naray has begun a second year research project aimed at determining the primordial Helium abundance in a sample of low surface brightness galaxies. She is working under the guidance of Dr. Stacy McGaugh and will compare her results to the primordial Helium abundances derived from other galaxy types.

During the past year **Zoe Leinhardt** completed her second year project to write and test an efficient hierarchical tree code to search for asteroid binaries in the output of N-body simulations. The code was successfully tested on preliminary data from collaborator Michel at the Nice Observatory in France. The search code is now being used by collaborators Bottke, Durda and Enke at the Southwest Research Institute in CO to analyze their large simulations (25,000 to 200,000 particles) of binary asteroid formation via catastrophic collisions (asteroid family forming events). The code is also being used by Dr. Richardson to analyze his simulations of asteroid formation via tidal disruption and graduate student Kevin Walsh to analyze his simulations of the tidal disruption of Comet Shoemaker-Levy 9.

Leinhardt is continuing work with Dr. Richardson on a project that she hopes will develop into a thesis. The long term goal of the project is to form several protoplanets from a large planetesimal disk (one million particles, several AU wide) including realistic fragmentation. In the past simulations of protoplanet formation have assumed either perfect accretion or used a fragmentation models based on laboratory impact experiments on Earth which are not in the same gravity regime as planetesimals. She intends to run a large scale (one million particle) simulation of the formation of protoplanets including both gravity and a realistic prescription for collisions. This problem is limited by computer capabilities - no current computer can follow the gravity and collisions between one million particles. As a result, the problem has been split up. The collisions between the planetesimals will be numerically modeled first creating a database of collision outcomes from all of the possible collisions between planetesimals in the planetesimal disk. When the collision database is completed it will be incorporated into the disk simulation as a fragmentation model. The collision database is close to being completed and a paper on the results should be submitted by the end of 2002. The entire project should be completed in two and a half years.

Jianyang Li, Patrick Harrington, and Kazimierz Borkowski of the North Carolina State University have completed a paper on the angular expansion and distance measurements of the planetary nebula BD+30 3639, using the HST two-epoch observations.

Li will present his thesis proposal defense shortly and start a thesis project on the optical scattering properties of cometary nuclei and dark asteroids, directed by Prof.A'Hearn. He will be mainly using the images from recent spacecraft encounters, with the help of ground-based photometric data to constrain the phase models of cometary nuclei and dark asteroids, and to study the regional surface scattering properties of cometary nuclei.

Scott Miller, working with Sylvain Veilleux, completed and successfully defended his thesis on ‘‘The Nature and Origin of Diffuse Ionized Gas in the Halos of Nearby Edge-On Galaxies.’’

G. Richard Murphy is currently working with Lee Mundy as part of the Evans SIRTF legacy team: ‘‘From Molecular Cores to Planet-Forming Disks.’’ He is helping to prepare data reduction and analysis tools in anticipation for the large amounts of data expected to be taken after SIRFT launches in early 2003.

Donna Pierce is working on a thesis in cometary chemistry with Prof. A’Hearn. She is examining the impact of concave surface topography on carbon monoxide chemistry in the circumnuclear coma. The results of this study will also provide a useful backdrop with which to analyze data from the Stardust, CONTOUR, and Deep Impact space missions.

David Rupke has completed the initial phase of his thesis, a study of massive outflows using absorption lines in the optical spectra of nearby ultraluminous infrared galaxies. Collaborators are his advisor, Prof. Veilleux of the University of Maryland, and Dr. Dave Sanders of the University of Hawaii. He is also involved in projects searching for warm ionized gas on the outskirts of nearby galaxies and studying ISO-selected luminous infrared galaxies with his advisor and collaborators.

Rahul Shetty is working with Stuart Vogel, Eve Ostriker, and Woong-Tae Kim investigating the structure and kinematics of gas in and around the spurs of M51. Kim and Ostriker (2002) have concluded from MHD simulations that gas flows in spiral potentials result in spur formation. Shetty, Vogel, Ostriker, and Kim are testing this theory with high resolution CO observations. Such observations will also be used to study the conditions that are favorable to star formation.

John C. Vernaleo has begun a second year research project to perform a parameter survey of relic radio galaxies using hydrodynamic simulations. The results of such a survey should be useful in guiding high resolution, three dimensional, or other more computationally expensive simulations of radio galaxies. The work is being done under the direction of Dr. Chris Reynolds.

B. Nikolaus Volgenau studies the kinematics of the early stages of stellar evolution and is particularly interested in the origin of stellar multiplicity. He is currently working on his thesis under the direction of Dr. Lee Mundy. This work involves the mapping of velocity structures of embedded cores in the Perseus molecular cloud. The velocity maps are created from emission lines of several molecular species, which trace a range of physical conditions. The goal is to ascertain the role of turbulence in the formation and evolution of embedded cores.

Kevin Walsh is completing a second year project on the tidal disruption of comet Shoemaker-Levy 9. Simulations are being run on the Beowulf cluster of computers under the direction of Dr. Richardson. The analysis will provide a very detailed model of the comet prior to its breakup and subsequent impact into Jupiter.

