Rice University
Department of Space Physics and Astronomy

6100 S. Main, Houston, Texas 77005-1892

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The following report covers the Department activities from October 1997 through October 1998. Updated research information, as well as course listings and our graduate brochure can be accessed on the Web at http://spacsun.rice.edu.

1. INTRODUCTION

In 1963, Rice University established the first Department of Space Science in the United States to support the manned and unmanned exploration of space. Today, the Department of Space Physics and Astronomy strives for excellence in graduate education and research across a broad spectrum of topics in physics and astronomy ranging from the Earth's climate and magnetosphere to observational and theoretical astrophysics.

2. PERSONNEL

2.1 Academic and Research Staff

The resident academic and research staff of the Department for the 1998/1999 academic year consists of twelve teaching faculty, three research faculty, and seven research scientists and postdocs. Seven adjunct faculty from neighboring institutions around Rice are also affiliated with the Department through research projects, teaching, and student advising.

2.1.1 Faculty

Chan, Anthony. Assistant Professor (Ph.D. Princeton 1991) - *Theoretical Plasma Physics; Space Physics*

Cloutier, Paul A. Professor (Ph.D. Rice 1967) - *Planetary Atmospheres; Spacecraft Instrumentation*

Dufour, Reginald J. Professor (Ph.D. Wisconsin 1974) - *Emission Nebulae and Galaxies; Chemical Evolution*

Few, Arthur A. Professor (Ph.D. Rice 1969) - *Atmospheric Electricity; Earth Systems Physics*

Freeman, John W. Professor (Ph.D. Iowa 1963) - *Solar Wind; Magnetospheric Physics*

Hartigan, Patrick. Assistant Professor (Ph.D. Arizona 1987) - *Shock Waves; Stellar Jets; T Tauri Stars*

Liang, Edison P. Professor (Ph.D. Berkeley 1971) - *Gamma-ray Bursts; Accretion Disks; Cosmology*

Michel, F. Curtis. Professor (Ph.D. CalTech 1962) - *Pulsar mechanisms; Physics of dense matter*

O'Dell, C. Robert. Professor (Ph.D. Wisconsin 1962) - *Structure and kinematics of HII regions*

Reiff, Patricia H. Professor [chair] (Ph.D. Rice 1975) - *Auroral physics; Magnetospheric experiments*

Weisheit, Jon C. Professor (Ph.D. Rice 1970) - *Plasma astrophysics; Globular clusters; QSOs*

Wolf, Richard A. Professor (Ph.D. CalTech 1966) - *Magnetospheric theory and computer modeling*

2.1.2 Research Faculty

Hill, Thomas W. Distinguished Faculty Fellow (Ph.D. Rice 1973) - *Magnetospheres of Earth, Jupiter, and Saturn*

Smith, Ken A. Distinguished Faculty Fellow (Ph.D. Rice 1976) - *Experimental Atomic & Molecular Physics*

Toffoletto, Frank. Faculty Fellow (Ph.D. Rice 1987) - *Magnetospheric Physics; Numerical Simulations*

2.1.3 Adjunct Faculty

Black, David C. (Ph.D. University of Minnesota 1970) Lunar and Planetary Institute - *Planetology; Origin of the Solar System*

Chang-Diaz, Franklin. (Ph.D. MIT 1977) Johnson Spaceflight Center - *Astronaut*

Horton, Wendell. (Ph.D. UCSD 1967) UT Austin - *Fusion; Magnetospheric Research*

Newman, Jim (Ph.D. Rice 1984) Johnson Spaceflight Center - *Astronaut*

Stepinski, Tomasz (Ph.D. University of Arizona 1988) Lunar and Planetary Institute - *Models of Magnetized Accretion Disks*

Winningham, David J. (Ph.D. Texas A & M 1970) Southwest Research Institute - *Experimental Space Plasma Physics*

Young, David. (Ph.D. Rice 1970) Southwest Research Institute - *Experimental Space Plasma Physics*

2.1.4 Research Scientists and Postdocs

Balashov, Yuri. Postdoctoral Research Associate (Ph.D. Notre Dame 1998) - *Philosophy of Science; History and Philosophy of Physics; Metaphysics*

Bötttcher, Markus. Postdoctoral Research Associate (Ph.D. 1997, MpI Bonn) - *Active Galactic Nuclei; Gamma Ray Bursts*

Law, Colin. Research Scientist (Ph.D. 1995, Rice) - *Magnetic Fields in the Dayside Ionospheres of Venus and Mars*

Lindsay, Bernard. Research Scientist (Ph.D. 1987, U. Belfast) - *Experimental Atomic and Molecular Physics*

Mangan, Michael A. Postdoctoral Research Associate (Ph.D. 1998, U. Georgia) - *Experimental Atomic and Molecular Physics*

Smith, Ian. Research Scientist (Ph.D. 1990, Washington Univ.) - *Multiwavelength Observations of Gamma Ray Bursts, Pulsars and Galactic Black Holes*

Spiro, Robert W. Senior Research Scientist (Ph.D. 1978, U.T. Dallas) - *Magnetospheric Simulations*

2.1.5 Emeritus Faculty

W. E. Gordon, J. W. Chamberlain, A. J. Dessler, R. C. Haymes, and R. F. Stebbings are Emeritus faculty of our Department.

