Indiana University
Department of Astronomy

Bloomington, Indiana 47405

This report covers research activities in the Department of Astronomy and the High Energy Astrophysics group for the period September 2000 through August 2001 inclusive.

1. INTRODUCTION

The Astronomy Faculty at Indiana University consisted of Professors: Haldan N. Cohn, Richard H. Duri-sen, R. Kent Honeycutt (Chair), Phyllis M. Lugger, Stuart L. Mufson, and Catherine A. Pilachowski; Assistant Professors: Constantine P. Deliyannis, Michael J. Pierce, and Liese van Zee; and Professors Emeriti: Martin S. Burkhead, Frank K. Edmondson, and Hollis R. Johnson. Other department members included Research Associate Thomas Y. Steiman-Cameron. Brice R. Adams and Eric Ost were members of the professional staff; William R. Kopp, Christina M. Lirot, and Brenda S. Records were members of the support staff. Graduate Students in the Department during the year were: Michael Baird, Kai Cai, Janet Casperson, David Herrick, Todd C. Hillwig, Styliani Kafka, Steven J. Margheim, Annie C. Mejia, Nicholas J. Mostek, Brian J. Rebel, Adam W. Rengstorf, Allen B. Rogel, Angela Sarrazine, Shawn D. Slavin, Aaron J.B. Steinhauer, and Heidi J. Tebbe.

The High Energy Astrophysics group at Indiana University is an interdepartmental (Astronomy and Physics) research group with faculty: Richard M. Heinz (Physics), Stuart L. Mufson (Astronomy), and James Musser (Phys-ics); Senior Scientist: Charles Bower; Graduate Students: Nicholas J. Mostek and Brian J. Rebel; Technical Staff: Mark Gebhard, Richard LeBeau, and Michael Simpson; Support Staff: Debbie McKinney.

The Bachelor of Science Degree in Astronomy and Astrophysics was received by Donald Adkins, Matthew Bavender, Emily Blecksmith, Clayton Carter, Laura Ciasto, Laura Hainline, Joshua Harbeson, and Larry Kirby. The Masters of Arts Degree was recieved by Brian J. Rebel.

2. RESEARCH

2.1 Instrumentation and Facilities

Research in the IU Department of Astronomy benefits from exceptional facilities for computing, networking, and data storage provided by University Information Technology Services (UITS). In particular, Indiana University has now acquired the largest university-owned supercomputer. UITS's IBM SP cluster has been expanded to triple its previous capacity and, as whole, can now achieve teraflop speeds. The cluster consists of ten frames containing one 2-cpu PowerPC thin node, one 2-cpu Power3+ thin node, one 4-cpu Power3+ wide node, 136 4-cpu Power3+ thin nodes, and 4 16-cpu Power3+ high nodes, for a total of 143 nodes and 616 processors. UITS is also home to a 64-processor Sun E10000 symmetric multiprocessing supercomputer, with 64 GB of shared memory and a peak computation rate of 51 gigaflops. This shared memory achitecture has proven ideal for computations by Durisen's astrophysical hydrodynamics group (see section 2.3). In addition, IU has just been awarded an NSF MRI grant of $1.8M for a large, distributed Intel-based Linux cluster and associated visualization equipment.

UITS also supports special-purpose GRAPE or GRA-vity PipE supercomputers which vastly accelerate collisional N-body particle simulations over what is possible with traditional parallel computers. These were upgraded by the acquisition of two MDGRAPE-2 boards and one GRAPE-6 computer. The MDGRAPE-2 boards are capable of accelerating a programmable, generalized force calculation for the purposes of simulating the effects of multiple force laws and non-Coulombic interactions, such as occur in astrophysical plasmas. The GRAPE-6 is an upgrade to IU's currently used GRAPE-4 machine (see Section 2.5), which is tuned to accelerate the gravitational force calculation, for simulations of the collisional environments of dense star clusters. The GRAPE-6 is a one teraflop machine, representing an increase in peak performance over the GRAPE-4 of roughly a factor of 30.

UITS facilities at the Indianapolis campus house the network operation center for the nationwide, high-performance Abilene network. The Bloomington campus shares a dedicated optical fiber link with Indianapolis, ensuring consistent, state-of-the-art connectivity to the network. The Massive Data Storage Facility at Indiana University's UITS is a multi-campus configuration of tape storage, disk cache, and IBM supercomputers running High Performance Storage System (HPSS) software. This facility provides researchers at IU with networked storage for project data, software, workstation backups, and long-term storage in the range of hundreds of gigabytes per user or project group. The system is currently configured with approximately 45 Terabytes of tape-based storage.

Work on the QUEST II CCD controller for Schmidt surveys has continued in collaboration with the Physics Departments at Yale University and at Indiana University. This camera consists of 112 CCDs, each having 600x2400 13-micron pixels. The camera controller uses the MFront interface board set with the control logic being implemented in Xilinx field programmable gate arrays. Board assembly is mostly finished and single-channel testing is underway with about 80% of the FPGA programming being completed.