Yuxuan Yang started thesis research under supervision of Dr. Richard Mushotzky and Prof. Chris Reynolds from September 2001. The thesis will focus on a deep large solid angle Chandra survey of ISO Lockman Hole North-west region. The project is designed to resolve several puzzles of the x-ray sources, presumably supermassive blackholes, that make up the x-ray background. This survey is currently the only large solid angle survey useful for understanding of the so called ‘‘cosmic variance’’ of XRB, and its correlation with large scale structure of the universe. This project is in colaboration with Amy Barger (U Wisconsin) and Len Cowie (U Hawaii). Maryland/Goddard team is leading the X-ray investigation.

5. FACULTY RESEARCH

5.1 Theoretical Astrophysics

The theory group is the fastest growing part of the department, boasting three new assistant professors hired since 1999. Currently there are five professors (Hamilton, Ostriker, Miller, Richardson, and Reynolds), three postdoctoral researchers, three research scientists, and many graduate students, all of whom specialize at least part-time in theory. Research opportunities for graduate students cover a broad spectrum from solar system to extra-galactic studies, fluid dynamics to particle dynamics, and classical mechanics to general relativity.

Doug Hamilton’s research focuses on the orbital dynamics of rings, moons, and planets. Hamilton was on sabbatical at the Southwest Research Institute (SwRI) in Boulder, Colorado for the 2001-2002 academic year, but continued to work remotely with students in Maryland. Graduate student Ke Zhang and Hamilton investigated several dynamical aspects of Triton’s capture by Neptune and the subsequent evolution of its orbit. Undergraduate Amanda Proctor and Hamilton showed that two of Jupiter’s small inner satellites, Amalthea and Thebe, were forced onto tilted orbits by past resonant interactions with the massive Galilean satellite Io. Hamilton and Bill Ward from SwRI showed that the 27 degree tilt of Saturn’s spin axis is due to an ongoing interaction with the planet Neptune.

Eve Ostriker is primarily interested in star formation, the interstellar medium, and spiral galaxies. This work includes: numerical simulations of the formation of dense gaseous structures (spiral arm spurs and giant clouds) in disk galaxies by magnetic/gravitational processes, and the relation to galactic-scale regulation of star formation; quantitative characterization of the physical and kinematic structures driven by hypersonic turbulence in model molecular clouds, for relation to observed continuum and line data in giant molecular clouds; and dynamical modeling and observational interpretation of the outflows driven by jets and wide-angle winds from protostellar systems.

Cole Miller’s work focuses on compact objects and what one can learn from them about strong gravity and dense matter. He is currently collaborating with Professor Doug Hamilton, graduate student Kayhan Gultekin, and undergraduate Mia Bovill on dynamical interactions of black holes in dense stellar clusters and the properties of the gravitational waves they emit. They are in close contact with the Laser Interferometer Space Antenna group at nearby Goddard Space Flight Center. Miller is also working with postdoctoral research Sudip Bhattacharyya on modeling X-ray bursts and quasiperiodic oscillations from black holes and neutron stars.

Derek Richardson models the dynamics of small bodies in the solar system using high-performance numerical codes. Research highlights include the largest simulations of planet formation ever performed, simulations showing the origin of asteroid families and satellites from collisions and tidal disruption, detailed studies of the dynamics of Saturn's rings in preparation for the upcoming visit by the Cassini spacecraft, and even simulations of sand grains. To support his research, he has put together a Beowulf cluster of PCs capable of large-scale parallel computation. Currently he is working with graduate students Zoe Leinhardt (on fragmentation models for planet formation simulations) and Kevin Walsh (on tidal disruption of asteroids and comets). Research opportunities include code development and modeling for a wide range of interesting dynamical systems.

Chris Reynolds has been investigating the spectral and temporal signatures expected from black hole accretion disks, especially those that probe relativistic aspects of these disks and black hole spin. Part of this has involved the use of 3-D magnetohydrodynamic disk simulations which have been performed in a continuing collaboration with Dr. Phil Armitage (U Colorado). In a separate program, Reynolds has been using hydrodynamic simultations to explore the interactions of radio galaxies with the hot intracluster medium of galaxy clusters. Part of this work is being performed by graduate student John Vernaleo as part of his second year project.

Postdoc Takayoshi Sano is studying the influence of dust grains on the magnetorotational instability in protostellar disks, as well as the influence of the instability on the vertical distribution of grains. Postdoc Tom Gardiner is developing a new magnetohydrodynamics algorithm that can be used with adaptive mesh refinement methods to study a wide range of problems in astrophysics, including turbulent fragmentation of self-gravitating molecular clouds.

The theory group also includes the Computational Astrophysics Group which develops and maintains several software packages. Available software includes NEMO: a Stellar Dynamics Toolbox.

Jim Stone, currently on leave, in collaboration with postdoc Neal Turner, has been studying the effect of radiation pressure on the magnetorotational instability (MRI) in accretion disks around compact objects. Radiation can have a significant effect on the saturation amplitude and density fluctuations in the turbulence driven by the MRI. Stone and postdoc Takayoshi Sano have been studying the MRI in weakly ionized protostellar accretion disks, including the Hall effect, ambipolar diffusion, and Ohmic dissipation in the induction equation. Stone, in collaboration with John Hawley and Steve Balbus, has continued numerical MHD studies of accretion flows onto black holes. Stone has also continued collaborative studies of compressible MHD turbulence in molecular clouds with Ostriker and graduate student Jason Vestuto.