2.2 Students

At the beginning of the 1998/99 academic year, 26 students were enrolled in full-time graduate study. Of these, four joined the department in August 1998. In addition, one junior and five senior undergraduate students were enrolled in our ''Space Physics and Astronomy Option'' study program towards obtaining a B.A. degree in Physics. During our May 1998 Commencement three Ph.D. and six M.S. degrees were awarded. The Ph.D. recipients and dissertation titles were:

C. Benjamin Boyle	Polar Cap Response to the Magnetic Cloud Event of 19-21 October 1995 (Advisor: Reiff)
Kirk A. Costello	Moving the Rice MSFM into a Real-Time Forecast Mode Using Solar Wind Driven Forecast Modules (Advisor: Freeman)
Robert S. Steen	Cryosphere-Atmosphere Interactions in the Global Climate System (Advisor: Ledley)

The M.S. recipients were:

Anthony Crider	Evolution of the Low-Energy Photon Spectra in Gamma-Ray Bursts (Advisor: Liang)
Parviz Ghavamian	Free-Free Radiation From Dense Interstellar Shock Waves (Advisor: Hartigan)
Cindy Marie Kurt	A Study of the Dusty SMC HII Region N88A (Advisor: Dufour)
Jinwen Song	Modeling Electromagnetic Fields of the Earth's Magnetosphere (Advisor: Toffoletto)
Andrew Urquhart	Polar Magnetopause Crossings of May 29, 1996: Implications for Magnetic Field Modeling (Advisor: Reiff)
Peter W. Walker	A Global Magnetic Potential Model for Venus' Ionosphere (Advisor: Cloutier)

3. FACILITIES

The department is located on the second and third floors of Herman Brown Hall, on the campus of Rice University. Most faculty, staff, and student offices occupy the third floor of the building, which also includes our computational and data analysis facilities. The networked computer facilities available in the Space Physics and Astronomy Department include several standalone Sun sparcstations (including a server ''spacsun''), a VMS cluster, three UNIX workstations consisting of an HP 9000/750, a DEC 3000/300 AXP and a Silicon Graphics Power Indigo 2 and numerous Macintosh computers. In addition, there is a 4-processor Alphaserver 4100/400/1gb which is typically used for the more CPU-intensive calculations. The Department has a color printer and slide maker, and has access to other peripheral devices within the University. A multimedia facility in our conference room enables speakers to present movies, slides, Web pages, and do video conferencing during talks. A thorough collection of scientific texts and research journals is maintained in the Department reading room and in Rice's Fondren Library.

Undergraduate and graduate students have the opportunity to use a variety of telescopes in education and research, ranging from small instruments located on the roof of Fondren Library to computerized 14-inch and 36-inch telescopes at the George Observatory, located in Brazos Bend State Park, 35 miles southwest of campus. In addition, students use facilities at the Lunar and Planetary Institute in nearby Clear Lake City, and the laboratories for space instrumentation development at the Southwest Research Institute in San Antonio, Texas. The department also maintains a laboratory in the Space Science and Technology building for the study of atomic and molecular collisions of aeronomic importance.

4. RESEARCH

4.1 Space Science

4.1.1 Atmospheric and Climate Studies

Professor A. Few's research interest is in atmospheric physics with a special emphasis on atmospheric electricity and Earth system science. In the experimental area he has data from a suite of instruments that operated at the South Pole for a three year period; these measurements monitor the total global thunderstorm activity, a parameter strongly influenced by global warming. Few is also active at the national level in global change and Earth system science education. He is an author-participant in the Global Change Instruction Program (NSF and NCAR), and in the Earth System Science Education Program (NASA and USRA). These programs share the goal of developing undergraduate courses and teaching materials in the interdisciplinary areas of global change or Earth system science.

Emeritus Professor R. F. Stebbings, Professor Ken Smith, and Research Scientist Bernard Lindsay continued their program to study the interaction of ions, atoms, and electrons with atoms and molecules. These interactions are essential to the understanding of a broad range of large-scale physical systems such as, planetary atmospheres, astrophysical plasmas, gas discharge lasers, semiconductor processing plasmas, and fusion plasmas. This research group has developed new techniques to study collisions of energetic ions and neutrals at an exceptionally detailed level. Much of the current program is directed toward understanding the basic physics of the collision processes which occur in the upper atmosphere and development of accurate data which are needed for modeling the atmospheres of the earth and the other planets.

The focus of recent work has been charge transfer of protons and oxygen ions with atomic oxygen. These processes are aeronomically very important and are also particularly difficult to deal with experimentally. In collaboration with Dean Sieglaff (Grove City College), the differential charge transfer cross sections for state-selected oxygen ions with several simple molecules were determined. These measurements are the first of their kind to be performed anywhere and have provided some insight into the cause of the large discrepancies between the total cross section data of different workers. Research has also continued into processes that involve electron collisions. Many electron impact ionization cross sections, particularly those for dissociative processes, are not well known. Over the past several years an apparatus specifically designed to make accurate electron-impact ionization cross section measurements has been utilized to study the electron-impact ionization of numerous atomic and molecular species. Results of the work on water vapor were published during the past year, and Postdoctoral Fellow Michael Mangan is currently completing measurements on NO_2 and CO.

4.1.2 Terrestrial Magnetosphere and Space Weather

The Rice modeling group meets weekly to compare notes on progress on the various models being developed and to report on meetings attended. This group consists of Research Faculty Tom Hill and Frank Toffoletto, who model magnetic fields, Professors Dick Wolf and John Freeman, Assistant Professor Anthony Chan, and Senior Research Scientist Bob Spiro, who model magnetospheric particles, and graduate students Trevor Garner, Steven Naehr, and Andrew Urquhart. Departmental guests are often invited to share views or report new results. These meetings provide a useful forum for the discussion of current topics and new ideas.

One topic that has received a great deal of attention at these meetings during the past year is the higher energy trapped particles that constitute the radiation belts. These particles are a serious hazard to scientific, navigation and communications spacecraft. A major question regarding radiation belt particles is whether they are accelerated locally within the magnetosphere or gain entry from outside and are accelerated adiabatically. A recent analysis by Freeman, Chan, Wolf, and former Rice undergraduate, Paul O'Brien has suggested the possible entry of energetic electrons from the magnetotail (Freeman *et al.*, 1998). Pursuing this question, Chan, working with the MHD code of Michael Hesse (NASA-GSFC) and Joachim Birn (Los Alamos) has attempted to determine if electrons can gain access from the tail and if adequate energy gains are possible. Preliminary work indicates the mechanism works and provides substantial energy.

In line with his interest in the radiation belts, Chan is the Principal Investigator on a project to model relativistic electrons in the Earth's magnetosphere. This project is part of the National Space Weather Program and is sponsored by NSF. Chan and graduate student Hee-Jeong Kim are studying physical mechanisms which may be responsible for the large flux variations which are observed during magnetic storms (Kim and Chan, 1997). Mechanisms which are being considered include fully-adiabatic flux changes, loss to the magnetopause, substorm-related injection, and acceleration and radial transport by drift-resonant interactions with low-frequency perturbations.

