# Pennsylvania State University
# Astronomy and Astrophysics
*University Park, Pennsylvania 16802-6305*

This report covers the period from September 1, 1995 to August 31, 1996.

## 1. PERSONNEL

### 1.1 Faculty

The regular members of the faculty during the academic year 1995-1996 were Professors Peter Mészáros (Department Head), France Córdova (on leave as NASA Chief Scientist), Eric Feigelson, Gordon Garmire (Evan Pugh Professor), Lawrence Ramsey, Douglas Sampson, Peter Usher, Daniel Weedman, and Aleksander Wolszczan; Visiting Professor George Pavlov; Associate Professors Robin Ciardullo, Donald Schneider and Richard Wade; Assistant Professors Matthew Bershady, Jane Charlton, Pablo Laguna and Louis Winkler; and Senior Research Associate/Associate Professors David Burrows and John Nousek.

James Beatty, Associate Professor of Physics, as of Fall 1995 holds a joint appointment as Associate Professor in Astronomy & Astrophysics. Curt Cutler, Assistant Professor of Physics and a researcher in the Center for Gravitational Physics and Geometry, as of fall 1995 holds a joint appointment as Assistant Professor of Astronomy & Astrophysics.

Research Associates in the program were George Chartas, Margaret Chester, Marcos Diaz, Audrey Garmire, Zhiyu Guo, Scott Horner, Ron Kollgaard, James Neff (also a member of the Graduate Faculty), Philippos Papadopoulos, Mark Skinner, Guy Stringfellow, Leisa Townsley, Robin Tuluie, and Alan Welty. Chester was appointed Visiting Assistant Professor of Physics at Bucknell University for the 1995-96 academic year. Joining the department as Research Associates are Christopher Churchill (formerly of the University of California–Santa Cruz, Lick Observatory), Eugene Moskalenko (formerly of the University of Wisconsin–Madison), Hans Peter Nollert (formerly of the University of Tubingen), Jerome Orosz (formerly of Yale University), and Frederick Ringwald (formerly of Planetary Science Institute).

Adjunct Associate Professors include Richard Griffiths at the Space Telescope Science Institute and Hans Kraus at the Oxford University Nuclear and Astrophysics Laboratory.

### 1.2 Visitors to the Department

Visitors to the department included William Krivan and Juergen Zimmerman (of the University of Tubingen) working with Pablo Laguna; István Horváth from the Central Research Institute for Physics, Budapest, Hungary, and Andrei Bykov from A.F. Ioffe Institute of Physics & Technology at the Russian Academy of Sciences, working with Peter Mészáros; Randy McKee from Ithaca College, as a summer instructor; Soma Mukherjee from the Indian Institute of Technology, India, and Wolfgang Brinkmann from Max-Planck Institut fur extraterrestrische Physik, working with Eric Feigelson; and Colleen Hartman, Goddard Space Flight Center, working with Richard Wade and Alan Welty. Dr. Bohdan Paczynski from Princeton University presented the 1996 Marker Lecture Series in April, with the general title of Gravitational Microlensing and the Search for Dark Matter.

## 2. ACADEMIC PROGRAM

### 2.1 Graduate and Undergraduate Majors

Thirty graduate and seventy-one undergraduate astronomy majors were enrolled during the academic year 1995-96. During that time eleven B.S. degrees and two M.S. degrees were awarded in Astronomy & Astrophysics. M.S. recipients were Christopher Baluta and Sara Maene.

### 2.2 Educational Initiatives

The Department continues as a Site for NSF's Research Experiences for Undergraduate program (Chester, PI and Ramsey, Co-PI). The Site Grant provides stipend and travel support for undergraduates to participate in research with faculty members. Five undergraduates from other colleges and universities were fully supported by the Site Grant, and three Penn State students received partial support. These eight students (and additional Penn State students supported under individual faculty research grants) participated in a variety of group activities. These included a colloquium series given by faculty and visiting scientists, a workshop on Modern Detectors and Observational Techniques, and an observing trip to the NRAO at Green Bank.

The Department inaugurated the Penn State Inservice Workshops in Astronomy in Summer 1996. The Workshops are designed to improve the knowledge and skills of middle- and high-school science teachers in astronomy. Seventeen high-school teachers, most from rural Pennsylvania, took two summer courses covering planets, stars, galaxies and cosmology. In addition to regular classes, teachers experienced many hands-on activities, heard guest lectures on forefront research and teaching methodology, and prepared lesson plans to share with their fellow workshop participants. The Workshops were led by Professors Usher, Weedman, and Winkler and were coordinated by Feigelson. See http://www.astro.psu.edu/outreach/psiwa for further information.

### 2.3 Outreach

The Astronomy Club entered its twenty-third year of service to the University and the local community, continuing its series of monthly Open Houses, and organizing trips, star parties, and other activities. It publishes a newsletter, *The Nittany Observer*, with a variety of excellent articles by Club members, graduate students, and faculty. The Club's Open Houses attract hundreds of visitors each semester to the roof of Davey Laboratory where the Departmental telescopes are housed. In addition, the Club makes available some of its own telescopes, and gives shows using the Department's planetarium. Usher is the Club's Faculty Advisor.

The department offered numerous lectures by faculty to Penn State alumni groups throughout the nation, as well as locally to civic and educational organizations, student groups and clubs, etc. The outreach committee hosted around 25 different scheduled tours for K-12 groups with their teachers, including planetarium demonstrations, under the coordination of graduate student Darren Williams. With the participation of a number of faculty and graduate student volunteers, it also scheduled a number of public lectures and demonstrations coinciding with events of public interest. For example, more than 300 people attended a ''Parent's Night'' open house last year, and nearly 1000 people visited a Davey Laboratory roof lecture and observing session one evening when Comet Hyakutake was visible.

## 3. RESEARCH ACTIVITIES

### 3.1 Instrumentation for Observing

#### *3.1.1 Optical*

agraphThe Hobby-Eberly Telescope

1995/1996 is the final year for the construction of the Hobby-Eberly telescope (HET). The building and all major structures were completed by early 1996. Since March 1996 the telescope has been in systems integration with cabling and electronics fleshing out the structural elements. There have been two major milestones this year. The first three mirror segments out of the 91 total were installed in late June. In September the tracker was finally delivered, thus putting in place the last item needed for first light. While the six month delay in the tracker delivery has set us back, the excellent in-factory acceptance test results give us a high degree of confidence that this vital element will come on line quickly. We expect first light sometime before the end of 1996.

There are currently seven segments in the telescope. The number of mirrors installed for first light will be between seven and eleven. The number of mirrors installed during this phase is determined by the need to test the mirror alignment system and to provide enough light to allow acquisition and tracking of bright stars for early engineering tests. Plans call for the mirror complement to grow to 21 by January, reach 66 by April and to have the full 91 installed by August 1997. Clearly the HET will be scientifically useful before all the mirrors are installed; the 66 mirror milestone in April will give us the collecting area of an 8 meter telescope!

With first light very close, the HET scientists are focusing on how best to utilize the telescope. After first light we expect the telescope to be in an intensive engineering test and evaluation phase for several months. After that we are planning to enter a science commissioning phase. That is expected to begin in March 1997 when about 10% of the time is anticipated to be available for early science observations. Our current plans call for the available time to ramp up to 50% by late summer 1997. During this commissioning time selected HET scientists will conduct observations chosen to exercise the telescope capability as well as to provide some scientific return. The serious delay in funding for the HET facility instruments leaves us without a facility instrument during the commissioning phase. This gap will be filled by an upgraded version of the Fiber Optics Echelle that was resident at KPNO from 1987 to 1996. This Upgraded Fiber Optics Echelle (UFOE) is currently being tested at Penn State (see below). Current planning has the commissioning phase ending with the installation of the first facility instrument in late 1997.

The major achievement this past year was to secure funding for the initial complement of HET facility instruments. As reported last year, we will have three facility instruments: a low resolution ($R=\lambda/\Delta\lambda\sim500-2000$) multi-slit focal plane spectrograph (LRS), a fiber coupled, medium resolution ($4000<R<20{,}000$) spectrograph with multi-object capability (MRS), and a high resolution ($30{,}000<R<120{,}000$) spectrograph (HRS), also fiber coupled. All these instruments have well-developed concept designs that were reviewed jointly in May 1996. The LRS is being funded by UT Austin, Stanford University and the University of Munich. Capital cost run about $700,000 for the LRS; Dr. Gary Hill from UT Austin is the instrument PI. LRS delivery to the site is planned for late 1997. The MRS is funded by the NSF ($1.1 million) and Penn State ($340,000) with Ramsey as the PI and Horner as instrument scientist. The MRS delivery is currently planned for first quarter 1998. The HRS is also funded in part by NSF ($600,000) with the remaining fraction of the estimated $1.8 million cost contributed by UT Austin. The HRS delivery is planned for third quarter 1998. In return for the NSF funding, the HET universities will make observing time available to the US community beginning in 1998.

The Hobby-Eberly telescope is an international collaboration between the University of Texas at Austin, The Pennsylvania State University, Stanford University, Ludwig-Maximilians-Universitaet Muenchen, and the Goerg-August-Universitaet Goettingen. For more information on the HET, its science programs or partnership contact L. Ramsey, HET project scientist, at lwr@astro.psu.edu. The latest information and picture can be view at http://www.astro.psu.edu/het/.

With the HET coming on line in the coming months, the Penn State Optical and Near IR (OIR) instrumentation team has focused this last year entirely in the design and implementation of HET instrumentation. Members of the OIR team this past year include Leland Engle, design engineer, Horner, MRS instrument scientist, Ramsey, graduate students Dave Andersen and Jason Harlow as well as undergraduate students Dave Fleig and Ben Rhoades.