5.2 Laboratory for Millimeter-wave Astronomy

The University of Maryland owns and operates the BIMA millimeter-wave interferometric array telescope in partnership with the University of California (Berkeley) and the University of Illinois. The BIMA array, located in Hat Creek, California, operates in the 1 millimeter, 3 millimeter and 1 centimeter wavelength bands. With a maximum baseline of 1.9 kilometers, an angular resolution as high as 0.1'' can be achieved in the 1 mm band. The BIMA array has the best angular resolution and image-forming capability of any millimeter-wave telescope. The telescope provides unique observations of a wide range of objects including molecular clouds, star-forming regions, protoplanetary and circumstellar disks, the Galactic center, evolved stellar envelopes, the molecular interstellar medium in galaxies, active galactic nuclei, Sunyaev-Zeldovich absorption by clusters, comets, planetary atmospheres and surfaces, and solar flares.

Technical developments are proceeding in preparation for a merger of the BIMA array with the California Institute of Technology Owens Valley Radio Observatory (OVRO) millimeter-array. The merged array will be relocated to a higher elevation site in the Inyo Mountains of California, resulting in an order of magnitude increase in sensitivity compared to the present BIMA array. The new array is called the Combined Array for Research in Millimeter-wave Astronomy (CARMA). The Sunyaev-Zeldovich Array (SZA) under construction by the University of Chicago is also expected to join CARMA.

The University of Maryland has a 2/7 share of the BIMA array; a corresponding share of the observing time is available to student and faculty researchers at the University of Maryland. The Laboratory for Millimeter-wave Astronomy (LMA) is the organization set up by the University of Maryland to manage its participation in the BIMA project. The LMA is part of the Astronomy Department; faculty associated with the LMA include S. Vogel (director), A. Harris, M. Kundu, L. Mundy, and W. Erickson (emeritus). Also associated with the LMA are Research Scientists M. Pound, P. Teuben, S. White, and M. Wolfire, scientific staff members K. Rauch and N. Amarnath, and postdoctoral fellows M. Das, A. Gibb, and G. Petitpas. Graduate students doing work with the array included Nicholas Chapman, Raquel Fraga-Encinas, Rick Murphy, Rahul Shetty, and Nikolaus Volgenau. A BIMA summer school is held most years at the observatory in Hat Creek for interested students and postdocs; typically several students from Maryland attend. Further information on BIMA and the LMA can be obtained at the BIMA web site, http://bima.astro.umd.edu.

5.3 The Goddard Connection

NASA's premier laboratory for astrophysics, Goddard Space Flight Center is located approximately 5 miles east of the University of Maryland campus. This is a world-class facility with an astrophysics program much larger than the University's. The Astronomy Department has a close working relationship with a number of the laboratories in the Goddard Space Sciences Directorate. In particular cooperative agreements exist with the ''Laboratory for High Energy

Astrophysics,'' and the ''Laboratory for Extraterrestrial Physics.'' These agreements allow a number (approximately 15) of our University of Maryland research faculty to work on site on exciting joint research projects. There are also a number (approximately 5) of Department of Astronomy graduate students pursing PhD thesis projects on site at any given time. For the most part astrophysical research at Goddard is based on a wide variety of satellite and balloon projects which span the entire extent of astronomy. In recent years thesis topics have included X-ray and gamma-ray emission from galaxy clusters, active galactic nuclei, black holes, neutron stars and supernova remnants. Summer internships are offered regularly to afford students the opportunity to explore research at Goddard without making a long-term commitment. A number of our teaching faculty have close collaborative relationships Goddard scientists. Among these are Assistant Prof. Cole Miller (High Energy Astrophysics, Gravitational Radiation), Assistant Professor Chris Reynolds (X-ray Astrophysics and Active Galactic Nuclei), Prof. Dennis Papadopoulos (Space Plasma Physics) and Prof. Marvin Leventhal (Gamma-Ray Astrophysics). Several Goddard Scientists are also Adjunct Professors in the Astronomy Department. They are, Dr. Nicholas White (Director of the Laboratory for High Energy Astrophysics), Dr. Richard Mushotzky (X-ray emission from galaxies and clusters of galaxies), and Dr. Neil Gehrels (Gamma-Ray Bursts). There is also the annual October Astrophysics Conference, co-arranged by the Astronomy Department and scientists at Goddard, that concentrates on a single topic in astrophysics each year. The topic for 2002 is ''The Emergence of Cosmic Structure.'' The conference runs for several days on the University campus and attracts of order 200 international scientists. During the course of the academic year scientists and students are encouraged to attend seminars and colloquium at both institutions. It is also worth noting that Goddard scientists regularly teach courses in the Astronomy Department.

The newly appointed assistant professor, Dr. Christopher Reynolds, is the first faculty member to be directly sponsored by the UMCP-GSFC cooperative agreement. A major component of his current research efforts is devoted to a detailed exploration of AGN central engine structure using high-quality X-ray spectra. In a continuing collaboration with Joern Wilms (Tuebingen, Germany), he is performing a detailed analysis of XMM-Newton data for the Seyfert galaxy MCG-6-30-15 — they hope to be able to diagnose time-dependent properties of the accretion disk within the immediate vicinity of the black hole (preliminary results from these data have been published as a MNRAS pink page; first author Wilms). Reynolds has recently started working with UMd-Physics graduate student Mr. David Garofalo on some theoretical models of accretion disks that are relevant to these data. He is also the lead investigator on a recent XMM-Newton observation of the Seyfert galaxy NGC4593, which was performed simultaneously with observations by HST-STIS, RXTE, and ground-based optical telesopes in Chile. With this extremely rich dataset, Reynolds and his collaborators will be able to examine the broad-band spectral energy distribution of this AGN, the physics of the UV/X-ray absorber, and the relativistic accretion disk.