A related topic that has received considerable attention this past year is a new class of energetic particle orbits whose existence was established last year by the Solar Energetic Particle Tracer model (SEPTR) built by recent Ph.D. student Seth Orloff with the support of the Mission Research Corporation and funded by the Defense Threat Reduction Agency. These orbits, called Shabansky orbits, are orbits where particles leave their mirror points at the equator and migrate to local magnetic field minima at the cusps on the day side of the magnetosphere. They are found to have a number of properties which open new possibilities for radial drift and acceleration mechanisms. One such property is the breaking of the second adiabatic invariant which can lead to interesting new trajectories. A paper on Shabansky orbits will be presented by Orloff and Freeman at the Spacecraft Charging Conference at Hanscom AFB in November, 1998 and a more detailed paper by Orloff, Freeman, Chan and Wolf is in preparation for submission to Geophysics Research Letters.

Also pursuant to the radiation belts, Freeman, Chan, Wolf and Spiro, together with researcher Bonnie Hausman are developing a first principles, dynamic test model of the more energetic trapped particles in the magnetosphere for the US Air Force Research Laboratory. This Dynamic Radiation Belt Test Model (DRBTM) will be based on the fully adiabatic model by Chan and Kim. It will be built into the framework of the successful Magnetospheric Specification Model and will use an Air Force statistical model for initial conditions and neural networks for boundary conditions. The DRBTM is designed to grow in stages as the understanding of the physics of relativistic electrons grows.

In collaboration with Dr. Brian Anderson (Johns Hopkins) and Dr. Mary Hudson (Dartmouth), Chan is studying transport and loss of ring-current and radiation belt particles by breaking of the first adiabatic invariant. This work involves detailed analysis of charged particle trajectories in realistic time-dependent magnetospheric fields. Chan also continued his theoretical studies of the effects of anisotropic plasma pressure and kinetic effects on MHD equilibrium and stability in the Earth's magnetosphere (Chan, 1998). Anisotropy can significantly lower both the wave eigenfrequency and the instability threshold for ballooning modes (pressure-gradient-driven MHD modes). Resonant wave-particle instabilities are also considered. These studies use linear gyrokinetic theory (a self-consistent kinetic theory of low-frequency waves and instabilities in plasmas). Theoretical results are compared with spacecraft measurements of wave and particle properties.

Elena Belova, Richard Denton and Mary Hudson at Dartmouth College, with help from Chan, have developed a hybrid MHD-gyrokinetic computer code to calculate the self-consistent nonlinear evolution of magnetospheric hydromagnetic waves and the induced particle transport (Belova *et al.*, 1997). Chan and collaborators C. Z. Cheng and Jay Johnson (Princeton) continue to study the kinetic effects on MHD modes in the Earth's magnetosphere.

The Rice Space Physics and Astronomy Department has become heavily involved with the NSF sponsored Geospace Environmental Modeling (GEM) program. All department space physics persons participate regularly in the annual Snowmass Summer Workshop. Wolf is chair of GEM Steering Committee and Freeman is GEM Workshop Coordinator.

Also in connection with GEM, Hill, Toffoletto, and Freeman have begun a project to make the Toffoletto-Hill open magnetosphere model and the Magnetospheric Specification Model (MSM) available to the space physics community. This work is being done as part of the GEM Geospace General Circulation Model (GGCM) program. It entails Internet displays of the outputs of the two models for standardized input conditions and the large storm of January, 1997. This is Phase I of the project. Under Phase II other researchers will be able to access and modify the models themselves, possibly substituting modules of their own for test and comparison. Also during the past year, the MSM has been incorporated into the real-time operations of the NOAA Space Environment Center and continuous output from the model is available on the Internet at http://sec.noaa.gov/rpc/msm/index.html.

Hill and Toffoletto continued to improve their open magnetosphere model. They participated in the GEM challenge to do model comparisons with Synoptic Weather Maps, and used their open magnetosphere model to derive polar cap convection patterns and open/closed boundary locations. A paper presenting the results of this has been published in the Journal of Geophysical Research. (Hill and Toffoletto, 1998). Also, Hill and Toffoletto and graduate student Andrew Urquhart are undertaking a study to compare auroral images taken by the polar spacecraft with the theoretical predictions of their open magnetosphere, model (Urquhart *et al.*, 1998). This project is supported by NASA as part of their Global Geospace Science Guest Investigator Program.

Hill and Toffoletto along with G. Erickson and M. Heinemann (Air Force Research Laboratory) undertook a concept study, supported by the NSF/GEM program, to look at the feasibility of assembling the first comprehensive global model of the magnetosphere that will be used as a community-wide research tool in Magnetospheric Physics. This global model is analogous to the global climate models that are found in the atmospheric community. The final report from this study is available on the Internet at: http://rigel.rice.edu/~toffo/GGCM_Concept_Report.html.

The Rice magnetospheric modeling effort has also led to other interesting collaborations. Wolf and Toffoletto continue their work with J. Birn (Los Alamos National Lab) and M. Hesse (NASA-GSFC) to develop the first self-consistent computational model of a substorm. A substorm is believed to be an intrinsic instability of the global magnetosphere and is a primary mechanism of energy release in the nightside tail region of the magnetosphere. This model couples three models of the magnetosphere: the Rice Convection Model (RCM), a model that is has been developed over many years to study the physics of the inner magnetosphere; the Los-Alamos/Goddard MHD model of tail dynamics, and an equilibrium code that has been developed through a Los-Alamos/Goddard/Rice collaboration. Preliminary results with a model that couples the RCM with the equilibrium model suggest that tearing instability occurs in the inner region of the magnetosphere after the system has been driven by the solar wind for several hours. Recent simulations have also shown that running the RCM with a self-consistent field model results in little or no plasma transport and energization from the far tail to the inner magnetosphere. This result has implications for the understanding of ring current formation during magnetic storms: some other mechanism, such as reconnection, must be invoked to produce and energize the ring current.