The Penn State Fiber Optic Echelle (FOE), resident at Kitt Peak since 1986 (Ramsey & Huenemoerder 1986, SPIE 627, 282), has served us for a decade, producing over 30 papers at Penn State alone. It was the first optical bench echelle spectrograph tailored to work with fibers. Its strength was the prism cross dispersed format, yielding more than an octave of spectral coverage at a resolving power of 10,000 and the good (for its time) efficiency on the sky of 8%. While the Upgraded Fiber Optic Echelle (UFOE) is a fundamentally different instrument than the FOE, it recycles much of the extant FOE optical bench hardware as well as the gratings and camera. The upgraded configuration is a simple white pupil spectrograph where the average pupil between the echelle and the grating cross disperser is re-imaged by a 2.5 m diameter, radius 400 mm, spherical mirror onto the entrance pupil of the 200 mm f/2 Nikkor lens used in the FOE. The baseline (in-house) 226 l/mm cross disperser is about 400 mm away from the echelle. The available 400 mm diameter pupil re-imaging mirror provides pupil re-imaging with minimal vignetting over the angular field of a 24 mm square CCD with the 200 mm focal length camera. The CCD system is a Photometrics system with a TK1024 CCD. The essential elements of the UFOE were assembled at Penn State during July 1996. We are currently optimizing the geometry to minimize the aberrations. The UFOE will be deployed at the HET site in February 1997. With the pupil transfer mirror, we estimated that the UFOE will have a 13% efficiency on the sky when used on the HET. The UFOE concept was developed by Ramsey. Engle has performed the required mechanical design. Harlow, assisted by Andersen, has performed the integration and testing. Rhoads has provided capable service in the fabrication and erection of various spectrograph components.

During this last year we have made substantial progress on the layout and design of critical MRS components. Much of this was accomplished before the NSF award was made in June 1996 and was made possible by advanced funding from the Penn State Eberly College of Science. In addition to developing a detailed optical bench layout concept we have completed a detailed preliminary design of the Fiber Instrument Feed (FIF). The FIF is the mechanism that is in the focal plane of the HET. It is a challenging design in that it must provide up to 10 multi-object probes over the 50 mm HET focal plane but have a total weight less than 50 kg. The initial design meets these goals with a weight of ~ 40 kg. The mechanical layout and FIF design effort was carried out by Engle. Rhoads constructed a full scale model of the FIF to allow us to explore how we will maintain the fiber positioners and upgrade the FIF. Other efforts on the MRS centered on testing of optical fibers. This was carried out by Fleig under Ramsey's direction. He showed that we will not likely be able to use hydrogenated fibers to achieve desired throughput over the entire 350–1800 nm bandpass desired. In addition to the fiber efforts, Fleig worked with Ramsey on exploring the potential for utilizing a near IR detector in the MRS. In August, Horner joined the MRS project as instrument scientist. Dr. Horner will play a major role in the design and implementation of the MRS.

The MRS will be used in spectral regions that are heavily cut up by absorption features due to molecules in the Earth's atmosphere. As an aid to planning observations, especially in the near infrared, Charlton, Ramsey, and Wade collaborated with Seiji Kato of the Penn State meteorology department in using the line-by-line radiative transfer model (LBLRTM) to predict detailed winter and summer average transmission curves for the atmosphere above the HET. LBLRTM is a standard tool in the geophysics and environmental science communities, but we have seen little reference to its use by astronomers.

Bershady has completed preliminary science design studies for two two-dimensional fiber arrays, called integral field units (IFUs), for the HET MRS. IFUs take advantage of the large light gathering power of the HET for medium resolution spectroscopy at low-surface-brightness. These are to be built as an upgrade for the MRS. The arrays are optimized for studies of galaxy disk kinematics in the range $0.05<z<1$. They complement designs for other 10–meter–class telescopes which focus on higher spatial resolution but are commensurately limited to higher surface-brightness for a given spectral resolution. The IFUs for the HET should be able to measure efficiently both disk rotation and velocity ellipsoids for moderately distant galaxies.

#### *3.1.2 X-ray*

*3.1.2.1 CCD Imaging Spectrometer on AXAF* The *AXAF* CCD Imaging Spectrometer (ACIS) instrument has been under construction this past year. The flight CCDs were completed and enough were calibrated using standard X-ray sources and reference CCDs that were calibrated at the synchrotron at BESSY in Berlin, Germany, to fabricate a flight focal plane and a spare focal plane. The calibration effort was carried out at MIT, where PSU graduate students Catherine Grant and Kaori Nishikida helped MIT and *AXAF* Science Center scientists collect and analyze data for three months.

One lot of CCDs was thinned and the backside of the CCD, away from the gates, was treated by a special ''refractory process'' that has been developed at the Lincoln Laboratory of the Massachusetts Institute of Technology, where the CCDs were manufactured. Three usable back-illuminated CCDs emerged from this processing. The ACIS team, together with the Science Working Group, elected to place these CCDs on one side of the spectroscopic array, with the cosmetically superior one in the launch lock position. This CCD is essentially flat and covers an 8' × 8' field of view, with the center of the CCD offset from the image center by about 2 arcminutes – this is where zero order occurs when the gratings are in place behind the X-ray mirrors.

Unfortunately, after a set of 19 CCDs had been calibrated, several CCDs developed loss of output in one of the four output amplifiers used to read out the CCD. This was traced to a failure in the flexprint used to connect the CCD to the electronics. The problem is thought to be caused by the large thermal expansion coefficient of an acrylic adhesive used in the flexprint. When the flexprint is cycled between $-150°$C and $+40°$C a number of times, the vias which connect the different layers of the flexprint together begin to crack and lose contact. This problem required that new flexprints be built using different materials and that the current CCDs be refitted with the new flexprints after they were thoroughly tested. This process will not be 100% efficient, so a new lot of CCDs was started at Lincoln Laboratory to ensure that an adequate number of CCDs will be available for the flight focal plane and a spare focal plane. This process has consumed about three months of schedule and means that the ACIS flight instrument will only be available for a month, at most, at the Spring 1997 calibration effort at the X-ray Calibration Facility (XRCF) at Marshall Space Flight Center (MSFC).

The optical light blocking filters, consisting of a lexan film 2000Å thick, coated with 1300Å of aluminum for the spectroscopic array and 1600Å for the imaging array, were fabricated by the Luxel Corporation. Townsley led the effort to calibrate the filter X-ray transmission to an accuracy of 1% on 15'' square areas of the filter for several energies at the University of Wisconsin Synchrotron Radiation Center (SRC). Chartas spearheaded the task of calibrating the filter transmission as a function of X-ray energy, especially near the absorption edges which are modified by EXAFS as compared to the absorption by free atoms. Unfortunately, all but one set of filters were degraded by the acoustic tests to which the filters were subjected during acceptance testing at Lockheed-Martin and probably cannot be used for flight. New flight filters are on order using 2000Å of polyimide instead of lexan, since the polyimide is a stronger plastic and can withstand the heat delivered to the films during aluminum deposition better than the lexan. The heat causes the lexan to stretch and sag which then causes more flexing of the filter during acoustic exposure. The one lexan filter from the previous set that survived acoustic test was tight on its frame.

A detailed calibration plan for calibrating the ACIS instrument at the XRCF was developed by Nousek. After the flexprint problem and schedule delays, this plan has had to be scrapped. A new plan that uses a 2-CCD ACIS system (2C) for the initial calibration phase is being developed. The 2C camera does not have all of the functions of the ACIS instrument. The 2C camera will enable a substantial fraction of the calibration to be carried out, but with less efficiency. Software for acquiring and analyzing data is currently under development by Pat Broos and Scott Koch.

Pending the resolution of the flexprint problem, the ACIS is currently scheduled to arrive at the XRCF in mid-March 1997 for about a one month of calibration with the X-ray telescope and transmission gratings. Following the calibration with the telescope, a period of operation of the ACIS with the X-ray sources at the calibration facility may be used to validate the CCD calibration against the XRCF standards. Then the ACIS will be integrated into the Spacecraft Instrument Module and ultimately the spacecraft for final testing before launch in August 1998.

*3.1.2.2 CUBIC* The PSU X-ray Astronomy Group has built a small instrument called CUBIC which will be launched in October 1996 on the Argentine $SAC-B$ satellite. $SAC-B$ is an international collaboration between Argentina (satellite fabrication), the U.S. (launch), Italy (solar panels), and Brazil (testing). The satellite carries four instruments from the U.S., Argentina, and Italy. $SAC-B$ is three-axis stabilized and will be launched into a 38° inclination circular orbit at 550 km altitude by a Pegasus XL rocket. $SAC-B$ is described further on the Web at http://www.astro.psu.edu/xray/cubic/SAC-B.html.

The CUBIC instrument is designed to make measurements of the spectrum of the soft X-ray diffuse background from 0.2–10 keV with energy resolution comparable to that of the *ASCA* SIS instrument. These data will provide new insights into the cosmic X-ray background above 2 keV (believed to be dominated by emission from distant active galactic nuclei), the 3/4 keV diffuse galactic background (not well understood currently), and the 1/4 keV diffuse background (believed to be dominated by emission from the hot intersteller medium within a few hundred parsecs of the Sun). In this lowest energy regime, it will complement the data taken by the DXS instrument, which measured this spectrum with higher spectral resolution over a small part of the sky.

CUBIC consists of a pair of X-ray CCDs operated in photon-counting mode which are exposed directly to the sky through an aperture that provides a 5 × 5 degree field of view below 1 keV and a 10 × 10 degree field of view above 3 keV. The fields of view of the two CCDs overlap on the sky, and the coarse pinhole camera design provides enough position resolution to allow up to 8 spectra from adjacent regions of the sky per pointing. Although specifically designed to study the diffuse X-ray background, CUBIC can also study isolated point sources too bright for observation by the *ASCA* SIS instrument. Further details of the CUBIC instrument design are available at http://www.astro.psu.edu/xray/cubic.

Spectral observations will utilize typical integration times of 2–4 days per observation. Our observing plan for the first six months of observations is now posted on the WWW, and includes the Cygnus Loop, the Vela SNR, the Crab nebula, the North Polar Spur, the Gemini-Monoceros ring, HZ43, and Sco X-1. We expect that this experiment will obtain unprecedented spectral data on the diffuse X-ray background.

The $SAC-B$ satellite has been in storage for over a year, awaiting the resolution of problems with the Pegasus XL launch vehicle. Beginning in August 1996, the satellite has been undergoing final tests at Ames Research Center and Vandenberg Air Force Base in preparation for its launch in October. All subsystems are performing nominally at this time.

Meanwhile, we have been processing and analyzing preflight calibration data. In August 1996, we obtained additional calibration data on the Mark V Grasshopper beamline of the SRC. These data, which include measurements of the quantum efficiency and energy resolution of a spare flight detector, are being analyzed now to refine our response matrix.