Indiana University is a partner in the WIYN Consortium, which operates a 3.5-meter telescope atop Kitt Peak southwest of Tucson, AZ. WIYN consists of the University of Wisconsin, Indiana University, Yale University, and the National Optical Astronomy Observatory. Indiana University has a 17% share in WIYN. The WIYN telescope instrumentation includes a wide field CCD camera with an atmospheric dispersion corrector and a multiple-object spectrograph which uses optical fibers to obtain spectra of up to 100 objects simultaneously over a one-degree field. The active optics of the WIYN telescope system delivers excellent image quality, and it is not unusual to obtain 0.5‟ images on good nights.

During the 2000-2001 academic year, members of the Department participated in discussions of upgrades to the Hydra Fiber Positioner and to the Bench Spectrograph. Honeycutt chaired the design review team for the positioner. Deliyannis carried out measurements of the throughput of the spectrograph and contributed to discussions about possible upgrades. Pilachowski agreed to serve as Project Scientist for the spectrograph upgrades. Six members of the faculty, including Cohn, Deliyannis, Honeycutt, Lugger, Mufson, and Pierce, were awarded observing time totalling 53 nights on the WIYN 3.5-meter telescope. Four graduate students and one undergraduate student participated in observing runs at the telescope.

The WIYN Consortium submitted a successful bid to acquire the use of the 0.9-meter telescope at Kitt Peak. This telescope is adjacent to WIYN and has a one-degree field of view, which matches the WIYN multi-object spectrograph field. The KPNO Mosaic CCD camera will be shared between the KPNO 4-meter and the 0.9-meter providing a one-degree imaging capability for those projects needing such a large field. At other times the 0.9-meter will be equipped with a smaller CCD imager for photometry. During the 2000-2001 academic year, a new control system has been installed by the WIYN Consortium, and the telescope is expected to return to operation in the Fall of 2001. As with the WIYN telescope, Indiana has a 17% share of the observing time on the 0.9-meter. The 0.9-meter will be used for the support of undergraduate research as well as research by faculty and graduate students.

RoboScope, a 0.41-meter telescope equipped for automated, unattended CCD photometry of stellar accretion systems and located in Morgan-Monroe State Forest near Bloomington, continues to collect long-term light curves of cataclysmic variables under the general direction of Honeycutt. Because of reduced funding the efficiency of the system has diminshed in recent years. Nevertheless, the light curves of many of the program objects now cover over 11 years. Migration of the RoboScope control software and hardware from VMS to Linux is a continuing large effort. Completion of this conversion will ensure that the system can remain operational to provide even longer time sequences for selected objects. A companion 1.25-meter telescope at this site for long-term automated spectroscopy of stellar accretion systems was completed and exercised in 1998. However, the optics were found to be unsatisfactory and were returned to the vendor for re-figuring. Acceptable optics are still not available. Once the optics difficulties are addressed, regular operations will begin.

The original Goethe Link Observatory, named for Dr. Goethe Link, near Mooresville IN, houses a 36-inch reflector and a 10-inch astrographic camera. This facility continues to be operated jointly by the Department and by the Indiana Astronomical Society, an amateur astronomy group in the Indianapolis area. Because of nearby urban lights, the 36-inch telescope is not currently used for research but is available to departmental staff for projects that can tolerate a brighter night sky.

The historic Kirkwood Observatory, which dates from 1900 and houses a 12-inch refracting telescope, is under renovation on the IU Bloomington campus. Work on the building and dome is being performed by a professional historical renovation contractor, and the Observatory will retain the 1900-1950 look and feel. The telescope itself is being renovated by departmental staff and will continue to be used for public nights and by students in descriptive astronomy classes. The observatory is expected to reopen early in 2002.

Two new 14-inch telescopes have been installed on the roof of Swain Hall West on campus for use by undergraduate majors. The telescopes are equipped with modern CCDs and spectrographs. This computer controlled equipment will serve our majors in providing a modern introduction to observational astronomy.

During 2000, the High Energy Astrophysics group has continued its participation in the MACRO (Monopole, Astrophysics, and Cosmic Ray Observatory) experiment in the underground Gran Sasso Laboratory in Italy (see section 2.8). This experiment is a joint Italian-American collaboration designed to search for GUT monopoles and other fractionally charged superstring particles and for astrophysical sources of muons and high energy neutrinos. In addition, MACRO continued its search for the neutrino signal from Type II supernovae in our Galaxy. Further, MACRO is investigating the composition of cosmic rays in the range of 10^{15}-10^{16} eV/nucleon. The detector was decommissioned in December 2000.