The Rice modeling effort has also lead to collaboration with colleagues from other countries. Freeman and Hausman are assisting Dr. Yohsuke Kamide (STELAB, Japan) in the testing of the Magnetospheric Specification Model (MSM) using Japanese developed electric field models.

In the area of collaborations with other departments at Rice, Toffoletto and P. Kloucek of the Computational and Applied Mathematics Department at Rice University and are continuing their collaboration in a project to adapt an unstructured finite element code to solve magnetospheric problems. Initial results from this work have shown that the use of nonconforming finite elements may be a useful and natural vehicle for magnetic field modeling and possibly MHD.

Rice space physics collaborations include commercial colleagues. As part of a team headed by Willard White (Mission Research Corporation) and funded by the Defense Threat Reduction Agency, Rice is providing several computational modules for inclusion in a comprehensive model of the Earth's space environment. Spiro is developing a ring-current/plasma-sheet module based on the Rice Convection Model, and Freeman and recent Ph.D. graduate Seth Orloff have provided a solar-energetic-particle module. Graduate student Trevor Garner has developed a procedure for assimilating real-time measurements of geosynchronous particle fluxes into the time loop of the calculation, and graduate student Stephen Naehr is developing a radiation-belt module.

Continuing with the magnetospheric modeling effort, Garner and Spiro are employing the Rice Convection Model for a detailed study of the major magnetic storm of June 4-6, 1991. Model predictions are being compared with observations by the CRRES and DMSP spacecraft. Extensive computer experiments are being conducted to determine the origins of different components of the storm-time ring current and to investigate how magnetospherically generated electric fields penetrate to the low-latitude ionosphere.

Wolf and recent Ph.D. graduate Chuxin Chen are completing work on a new theory to explain the bursty bulk flows that are observed in the Earth's plasma sheet. In the process, they developed a convenient mathematical formalism for describing the motion of a thin MHD plasma filament through a medium.

In a somewhat different area, Chan and graduate student Tim Glover are working in collaboration with NASA astronaut Dr. Franklin Chang-Diaz and his team at the Advanced Space Propulsion Laboratory (ASPL) of the Johnson Space Center. The primary objective of the ASPL is to develop plasma rocket technology for NASA interplanetary missions. A research version of a plasma rocket which uses magnetically-confined high-temperature plasma is currently being developed at the ASPL.

Professor Patricia Reiff's research group is active in studies of the Earth's magnetosphere and space weather. Reiff is a Co-Investigator on the POLAR spacecraft. She and graduate students Andrew Urquhart and Vance Henize are studying the detailed response of the magnetosphere to changes in the interplanetary field, particularly when the IMF is nearly parallel to the Earth's field near the boundary. Reiff is also a Co-Investigator for the IMAGE mission which will fly January 1, 2000 and the ESA/Cluster2 spacecraft scheduled for launch in the year 2000. IMAGE will use new techniques such as neutral atom imaging and radio sounding for remote sensing of the entire magnetosphere.

Reiff continues to be heavily involved in public outreach. She is Principal Investigator for the NASA outreach program ''The Public Connection'' which creates computerized exhibits and planetarium shows for museums and schools, and is currently involved in the development of a 3-dimensional projection system that can place an audience in the middle of a galaxy or the magnetosphere.

4.1.3 Solar System Plasmas

Professor Paul Cloutier and his students continued their analysis of 14 years of Pioneer Venus Oriter data. Accomplishments to date include extensive study of the dayside ionosphere of Venus covering a variety of topics, such as (1) wave-particle mechanisms at the ionopause, including missing pressure in the Venus ionosphere, and a model of superthermal ion behavior; (2) structure and dynamics of the Venus ionopause and ionosphere, including Venus ionopause formation, and magnetic signatures and structure in the dayside Venus ionosphere; and (3) flows and fields in the Venus ionosphere, including refinement of the flow/field models of the ionosphere with comparative applications for other solar system bodies. In addition, progress continues to be made in understanding the dynamics of the nightside ionosphere of Venus, such as the structure, instabilities, and electric field noise in Venus's ion troughs.

Recent work includes the discovery of a magnetic field rotation at the dayside Venus ionopause which correlates with the boundary between postshock solar wind flow and Venus thermal ions. From thse observations a new configuration for the dayside magnetic field draping has been derived. In addition, a new current system to account for this changing field orientation is being explored. These new features of the dayside have instigated a reexamination of the mechanics driving the solar wind interaction at Venus. While the data currently available is specific to Venus, there is a great opportunity for comparative atmospheric studies.

Assuming Mars also represents a non-magnetic obstacle to the flow, as past experimental observations indicate, the field diagnostics established at Venus make it possible to probe the structure of the Martian ionosphere using magnetometer data in the absence of ion mass spectrometer data. This discovery has led to diagnostic tools for interpretation of the Mars Global Surveyor magnetometer experiment data, for which Cloutier serves as Co-Investigator. Early results from the MGS project indicate a crustal remnant field of surprising variation across the surface of the planet. Already data have shown what appear to be a range of solar wind interactions taking place including one similar to Venus. The next year will be very busy analyzing the vast amounts of data from MGS.

Currently Cloutier and graduate students Dana Crider and Yue Chen are working on analyzing data from the Mars Global Surveyor spacecraft, determining the extent of the Venus-like Martian solar wind interaction. Cloutier and graduate student Pete Walker are working on a current model for Mars based on Venus's ionosphere. Research Scientist Colin Law is also working on Mars Global Surveyor data analyzing results from the first science phasing part of the mission.

4.2 Galactic Astronomy

4.2.1 Star Formation and Stellar Jets

Assistant Professor Patrick Hartigan continued his research into the formation of stars and the physics of shock waves within stellar jets.

Hartigan is PI on an HST project with S. Kenyon (CfA) to examine spectra of close binary T Tauri stars to determine how material accretes onto very young binary systems when they are still surrounded by their nascent disks of gas and dust. The new data will test predictions of theoretical models that indicate higher mass accretion rates for the less massive component. The first observations are scheduled for late Novemeber 1998, and will continue though the year 2000. Graduate student Dimitris Stamatellos will be working with Hartigan and Adjunct Professor David Black of LPI to model disk accretion onto protobinaries within the next year.