The CUBIC processing and analysis software is nearly complete. Data from the satellite telemetry stream are processed by IDL software written at PSU which monitors instrument housekeeping for health and status and which extracts science data and generates XSPEC-compatible spectral files. We are nearing completion of target scheduling software. After launch, the CUBIC instrument will be operated from Penn State via a ground station outside of Buenos Aires. Command sequences from PSU will be transmitted via Internet to the ground station for uplinks to the satellite, and data captured from the satellite at the ground station in Argentina will be remotely analyzed from PSU to monitor instrument status.

*3.1.2.3 Sounding Rocket Payloads* The PSU astronomy sounding rocket program continued successfully this year with a flight from Woomera, Australia to observe X-rays from the 3/4 keV diffuse enhancement south of the galactic plane. The instrument for this flight was a CCD camera utilized as a non-imaging, non-dispersive X-ray spectrometer; it served as a pathfinder for the CUBIC instrument.

Superconducting Tunnelling Junction (STJ) detectors offer an exciting alternative to bolometers for highly efficient detectors with energy resolution on the order of 10 eV. In addition to a higher operating temperature, STJs have the advantage of being able to provide position resolution within the detector. A collaboration with Dr. Hans Kraus of the Technical University of Munich has been established, in which we plan to fly a detector developed in his laboratory on a sounding rocket. We are currently developing both X-ray mirrors and support electronics for this flight.

We are collaborating with MSFC to build a three-shell grazing incidence telescope fabricated from electroformed nickel mirrors. We have begun the mandrel design for the outer mirror pair and expect to begin fabricating these mirrors in early 1997.

*3.1.2.4 CCD Detector Physics* As part of his dissertation research, Ralph Kraft developed a new technique for measuring the quantum efficiency of a CCD at a white-light port on a synchrotron beam. The CCD was exposed to the broadband synchrotron beam generated by the SRC's Alladin light source using a very low beam current (approximately 5–10 electrons) to avoid saturating the detector. The inherent energy resolution of the CCD was then used to produce a spectrum of the beam. A model of the CCD detector response was fit to the measured data, adjusting parameters of the model such as dead-layer thickness and depletion depth until an acceptable fit was obtained. Kraft showed that this technique provides an efficient means of measuring the quantum efficiency of the detectors and of obtaining information on the device physics, including modeling of charge splitting. A similar technique has since been used to calibrate CCDs for the PSU/MIT ACIS instrument on the $AXAF$ satellite.

Considerable effort has been devoted to developing backside-illuminated CCDs over the past decade because of their higher soft X-ray quantum efficiency and improved low energy response. However, all backside-illuminated CCDs developed to date suffer from poor energy resolution caused by problems with the backside surface. As an alternative, we have been developing thin-gate frontside-illuminated CCDs which have improved quantum efficiency compared to standard CCDs (although not as good as backside-illuminated chips) but which still retain the good energy resolution of standard CCD designs. As a follow-on to his thesis work, Kraft showed that thin-gate frontside-illuminated CCDs are superior to current backside CCDs for determination of spectral parameters for many astrophysical objects, in spite of the lower count rate obtained with the frontside technology.

*3.1.2.5 $XMM$ Optical/UV Monitor Telescope* $XMM$ is a cornerstone mission of the European Space Agency's Horizon 2000 program of scientific space missions. The Optical/UV Monitor ($^{XMM}$OM) is a 30 cm modified Ritchey-Chrétien telescope co-aligned with the X-ray telescopes on $XMM$. $^{XMM}$OM will feed a photon counting detector operating in the blue and UV regions of the spectrum ($1600-6000$Å). The $^{XMM}$OM instrument is being developed by a multi-national consortium consisting of the United Kingdom, United States, and Belgium.

Penn State led the US consortium, consisting of Penn State, Sandia National Laboratories, and Los Alamos National Laboratory. The US consortium is responsible for the development of the hardware and software for the $^{XMM}$OM Digital Processing Unit. Over the last year, Horner continued in the role of US Project Manager and Welty continued as Project Scientist. Progress continued on the development, testing, and documentation of the flight, simulation, and analysis software. Activities this year centered on expanding on the simulation software and debugging and testing the flight software. Significant progress was also made in the fabrication of hardware. The Structural and Thermal Model (STM) of the Digital Processing Unit was fabricated in the machine shops at Penn State, underwent environmental testing at Sandia, and was delivered to ESA. The flight enclosure and the electronics module frames were also fabricated at Penn State.

The US consortium has remained on schedule for delivery of the Engineering and Qualification Model in April 1997, and delivery of the Flight Model in July 1997.

agraph$ASCA$ Penn State faculty carried out analysis projects using the US-Japanese ASCA satellite. Some of these projects were based on observations conducted during the PV phase operations, where the Penn State team was entitled to participate through the contributions they made to building the satellite and developing ground software for the mission. Other projects resulted from successful guest investigations, awarded through competitive peer review. Nousek and others from the ASCA team studied X-ray emission from M82, the nearest starburst galaxy. Nousek and Kim Weaver (Johns Hopkins) collaborated on ASCA observations of NGC2992 and MCG -5-23-16. These are bright AGNs with strong Fe line emission. Study of these galaxies gave insight into the presence of a molecular torus in NGC 2992 and complex Fe line emission which is indicative of general relativistic effects from the black hole in MCG -5-23-16.

*3.1.2.6 $Astro-E$* Nousek was one of five American scientists named to serve as Experiment Advisers to the Japanese $Astro-E$ mission. $Astro-E$ will carry US X-ray telescopes and an X-ray calorimeter from the Goddard Space Flight Center, CCD cameras from Japan and MIT, and a hard X-ray detector from the University of Tokyo and ISAS. Launch is tentatively set for 2000, with annual trips by the Experiment Advisers to Japan for science working group meetings through that time.

*3.1.2.7$HTXS$* Nousek and Garmire participated in meetings of the High Throughput X-ray Spectroscopy mission working group. This group, under the joint leadership of Dr. Harvey Tananbaum (Smithsonian Astrophysical Observatory) and Dr. Nicholas White (Goddard Space Flight Center), is working to define a major mission of spectroscopic discovery in the timeframe after $AXAF$. The key concepts are large collecting area telescopes on multiple satellites and high spectral resolution detectors.

### *3.1.3 Radio*

*3.1.3.1 Millisecond Pulsar Receiver* Graduate student Brian Cadwell, undergraduate student Bryan Jacoby, and Wolszczan have completed construction of a new portable pulsar backend, the Penn State Pulsar Machine–2 (PSPM–2). The PSPM–2 is a 2 × 64 × 3 MHz fast–sampled filterbank designed to work with medium–sized radiotelescopes. It has been installed at the 32 m dish of the Toruń Radio Astronomy Observatory in Poland to begin a biweekly, long–term timing of about 100 of the strongest pulsars at 1.4 GHz.

The PSPM–1, a 128–channel pulsar machine built by Stuart Anderson (CalTech), Cadwell, Jacoby, and Wolszczan in 1994 and installed at Arecibo, has become an open access, user owned pulsar backend operated and maintained by the Arecibo Observatory. It is beginning its service as a tool to conduct fast sampled searches for millisecond and submillisecond pulsars with the Arecibo radiotelescope.

## 3.2 Observational Research

### *3.2.1 Stellar Astronomy*

*3.2.1.1 Proto-Planetary Systems* Neff, in collaboration with K.-P. Cheng (California State, Fullerton), obtained very high resolution, high signal-to-noise spectra of nearby A stars using the NSO McMath-Pierce stellar spectrograph, the McDonald Observatory's 2.7 m coude echelle, the CTIO 1.5 m echelle, and the Mount Stromlo 1.9 m coude echelle. They are using the narrow Ca II K and Na I D circumstellar absorption features as probes of the dynamics of the proto-planetary environment. The entire sample of northern-hemisphere stars has been observed at NSO, and the southern survey is being conducted at Mount Stromlo. They have discovered circumstellar gas around twelve of the northern candidate proto-planetary systems. Using extremely high-resolution (R>200,000) spectra obtained at the McDonald Observatory, they are monitoring these twelve sources for variablity. One of these, 2 Andromedae, was also observed with the Hubble Space Telescope. The HST data show absorption due circumstellar gas at the systemic velocity, and the ground-based data show variable red-shifted Ca II K features.

*3.2.1.2 Accretion Disks* Wade continued an investigation with Diaz and I. Hubeny (GSFC) of the spectra of accretion disks in close binary systems, in particular cataclysmic variables, in which the star at the center of the disk is a white dwarf. A grid of steady-state, LTE, synthetic disk spectra was constructed for the far-ultraviolet region, suitable for comparison with observations made by *VOYAGER*, *HUT*, and (with modification) *ORFEUS* and *FUSE*. These model spectra are based on a modeling of the local vertical structure of the disk, taking into account energy generation, opacities, and hydrostatic balance. These model spectra are for a variety of central star masses, mass accretion rates, and viewing angles, and the important effects of limb darkening and doppler broadening are included. The grid is being extended to the mid-ultraviolet, for comparison with observations made with the *IUE* and *HST* spectrometers.

In connection with this modeling effort, it was established that a popular formula for estimating the local surface gravity in such disks (due to Herter *et al.* 1979, ApJS 39, 513) gives results that often are in error by more than 1 dex. Contrary to assertions by Herter et al., this does have a noticeable effect on the spectra. Development is underway of improved formulas to estimate gravities, without the need for a complete model of the vertical structure.

The models generated have been used in preliminary investigations of the far-UV spectrum of the dwarf nova Z Cam (during standstill) as observed by *ORFEUS* (in collaboration with C. Mauche, LLNL), and of the mid-UV spectrum of V795 Her as observed by *HST* (in collaboration with S. Rosen, U. Leicester). Agreement between models and observations is far from perfect, especially since the models do not account for wind emission or absorption. Nevertheless the models, with their full computation of (LTE) absorption line structure in the photosphere, are of some use in constraining the geometry and range of effective temperatures in the disk. Initial experiments with non-LTE effects in the Si IV lines suggest that major improvements in the fits are possible.