Reynolds is also continuing his work on the impact that radio-loud AGN have on their host galaxies and galaxy clusters. As part of a second year project, Mr. John Vernaleo (a UMd-Astronomy graduate student) is running a set of 2-dimensional hydrodynamical simulations aimed at exploring the environmental impact of a radio-galaxy as a function of its power and on-time. These simulations will provide important parameters needed for semi-analytic models of galaxy and cluster evolution. In addition to this parameter survey work, Reynolds and Vernaleo plan to perform more detailed simulations aimed at exploring the effects of 3-D, magnetic fields, and thermal conduction. Finally, these simulations will be compared with X-ray data from the Chandra observatory, which allows one to directly image the interaction between a radio-galaxy and the X-ray emitting intracluster medium. Reynolds is the principal investigator of a recent (mid-Sept 2002) Chandra observation of the environment of 3C401 which will allow the jet/intra-cluster medium interaction to be studied.

5.4 Comets and Asteroids, Deep Impact, and the Small Bodies Node

Dr. Mike A'Hearn is Principal Investigator for the Deep Impact mission. This is a NASA-funded Discovery class mission to chase down periodic comet Tempel 1, throw half a ton of copper at it, and observe both the crash and the crater created. Scheduled for launch in January 2004 with comet impact in July 2005, Deep Impact will provide unique opportunities to study both the interior and exterior composition of the comet. The mission passed Critical Design Review in January 2002 and is not in Integration Testing.

In addition to the research opportunities, other Deep Impact collaborations are planned. For example, the Small Telescope Science Program, supported on campus by Research Associate Stephanie McLaughlin, will coordinate the efforts of amateur and professional astronomers to observe Tempel 1; and Dr. Lucy McFadden is collaborating with the Fiske Planetarium at the University of Colorado to support a Deep Impact-specific planetarium show.

Although the data-taking part of the Near Earth Asteroid Rendezvous (NEAR) Mission ended in 2001, the data analysis program has only just gotten underway. Dr. McFadden is part of the team that recently completed analysis of the NEAR infrared spectra and prepared the results for publication. Dr. McFadden is also a Co-Investigator in the recently selected DAWN mission, a NASA spacecraft that will rendezvous with two of the largest asteroids Ceres and Vesta, in the coming decade.

Data from completed missions also play a significant role in planning for future missions and analyzing data return. NASA's Planetary Data System (PDS) is the designated archiving and distribution center for data from previous and current NASA missions and is a prime consultant for planning data handling for upcoming missions. The Small Bodies Node of the PDS, located here in the Astronomy Department under the direction of Drs. Mike A'Hearn and Ed Grayzeck, is deeply involved in preparations for the Deep Impact and CONTOUR missions and is revising and upgrading the recently received NEAR mission archive. In addition, the SBN has undertaken a restoration of the VEGA spacecraft MISCHA data taken during the mission to comet Halley and is mining the archives of the Hubble Space Telescope for comet and asteroid observations.

While the principal task of the Small Bodies Node is to archive and distribute data (space-based and ground-based), the SBN also uses its expertise and facilities to support the collection of new and significant research data sets. SBN personnel are collaborating with Dr. Mark Sykes at the University of Arizona (Tucson) to develop an automated system for collecting ground-based spectra and supporting documentation from observers through a web-based form. Mathew Knight, a graduate student here at UMD, is collecting SOHO observations of sun-grazing comets into a single, archivable set for further research.

In fact, access to these mission and ground-based data sets enhances the research and collaboration opportunities for both faculty and graduate students, Matthew Knight will be working with Drs. A'Hearn and Doug Hamilton to analyze the SOHO comet data. Other graduate students and their projects include Donna Pierce, who is working with Dr. A'Hearn on the chemistry of cometary coma; Jianyang Li, also working with Dr. A'Hearn on the scattering function of comet nuclei and dark asteroids; and Jian Chen is working with Dr. Carey Lisse to develop a model for the dynamic evolution of cometary dust.

The proximity of Goddard Space Flight Center (GSFC) provides additional opportunities. Graduate student Kelly Fast is working with Dr. A'Hearn on campus and Dr. Ted Kostiuk at GSFC, studying Martian ozone.

C. M. Lisse, with Mike A'Hearn, continued to expand the IR statistical survey of cometary dust and nuclei. Trends in dust emission by dynamical class and comet age were found, and a comparison to the literature database of previous observations to test the statistical signifigance of the results supported the findings.

C. M. Lisse, with Damian Christian (JHU/FUSE) and Konrad Dennerl (MPE, Germany) continued to observe cometary x-ray emission with Chandra and XMM. The initial finding of line emission from comet LINEAR S4 has been confirmed. A search for high resolution line structure was attempted with the Chandra LETG grating, and for high spatial resolution with rapid imaging using the ACIS array. results of these new observations are pending. The first detection of x-ray emission from Venus was found using Chandra, and shown to be due mainly to scattering of solar x-rays, unlike the charge exchange driven emission from comets.