The High Energy Astrophysics group is now involved in an effort to expand the experimental reach of neutrino oscillation parameter space to include the region that best accounts for the peculiar atmospheric neutrino results obtained by the SuperK experiment in Japan. This experiment, called MINOS, will study muon neutrinos that have been directed to northern Minnesota from Fermilab. The experiment will explore the neutrino mass region below $1eV^2$. Neutrinos in this mass range would account for some fraction of the non-baryonic dark matter in the universe as well as hot dark matter postulated to explain large scale structure. Civil construction of the experimental halls at Fermilab National Laboratory and at Soudan MN was begun in 2000. Far detector construction at Sonta was begun in August 2001. The MINOS experiment will turn on in late 2005. The Indiana HEAP group is responsible for the fiber optic cables and the mulitplexing boxes (MUX boxes) that route the fiber optic cables to the multipixel PMTs.

The balloon flight program of the High Energy Astrophysics group is currently involved with the HEAT (High Energy Animatter Telescope) experiment. The first HEAT flight took place in May 1994 from Ft. Sumner NM. The second flight took place in August 1995 from Lynn Lake, Alberta. The third and fourth flights took place in May 1999 and May 2000 from Ft. Sumner NM. A fifth and final flight will take place in April 2002. The first two flights measured the cosmic ray positron spectrum in the range 5-50 GeV using a superconducting magnet spectrometer, along with TRD detectors, a calorimeter, and time-of-flight detectors. The third and fourth flights measured the abundance of low energy cosmic ray antiprotons. The fifth flight will be another flight to measure antiprotons.

Instrumentation development in the Department utilizes departmental laboratories for mechanical, electronic, and optical design and construction.

2.2 Solar System

Durisen, B.K. Pickett (Purdue U. Calumet), P. Cas-sen (NASA-Ames), and Mejia are continuing their study of the possibility that gas giant planets might form directly by gravitational instabilities in protostellar disks. This group has recently completed a new set of 3D hydrodynamics simulations with much higher resolution and a wider variety of assumptions about disk thermal physics. Under conditions of high effective cooling, dense clumps do form in their disks, but they appear to be transient. In none of the simulations has a clump been seen to persist for an entire orbit period. When the disk is treated as adiabatic or has strong shock heating, dense clumps do not form at all. Although this seems at odds with recent calculations by A. Boss (Carnegie Inst. Washington), bound clump formation is a difficult problem. It is probably premature to conclude whether or not this planet formation mechanism actually works. Simulations with more physics and still higher resolution are required. A collaboration has been initiated with T.W. Hartquist and S. Falle (U. Leeds) to pursue this problem using adaptive mesh refinement techniques. Related work on simulations of protostellar disks is also underway as reported in Section 2.3.

Over many years, Durisen and various graduate and undergraduate students have developed a code which calculates the effects of ballistic transport in planetary ring systems. Ballistic transport is the net transport of mass and angular momentum due to exchanges of ejecta from hypervelocity meteoroid impacts onto ring particles. This mechanism can, in principle, explain the production and maintenance of features seen near the inner-edges of Saturn's A and B Rings. However, the best simulations published to date do not agree with the observed rings in important details. Durisen and Herrick have modified the code to handle two independent ejecta distributions at once – the high speed, primarily prograde ejecta from nondisruptive cratering events and the lower speed, retrograde ejecta from meteoroid impacts which catastrophically disrupt ring particles. To complete his Master's thesis, Herrick will be using the code to determine whether simulations with dual ejecta distributions give better results.

2.3 Stars

Durisen, Pickett, J.N. Imamura (U. Oregon), M. Bate (U. Exeter), and M.F. Sterzik (ESO) have completed their multi-code study of the dynamic barlike mode in polytropic stars. Contemporary grid-based and SPH hydrodynamic codes were used at high resolution to determine the effects of different assumptions about shock dissipation and heating on the outcome of the instability. At least for the idealized case of a polytropic equation of state, it seems unlikely that the nonlinear outcome of dynamic barlike instability is a binary star. Alternatively, N. Lebovitz (U. Chicago) has suggested that a binary may be the outcome when stars contract slowly from stable to unstable conditions. Durisen, Imamaura, and Pickett have calculations underway which mimic contraction due to slow cooling and find little difference in the computed outcome. No binary forms.

Imamura, Durisen, and Pickett have extended barlike mode studies to the special case of objects called ‘‘fizzlers.’’ These are equilibrium objects with densities between those of white dwarfs and neutron stars. In this density regime, a nonrotating star would be unstable to collapse due to the softness of the equation of state; but, since the 1970's, it has been known that rapid rotation can stabilize radial modes. When the iron core of a massive star collapses with finite angular momentum, a supernova event can be substantially delayed or prevented altogether by the formation of such an object, hence the name ‘‘fizzler.’’ For sufficiently rapid rotation, fizzlers become susceptible to secular (gravitational radiation time scale) and dynamic (rotation period time scale) instabilities of nonaxisymmetric modes, especially the barlike modes. Interest in these hypothetical states and their instabilities has been heightened by construction of LIGO and by observational evidence that some neutron stars and black holes produced by massive stars may have very high initial rotation rates.