The model disk spectra were also used in support of analysis of the *HUT* spectrum of Z Cam obtained during the *ASTRO*−2 mission (in collaboration with C. Knigge, *et al.*, STScI and Johns Hopkins University). Uncertainties in the distance and interstellar reddening of Z Cam propagate strongly into the conclusions that can be made concerning the structure of the disk. The same class of wind model used by Knigge to describe the profiles of the UV resonance lines in UX UMa, which is an eclipsing system, can be used to describe the wind lines of Z Cam, which is not eclipsing.

Accurate and complete computation of the specific intensities emerging from an accretion disk has been used to explain the ultraviolet eclipse photometry of the dwarf nova Z Cha published earlier by E.L. Robinson (University of Texas/Austin) and coworkers (1995, ApJ 443, 295). Without limb darkening, it appeared necessary to invoke a rather geometrically thick disk to account for the apparent ''front–back'' asymmetry in disk surface brightness. Working with Robinson and J.H. Wood (Keele Univeristy, UK), Wade has explained about half of the apparent thickness of the disk in terms of differential limb darkening between the front and back portions of the visible face of the disk, leaving the other half to be explained by geometrical effects as before. Now, however, the inferred thickness of the disk is completely self-consistent with models of the vertical structure.

Wade, Diaz, I. Hubeny (GSFC) and K. Long (STScI) have a Cycle 6 program to use the Goddard High Resolution Spectrograph on board *HST* to observe several high luminosity cataclysmic variables (CVs) that are oriented close to face-on. This is complementary to other programs that are using *HST* to study several eclipsing CVs. The specific property of interest in the face-on systems is that the doppler broadening of the disk absorption spectrum is minimized, so that individual lines or characteristic blends appear sharper and with more contrast. Even so, the modulation of the spectrum at the resolution employed is expected to be only a percent or two (between the very strong wind lines). Data have so far been obtained for RW Sex and BZ Cam, and have adequate signal-to-noise to allow detailed modeling to proceed. The data are also acquired with moderate time resolution, to enable the variability of the wind lines to be assessed.

*3.2.1.3 Pre-Main Sequence Stars* A long-term study, in a collaboration between Feigelson, David Huenemoerder (MIT) and Warrick Lawson (ADFA), based on *ROSAT* observations of the Chamaeleon I star forming cloud, has led to a doubling of T Tauri stars placed on the Hertzsprung-Russell diagram. These results have implications for several topics, including the wide range for the longevity of circumstellar disks ($10^5-10^7$ yr), long star formation history (20 Myr), and the initial mass function. The distribution of stellar ages, combined with the recent *ROSAT* discoveries of weak-lined T Tauri stars dispersed widely around nearby clouds, led Feigelson to study the dispersal properties of T Tauri stars. He concludes that two processes may dominate: slow dispersal of stars ($\Delta v \simeq 1$ km/s) due to thermal motions in the cloud cores, and rapid dispersal of stars ($\Delta v > 5-10$ km/s) due to turbulent motions in cloud complexes. T Tauri kinematics, especially for dispersed stars that are most readily found in X-ray surveys, may thus give insights into dynamical processes of star formation.

A number of further observational X-ray studies of young stars have been conducted. Graduate student Lee Carkner, working with Feigelson and other collaborators, reports a *ROSAT* and *ASCA* study of the active L1551 cloud in the Taurus-Auriga complex. Several dozen X-ray sources are found, mainly young stars. Powerful flares were detected from the weak-lined T Tauri star V826 Tau and from the extremely young classical T Tauri star XZ Tau. However, the three embedded protostars in the cloud were not detected.

An *ASCA* observation of the Coronet Cluster of protostars in the R Corona Australis cloud, hwoever, did uncover an unusual cluster of hard X-ray sources. This work, by K. Koyama (Kyoto) and collaborators including Feigelson, may have important implications for protostellar astrophysics: X-rays may play a role in disk-outflow coupling, disk-star accretion and star formation self-regulation via photoionization. Feigelson also participated in a *ROSAT* study of more distant star forming regions in the Monoceros and Rosette molecular clouds, and continued radio continuum study of the remarkable magnetically active T Tauri star HD 283447.

*3.2.1.4 Late-Type Active Stars* O'Neal and Neff (in collaboration with S.H. Saar, CfA) are directly measuring the mean temperature and total area of starspots on late-type stars. They have completed an analysis on the most heavily spotted star known (II Pegasi) and an initial survey of active giant stars. Using observations obtained with NICMASS at the KPNO coude feed, they have demonstrated the utility of the OH band at 1.563 $\mu$m as a diagnostic of spot temperature. They have combined constraints derived from molecular bands with Doppler imaging of the atomic lines (in collaboration with N. Piskunov at Uppsala) to show that spots on II Peg are significantly cooler than determined from Doppler imaging alone.

In collaboration with R. Dempsey (STScI), Neff used the Hubble Space Telescope to obtain high-resolution spectra of several ultraviolet emission lines from the active binary star V824 Ara. This star was observed nearly continuously throughout its 1.6 day period by taking advantage of *HST*'s continuous viewing zone. The data are being used to image the outer atmosphere of V824 Ara at several levels from the chromosphere up into the corona.

*3.2.1.5 Interacting Binary Stars* Ringwald continued his research on cataclysmic variable binary stars, their evolution, and the physics of their accretion disks and outbursts. With Wade and Orosz, he began a program to use HET to study their progenitor stars and origin in common envelope evolution, in which a star expands and engulfs a companion.

BZ Camelopardalis was shown to be the first cataclysmic variable with an optical spectrum revealing a wind from its accretion disk. One project involved high-speed, high-resolution spectra taken with the 4.2 m William Herschel Telescope. Time-resolved ultraviolet spectra were also taken with the Goddard High Resolution Spectrograph aboard *HST*.

Wade has been working with Penn State undergraduate Kevin McGouldrick and R. Polidan (GSFC) to make the *VOYAGER* Ultraviolet Spectrometer (UVS) archive of observations of cataclysmic variable stars more accessible. The *VOYAGER* 1 and 2 spacecraft have observed many of these stars, often for days or weeks at a time, and the database is unique in wavelength coverage and temporal coverage. Since the UVS are slitless spectrographs on a platform that is not 3-axis stabilized, there are instrumental signatures of the UVS that make it difficult to analyze the archived data, and the archive itself is awkward to interrogate. As a first step, a catalog of observations is being prepared, showing for each variable star the log of observations and preliminary estimates of count rates in two wavelength bands, one of which is shortward of the Lyman edge. In conjunction with similar data to be tabulated for observations of blank sky, this will allow archived observations to be identified that will be most fruitful upon further study. A number of FORTRAN and display tools were developed as a part of this effort. A bibliography of published results on UVS observations of cataclysmic variables is also being prepared.

Wade and graduate student Jason Harlow used the Kitt Peak 2.1 m telescope to measure the red spectra and radial velocities at different epochs of many of the stars belonging to a group of composite spectrum binaries studied by Ferguson, Green, and Liebert (1984, ApJ 287, 320). These are systems consisting of a hot subdwarf and a late-type main sequence star. Some will have evolved through a common-envelope (CE) stage of evolution and will have short orbital periods and high orbital velocities. Because the Ferguson et al. sample was drawn in a well-defined manner from the PG catalog, the sample is worth studying in detail, to establish the fraction of post-CE binaries and their distribution of orbital periods. PG1224+309 stands out so far, in having both a large scatter in radial velocity of both stars (properly antiphased) and a large rotational velocity for the late-type star. Most of the other systems studied show only upper limits on velocity variability from night to night or year to year. (A similar 2.1 m observing run was carried out the previous year.) Follow-up observations of PG1224+309 and other interesting targets are planned.

*3.2.1.6 Central Stars of Planetary Nebulae* Ciardullo and H. Bond (STScI) have completed their survey for non-radial pulsations in hydrogen-deficient planetary nebula central stars. In all, 29 hot, hydrogen-deficient planetary nebula nuclei (PNN) were monitored, and 6 were found to have low-amplitude pulsations, similar to K 1-16 and PG 1159−035 (GW Vir); this brings to 14 the number of PNNs and isolated white dwarfs now known to belong to this class. Time series analyses show that the PNN pulsators have longer pulsational periods (11.5 to 31 min) than their GW Vir white-dwarf counterparts, but within the PNNs there is little correlation between spectral subtype and pulsation period. In addition, all of the PNN pulsators have power spectra that are highly variable on timescales of months or less; this is in contrast to the GW Vir white-dwarf pulsators, whose power spectra generally vary only on time scales of years.

Ciardullo and graduate student M. Sipior, in collaboration with H. Bond, L. Fullton, and K. Schaefer (STScI), are using *HST* $V$ and $I$ snapshots of $\sim$100 Galactic planetary nebulae in order to identify PN central stars in wide binary systems. By performing photometry on the (presumably) unevolved companion stars, reliable distances to those PN with companions can found via simple main-sequence fitting. These distances will be used to calibrate the Galactic planetary nebula distance scale, and should enable us to derive an absolute zero point to the [O III] $\lambda$5007 planetary nebula luminosity function. The results to date are encouraging: $\sim$20% of the targets are observed to have nearby companions. Statistical tests are now underway to estimate how many of these companions are, in fact, physically associated with the PN.

*3.2.1.7 Novae* Ringwald published an atlas of optical spectra of novae. These ‘‘old novae’’ had outbursts between 1783 and 1986; the spectra were taken to search for evolution over decades or centuries. They show surprisingly little evidence of nova hibernation, or of any changes at all, aside from the fading of the nebular lines. Indeed, old novae look remarkably similar to each other, except for effects wholly attributable to their orbital inclinations. Several lines of evidence suggest that these systems’ white dwarfs can remain hot for surprisingly long, however. Doubt was also cast on nova hibernation theory with a detailed study of the oldest securely known nova, WY Sge (Nova 1783), and with a refutation of a recent claim that the suspected nova of 1667 had been recovered.

*3.2.1.8 Pulsars* Pavlov, Stringfellow & Córdova analyzed results of *HST* Cycle 4 observations of nearby pulsars with the *HST* Faint Object Camera. Each of the deep images of the fields around the pulsars PSR B0656+14, B1929+10, and B0950+08, obtained with a broadband UV filter, contains an object whose position is compatible with the radio position of the pulsar. A comparison with *ROSAT* data and theoretical models shows that the radiation detected from the middle-age PSR B0656+14 is mainly of a nonthermal origin. The UV-optical radiation from the old PSR B1929+10 and B0950+08 is likely to be emitted from the neutron star surfaces, with temperatures $(1-3)\times10^5$ and $(7\pm1)\times10^4$ K, respectively.