C. M. Lisse, with A. Schultz (STScI) and Y. Fernandez (UH, formerly UMD), found a new IR bright, optically faint IR source, LSF1, 7'' SW of the Vega-like system HD155826. This system, which had the most extreme 12 - 60 colors in the Aumann 1984 IRAS catalogue of Vega-like objects, has now been shown to consist of a normal G-type star; the long-wavelength IR emission found by IRAS arises from LSF1, which is most probably an extreme carbon star or a Type II YSO. A. Suchkov (STScI), A. Schultz (STScI), and C. M. Lisse demonstrated a new, simple method of searching F-type stars in the Rho Oph association using ubvy and near-IR colors for the presence of circumstellar dust. Of some 500 candidate systems, some 23 disk systems were found.

C. M. Lisse and D. W. Wellnitz continued to support the Deep Impact Discovery Mission project through the Integration and Test Phase of the mission.

5.5 Galaxies and the Universe

Prof. McGaugh is currently focusing on trying to understand the apparent coupling between dark and luminous mass in spiral galaxies. This is related to the cusp-core halo structure controversy and has a number of striking ramifications for galaxy formation theory. His work also includes observations and analysis of galaxies with low surface brightness and their implications for dark matter or dark matter alternatives.

Dr. Sage is working on a comprehensive study of the gas (CO, HI, and X-ray emitting) and dust (sub-mm emission) contents of lenticular or SO galaxies.

In collaboration with D.-C. Kim (Seoul National U.) and D.-B. Sanders (U. Hawaii), Veilleux recently published the results from a large optical and near-infrared imaging study of the 1-Jy sample of ultraluminous infrared galaxies (ULIRGs). This is the culmination of a research effort started more than seven years ago. Trends between merger phase, infrared colors, and the presence of an AGN were detected. Objects with ''warm'' quasar-like infrared colors show signs of AGN activity and are generally found in advanced mergers, based not only on the apparent nuclear separation but also on the morphology of the tidal tails. The hosts of ULIRGs show a broad range in luminosity, size, and surface brightness with considerable overlap with the hosts of quasars. These results suggest that the evolutionary sequence ''cool'' ULIRGs ⇒ ''warm'' ULIRGs ⇒ quasars applies to at least some (though admittedly probably not all) ULIRGs and quasars. Veilleux and collaborators are now currently investigating the properties of ULIRGs at larger redshifts.

Veilleux, G. Cecil (UNC), J. Bland-Hawthorn (AAO), P. L. Shopbell (Caltech) and Maryland graduate students Rupke and Miller have continued their multiwavelength survey of nearby galaxies to quantify the effects of star formation and nuclear activity on the surrounding environment. Over the past two years, they have focused their attention on obtaining very deep narrow-band optical images of normal, starburst and active galaxies using the Taurus Tunable Filter (TTF) on the Anglo-Australian Telescope. This unique instrument has allowed them to probe the environment of nearby galaxies down to unprecedented flux levels (about an order of magnitude fainter than that of published data). In active and starburst galaxies, they find ionized filaments which often extend out to several tens of kpc, sometimes beyond the H I edge of the host galaxy. Filamentary complexes are seen extending a few kpc above and below the disks of normal star-forming galaxies. Both the mass and extent of the extraplanar material in these galaxies appear to be correlated with the local surface density of star formation activity in the disk. Emission-line ratio maps constructed from multi-line imaging of these objects reveal line ratios which are not H II region-like. A detailed spectroscopic analysis of the results on normal disk galaxies suggests that the extraplanar gas is primarily photoionized by the highly diluted and filtered radiation from OB stars in the disk. However, the effects of a secondary source of ionization are visible in several galaxies (this is part of Miller's Ph.D. thesis). In active galaxies, the primary source of ionization of the extended nebula is either the AGN itself or shock excitation. Multi-line imaging slightly shifted in velocity space provides strong constraints on the kinematics of the warm ionized gas. In all cases studied so far, the gas appears to be bound to the host galaxy.

Using the technique of tunable-filter imaging described above, physics graduate student David Rupke and Veilleux designed a new method to search for galactic winds in nearby and distant galaxies using the large excitation contrast between the disk of the host galaxy and the wind material. This technique represents a promising new way to identify wind galaxy candidates before undergoing more time-consuming spectroscopic follow-ups.

G. Cecil (UNC), J. Bland-Hawthorn (AAO), and Veilleux recently published a paper describing the results of an analysis of data obtained with Chandra of the nearby galaxy NGC 3079 and its spectacular superbubble. The exquisite spatial resolution of Chandra allowed them to resolve the fine structure of the superbubble and compare the results directly with their HST data and superwind models. This comparison allowed them to better constrain the density of the superbubble and therefore its energetics.

Under the supervision of Veilleux, physics graduate student David Rupke is continuing his study of galactic winds at small and large redshifts in an effort to evaluate their impact on the environment. Several runs on the Keck II and KPNO/Mayall 4-meter telescopes have been used to acquire high-quality spectra to look for and study the blueshifted Na ID absorption line feature in these objects. A paper summarizing the results so far on the low-redshift galaxies was recently published in the Astrophysical Journal.