Imamura and Durisen have already shown, from linear analyses using a hot, lepton-rich fizzler equation of state, that the secular and dynamic stability limits tend to be constant in mass for a given entropy and lepton fraction. As the fizzler material cools and deleptonizes, these mass limits drop from two or more solar masses to one or less. This happens on a time scale (seconds) which is much shorter than the time scale for secular growth of the barlike modes. So, if a fizzler forms during the collapse of a massive star's core, it is the dynamic barlike instability which will dominate the subsequent evolution. Imamura, Pickett, and Durisen are now completing analysis of two long 3D hydrodynamic simulations of barmode unstable fizzlers.

Durisen, Mejia, Pickett, Cai, Cassen, Imamura, D. Woolum (Cal State Fullerton), D. Berry (IU's University Information Technologies Services), and J. Rosheck (IU undergraduate) are continuing their research on gravitational instabilities in disks around young stars using 3D hydrodynamic simulations. In addition to the gas giant planet formation project mentioned in Section 2.2 above, this work includes the following (names in parentheses are those with primary responsibility): (1) simulations of externally forced spiral waves in disks (Pickett and Cassen), (2) development of a more realistic equation of state which includes the effects of major phase transitions, such as the ionization and dissociation of hydrogen (Woolum, Cassen, and Pickett), (3) implementation of this equation of state in 2D and 3D hydro codes (Pickett and Durisen), (4) introduction of progressively more realistic treatments of heating and cooling, energy transport, and shear viscosity (Mejia and Durisen), (5) wave propagation analyses (Cai and Durisen), (6) 2D and 3D visualization of results (Rosheck, Durisen, Mejia, and Pickett), (7) increasingly parallelized and portable versions of the 3D hydro code (Berry), (8) an improved Poisson solver (Berry), and (9) an improved treatment of artificial viscosity (Pickett).

The ultimate goal of this long-term collaboration is to understand the behavior of gravitational instabilities in protostellar disks. In particular, under what conditions do they produce significant mass and angular momentum transport? Is such transport sustained or episodic? What are the observational consequences? Can planets or brown dwarfs ever form from a disk by direct gravitational condensation? Work to date has demonstrated that the nonlinear behavior of instabilities depends critically on the thermal energetics of the disk. This means that the disk physics must be computed in greater detail than anyone has so far attempted.

During the past year, in addition to some progress in all the areas mentioned above, Durisen, Mejia, Pickett, and Hartquist have shown that gravitational instabilities in the outer regions of large (1000 AU) disks in massive protostars create conditions conducive to maser prodcution, particularly for species like methanol. Linear alignments of methanol masers with Keplerian kinematics and large spatial extent are in fact seen in some massive protostars

Durisen, M.F. Sterzik (ESO-Chile), and Pickett are continuing their investigations of binary formation by small cluster decay, particularly the effects of a process that they have dubbed the ‘‘two-step IFM.’’ The two steps involve picking a total cluster mass based on a protostellar cloud mass spectrum and then constraining the sum of the component masses, chosen from another stellar mass spectrum, to be equal to the selected cluster mass. A two-step IMF combined with few-body system decay gives much better agreement with observed binary fractions and mass ratio distributions as a function of stellar mass then one-step stellar mass selection. The improvement is greater than that obtained by other researchers by including dissipation due to disk collisions in the decay of young few-body clusters. The group is currently extending the work to a consideration of brown dwarf masses and comparisons with new datasets on binary characteristics as a function of spectral type.

Baird, Rogel, Slavin, and Durisen, in collaboration with B. Elmergreen (IBM), are planning a study of the binary characteristics which result from the dynamics of a star forming region when the stars form from fractal density and velocity distributions, as expected for a turbulent molecular cloud complex. The plan calls for N-body calculations using Starlab by the IU collaborators, while Elmergreen will generate initial conditions.

Durisen and J.M. Alcalá and E. Covino (Osservatorio Astronomica di Capodimonte) are completing analysis of WIYN/Hydra observations of Guide Star Catalog stars in fields where the ROSAT All Sky Survey indicates an excess of young star candidates but which contain little or no molecular gas. Lithium abundances will help to determine if these objects are actually youthful stars whose molecular clouds have already dissipated. At least one group of young stars near Orion seems confirmed.

Pilachowski, with A. Quillen (U. Rochester) and C. Grady (GSFC), is investigating the role of planetesimals in planet formation and planetary system evolution by detecting and monitoring falling evaporative bodies in stars in young star clusters such as NGC 2264. Studies of the A stars in this cluster with the 3.5-meter WIYN telescope have identified several instances of variable Ca II K line profiles which will be further investigated at higher spectral resolution with other telescopes.