Hartigan is a Co-I on a team led by B. Reipurth (Colorado) to examine proper motions of HH objects with HST. Observations of HH 1 have been taken, and those for HH 34, HH 47 and HH 111 are scheduled within the next year. The HH 1 data show obvious movement of emission line knots relative to images taken a few years ago, as well as marked variability in the brightness of some objects. The observed motions within jets will be compared with predictions from numerical simulations, and will help to quantify how energy and momentum is transferred in these collimated supersonic flows. Hartigan and collaborators completed a paper on this subject for the Protostars and Planets IV meeting that will be included as a review chapter in the book scheduled for publication in 1999.

Ultraviolet emission lines can be important diagnostics of physical conditions within shock waves. Hartigan led a project that included collaborators from CfA and Colorado to study the bow shock HH 47A in the ultraviolet with the Faint Object Spectrograph on HST. The new spectra show that the blue continuum that continues into the UV has a spectral energy distribution consistent with that expected from 2-photon emission. Strong resonance lines of [Fe II] are visible in the spectrum, and the relative fluxes of these lines can be used to infer the optical depth of the emitting region. Shock models of the emission lines reproduce the observed optical and ultraviolet fluxes only with the inclusion of secondary shocks within the cooling region. These shocks will have a strong magnetic field as a result of the passage of material through the primary shock, and this field may be important in the gas dynamics of the cooling regions. Hartigan has also obtained time with NASA's new Far Ultraviolet Spectroscopic Explorer (FUSE) to study the far-ultraviolet emission lines from both a low-excitation and a high-excitation HH object. These data have yet to be scheduled, but will probably be taken sometime in 1999.

Hartigan and collaborators J. Morse (Colorado) and P. Paliunas (GSFC) are working to reduce a set of data taken in December 1996 at the KPNO 4-m telescope for the young stellar outflow L 1551. Initial results presented at the Protostars and Planets IV meeting show that the Herbig-Haro object HH 29 appears to create a complex of shock waves as faster flow overruns a slower obstacle. Because the FP data give a spectrum at each point in the flow, it is possible to study the dynamics of these systems in detail.

Hartigan is PI on a project that includes J. Bally and J. Morse at Colorado to study the massive star formation region Cepheus A with narrow band emission line HST images. The goal is to examine how the spatial distributions of Hα emission, which outlines the location of shocks, and [S II] emission, which shows where the gas cools, vary across the region. Cepheus A is probably the best example of a simple, extended bubble driven by a high velocity flow, and the goal is to understand how energy and momentum propagate in flows from massive stars, and determine the degree to which instabilities affect the observed structures. The images are scheduled to be taken sometime near the end of 1998. To supplement this study, Hartigan has obtained observing time on NASA's Infrared Telescope Facility (IRTF) on Mauna Kea in late December 1998 to study the H_2 emission from Cepheus A.

O'Dell has continued to investigate the circumstellar disks around the young low mass stars in the Orion Nebula cluster. The primary issue with these ''proplyds'' is how long they can survive photoablation by the ionizing flux from $\Theta^1 C$ Ori. Their ionized atmospheres are nearly exponential (O'Dell 1998a), which at first examination indicates that they are in equilibrium against a constant outside force; however recent work by W. J. Henney indicates that the same distribution obtains for a freely expanding atmosphere (O'Dell 1999a). A direct measure of the mass loss rate is being derived from high velocity resolution spectra of the proplyds obtained with the Keck I telescope. The primary challenge in the analysis is the accurate subtaction of the nebular background, which is being done using HST WFPC2 images. These same objects are being investigated in a collaborative program with John Bally (Colorado) where recent WFPC2 results are being compared with earlier studies to trace the motion of shocked features away from the proplyds, in the fashion of Herbig Haro objects in isolated star formation regions. In addition to finding numerous shocks, there are at least half a dozen detected microjets, these being jets of no more than a few hundred AU in length being traced immediately back to the part proplyd. Two more protoplanetary disks seen in silhouette against the bright nebular background have also been discovered. The results of Hartigan and O'Dell's Fabry Perot study of rapidly moving gas in the Orion Nebula has now been published (O'Dell *et al.* 1997).

4.2.2 H II Regions

A review article summarizing the structure of the Orion Nebula (M42) has been prepared by O'Dell (1999b). This object is unique in that we have an accurate three dimension model for the main ionization front. The primary uncertainty is understanding the motions within the nebula because all emission lines are broadened by about 9 km s^{-1} in addition to the broadening expected from thermal, instrumental, and turbulent broadening. This means that about as much energy is carried in this unexplained mechanism as is carried by the results of photoionization. Mechanisms for explaining this extra source of energy are being pursued in collaboration with Gary Ferland (Kentucky) and with Keck I spectra within the senior thesis project of Rice undergraduate Chris Coco.

Professor Reginald J. Dufour continued several collaborative studies of abundances and physical conditions in Galactic and extragalactic HII regions utilizing UV-optical-NIR spectroscopy from ground-based and space-borne telescopes. Much of his previous collaborative research was summarized in the paper ''UV spectroscopy of HII Regions from IUE to HST'' presented at the 1997 November Conference *Ultraviolet Astrophysics*, *Beyond the IUE Final Archive* held in Sevilla, Spain (Dufour & Kurt 1998). A study of the N/O abundance and temperature fluctuations in the Orion Nebula using HST FOS UV-optical spectroscopy has been published (Rubin *et al.* 1998a), as well as the results of ISO observations of IR He^+ lines (Rubin *et al.* 1998b). More recently, he presented a paper on the abundances and physical conditions of the Orion Nebula, based on HST FOS UV-optical spectroscopy, at the 1998 October ESO Conference ''Chemical Evolution from Zero to High Redshift,'' held in Garching, Germany. He is among a group (including C. R. O'Dell), headed by R. H. Rubin at NASA-Ames, who anticipate a wealth of new scientific results from HST STIS observations of the Orion Nebula scheduled for 1999.