Pavlov, Zavlin, Becker and Trümper fitted the soft X-ray and EUV spectra and light curves observed from the nearby binary millisecond pulsar J0437–4715 with model spectra and light curves of radiation emitted from hot pulsar polar caps of pure hydrogen, helium and iron composition. The models take into account the frequency-dependent anisotropy of the emergent radiation (limb-darkening) and the gravitational redshift and bending of the photon trajectories. The analysis of both the *EUVE* and *ROSAT* data indicates that the radiation may originate from two polar caps of areas $\simeq 2-3$ km$^2$ covered with hydrogen and/or helium with an effective temperature of $\simeq(0.9-1.0)\times10^6$ K; the positions of the caps coincide with those inferred from radio pulse polarization properties.

Anderson, Cadwell, Jacoby, and Wolszczan, Foster (NRL), and Kramer (MPIfR) have analyzed the timing data for PSR J0538+28, a 143 ms radio pulsar in the supernova remnant S147, collected with the Arecibo and Effelsberg radiotelescopes. Based on a positional coincidence of the two objects, the reasonable similarity of their distances and ages, and statistical arguments, it is likely that PSR J0538+28 and S147 are physically associated.

Kramer and collaborators (MPIfR), Wolszczan, and Camilo and Taylor (Princeton) have timed 21 millisecond and binary pulsars with the 100 m Effelsberg radiotelescope over a period of 2 years. These measurements have been essential in providing a continuation of the millisecond pulsar timing during the Arecibo upgrade in 1994–96 and have been used to study pulse morphology and radio spectra of these objects in the 1.4–1.7 GHz frequency range. Xilouris and collaborators (MPIfR) and Wolszczan have used these data to study polarization properties of the millisecond pulsars.

*3.2.1.9 Globular Clusters* Schneider, P. Guhathakurta (UCSC), B. Yanny (FNAL), and J. Bahcall (IAS) are continuing their analysis of *HST* images of the centers of Galactic globular clusters. In the past year they have published a study of the core of M15; this cluster apparently has a cusp of stars in the very center, and the stellar distribution is consistent with the expected profile if the cluster harbors a relatively massive ($10^3 M_\odot$) black hole. A recent investigation has identified 15 candidates for blue stragglers in the core of M13.

### 3.2.2 Extragalactic Astronomy

*3.2.2.1 Stellar Populations* Ciardullo and graduate student R. McMillan have completed a comparison between the positions of Type Ia and Type II supernovae (SNe) and spiral arms, finding that both types of SNe are more likely to go off near the centers of arms. However, Type Ia SNe are less tightly concentrated around the arms than Type II SNe, and are indistinguishable from the distribution of the general stellar population. This indicates that Type Ia SNe must occur in a population old enough to have diffused away from its formation regions. In a continuing effort to constrain the ages of SN progenitors, McMillan and Ciardullo are now examining the scale-height of SNe that have gone off in edge-on galaxies, and the underlying colors of the regions in external galaxies that have hosted SNe.

Ciardullo, A. Shafter (SDSU) and C. Pritchet (U. Victoria) have continued their H$\alpha$ nova survey in M101, M51, and the Virgo Cluster. In 1990, Ciardullo noted that the nova production in spiral bulges and elliptical galaxies (normalized per unit infrared luminosity) were very similar, but that the absolute nova rates of spiral disks appeared to be extremely low. If true, this is a remarkable statistic, since it not only provides an important constraint on close binary formation in different environments, but it also argues strongly against the most common model for Type Ia supernovae, that of accretion onto a $1.4M_{\odot}$ core. The preliminary analysis of this new survey appears to confirm the idea that the infrared-luminosity specific nova rate for all stellar populations is approximately the same. The result contradicts the assertion by Della Valle *et al.* (1994, Astr. Ap. 287, 403) that disk-dominated systems are prolific nova producers.

*3.2.2.2 Distance Scale* Ciardullo, graduate student J. Feldmeier, and G. Jacoby (NOAO) have successfully expanded their planetary nebula luminosity function work to spiral galaxies. By comparing on-band/off-band [O III] $\lambda$5007 images with images taken in H$\alpha$ and broadband $R$, Ciardullo and collaborators were able to identify 65 PN candidates in M101, 64 PN candidates in M51, and 74 PN candidates in M96. They then used these data to derive distances to the galaxies via the planetary nebula luminosity function. Their distance to M101 is in excellent agreement with that from the *HST* Distance Scale Key Project, and their M51 result agrees well with a measurement by Tonry using surface brightness fluctuations. The M96 distance is inconsistent with an *HST* Cepheid result found by Tanvir *et al.* (1995, Nature 377, 27), but is consistent with the Key Project distance to M51, another member of the Leo I Group. These results suggest that, contrary to model predictions, the cutoff in the [O III] luminosity function is insensitive to age.

Ciardullo, Feldmeier, and G. Jacoby also observed three ''overluminous'' planetary nebulae in the Virgo Cluster with *HST*, in an attempt to determine the nature of the objects by resolving them. Only one overluminous object was detected, and it was unresolved. The analysis of these objects is continuing, but it now appears that these objects are normal PN that are in the foreground of the Virgo Cluster in intergalactic space. The observations are consistent with the idea that a substantial fraction of the mass of Virgo is made up of intracluster stars.

*3.2.2.3 UV Properties of Galaxies* Schneider is a member of a group of astronomers who have conducted the first large systematic survey of the ultraviolet properties of the centers of nearby galaxies. This survey contains *HST* images of the inner 20 arcseconds of 110 galaxies; the data reveal a wide range of morphologies and ultraviolet luminosities: bright compact nuclear point sources, compact young star clusters in circumnuclear rings, centrally peaked diffuse light distributions, and galaxies with weak or undetected ultraviolet emission.

*3.2.2.4 Dwarf Galaxies* Graduate student Sally Hunsberger, Charlton, Ciardullo, and D. Zaritsky (Lick Observatory, UCSC) have continued their observational study of dwarf galaxies in the compact group environment. A survey of 42 of the Hickson compact groups found 47 candidate dwarf galaxies associated with 15 tidal features. In order to establish the nature of these objects, the group will measure the metallicities of the candidates through emission line studies with the KPNO 2.1 m telescope. Also, Cycle 6 *HST* WFPC2 images of HCG 92 are planned and will allow surface brightness profiles and morphologies in $B$, $V$, and $I$ to be determined for the dwarf candidates. Another goal of the HST program is to study the formation of smaller star forming regions, such as globular clusters, in the tidal debris and central regions of compact group mergers.

*3.2.2.5 Active Galaxies and Quasars* Schneider, J. Bahcall, and S. Kirhakos (Institute for Advanced Study), have obtained *HST* images of 20 nearby, luminous quasars. The observations, through a very broad-band red filter, were designed to investigate the properties of the host galaxies of the quasar sample. The *HST* data reveal that luminous quasars live in a wide variety of environments: luminous ellipticals and spirals, interacting galaxies, and a number of quasars whose host galaxies are near the detection limit of the observations (approximately L*).

The host galaxies of quasars are clearly more luminous than one would expect if the hosts were drawn from the field luminosity function (the median luminosity of the 20 galaxies is well over L*). Radio-loud quasars always have elliptical or interacting hosts (albeit the sample size is small), whereas radio-quiet quasars can appear in either elliptical or spiral galaxies. There is no evidence that the presence of the quasar has any disturbing influence on the morphology of the galaxy; in particular, two of the hosts are classic spiral galaxies. The number of close companion galaxies is much larger than one would expect by chance.

Usher continued research on faint objects of the North and South Galactic Caps. Work on the morphological definition of complete quasar and faint blue object samples continued in collaboration with summer NSF-REU student Dirk Fabian and the results published in the Astronomical Journal and on CD-ROM. This work extended previously published results based on the US survey of brighter quasars and AGNs by use of PG and other optically selected objects. Images were examined on Palomar Observatory Sky Survey prints and given morphological types that are extensions of the original system of the US survey. The results confirm the existence of a ''twilight zone'' in the Hubble Diagram ($B$ magnitudes vs. redshift $z$) in which there is a mix of resolved and starlike objects, and extend the definition of the zone to brighter magnitudes. The upper limit of this mix of types is found to be given by the semi-empirical curve $B=21-0.75z$. This result is in essence the first quantified definition of a 'quasar' as seen through the lens of a camera of the 1.2 m Schmidt design.

*3.2.2.6 BL Lacertae Objects* Kollgaard led two radio studies of BL Lac objects. First, his team (which includes graduate student Sally Laurent-Muehleisen, undergraduate Christopher Palma, and Feigelson) completed VLA mapping of $HEAO-1$ selected BL Lacs and conducted a thorough comparison of X-ray selected BL Lacs, radio selected BL Lacs and radio galaxies. The loci of the three groups in the radio core vs. extended power diagram support standard ''unified schemes'' based on relativistic beaming, where the jets are oriented about 60°, 20°, and 10° from the line-of-sight for radio galaxies, X-ray BL Lacs, and radio BL Lacs, respectively. Also, jet Lorentz factors are constrained to exceed $\simeq 6$. Second, Kollgaard (with Denise Gabuzda of the Lebedev Institute and Feigelson) conducted a VLBI study of four X-ray selected BL Lac objects. All show core-jet morphologies similar to radio BL Lacs, but their jets seem to fade more quickly. This suggests that some physical factor in addition to orientation differentiates the two groups.

Laurent-Muehleisen completed her dissertation on the creation of a new large sample of X-ray selected BL Lacs. Together with Kollgaard, Feigelson, undergraduate Pamela Ryan and scientists from the Max-Planck Institutes, she obtained high-resolution radio images of $>2000$ radio-loud sources in the *ROSAT* All-Sky Survey. This gives arcsecond positions which permit unambiguous optical identification. From this large population, she obtained spectroscopic observations and redshifts over 10% of the celestial sphere. Most are emission line AGN (radio quasars and Seyferts) or radio galaxies, but 77 are BL Lac objects (half previously known). This is the largest BL Lac sample to emerge from a well-defined flux limited survey. They show that the dichotomy previously noted in the spectral energy distributions of X-ray and radio selected BL Lacs was largely an artifact of poor sampling. The new *ROSAT*–GreenBank sample shows a smooth distribution of properties.