A. S. Wilson, in collaboration with Maryland postdocs A. J. Young, D. A. Smith, and Y. Terashima and graduate student Y. Yang, has continued X-ray studies of active galaxies with the Chandra X-ray Observatory. Work published recently includes Chandra imaging-spectroscopy of the radio galaxies Pictor A, Cygnus A and M87, the Seyfert galaxies Circinus, NGC 1068 and NGC 4151, and the low luminosity active galaxies M51 and NGC 4258. Studies have also been made of the X-ray emission from the intracluster medium (ICM) around Cygnus A and M87 (i.e. the Virgo cluster). In both cases, we find evidence of significant power being deposited into the ICM by the radio jets and lobes. In Virgo, there are depressions in the X-ray surface brightness corresponding to the inner lobes, but no evidence of shock-heated gas surrounding them. A previously known arc in the X-ray distribution corresponds to a large-scale ridge in the radio image. Lastly, there are also at least two approximately circular (centered near the nucleus) ''edges'' in the X-ray brightness distribution, the radii of which are slightly larger than the nuclear distances of the inner radio lobes and intermediate radio ridges, respectively. We speculate that these discontinuities may be spherical pulses or ''fronts'' driven by the same jet activity as is responsible for the radio structure; such pulses are found in recent numerical simulations. These results provide good evidence that the nuclear activity affects the ICM. We show that the gas in the arcs is cooler than, and probably over-pressured with respect to, the ambient ICM. The metal abundances of the cooler gas in the arc are somewhat enhanced relative to the ambient ICM, favoring a ''buoyant plume'' origin for the X-ray arc, in which ambient gas near the nucleus is entrained by buoyant radio plasma and carried to larger nuclear distances. In Cygnus A, the dominant gaseous structure is prolate spheroidal, a structure which apparently represents intracluster gas which has been swept up and compressed by a cavity inflated in this gas by relativistic material which has passed through the ends of the radio jets. The limb-brightened edges of the cavity are slightly hotter ($\simeq 6$ keV) than the inner part of the undisturbed cluster gas itself, presumably as a result of heating by a bow shock driven by the expanding cavity into the ICM. Current work is devoted to an exploration of the dynamics of the cavity which will allow, for the first time, the true power of the jet in Cygnus A to be derived.

Wilson, in collaboration with a team led by L. Colina, made the first detection ever of a supernova in the nuclear region of a galaxy with a luminous, QSO-like nucleus. The detection was made in the radio band, allowing obscuration and confusion with the nuclear activity to be overcome. S. Immler, Wilson & Terashima have detected SN 1994I in M51 with Chandra, which represents the first unambiguous X-ray detection of a type Ic supernova. Assuming the X-ray emission arises from shock-heated circumstellar material, the mass-loss rate of the pre-supernova star can be derived. By combining the results with a tentative earlier X-ray detection by ROSAT, we infer a constant mass-loss rate and a constant wind velocity for the pre-supernova progenitor.

Wilson prepared invited papers on ''The effect of radio galaxies on cooling flows'' and ''Chandra X-ray studies of extragalactic jets '' for the annual U. K. National Astronomy Meeting, held at Bristol in April 2002.

Smith and Wilson have observed the non-nuclear compact X-ray sources in the spiral galaxy NGC 1068 with *Chandra*. The general association of a class of objects called ultraluminous X-ray sources (ULXs) with regions of ongoing star formation makes NGC 1068 a particular interesting target, since it is one of the most luminous starbursts in the local universe. We detect five sources with isotropic X-ray luminosities (after correcting for absorption) exceeding 10^{39} erg s^{-1}, considerably higher than he Eddington luminosity of a 1.4 neutron star. The brightest compact source in NGC 1068 has a spectrum which is much harder than that found in Galactic black hole candidates or other ULXs, and may indicate the presence of inverse Compton scattering of synchrotron photons in a jet, or other physical processes such as complex absorption. The ratio of the number of sources with isotropic luminosities above $\simeq 2.1\times 10^{38}$ erg s^{-1} (i.e., sources with luminosities exceeding the Eddington limit for a $1.4\,M_{\odot}$ neutron star) to massive ($\gtrsim 5\,M_{\odot}$) star formation rate, as estimated from the 40–120μm far-infrared luminosity, is within a factor of two for our sample of spiral galaxies, so supporting the association of black hole X-ray binaries with ongoing star formation.

Using a *Chandra* observation of the radio galaxy Cygnus

A, Smith and Wilson, in collaboration with Terashima, Arnaud, and Young, studied the X-ray emission from the cluster of galaxies, the prolate limb-brightened cavity inflated in the intra-cluster medium by relativistic particles in the radio jets, and the curved bands that run across the cavity and appear to be the projections of ''belts'' of gas. The temperature of the X-ray emitting intra-cluster gas drops from $\simeq 8$ keV more than 100 kpc from the center to $\simeq 5$ keV some 80 kpc from the center, with the coolest gas immediately adjacent to the radio galaxy. There is a metallicity gradient in the X-ray emitting gas, with the highest metallicities ($\sim$ solar) found close to the center, decreasing to ~ 0.3 solar in the outer parts. We have used the assumption of hydrostatic equilibrium to derive a total cluster mass within 500 kpc of $2 \times 10^{14} M_{\odot}$ and $2.8 \times 10^{14} M_{\odot}$, and a gas fraction in the cluster within 500 kpc of 0.055 and 0.039 for a constant and centrally decreasing temperature profile, respectively. The limb-brightened edge of the cavity is hotter than the innermost region of the cluster gas, indicating heating by the expanding, jet-driven cavity, while the ''belts'' of X-ray emission are cooler. The ''belts'' may be cooling gas breaking through the cavity and eventually fuels an accretion disk around the black hole at the center of the radio galaxy. Alternatively, the ''robustness'' of the cavity in the equatorial regions may be lower than near the hot spots, allowing cluster gas to break into the cavity as a result of Kelvin-Helmholtz or Rayleigh-Taylor instabilities. Within the cavity, there is evidence for diffuse X-ray emission, in addition to the X-ray emission related to the jets and hot spots.