Dufour and graduate student Brent Buckalew have been analyzing the first HST STIS spectra of an HII region, NGC 7635 - the ''Bubble Nebula'' - as part of a collaboration (including P. Hartigan) lead by Dr. D. K. Walter of South Carolina State University (Ph.D., Rice 1993). The preliminary results of this investigation will be presented at the IAU Symposium No. 193 on Wolf-Rayet Stars and Starburst Galaxies at Puerta Vallarta, Mexico in 1998 November. At present, our analysis indicates very little change in the physical conditions and abundances of C & N in the wind-driven bubble produced by an Of6.5III star compared to the surrounding HII region. These HST STIS results are further supported by ground-based spectroscopy of the bubble obtained by graduate student Parviz Ghavaminan using the Mt. Hopkins 1.5m telescope in 1998 October.

4.2.3 Planetary Nebulae

The ionization structure of the very close, large Helix Nebula has been determined by O'Dell (1998) from a program of spectroscopy and quantitative imaging from CTIO. Long slit spectra were obtained northward from the central star, covering the multiple zones of ionization. These calibrated spectra were supplemented by emission line and continuum images with the Curtis Schmidt telescope. The filters isolated Hβ, [O III], and He II emission. The surprising result was obtained that the central dark region of the Helix Nebula, which is commonly viewed as being the hole in the middle of a toroidal ring, is actually filled with material of about the same density as the optically bright outer portions. The low visibility arises from the material there being highly ionized and at an elevated temperature. Only the He II emission is an effective emitter in such a region, the heavy ions there lacking strong optical emission lines. The cause of the elevated electron temperature in the inner region is probably due to photoelectric heating, which becomes much more important at the low gas densities and intense UV radiation field that applies. An earlier study of the filamentary knots within the Helix Nebula has now been published (Burkert & O'Dell 1998).

In collaboration with Drs. R. Rubin (NASA-Ames) and P. Harrington (Maryland), Dufour and undergraduate student Matt Browning, analyzed HST WFPC2 imagery of the planetary nebula NGC 6818 to produce high spatial resolution maps of extinction by local dust and temperature variations in NGC 6818. The results were presented in a poster at the 1998 June San Diego AAS meeting. More recently, the group have produced detailed color-coded images of NGC 6818 and NGC 6210 which now appear in the ''Gallery of Planetary Nebulae'' web site at STScI. More detailed photoionization-model based analyses of these results are currently being prepared for publication.

Dufour, R. Henry (Oklahoma), and K. Kwitter (Williams College) completed a UV-optical spectroscopic and imagery study of the nearest planetary nebula, NGC 7293. The imagery and photoionization model results independently confirm the ''thick disk'' geometrical model of O'Dell, rather than earlier torus models. The derived He/H, C/O, and N/O values are consistent with a $6.5M_{\odot}$ progenitor which underwent three phases of dredge-up and hot bottom burning before forming the planetary nebula.

4.2.4 Supernovae Remnants

Hartigan and graduate student Parviz Ghavamian are working on a project that will become part of Ghavamian's Ph.D. thesis, which is to study the line profiles and Balmer decrements of nonradiative shocks in supernova remnants. In collaboration with J. Raymond (CfA) and C. Smith (CTIO) they plan to investigate several aspects of shock physics that can only be studied in nonradiative shocks, such as (1) whether or not the particle energy distribution is Gaussian, (2) the degree of temperature equilibration between electrons and protons immediately behind the shock, (3) the importance of Lyman line trapping in resonance lines of H, and (4) the effect of magnetic field orientation on electron-proton temperature equilibration.

Using the facilities at Fred Lawrence Whipple Observatory and CTIO, Ghavamian and his collaborators have acquired deep optical spectra of Tycho's supernova remnant, RCW 86 and nonradiative portions of the Cygnus Loop. A numerical shock code currently under development will be used to interpret the observations. Spectroscopic evidence for a photoionization precursor in Tycho's SNR will be presented in a paper to ApJ Letters before the end of 1998. Ghavamian is also co-investigator on a FUSE proposal by J. Raymond to study the far ultraviolet spectrum of nonradiative shocks in the Cygnus Loop. The proposal has been granted observing time during the first half of 1999.

4.2.5 Astrophysical Plasmas, Neutron Stars, and Black Holes

Professor Jon Weisheit and his collaborators continue to investigate a wide range of phenomena in plasmas having high energy density, either because of intense, embedded magnetic fields or because of large particle densities. Most of the past year Weisheit was a visiting scientist at Los Alamos National Laboratory, on sabbatical leave from Rice.

With former Rice student Michael Murillo, now at Los Alamos, Weisheit has written and recently published a comprehensive review of dense plasma effects on atomic collisional ionization events. A major goal of this work was to delineate the regime of validity for a linear-response treatment of plasma density fluctuations coupled with a semiclassical treatment of the collisional, bound-free transition; this work has set the stage for future studies involving strongly coupled atomic states and nonlinear fluctuations. Although the immediate applications are to laboratory plasmas produced by intense laser irradiation of solid targets, such plasmas are beginning to be used to probe the physics of astrophysical plasmas with similar temperatures and densities (specifically, those commonly associated with compact objects).

With graduate student David Geller, Weisheit explored the influence of megagauss magnetic fields on the elementary process of electron-ion scattering, through direct numerical integration of the equations of motion. Several special cases were found to have accurate analytical approximations. Because the field inhibits (transverse) deflections, the familiar Coulomb logarithm of Spitzer can be much reduced from its field-free value, and this affects plasma transport coefficients for electrical and thermal conduction. This research was presented at a 1997 international conference on non- ideal plasma phenomena, and then published in the journal Physics of Plasmas. Subsequently, Geller and Weisheit tackled the problem of radiation from strongly magnetized plasmas, focusing first on the topic of bremsstrahlung and how intense B fields modify familiar free-free gaunt factors. Again, a combination of direct numerical computation plus analytical treatment of important, special cases has led to useful formulae for the generalized gaunt factors. As a by-product, they also obtained a realistic expression for the width of the cyclotron feature. This work is being prepared for publication as a companion to their earlier article. Graduate student Menelaos Sarantos and Weisheit are now extending the research to address the diagnostically important issue of bremsstrahlung polarization by intense fields. Their main goal is a better understanding of the polarized continuum radiation from white dwarf stars known (from Zeeman studies) to have very strong magnetic fields.