*3.2.2.7 Galaxy Clusters* Schneider and collaborators have recently published the Palomar Distant Cluster Survey (PDCS) Catalog, which was constructed from *V* and *I* observations obtained at the 5 m telescope on Mount Palomar. This survey covers approximately 5 square degrees, and contains 79 clusters of galaxies with estimated redshifts between 0.15 and 1.0. A matched-filter algorithm was developed and employed to identify the cluster candidates by using positional and photometric data simultaneously. (The catalog also includes a list of 28 additional clusters that did not me*et al.*l of the selection criteria, but include some of the most distant systems detected in the survey.) From the photometric data alone, one can conclude that there is not any significant evolution in the number density of clusters back to a redshift of approximately 0.6, but the number density of rich clusters found in the PDCS is about five times larger than that found by Abell. Constraints on cluster densities at redshifts larger than 0.6 will be possible once spectroscopic redshifts have been obtained for a large subset of the clusters.

*3.2.2.8 QSO Absorption Lines* Schneider is a member of the *HST* Quasar Absorption Line Key Project. Over the past few years, this team has acquired ultraviolet spectra (R $=1300$) of dozens of bright quasars to investigate the properties of low-redshift gas, either intergalactic or associated with galaxies. They have recently published an analysis of the evolution of the systems that produce Lyman-limit absorption (the distribution between redshifts 0 and 4 appears to be well-represented by a single power-law, contrary to the results of previous studies using *IUE*), and the first detailed investigation of the Lyman-$\alpha$ forest at redshifts slightly larger than one (confirming, using a much larger data set, the indications from early *HST* observations that the number of low-redshift lines is much larger than expected based on extrapolations of ground-based data, and finding that about half of the hydrogen lines associated with metal-line systems exhibit clustering on scales of a thousand kilometers per second).

In the summer of 1996, an unusual broad absorption line system was identified in the *HST* spectrum of PG 2302 $+029$; its properties (e.g., the shape and width of the lines, the relative strengths of the low and high ionization species) are unprecedented. It is unknown at this time whether these features are produced by an extreme form of ejection mechanism (gas associated with the quasar), arise from a dynamically active intervening system, or represent a new class of absorber.

*3.2.2.9 MgII Absorption Line Systems* Churchill, with C. Steidel (Caltech) and S. Vogt (Lick/UCSC), completed a study of the relationship between the properties of redshift 0.5–0.9 absorbing galaxies and their MgII absorption profiles. Information on the spatial and kinematic distribution of the low ionization gas was obtained from Keck/HIRES resolution 6 km/s spectra, while the galaxy luminosities, impact parameters, and rest-frame $B-K$ colors were obtained from ground-based images. In a sample of 15 galaxies, there were no correlations between galaxy properties and absorption properties at the $2.5\sigma$ level. This indicates that the gas in galaxies is not in a simple, smooth distribution. Rather, the absorbing gas is likely to be produced by ongoing events and mechanisms that vary over a few Gyrs, providing one source for the observed scatter in the absorption properties. Work is underway to incorporate information about high ions (from *HST*/FOS) and about the morphologies and orientations of absorbing galaxies (from *HST*/WFPC2).

The study of MgII absorption over a larger interval of redshift promises to quantify shifts in epochs of galaxy development, perhaps from one type of predominant galaxy/halo gas processing phase to another. Churchill has found that the cloud-cloud velocity dispersion (characterized by a Gaussian width) evolves from $\sigma=140$ km/s at $0.9<z<1.7$ to $\sigma=60$ km/s at $0.4<z<0.9$. One possible interpretation would be that galactic ''halo'' gas dynamically is settling deeper into potential wells during this epoch. Further analysis and interpretation will appear in a paper in preparation by Churchill, S. Vogt (Lick/UCSC), and Charlton.

### 3.2.3 High Energy Astrophysics

*3.2.3.1 Eridanus Enhancement* Burrows and Guo continue to work on soft X-ray emission from the ''Eridanus Enhancement,'' a large diffuse feature produced by emission from the interior of the Orion-Eridanus superbubble, using *ROSAT* sky survey and pointed observations to obtain more detailed spectral and spatial information. *ROSAT* sky survey data provide a wealth of detail on small angular scales not visible in previous X-ray maps of this object, including the discovery of a number of shadows cast against the X-ray enhancement, presumably by clumps of neutral material in its shell. *ROSAT* PSPC pointed observations have been analyzed to investigate spectral variations across this object, and are also producing a number of unexpected shadow detections. The latter have been used to constrain the physical location of the absorbing clouds, using 21cm observations to determine the radial velocities of the absorbing clouds and optical absorption measurements to constrain the distances to these clouds. This work constituted the dissertation research of Guo and has led to improved constraints on the distance to the edge of the Local Hot Bubble surrounding the solar system.

### *3.2.4 Observational Cosmology*

Graduate student Anna Jangren and Bershady have continued to work on determining the distribution and correlation between image concentration, color, and surface brightness of galaxies. They have measured such parameters for large samples of galaxies spanning a wide range of redshifts with ground- and space-based multi-band images. The primary goal of this project is to determine how correlations observed locally change at higher redshift, and to use such changes to understand the physical mechanisms responsible for galaxy evolution. A second aspect of this investigation, which includes graduate student David Andersen, is to determine if the correlation between concentration and surface-brightness can be used to estimate redshifts. The possibility is compelling because concentration is distance-independent while surface-brightness fades rapidly with redshift. In all aspects of these studies there has been a great need for statistical methods to measure correlations between variables with intrinsic scatter. With M. Akritas (PSU), Bershady has worked to complete such analytical tools.

The technique of using multi-band photometry to estimate galaxy redshift (photometric redshifts) has been improved and refined during the past year by Bershady and Andersen. They have used photometric redshifts to begin a novel study of the faint end of the field galaxy luminosity function. Photometric redshifts are used to winnow down a magnitude-limited sample to an (estimated) volume-limited field galaxy sample. Confirmation and precise redshifts are then efficiently obtained using the Kitt Peak WIYN 3.5 m telescope and the Hydra multi-fiber spectrograph. When the survey is completed within 1–2 years, they expect to have substantially improved estimates of the slope of the faint end of the nearby field galaxy luminosity function, as well as the slope's dependence on color. This slope is critical for understanding the excess of faint blue galaxies seen in deep images.

Bershady and Steven Majewski (U. Virginia) have begun a systematic search of very luminous high redshift galaxies in their 4 m plate fields covering over a square degree. An upcoming observing run at KPNO will be devoted to their spectroscopic confirmation. A critical aspect of this study is the prediction of the colors of high redshift galaxies. Detailed modeling of the statistical distribution of high redshift galaxy colors is underway by Janet Geoffroy, Charlton, and Bershady. An alternative approach is also being explored by Weedman, Bershady and Schneider: the morphology of identified high redshift galaxies in the Hubble Deep Field can plausibly be used to define selection criteria which do not require expensive $U$ band photometry.

Bershady and collaborators are attempting to reveal the nature of blue, compact, emission-line galaxies (CNELGs). In an effort to understand if these sources are proto-dwarf-ellipticals, HST images and Keck high-resolution spectroscopy (to measure line-widths) have been gathered and analyzed by David Koo (UCSC), Rafael Guzman (UCSC), and Bershady. New high resolution images from HST have recently arrived and are being analyzed by Jangren and Bershady. They have discovered that these objects have an unusual correlation between image concentration and color not observed in local galaxies. If these are indeed an evolved population at intermediate redshift, larger surveys over a wider range in redshift may be able to catch these galaxies ''in the act'' of evolving.

Bershady is also studying the evolution of the mass-to-light ratio of spiral galaxies. Bershady, in collaboration with C. Mihos (JHU), has almost completed an analysis of rotation curves of roughly 20 galaxies to look-back times of 3–5 Gyr. New observations over the past year have included further spectroscopy at Lick Observatory and high resolution images from CFHT with Nicole Vogt (UCSC) and Brad Gibson (MSSSO). Preliminary results show very little evidence for evolution in this sample (i.e., $H_0$ is measured to be between 60 and 90 km/s/Mpc), in contrast to results from other groups. Bershady's pilot survey will be greatly increased in coming years with the advent of the Hobby-Eberly Telescope.

## 3.3 Theoretical Studies

### *3.3.1 Theoretical Astrophysics*

*3.3.1.1 Cosmology of Gamma Ray Burst Sources* A. Mészáros and P. Mészáros presented the exact analytic expressions for the cosmological number counts of bursting sources, and calculated the mean redshifts and time dilations as a function of the flux range, as well as the dispersion of these quantities, for various values of the density evolution and the luminosity function dispersion. Time dilation values of 2.25 as reported in the literature are found to imply redshifts which, while large, are within one standard deviation of conventional redshifts associated with galaxy formation.

Horváth, P. Mészáros and A. Mészáros carried out detailed chi-squared fits of relativistic cosmological number count distributions under the above assumptions to the 2B BATSE and the PVO catalogue of gamma bursts. The results indicate that for standard candles the 2B/PVO data are compatible with a comoving constant source density, but to within one standard deviation are also compatible with density evolution steeper by up to two powers in $1+z$ or also significantly flatter. For a nontrivial power law luminosity function slope of about 1.9, the range of maximum to minimum luminosity may be as large as $10^2$, compatible with having 90% of the observed sources with a luminosity within one decade of each other.

D. Reichart and Mészáros investigated Einstein-de Sitter cosmological models with a power-law luminosity of arbitrary slope as well and density evolution as a power of redshift. These were chi-square fitted to the number vs. peak flux counts in the 3B BATSE catalogue, and the recently published data on time dilation and spectral softening versus peak flux. The results provide a unique solution to the luminosity range of the bursts, as well as to the maximum redshift. The 90% width of the observed luminosity distribution can be as large as 100. If the redshifts of BATSE's faintest bursts are to be compatible with those currently known for galaxies, a standard candle luminosity is unacceptable.