The main focus of Andrew Young's research over the past year as been the analysis of Chandra observations of active galaxies and clusters of galaxies in collaboration with Andrew Wilson, David Smith and Yuichi Terashima. In particular, he has studied (i) the heavily absorbed nucleus of Cygnus A and the spatially extended soft X-ray emitting gas around it, and (ii) the hot intra-cluster medium of the Virgo cluster in which we see large plumes of cold, metal rich gas that may be trailing behind bubbles of plasma inflated by M87's jet, and are buoyantly rising out of the cluster. With collaborators in Cambridge, UK, Andrew has also been studying a very deep XMM-Newton observation of the Seyfert 1 galaxy MCG−6-30-15, an object famous for its relativistically broadened and skewed iron X-ray emission line. Andrew is presently working on Chandra observations of jets and hot spots in a number of radio galaxies, and Chandra observations of the nucleus of the low luminosity AGN NGC 4258.

5.6 Solar Radio Physics

The solar radio physics group consisted of Drs. Kundu, White, Garaimov, and Grechnev. Their work was centered around four areas.

5.6.1 Observations and Models of Flaring Loops

Using the imaging data obtained with the VLA and the Nobeyama Radio Heliograph (NoRH) at 5, 15, 17 and 34 GHz the group investigated the structure of coronal magnetic fields during flares. We compared the observations with calculations of gyrosynchrotron emission from an inhomogeneous magnetic loop in order to determine the conditions in the flaring loop. The absence of electrons above 210 keV is necessary in this model to explain why no emission is observed from the loop top at 15 GHz. This model reproduced well the high frequency radio spectrum as well as the VLA spatial structure. We also used NoRH 17 and 34 GHz along with Yohkoh/SXT, HXT and magnetic field data which provide important constraints on model input parameters. The SXT images give the morphology of the flaring loop. We choose a set of parameters so that the model loop visually resembles the observed SXT flaring loops. Using the constraints on electron energy spectral index from HXT and magnetic field data and a loop thickness of about 2'' we easily reproduce the observed morphology of flares at 17 and 34 GHz.

5.6.2 Microwave Spatial Structure of Flaring Regions: Interaction of Loops Causing Flares

We have detected a class of microwave flares in which the NoRH images show that at 17 GHz a compact brightening occurs at the main flare site as well as a brightening near a remote region of opposite polarity. The main flare site is the location of an emerging flux whose interaction with an overlying loop results in the onset of flares; it is the site of enhanced soft X-ray brightening. The 17 GHz brightenings in the remote sources (separated from the main flare sites by about 10^5 km) are delayed by some fractions of a second, implying that high energy electrons produced at the main flare site propagated over to the remote site.

5.6.3 Energetic Electron Populations in Solar Flares

Millimeter interferometers are sensitive enough to detect MeV-energy electrons even in small flares, and that they are commonly produced in flares of all sizes. MeV-energy electrons often seem to be different populations than the hard X-ray emitting electrons. We also studied the spatial structure of sources of a class of radio bursts with simple spiky time profiles found to be common at millimeter wavelengths. These bursts are of short duration, with a fast 2-4 sec rise times followed by a rapid exponential decay. When mapped at high spatial resolution with the Nobeyama Radio Heliograph (NoRH), the radio images show direct evidence that the radio sources are compact bipolar loops with source sizes less than 5''.

5.6.4 Radio Searches for Diagnostics of Magnetic Reconnection in Solar Flares

Magnetic reconnection has always played a key role in solar flare models since the early days. Specifically it has been proposed that magnetic reconnection in current sheets is the primary energy source in solar flares. However, providing direct evidence of reconnecting current sheets is not easy and most observations in the past in all spectral domains have been necessarily interpretative. The strength of radio lies in its sensitivity to energetic electrons traveling on coronal magnetic fields: such electrons radiate strongly via the gyrosynchrotron mechanism, whereas they only produce bremsstrahlung hard X-ray photons when they encounter high-density plasma. Nonthermal electrons trapped close to a neutral sheet may well produce observable radio emission even when their hard X-ray emission is weak. We clearly cannot resolve current sheets but may be able to detect macroscopic signatures at NoRH resolution associated with them. We have identified several flares in the NoRH archive in which there is possible evidence of magnetic reconnection in the radio domain. In one specific event, the microwave imaging observations (NoRH data) as well as SXT images show two apparently intersecting loops, at the intersection point there seems to be a bright microwave blob whose brightness temperature is much higher than one expects just from the alignment of the intersecting loops. We believe that this is the reconnection region. It has all the properties generally attributed to a reconnection region in soft X-rays.

5.7 Space Plasma Physics

The space plasma physics group consists of Drs. Goodrich, Guzdar, Lyon, Milikh, Papadopoulos, Sha, Sharma, and Sitnov and physics department graduate students Merkine and Ukhorskiu.