Standard stellar evolution predicts that late F stars should have essentially retained their initial surface lith-ium (Li) abundance because their convection zones are too shallow to destroy it at their base. Yet observations reveal Li depletions, sometimes quite severe (the ‘‘Li gap’’). Several physical mechanisms, which are not usually included in stellar evolution calculations, have been proposed to account for the Li depletions. These mechanisms include mass loss, microscopic diffusion, and various types of slow mixing driven by either waves or rotation. Identifying which of these (if any) might really be at work not only is of vital interest to advancing our knowledge of stellar interiors but also may have serious implications in other contexts, such as in evaluating the Big Bang Li abundance, and its implications for testing models of Big Bang nucleosynthesis (BBN) and cosmology.

Deliyannis and M. Pinsonneault (Ohio State) followed up a suggestion they made earlier and brought attention to Be observations in late F stars, proposing that such observations are crucial for discriminating between scenarios. Be survives to about twice the depth that Li does. It was argued that, while all proposed mechanisms can produce a Li gap, each leaves a different Be signature. In the case of mass loss, all the Li must be depleted before any measurable Be gets depleted. In the case of diffusion (for the cool side of the Li gap), Li and Be depletion occurs at similar rates. In the case of slow mixing, both Li and Be are depleted simultaneously, at a rate that depends on how the mixing is done. For example, in the models with wave-driven mixing, mixing is confined fairly close to the surface, so Li goes down much faster than Be. In the models with rotationally-induced mixing, the mixing is more extensive, so Li goes down more slowly compared to Be, though though still faster than Be. It was pointed out that the star 110 Her might be especially important. This star is depleted in Be by a factor of 5 - 10 and, yet it still contains detected Li, which is in turn depleted by a factor of 100 - 200. Such a depletion pattern requires specific circumstances; this star could very well be the smoking gun of the responsible mechanism. If 110 Her is representative, then both mass loss and diffusion are argued against, and slow mixing is strongly favored.

Following up the original suggestion of Deliyannis and Pinsonneault, a survey was undertaken to study Li and Be abundances in solar-type stars, to ascertain how common the 110 Her phenomenon might be. Deliyannis, together with A. Boesgaard (U. Hawaii), A. Stephens (U. Hawaii), J.R. King (STScI), S. Vogt (UCSC) and M. Keane (CTIO) reported first results of this survey based on Li data from the University of Hawaii 2.2-meter telescope + Coude ($R \sim 80{,}000$) and Keck I 10-meter telescope + HIRES ($R \sim 45{,}000$; $S/N \sim 800$ - 1500 per pixel), and Be data from the Canada-France-Hawaii 3.6-meter telescope + Gecko ($R \sim 120{,}000$) and Keck I + HIRES. 110 Her is not unique. The program stars with both Li and Be detected show that (a) Li and Be depletion are closely correlated and (b) surface Li diminishes more rapidly than does surface Be. The remaining stars with upper limits are consistent with this trend. These results suggest that simultaneous Li and Be depletion is a normal process that F stars and early G stars undergo. The Li-Be trend argues strongly against the mass loss and diffusion mechanisms and strongly supports slow mixing as the cause of the light element deficiencies. Moreover, models with rotationally-induced mixing are in better agreement with the data than models with wave-driven mixing. The conclusions also support the idea that rotationally-driven mixing has depleted the Li abundances of halo dwarfs from a higher primordial Li abundance, with implications for testing models of BBN. Parts of the work described above have been published; additional data from this program were analyzed during the past years.

Honeycutt and collaborators continued work on the accretion process in Algols and in cataclysmic variables, such as V630 Cas and LQ Peg. The major work using RoboScope data appeared as a discussion of the nature of stunted outbursts in nova-like CVs. Stunted outbursts are 0.4-1 mag eruptions that sometimes appear in nova-like CVs. They resemble the outbursts of dwarf nova in spacing and width but are of much smaller amplitude. However, nova-like CVs are widely considered to have accretion disks that are too hot for the thermal disk instability that is responsible for dwarf nova outbursts. In this paper Honeycutt argues that stunted outbursts are due to thermal disk instabilities after all, and that they appear of smaller amplitude because they are seen against an unknown brighter background source of light. An intriging candidate for this extra light is nuclear burning of accreted hydrogen on the surface of the white dwarf, but this hypothesis requires a new paradigm for the nature of nova-like CVs.

2.4 WIYN Open Cluster Study (WOCS)

Star clusters are superb astrophysical laboratories containing cospatial and coeval samples of stars with similar composition. Open clusters are particularly valuable because they span a wide range of age, metallicity, richness, and galactic radius. As such, open clusters are the observational foundation for stellar astrophysics, provide essential tracers of galactic structure and evolution, and are unique stellar dynamical environments. Indeed there are few fields in astrophysics which do not in some way rely on results derived from open cluster studies. Recent advances in instrumentation are driving a renaissance in the study of open clusters.