*3.3.1.2 Physics of Gamma Ray Bursts* A. Bykov (Ioffe Phys Tech Inst, St. Petersburg, Russia) and Mészáros investigated nonthermal sources such as gamma-ray bursts, AGN, or galactic jet sources, where one expects both relativistic and transrelativistic shocks acompanied by MHD turbulence. These sites are electron and positron accelerators leading to a modified power law spectrum, with an electron energy index which is very hard (slope -1 or flatter) up to some comoving frame break energy. For gamma-ray bursts, the Lorentz factor reaches $\sim 10^3$ for electrons accelerated by the internal shock ensemble on subhydrodynamical time scales. For electrons accelerated on hydrodynamical timescales in the external shocks, similarly hard spectra are obtained, and the break Lorentz factor can be as high as $\sim 10^5$. Radiation from these nonthermal electrons give photon spectra with shapes and characteristic energies in qualitative agreement with observed generic gamma-ray burst and blazar spectra. This scenario provides a plausible way to solve one of the crucial problems of nonthermal high energy sources, namely the efficient transfer of energy from the proton flow to an apropriate nonthermal lepton component.

Graduate student Hara Papathanassiou and Mészáros calculated the gamma-ray spectra expected from internal shocks in time-varying relativistic wind models of gamma bursters, for a variety of wind parameters. The spectra extend from the optical through the TeV range, and are compared to the expected sensitivity of the *HETE* spacecraft in the UV, X-ray and gamma-ray ranges. The relative strength of the emission in these different energy bands can provide valuable the information on the particle acceleration, radiation mechanisms, and the possible types of models.

Mészáros and M.J. Rees (Cambridge University) discussed the evolution of cosmological gamma-ray burst remnants, consisting of the cooling and expanding fireball ejecta together with any swept-up external matter, after the gamma-ray event. They show that significant optical emission is predicted which should be measurable for timescales of hours after the event, and in some cases radio emission may be expected days to weeks after the event. The flux at optical, X-ray and other long wavelengths decays as a power of time, and the initial value of the flux or magnitude, as well as the value of the time-decay exponent, should help to distinguish between possible types of dissipative fireball models.

Mészáros and Rees also discussed the properties of magnetically dominated jet-like outflows from stellar mass black holes surrounded by debris tori resulting from neutron star disruption. These jets may have narrow cores (along the rotation axis) which are almost free of baryons and attain very high bulk Lorentz factors of $\sim 10^6$. The jets give rise to a characteristic GeV emission as well as to relativistic shocks producing the usual MeV bursts. Because the outflow is highly directional, the properties of the observed gamma-rays would depend on the viewing angle relative to the rotation axis. Even for the most intense bursts, which under the assumption of isotropic emission and substantial redshifts would be inferred to emit $10^{52}-10^{53}$ erg, the efficiencies required are only $10^{-2}-10^{-4}$.

Graduate student Alin Panaitescu, L. Wen, Laguna and Mészáros numerically modelled the interaction between an expanding fireball and a stationary external medium whose density is either homogeneous or varies with distance as a power law. The evolution is followed until most of the fireball kinetic energy is converted into internal energy. The density, pressure and flow Lorentz factor profiles are calculated for all stages, including shock and rarefaction wave reflections, both in the adiabatic and radiative regimes. For cooling times shorter than the dynamic time, bolometric light-curves are computed for bulk Lorentz factors 50, 100 and 200. The numerical light-curves are compared with analytic results and it is found that, for a homogeneous external medium, there is a simple scaling relationship among light-curves obtained for different parameters. The light curves for power law external densities are similar in shape to those in the homogeneous case. The implications of a comparison of the results with observed gamma-ray burst time histories were discussed.

*3.3.1.3 Accretion Powered Pulsars* Bulik, Mészáros, graduate student Brian Thomas, and colleagues at Tokyo University derived the physical characteristics of the polar caps of the accreting pulsars Vela X-1 and 4U1538-52, by means of chi-squared to a detailed physical model of the accretion column involving asymmetries and cap structure.

U. Kraus and Mészáros, in collaboration with Blum, Schulte and Ruder from the University of Tuebingen (Germany) developed a method for deriving beam shapes of accreting X-ray pulsars. The method decomposes the observed light curves into their Fourier components and finds the minimum number of beam elements needed to achieve a fit to derive the polar cap magnetic geometry.

*3.3.1.4 Radiation Processes in Compact Objects* Potekhin (Ioffe Institute for Physics and Technology, Russia), Pavlov, and Ventura (University of Crete, Greece) considered photoionization of the hydrogen atoms in strong magnetic fields, $10^{10}-10^{13}$ G, with allowance for coupling of electron states with different Landau numbers. This nonadiabatic approach enabled them to prove that the photoionization process is allowed for photons polarized perpendicular to the magnetic field at frequencies lower than the electron cyclotron frequency, contrary to the conclusion of many previous papers based on the adiabatic approximation. Coupling between closed and open channels leads to the autoionization of quasi-bound energy levels, which gives rise to Beutler-Fano resonances of the photoionization cross section. The corresponding spectral features can be observed in radiation emergent from surface layers of neutron stars with magnetic fields $10^{10}-10^{11}$ G.

Bezchastnov (Ioffe Institute for Physics and Technology, Russia), Pavlov, Shibanov (Ioffe Institute), and Zavlin (MPE, Germany) considered Thomson scattering of photons on electrons and protons, and absorption and emission of photons in free-free transitions of these particles, in a completely ionized electron-proton plasma of a temperature $T\sim 10$ keV in a superstrong magnetic field $B\sim 10^{14}-10^{16}$ G. Such a plasma is believed to exist in radiating layers of neutron stars associated with Soft Gamma-Ray Repeaters (SGRs). The radiative opacities are employed to construct model photospheres and to calculate the spectral flux and specific intensity emitted by these objects. The photospheres can be in hydrostatic equilibrium if the magnetic field exceeds $10^{14}-10^{15}$ G. The proton cyclotron absorption feature at an energy of a few keV can be used for the direct measurements of the superstrong magnetic fields of SGRs.

Bulik (Univ. of Chicago) and Pavlov investigated polarization properties and absorption coefficients of the normal modes of radiation in a strongly magnetized hydrogen gas. The bound-free and bound-bound absorption spectra are considerably different for the ordinary and extraordinary normal modes; they strongly depend on the angle between the magnetic field and wave vector of radiation.

Zavlin (MPE, Germany), Pavlov, and Shibanov (Ioffe Institute, Russia) investigated neutron star atmospheres with low magnetic fields, $<10^{8}-10^{10}$ G, which do not affect opacities and equation of state of the atmospheric matter. They computed the atmospheric structure, emergent spectral fluxes and specific intensities for hydrogen, helium and iron atmospheres for a wide domain of effective temperatures and gravitational accelerations. The model atmosphere spectra differ substantially from the blackbody spectra: the spectra of light element atmospheres are harder at high energies, whereas the iron atmosphere spectra display prominent spectral features in the soft X-ray range. The emergent specific intensity is anisotropic, with the anisotropy depending on energy. The results are applicable for interpreting observations of thermal radiation from low-field neutron stars, particularly recycled pulsars.

Zavlin (MPE, Germany), Pavlov, Shibanov (Ioffe Institute, Russia), Roger and Iglesias (LNL) investigated convection in atmospheres of neutron stars with low magnetic fields. They showed that, in photospheres composed of light elements, convection arises only at relatively low effective temperatures, $<(3-5)\times 10^{4}$ K, whereas in the case of iron composition it arises at $T_{\rm eff}<3\times 10^{5}$ K. Convection changes the depth dependence of the atmospheric temperature and the shapes of the emergent spectra.

Pavlov, Zavlin, Trümper and Neuhäuser (MPE, Germany) showed that an analysis of multiwavelength observations of isolated neutron stars based on neutron star atmosphere models can be used not only to evaluate the neutron star effective temperature, but also to determine chemical composition of its surface. To demonstrate how this new method can be applied to a specific object, they calculated broad-band expected spectra of the old isolated neutron star candidate RXJ 1856.5–3754, based on fitting its soft X-ray spectrum with atmosphere models of different chemical compositions. They showed that the optical/UV flux expected from this object depends drastically on the composition of its surface: the neutron star covered with hydrogen would be 5–6 magnitudes brighter than the neutron star with an iron surface.

*3.3.1.5 Globular Cluster Evolution* Graduate student Roger Bartlett and Ciardullo are continuing their study of the evolution of systems of globular clusters associated with parent galaxies. Their objective is to model the physical changes in the population of globular clusters over a Hubble time, such that the cluster luminosity function evolves from an initial power law form, as observed in the Antennae galaxies, to the log-Gaussian form seen in the Milky Way, M31, and the giant ellipticals of Virgo and Fornax. The dynamical effects being considered are the evaporation of stars due to internal cluster relaxation, the loss of mass from evolving stars within clusters, and dynamical shocks induced externally by the passage of a cluster through the disk or close to the bulge of the parent galaxy. Bartlett and Ciardullo aim to quantify the evolution of entire systems of globular clusters, and to constrain the physical characteristics of cluster systems present at the time of galaxy formation.

### 3.3.2 Computational Astrophysics

*3.3.2.1 Globular Clusters* Undergraduates H. Burkert and R. Klinger, working with Laguna and Charlton, have performed N-body computations to predict the distortion of the outer layers of globular clusters that will arise when they pass through the bulge of a galaxy. Tidal forces produce a gradual ''twisting'' of the outer layers of the cluster. A preliminary study of feasibility indicated that these effects should be observable against the typical stellar density toward the Milky Way bulge, for appropriately selected clusters.

*3.3.2.2 Lyman-alpha Forest* Charlton teamed up with P. Anninos, Y. Zhang, and M. Norman (NCSA/UIUC) to complete an analysis of the Ly$\alpha$ absorbing structures in a large cosmological N–body/hydrodynamic simulation. The analysis was based on double lines of sight through the numerical results at redshifts 3, 2, and 1, and involved producing and analyzing simulated spectra pairs at various separations. Comparisons to the results of observational analyses of spectra of close pairs of quasars guide conclusions about the shapes and sizes of the Ly$\alpha$ forest structures.

### 3.3.3 Atomic Physics

Sampson and collaborators have continued their work on fully relativistic calculations of atomic properties of highly charged ions and on applications of the results. In collaboration with scientists at the Naval Research Laboratory, the atomic data on F-like and Ne-like selenium ions was used in the diagnosis of high temperature selenium plasmas. In other work, the effects of the hyperfine interaction on the circular polarization of Sc XX X-ray lines was considered. Also, their relativistic distorted wave collision strength program for fine structure transitions was modified to treat hyperfine stucture transitions and was used to calculate the collision strength for excitation of the upper hyperfine structure component of the ground level of Li-like Fe-57, which produces the 3.071 mm line of astrophysical interest.