Professor F. Curtis Michel continues to maintain his program of theoretical research on the properties of neutron stars and their evolution. The major direction here is to simulate the particle motions about a rotating neutron star with an *inclined* magnetic field. An extension of earlier work with Jurgen Krauss-Polstorff has been undertaken with Research Scientist Ian Smith and graduate student Peter Thacker. Michel and collaborators have been able to simulate shutdown pulsars (aligned, with only emission of particles from surface), pair-production configurations (aligned, with pair production if E-fields sufficiently large), and have shown that the entirely filled magnetospheres originally proposed collapse to the inactive dome/torus configuration. The so-called Goldreich-Julian model cannot be made to work (although it— apparently—continues to be taught). Future efforts will attempt to extend this work to the more interesting inclined magnetic field to see if a viable model for pulsar action can be found using only physics currently known.

Michel continues to be involved with analysis of HST images of the Crab Nebula which show *major* variations in the so-called ''wisps'' on times scales a short as a *week*, in collaboration with a group headed by Jeff Hester (ASU). A follow-up observation program has be delayed owing to various HST problems.

Michel has also been collaborating with Hui Li (LANL) on numerical calculations directed at simulating winds from pulsars. Of particular interest are the polar regions where the HST images suggests that an enhanced jet of relativistic wind is flowing. A portion of this work will be submitted as a Physics Report to hopefully provide a standard jumping off point for the initial electric and magnetic fields about a pulsar (laborious and error prone to derive from scratch). Since the pulsar electromagnetic fields are so extremely large, Michel developed a new way of calculating the interaction of a plasma with large amplitude electromagnetic waves. The assumptions of standard plasma physics are inapplicable to such calculations. Introductory discussion of this work will be presented at the Austin AAS meeting.

Professor Edison Liang and his group continued to focus on two major areas in high energy astrophysics: gamma-ray bursts and Galactic black holes. In the field of galactic black-hole candidates, postdoctoral fellow Markus Böttcher and collaborators have focussed on modelling the rapid aperiodic variability of X-ray emission of candidate objects, using a time-dependent Monte-Carlo Comptonization code. Böttcher investigated observable signatures of different source geometries in Compton scattering scenarios for the aperiodic variability of galactic black hole candidates, and proposed a new, dynamical model for the observed hard time lags in the X-ray signals of these objects that involves a hot spot in a cold accretion disk which drifts inward through a hot corona surrounding the accreting black hole. This model explains all the relevant observed features of the rapid aperiodic variability of GBHCs and overcomes the problems of previous Comptonization models, which suffered from the necessity to assume an extremely large hot, Comptonizing corona. A group led by Böttcher developed a self-consistent Comptonization and line transfer code to treat the radiation feedback in accretion-disk corona models.

4.2.6 High Energy Astrophysics

This year has been an exciting one for the study of the enigmatic gamma-ray burst sources because fading counterparts at wavelengths other than gamma rays have been found for the first time in the 30 years of study of these objects. Liang and graduate student Tony Crider completed the analysis of a large data base of BATSE gamma-ray burst spectra and confirmed the prevalence of the decay law discovered by Liang and Kargatis in 1996, namely, that the spectral break energy decays exponentially as a function of the photon fluence. They also found more convincing evidence that at early times the spectral turnover is often very steep and the slope decreases with time as the burst progresses. These results strongly rule out optically thin synchrotron as the radiation mechanism in gamma-ray bursts. Liang, Böttcher, and Crider have also systematically explored different possible interpretations of the spectral turnover. So far they have ruled out external photoelectric absorption, internal synchrotron and bremsstrahlung self-absorption. At present they still favor saturated Comptonization as the most likely origin of the spectral turnover and its evolution.

Following up on earlier work by former student Chuan Luo, Liang and graduate student Dechun Lin investigated the formation of the global spectrum of black hole accretion disks using the transonic disk solutions found by Luo and Liang. They found that in general a gradual transition between the optically thick outer disk and the optically thin inner disk leads to a transition zone of high Thomson depth and high temperature, which emits a conspicuous Wien hump. This is not observed. Hence they concluded that the optically thick-thin transition must be very sharp. A first-principles mechanism must be searched for to explain this sharp transition. Lin and Liang also completed work on the radiation spectra of hybrid thermal and nonthermal relativistic plasma.

Research Scientist Ian Smith has been leading international teams of observers in the search for sub-millimeter-wave emission from fading gamma-ray bursts using the SCUBA instrument on the James Clerk Maxwell Telescope in Mauna Kea, Hawaii and millimeter-wave emission from the Berkeley-Illinois-Maryland Array in Hat Creek, CA. The discovery of a fading sub-millimeter counterpart to GRB 980329 was particularly interesting. There is an indication that there is a quiescent sub-millimeter source at this location, which would imply that this very bright burst occurred in a very high redshift galaxy.

Smith has also been leading international collaborations in performing multiwavelength observations of three Galactic black hole candidates. GX 339-4 was observed in 1996 in radio (ATCA, MOST), optical (Keck), X-rays (RXTE), and gamma rays (CGRO). These observations revealed several interesting variability and spectral features, though they were not all simultaneous. Smith and collaborators are currently setting up a better coordinated campaign on this source for the summer of 1999. Simultaneous observations of GRS 1758-258 were performed in August 1997 in radio (VLA), infrared (IRTF, ESO), X-rays (RXTE), and gamma rays (CGRO). This was the most comprehensive study ever made on this source, and the data is currently being analyzed. Detailed X-ray observations of 1E 1740.7-2942 using RXTE were made in November 1997.