Members of the WIYN collaboration have initiated WOCS, a project dedicated to comprehensive photometric, astrometric, and spectroscopic studies of a select set of open clusters spanning the range in age and metallicity. There are two main WOCS goals: (1) comprehensive and definitive photometric, spectroscopic, and astrometric databases for new fundamental clusters and (2) a body of investigations which address critical astrophysical problems through study of open clusters. Some subjects under active investigation within WOCS include: detailed testing of core convective overshoot and implications for stellar lifetimes; photometric monitoring of periods for study of surface angular momentum evolution; delineation of faint main sequences to test stellar evolution theory of very low mass stars; discovery of white dwarf sequences as independent dating mechanisms; abundance analyses for studies of galactic chemical evolution and primordial abundances; binary populations; stellar evolution in close binary environments; initial and present-day mass functions.

The centerpiece of WOCS is the WIYN 3.5-meter telescope at Kitt Peak, although other telescopes (such as the KPNO and CTIO 0.9-meter telescopes) are used to support this effort. WIYN's primary instruments are 1) Hydra, a multi-object spectrograph that can observe up to 100 objects in low, medium, or even high (R $\sim$ 30,000) resolution mode over a 1-degree field and 2) an imager that takes advantage of the best seeing at Kitt Peak.

The primary WOCS interests at Indiana are photometry and spectroscopy. Open cluster photometry provides an ideal research experience for undergraduates, since they can obtain state-of-the-art research skills while studying fundamental astronomy with scientific goals that are within their intellectual grasp for that stage in their career. Deliyannis and students Steinhauer, Sarrazine, Hainline, Bavender, Raffauf, Freeland, Blecksmith, Hilbrich, and Hall have been working with 0.9-meter and WIYN data of the open clusters NGC 188 (one of the oldest Galactic clusters), NGC 2420 (the nearest significantly metal-poor cluster), M35 (a very rich, nearby, Pleiades-like cluster), NGC 3532 (a very rich, nearby, cluster with age intermediate to that of the Pleiades and the Hyades), NGC 1817 (a rich, Hyades-age cluster), M34 (a nearby cluster with age intermediate to that of the Pleiades and the Hyades), NGC 2158 and NGC 6819 (both very rich clusters somewhat older than the Hyades). These studies will provide updated measurements of the reddenings, distances, and ages of these clusters; the precision photometry will also be used to estimate stellar temperatures, as needed for WOCS spectroscopic studies.

Deliyannis, Steinhauer, and Margheim are working on WOCS spectroscopy. The primary goals of WOCS spectroscopy at Indiana are (1) to determine cluster metallicities and (2) to use Li in star clusters as a probe of physical processes occurring in stellar interiors. The standard stellar evolution theory cannot explain existing Li observations; it is thus very interesting to determine what additional physics is operating in stars. A sample of the questions being addressed: (1) What is the physical mechanism that creates the Boesgaard Li gap? (2) Is the solar Li depletion normal? (3) Do cool solar-type stars deplete their Li during the main sequence, and, if so, what is the physical cause? (4) Does the decline of Li with age in the Li plateau region represent Li depletion in stars, Galactic Li enrichment, or both – and how does this relate to the halo Li plateau, the Big Bang Li abundance, and Big Bang cosmology?

2.5 Globular Clusters

Pilachowski, together with K. Sandstrom (Harvard U.) and A. Saha (NOAO), has investigated the metallicities of 29 RR Lyrae variables and five red giants in the globular cluster M3. Metallicities have been determined from moderate resolution spectra taken with the Hydra multi-fiber spectrograph on the 3.5-meter WIYN telescope. Color indices in the Gunn *uvgri* system taken on the Kitt Peak 0.9-meter telescope were used in conjunction with synthetic colors to estimate the temperature and gravity of each star. Similar metallicities were found for both the RR Lyrae variables and the giants after correcting for overionization of Fe I in the variables, and [m/Fe] ratios were derived for Mg, Ca, Sc, and Ti. The metallicities derived for M3's RR Lyrae variables show no dependence on either temperature at minimum light or period. This work continues with a Baade-Wesselink analysis of the variables based on WIYN/Hydra radial velocities and light curves obtained with the KPNO 0.9-meter telescope.

The carbon isotope ratio ($^{12}C/^{13}C$) has been determined in 15 metal-poor ($-2.4 \leqslant$ [Fe/H]$\leqslant -1.0$) field halo giants by Pilachowski, L. Keller (Cornell), and C. Sneden (UT Austin) from spectra of the ^{13}CO v=3–1 and v=2–0 bandheads and surrounding ^{12}CO and ^{13}CO R-branch lines. The isotope ratios are consistent with previous measurements for stars in the sample with $^{12}C/^{13}C$ ratios determined either from the infrared first overtone bands of CO or from the optical G-band or red system bands of CN. They also compiled carbon isotope ratios from the literature for a much larger sample of field and cluster giant stars spanning a wider range of metallicities ($-2.4 \leqslant$ [Fe/H]$\leqslant$solar). Combining these data, Pilachowski and her co-workers confirmed the decline of the isotope ratio as stars evolve up the red giant branch and have identified a trend towards higher levels of mixing in more metal-poors stars. Standard red giant first dredge-up models do not predict the cabon isotope ratios observed in the more evolved (higher luminosity) metal-poor stars, but more recent models that account for other mixing mechanisms can explain these data, even for very metal-poor stars like those observed in the Galactic Halo.