### *3.3.4 Statistical Astronomy*

*3.3.4.1 Methodology* The monograph *Astrostatistics* by G. J. Babu (Statistics, Penn State) and Feigelson was published. It serves to introduce students and researchers in astronomy and statistics to methodological problems in the field. It includes an overview of each field, samplings of contemporary research problems, and discussions of research problems and possible methods for their solution. They also organized an international cross-disciplinary conference, ''Statistical Challenges in Modern Astronomy II,'' held at Penn State in June 1996, five years after the first interdisciplinary conference. Invited talks by astronomers and statisticians were followed by commentaries by researchers in the other field. Proceedings will be published by Springer-Verlag in 1997.

Feigelson gave talks on astrostatistics for the Interface '96 meeting at the Sydney International Statistical Congress and for the IAU Symposium 179 on astronomical surveys. He emphasized the importance of multivariate statistics for observational astronomy. Astronomical surveys present methodological challenges with their heteroscedastic measurement errors, truncation (flux-limits) and censoring (non-detections) in all variables, and parameter estimation for nonlinear astrophysical models.

*3.3.4.2 Statistical Consulting Center* Feigelson also participates in the Statistical Consulting Center for Astronomy, operated at the Penn State Department of Statistics under the direction of Prof. M. G. Akritas. The Center has received and answered dozens of questions (see http://www.stat.psu.edu/scca). Topics discussed include time series analysis of Poisson arrival times, parameter estimation and confidence intervals using chi-squared and likelihoods, robust methods, clustering algorithms, comparing censored samples, treating measurement errors in goodness-of-fit and multivariate problems, and goodness-of-fit and confidence intervals from truncated samples. Two papers have been prepared on testing for partial correlation with censored data and linear regression for data with both measurement error and intrinsic scatter. A Web site with hypertext links to statistical source codes potentially useful to astronomers can be found at http://www.astro.psu.edu/statcodes.

### *3.3.5 Cosmology*

*3.3.5.1 QSO Absorption Lines* To complement the observational program described above, Charlton and Churchill have designed various types of models of MgII absorbing gas. The overall goal of this effort is to obtain a description of both the high and the low ionization species of gas in galaxies, and an understanding of the relationship between the properties of their gas and their stars. These are all essential elements in constructing a complete history of galaxy formation and evolution.

Nearly all galaxies exhibit MgII absorption lines at any impact parameter less than 30–40 $h^{-1}$ kpc, and for nearly every MgII absorber a galaxy can be identified within this distance. Charlton and Churchill conducted a Monte–Carlo ''survey'' of QSO fields, in which the model absorbing galaxies were constructed of ''clouds,'' either in a spherical halo or in a randomly oriented disk. Both geometric models are consistent with the observations, once selection procedures are considered. If gaseous disks make a dominant contribution to the MgII column density for many absorbers, then a correlation is predicted between absorption properties and the orientation of the disk. *HST* observations of large numbers of absorbing galaxies should soon provide strong constraints on the geometric distribution of absorbing gas.

To develop intuition about what combination of components in and around galaxies give rise to MgII absorption profiles, Charlton and Churchill have been constructing kinematic models. Absorbing gas clouds were set up in either a rotating disk, an isothermal halo velocity distribution, or a radial infall model. Model galaxies were viewed at various orientations and impact parameters to generate synthetic spectra as would be observed by the Keck/HIRES. Even a simple kinematic model gives rise to a large variety of profile morphologies. For nearly every observed MgII absorber, a ''match'' can be found among the ensembles of simulated spectra. Rotating disk models are quantitatively distinct as a population, with a smaller typical velocity spread between subcomponents. A statistical analysis is underway.

Graduate student Suzanne Linder is completing a thesis that explores the relationship between galaxies, including dwarfs and low surface brightness galaxies, and Ly$\alpha$ absorption at low redshift. Luminous, ordinary galaxies are unlikely to have a large enough total cross section to explain all Ly $\alpha$ absorption, but low surface brightness galaxies are generally quite rich in gas and must also cause some absorption. Linder began with the hypothesis that all low column density absorbers arise from lines of sight through ionized extensions of galaxy disks, and used the observed numbers of Ly $\alpha$ absorption lines to constrain the number density of galaxies. This work was based upon a code that chooses random lines of sight through a model population of galaxies (including extended dwarf and low surface brightness galaxies), with the model parameters based upon observed distributions. These models predict little or no observed correlation between galaxy impact parameter and absorber column density, consistent with observations. Absorption at low impact parameters ($<$300 kpc) is dominated by dwarf and low surface brightness galaxies which would be difficult to identify. Overall, absorption is dominated by luminous galaxies, but the impact parameters are typically so large that it is difficult to observe a definite absorber-galaxy connection.

*3.3.5.2 Computational Cosmology* Laguna and Tuluie investigated the imprint of nonlinear matter condensations on the Cosmic Microwave Background (CMB) in $\Omega_0<1$ cold dark matter universes. The study concentrated on the secondary temperature anisotropies induced by time varying gravitational potentials occurring after decoupling. Specifically, they investigated the importance of the Rees-Sciama effect due to intrinsic changes in the gravitational potential of forming, nonlinear structures, proper motion of nonlinear structures, and late time decay of gravitational potential perturbations in open universes. CMB temperature anisotropies were obtained using photon ray-tracing techniques. They tested, in particular, the dependence and relative importance of these secondary temperature anisotropies as a function of the scale of the underlying matter (voids, superclusters) and as a function of $\Omega_0$. They found that, in low density models, all three sources of anisotropy can be relevant, reaching levels of $\Delta T/T \sim 10^{-6}$. Furthermore, they also obtained that, for $\Omega_0 < 1$, at large scales the secondary temperature anisotropies are dominated by the decaying potential.

Laguna and Peter Anninos (NCSA) are studying the nature of the collapse of matter at super-horizon scales. Current effort involves finding solutions that lead to ''Silent Universes,'' that is, matter dominated solutions for which the magnetic part of the Weyl tensor vanishes. It can be shown that, under this assumption, once the initial value problem is solved, the dynamics of the gravitational field for each ''fluid element'' is governed by ordinary differential equations in time and thus communication between neighboring elements is absent; all the communication is encoded in the initial data. The main goals here are to investigate how wide the class of initial value problem solutions is for silent universes and to investigate how the collapse proceeds for super-horizon structures in a fully 3D simulation.

### *3.3.6 Numerical Relativity*

Papadopoulos and Laguna, in collaboration with Roberto Gomez and Jeff Winicour (Pittsburgh), studied a Cauchy-characteristic initial value problem for the Einstein-Klein-Gordon system with spherical symmetry. Initial data were specified on the union of a space-like and null hypersurface. The development of the data was obtained with the combination of a constrained Cauchy evolution in the interior domain and a characteristic evolution in the exterior, asymptotically flat region. The matching interface between the space-like and characteristic foliations was constructed by imposing continuity conditions on metric, extrinsic curvature and scalar field variables, ensuring smoothness across the matching surface. The accuracy of the method was established for all ranges of $M/R$, most notably, with a detailed comparison of invariant observables against reference solutions obtained with a calibrated, global, null algorithm.

Papadopoulos and Laguna also investigated the Cauchy +characteristic initial value problem for the scalar wave equation in the background geometry of a non-rotating black hole. Previously reported work considered the coupled system of scalar waves and geometry up to the point of black hole formation. Here, the time evolution after the formation of the black hole was pursued, using a Cauchy +characteristic formulation of the governing equations perturbed around the black hole background. An extension of the matching scheme allows for arbitrary matching boundary motion across the coordinate grid. As a proof of concept, the late time behavior of the dynamics of the scalar field was explored. The power-law tails in both the time-like and null infinity limits were verified.

Krivan, Papadopoulos and Laguna performed a numerical study of the evolution of a massless scalar field in the background of slowly rotating black holes. To first order in the angular momentum of the black hole, the scalar wave equation yields two coupled one-dimensional evolution equations for a function representing the scalar field in the Schwarzschild background and a second field that accounts for the rotation. Solutions to the wave equation were also obtained for rapidly rotating black holes. The study showed that, for rotating black holes, the late time dynamics of a massless scalar field exhibit the same power-law behavior as in the case of a Schwarzschild background independently of the angular momentum of the black hole.

*3.3.6.1 Cosmological Topological Defects* Laguna, in collaboration with Richard Matzner (Texas) and Luis Bettencourt (London), performed full field numerical evolutions of the collision of two Abelian type I cosmic strings. They showed that, for collisions at small but characteristic relative velocities and angles, these cosmic strings do not exchange ends and separate as is assumed generally in effective network evolutions. Rather, the interacting strings form local higher winding number bound states, which promote multiple local scatterings at right angles and prevent intercommutation from happening. This can lead to considerably different string network evolutions and their associated cosmological phenomena.

Laguna and Wojciech Zurek (Los Alamos) carried out a numerical study of order parameter dynamics during second order (Landau-Ginzburg) symmetry-breaking transitions showing that the density of topological defects (kinks) is proportional to the fourth root of the rate of the quench. This confirms the more general theory of domain-size evolution in the course of symmetry breaking transformations proposed by Zurek. Using these ideas, it is possible to compute the density of topological defects from the quench timescale and from the equilibrium scaling of the correlation length and relaxation time near the critical point.

### *3.3.7 History of Astronomy*

In two related papers, Usher developed the case that William Shakespeare knew more about the astronomical revolutions of the sixteenth century than has hitherto been thought. These studies help shed light on the question of why the Bard's vision of astronomy as evinced in his plays and sonnets is apparently limited to that of the geocentric Ptolemaic model. In the case of *Hamlet*, Usher summarized evidence of previous workers; for example, the astronomer Payne-Gaposchkin has pointed out that Shakespeare probably knew more about the Copernican Revolution than can be gleaned from a superficial reading of the play, for he makes the Prince a student at the University at Wittenberg, where Rheticus first established the mathematical foundation of heliocentricism and promoted Copernicus' *De Revolutionibus*. Usher presented other arguments that *Hamlet* amounts to a redefinition of universal order and humankind's position in it.

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