5.7.1 Nonlinear Dynamics and Complexity

The magnetosphere, like many systems in nature or laboratory, exhibit complex behavior, arising from the inherently nonlinear and dissipative properties. Analysis of the observational time series data of the magnetosphere using the techniques of nonlinear dynamical systems has shown that its dynamics have a component that is low dimensional, and thus its behavior can be predicted. This is the first large scale natural system which exhibits low dimensional behavior. For specified solar wind conditions these techniques can predict the occurrence and intensity of magnetic storms and substorms, and can be used as a forecasting tool for space weather. Along with the global and low dimensional features the magnetosphere also exhibits multi-scale features characterized by a power law of the scales present. The presence of the global and multi-scale properties can be reconciled in a comprehensive model based on phase transition physics. The global or low dimensional behavior corresponds to the well known first order phase transitions and the multi-scale behavior to the scale invariance properties at second order phase transitions. A new data-derived model STADY combines the dynamical features to predict the global behavior and the multi-scale features to compute the conditional probabilities of extreme events based on statistics.

5.7.2 Global MHD Simulations of Solar Wind - Magnetosphere Coupling

Numerical modeling is crucial to the understanding of space plasmas, and a range of different simulation codes are needed to model different phenomena. The dynamics of the magnetosphere in full three dimensions is carried out using a magnetohydrodynamic (MHD) model, a state of the art global scale code that utilizes the computing power of modern supercomputers. This code can simulate the magnetospheric conditions from spacecraft measurements and thus provide a comprehensive picture of the response to the solar wind variations. The global MHD code has been used to simulate key events of interest. Simulations of the Earth's magnetosphere on Feb 9-10 1995 for northward interplaneetary magnetic field and comparison of the lobe field with Geotail observations have helped identify the solar wind conditions under which the magnetosphere remain relatively quiet. On the other hand the simulations of the 10 January 1997 magnetic storm represent an extreme case. For this case a model was developed to calculate the perturbed magnetic field at ground magnetometer stations and these were compared with the actual data. The polar cap potential is one of the key features that identify substorms and the ability to reproduce their observed behavior is one of the important issues of simulations. The MHD code was used to identify the main reasons for the saturation of the plor cap potential. The phase transition like behavior of magnetospheric substorms was studied using the data from global MHD simulations that required hundreds of hours of supercomputer time. The global nature of substorms showed characteristics of phase transition of the first order and the multi-scale behavior was quantified in terms of power spectral index and a critical exponent.

5.7.3 Magnetic Reconnection in Collisionless SpacePlasmas

Magnetic reconnection is one of the key plasma processes in astrophysics and space physics. The release of energy in stressed magnetic field configurations into plasma energy is marked by very short time scales, and leads to many important observable events. In space physics this energy release is the cause of the visible auroras and many observations in space as well as ground. In terms of plasma processes magnetic reconnection is collisional plasmas are well understood. However in collisionless systems, such as Earth's magnetosphere, the processes leading to magnetic reconnection has been one of the most controversial subjects. Reccently there has been advances in the understanding of the rate of reconnection but its onset has eluded plasma physicists for many decades. The main difficulty has been the complicated particle trajectories in the stressed magnetic configurations in which the reconnection take place. The analytical methods have not been able to treat stability problem adequately and particle simulations have lacked the supercompter power and sophistication to resolve the small scales in space and time relevant for the plasma processes in play.

A combination of analytical techniques and computational tools have been used to resolve the problem of reconnection onset. A careful analysis of the particle distributions, which recognizes self-consistently the existence of trapped and passing electrons have been shown to destabilize the tearing mode, crucial for the onset of reconnection. The stability of the tearing mode have been debated for two decades and this result is an important landmark in the understanding of reconnection onset in complex magnetic field geometries. This process is currently under study using particle simulations.

5.7.4 Modeling Ionospheric Processes

The ionosphere is the region where many consequences of the solar wind energy and momentum coupled to the magnetosphere are manifested, e.g., the visible auroras. The ionospheric processes in the global MHD code are modeled through a parametrized model of the ionospheric conductivity. New techniques for coupling the effects of plasma instabilities to the global MHD code have been developed by building models of their saturation and these techniques have led to improvements in the agreement between the simulations and observations.

The interaction of powerful radio emissions with the ionosphere leads to numerous physical processes and these have been modeled using a two-dimensional and fully nonlinear code. This code yields the spatio-temporal development of the thermal self-focusing instability of high-power radio waves in the ionosphere. In one of the cases studied in detail, the heater wave equation is coupled with an equation for the electron temperature, and with an electron density equation. The model describes the spatial spectrum of temperature and electron density irregularities along with their temporal behavior. The heating also generates low frequency waves (ELF) when the radio waves are modulated. The model results agree with the first observations of the ELF emission generated by the modulated ionospheric radio wave heating using the HAARP facility. These results imply that the polarization of the artificial ELF emission can be controlled by changing the frequency or polarization of the radio wave. A new class of ionospheric heating experiments have been recently initiated. In these experiments the frequency of the transmitted signals exceeds the critical plasma frequency of the F-peak. The HF radiation is received by detector on the WIND satellite, which reveals the spiky structure of the signal. These were explained using a theoretical model that combines the effect of irregularities in the ionosphere with diffraction analysis in the wave propagation after encountering the F-peak.

5.8 And All the Rest

The department also has ongoing research on planetary nebulae (Harrington), stellar abundances (Balachandran), history and sociology of astronomy (Trimble), and other topics which you can find out about by visiting us in person or on the web.

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Virginia Trimble and Susan Lehr