Pilachowski, in collaboration with C. Sneden, R.P. Kraft (UCSC), R. Cavallo (LLNL), and others, is continuing to investigate abundance variations in globular clusters. The evolution of stars can be examined in detail through changes in the abundances of elements at the stellar surface from nucleosynthesis and mixing inside a star. These changes tell us about the physical conditions inside the star and about processes that create and bring new elements to the surface. Much of her work has involved exploration of abundance changes in low-mass, red giant stars to improve our understanding of stellar evolution.

Pilachowski's previous work on giants in the M13 globular cluster established the role that nucleosynthesis and mixing play during evolution. In collaboration with Sneden, Kraft, and E. Langer (Colorado College), she has demonstrated that proton-capture nucleosynthesis, including not only the CN and ON cycles, but also the NeNa and MgAl cycles of hydrogen burning, is occurring in M13 giants. Similar studies have been carried out in M15 and M92 and are underway in M3 and other clusters.

In collaboration with Deliyannis, Sneden, Kraft, and others, Pilachowski continues to investigate abundance variations in globular clusters. With the Hydra multi-fiber spectrographs on WIYN and the Blanco 4-meter telescopes, she has accumulated spectra of more than 700 giants in more than a dozen globular clusters to survey lithium, Hα emission, and several critical abundances (e.g., barium, europium, aluminum). Preliminary analysis of the Li I observations suggest that Li-rich cluster giants fall into two groups. Stars near log $L/L_\odot$=1.8 have lithium abundances similar to field giants, consistent with dilution from an initial main sequence lithium abundance of log (Li)=2.3. Lithium does not appear to be present in other cluster giants at the same luminosity but might be detected in spectra of higher signal-to-noise ratio and resolution.

At somewhat higher luminosity (log $L/L_\odot$=2.8) giants have higher lithium abundances than are seen among typical field giants at the same luminosity. Approximately 6% of cluster giants brighter than M_V=0.75 show measurable lithium. Lithium may be brought to the surface of these giants as the unstable isotope ^{7}Be, which decays to ^{7}Li, through mixing induced by differential internal rotation.

Deliyannis continues programs to study lithium in globular cluster dwarfs, with the purpose of evaluating both stellar interior and galactic processes that may have affected the Li abundances contained in the surfaces of these stars and therefore estimates for the primordial Big Bang abundance. Together with Boesgaard, Stephens, and King, Deliyannis published results for M92, and observations in M13, M71 and M5 have been obtained and are being analyzed. All of the data for these clusters were taken with the Keck I 10-meter telescope. As was the case in M92, preliminary indications in M13 are that there exist otherwise apparently identical stars that have Li content differing by at least a factor of 2 – 3.

Together with J. Thorburn (Yerkes Obs.), M. Rich (Columbia U.), E. Rubinstein (Yale U.), and J. Orocz (Penn State), data were taken at the CTIO 4-meter telescope + Argus multi-object spectrograph in echelle mode of about 40 stars in NGC 6397. Analysis is ongoing and will include other southern clusters in the future. Like the previous clusters, NGC 6397 also shows a scatter in Li at the same T_{eff}. Furthermore, stars past the turnoff agree remarkably well with field halo stars in that both sets of stars, (a) establish a Li plateau near the turnoff, (b) experience subgiant Li dilution by about a fcator of 10 – 20 near T_{eff} = 5400 K, (c) establish a diluted plateau from T_{eff} = 5300 to 5000 K, and (d) experience sudden and severe Li depletion with giant branch evolution past 5000 K, which is probably related to in situ giant branch mixing.

Cohn, Lugger, and Slavin continued a program to study globular cluster dynamical evolution using the Indiana University GRAPE-4 N-body supercomputer that was provided to their research group by J. Makino (Tokyo U.). Indiana University's Information Technology Services has provided strong support for this program and has recently acquired GRAPE-6 and MD-GRAPE-2 systems (see section 2.1). The GRAPE work has concentrated on the effect of hard binaries on the global evolution of clusters through core collapse.

Lugger, Cohn, Slavin, G.K. Drukier (Yale U.), and B. Murphy (Butler U.) continued a program to use the WIYN telescope to study the global dynamics of globular clusters. Their cluster sample now includes M13, M15, M56, and M92@. The Hydra multi-object spectrograph is used to obtain several hundred high-accuracy stellar velocities per cluster over a radial range extending from the inner arcminute to the tidal radius. Likely cluster members are selected for spectroscopy by use of 3-color Washington photometry from large mosaics obtained with the WIYN imager. The velocity dispersion profiles of M15 and M92 show a flattening and possible upturn in the outer halos of these clusters that may provide evidence for heating by the galactic tidal field and/or stellar ejection from the central regions. In contrast, M13 shows: (1) a continuously decreasing velocity dispersion profile, suggesting little tidal heating, and (2) evidence for radial anisotropy in the halo, consistent with results from previous proper motion studies. Thus, M13 appears to provide a reasonable approximation to an isolated cluster.