Together with an international team of observers, Smith has been making significant progress in a program of multi-wavelength observations of the Soft Gamma-Ray Repeaters, and wrote the most recent review article on this subject. However, this review is already out of date! Smith was involved in the discovery of slowly spinning neutron stars in two of the sources. The slow rotation and rapid slowing of the rotation are consistent with the ''magnetar'' model in which these particular neutron stars have enormous magnetic fields thousands of times larger than an ordinary neutron star.

He has continued his long-term programs of infrared observations of these sources, and modeling of the burst spectra.

On the basis of the blast-wave model for cosmological gamma-ray bursts, Böttcher and Dermer investigated the high-energy gamma-ray signatures of cosmic-ray acceleration in gamma ray bursts. They developed a simple parametric description of of the blast wave model, predicting the existence of yet undiscovered classes of burst sources corresponding to clean and dirty fireballs with peaks in the νF_ν spectra above and below the $\sim 30 - 300$ keV range, respectively. The group continues to investigate the general phenomenology of gamma-ray bursts, and has recently developed a time-dependent photoionization code which was used to predict evolving absorption and fluorescence line features from gamma-ray burst environments.

Michel's work with Ben Eastlund and Ben Miller on pulsed gamma rays from pulsars was published, showing that pulsed gamma rays need not come from polar caps but rather can be produced by an isotropically filled magnetosphere. The idea is that energetic particles can be temporarily trapped near the ''light-cylinder'' and they radiate anisotropically during their tenure there. It is not necessary to invoke beaming out of the magnetic polar caps (the standard textbook cartoon).

4.3 Extragalactic Astronomy

Dufour is collaborating with several groups in the study of the stellar populations and abundances of star-forming galaxies using a combination of HST and ground-based imagery and spectroscopy techniques. He concluded a collaboration of the stellar properties and star-formation history of the Local Group dwarf galaxies Sextans A and GR8 with a group lead by E. Skillman (Minnesota), and continues to work on I Zw 18 using HST WFPC2 observations which are expected to be completed in early 1999. Additionally, Dufour has begun collaborating with C. Esteban & D. I. Mendez (Spain) to study the star formation properties of Wolf-Rayet Galaxies and potential affects that the winds from these objects have on the dynamics and abundances of the nearby interstellar medium. Recently, graduate student Brent Buckalew joined this effort and received a three-year NASA GSRP fellowship for multiwavelength observations of Wolf-Rayet Galaxies. Observing time has been granted with telescopes at the Canary Is. and at KPNO for CCD imagery and spectroscopy of several of these rather rare types of starburst galaxies. We have also applied for HST time to do a detailed imagery and UV-optical study of the Wolf-Rayet galaxy NGC 3125.

Dufour is also among an international group of collaborators studying carbon and nitrogen abundance gradients in nearby spiral galaxies using HST FOS UV-optical spectroscopy, lead by Dr. D. Garnett (Arizona). The results of observations for NGC 2403 and M101 have been accepted for publication in the *Astrophysical Journal* in early 1999 (Garnett *et al.* 1999), and show that the C/O gradient across their disks increases with O/H in a manner previously found for irregular galaxies, but C/N shows no correlation with O/H. The implications of these results is that stellar winds from massive stars have an important effect on the yields and evolution of C & O abundances, but little effect on N abundances. Towards a better understanding of this, Dufour and Garnett have proposed an extensive study of HII regions in the Magellanic Clouds using the HST STIS for 1999/2000.

Böttcher continued to model simultaneous broadband spectra of blazars, using a self-consistent time-dependent jet radiation code. The code was recently applied to PKS 0528 +134, BL Lac, and Mrk 501. Böttcher has also investigated mechanisms for high-energy flares in blazars, with special emphasis on the recently proposed synchrotron-mirror mechanism.

4.4 Laser Astrophysics

A new collaborative program with the Lawrence Livermore National Laboratory to simulate astrophysical phenomena with the big lasers was begun last year. Graduate student Katherine Keilty and Liang, working with LLNL colleagues, have been using the radiation-hydro code HYADES to simulate micro-blast waves generated by the interaction of intense lasers with low-Z targets. Such experiments allow them to study the early evolution of radiative blast waves and the scaling properties of laboratory blast waves to astrophysical ones. Preliminary results from 1-d simulations seem to agree very well with data from the Falcon laser heating gas jets.

Liang, Scott Wilks and Max Tabak (LLNL) have also been studying the generation of electron-positron plasmas using ultra-intense lasers heating High-Z targets (e.g. gold foils). They concluded that under optimal conditions one may produce pair densities as higher as 10^{21} cm^{-3}, which is 10^{-3} of the background electron density. After expansion these pairs may form a relativistic fireball which would mimic the conditions of a gamma-ray burst. Detailed dynamics of such micro-fireballs are being investigated by Liang and Wilks using Particle-in-Cell plasma simulation codes.

4.5 Instrumentation Development

Progress continues on construction of the IRFP, a fully cryrogenic high resolution Fabry-Perot spectrometer that will operate in the 1 – 2.5 μm range. Partners in this collaboration include P. Hartigan at Rice, G. Cecil at UNC, J. Morse at Colorado, and the staff of CTIO. Construction of the dewar has been completed and the electrical feedthroughs into the dewar are currently being configured. The instrument will be installed initially at the 1.5-m and 4-m telescopes at CTIO in Chile, and after a checkout period will be made available to the general astronomical community.

The Department has purchased a set of Cousins UBVRI filters that can be used with a CCD at the 0.9-m telescope at George Observatory south of Houston. Hartigan and Dufour are currently working to get this system operational, which should provide the Department a convenient means to get scientifically useful photometry. A spectrograph on loan from Sam Houston State University is also being configured to operate at George Observatory.

4.6 Philosophy of Science

Postdoctoral Researcher Yuri Balashov has been studying ontological issues arising in contemporary physical theories (relativity theory, quantum mechanics, and particle physics). These issues include (but are not restricted to) laws of nature, persistence over time, the philosophy of time and becoming, and the nature of fundamental physical properties. He is currently working on a book entitled *Special Relativity and Ontology*, and is also co-editing (with G. Gorelik and V. Vizgin) a volume *Einstein Studies in Russia* to be published by Birkhaeuser in the series entitled *Einstein Studies*.

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