Lugger and Cohn continued their participation in a collaboration with J. Grindlay (Harvard U.), P. Edmonds (Harvard U.), A. Cool (San Francisco State), and C. Bailyn (Yale U.) to search for cataclysmic variables and other X-ray binaries in globular clusters using HST and Chandra. HST WFPC2 and NICMOS images of collapsed-core globular clusters are used to identify candidate CVs based on photometric measures of hydrogen-line emission. Recent results from this program include the following. (1) A study of stellar variability in the core of the extremely metal-rich globular cluster Terzan 5 which detected an RRab Lyrae variable, with a period of 0.6 days, and a second binary that is probably an eclipsing blue straggler or possibly the counterpart to the LMXB. (2) A study of the infrared color-magnitude diagram of Terzan 5 which has resulted in new determinations of its reddening, distance, metallicity, and spatial structure. The new distance value of 8.7 kpc places the cluster very close to the Galactic Center. This is consistent with the finding that the metallicity is at least solar and possibly even higher. The finding that Terzan 5 can be fit with a high-central-concentration King model suggests that it is in a pre-collapse state that is likely to be supported by energy release from a population of primordial binaries in the core. (3) A study of the $\sim$200-member Chandra X-ray source population in the luminous, high-metallicity globular cluster 47 Tuc. A major 300 ksec Chandra Cycle 3 allocation has been made for follow-up observations to constrain the complete CV and millisecond pulsar populations in 47 Tuc. (4) A 50 ksec Chandra allocation has been awarded to Cohn and Lugger in the Cycle 3 competition to image the collapsed-core globular cluster M30 (=NGC 7099). Since M30 does not contain a high-luminosity X-ray source, there is a potential for detecting a large population of low-luminosity sources similar to that in 47 Tuc.

2.6 Galactic Astronomy

Cohn and Lugger, with graduate students Slavin and Rogel, are participating in the ChaMPlane survey that is being carried out by a consortium led by Grindlay. The objective is to identify a large sample of serendipitous X-ray sources in deep Galactic Plane Chandra fields, in order to identify and measure the populations of accretion-powered binaries in the Galaxy. The primary goal is to identify cataclysmic variables and quiescent low-mass X-ray binaries, in order to determine the luminosity functions of these objects. The secondary goal is to determine the distributions in the Galaxy of Be X-ray binaries and stellar coronal sources. Deep Chandra field observations have sufficient sensitivity to reach such objects over a substantial fraction of the Galactic Disk. Each of about 100 Chandra fields is being imaged in Hα, R, V, and I using the mosaic cameras on the CTIO and KPNO 4-meter telescopes. Objects are selected for spectroscopic follow-up based on Chandra detection and/or Hα excess. A WIYN/Hydra run in Jan. 2001 produced spectra for about 75 objects in each of two ChaMPlane fields. These observations resulted in the discovery of an R $\sim$21 CV and several other Hα excess objects and as many as nine quasars with redshifts ranging up to 4.2. An NSF grant subcontract has been awarded to Cohn and Lugger to support this research.

2.7 Galaxies and Cosmology

In collaboration with J. J. Salzer (Wesleyan U.) and E.D. Skillman (U. Minnesota), van Zee is investigating the kinematics and neutral gas distribution of starbursting dwarf galaxies. Recently obtained HI synthesis maps (VLA) of 4 blue compact dwarf galaxies and 5 quiescent dwarf irregular galaxies will be analyzed to determine the shape of the rotation curve and the concentration of the neutral hydrogen distribution. This project explores the suggestion by van Zee and collaborators that starbursting dwarf galaxies are intrinsically different from quiescent gas-rich dwarf galaxies. Based on small samples of both types of galaxies, starbursting dwarf galaxies appear to have steeper rotation curves and more centrally concentrated gas distributions than quiescent dwarf irregular galaxies. In other words, starbursting dwarf galaxies appear to be centrally concentrated in both baryonic and dark matter. If this result is confirmed, it would provide a natural explanation for the starburst phenomenon. The present sample includes dwarf galaxies with a range of structural parameters and current star formation rates. The expanded sample will be used to determine if the apparent structural and kinematic differences are statistically significant. In a related project, Tebbe and van Zee have begun analysis of moderate resolution HI synthesis data of gas-rich dwarf galaxies to investigate the dark matter distribution in these intrinsically small galaxies. This project will form the majority of Tebbe's Master's thesis.

As part of a cohesive study of dwarf galaxy kinematics, van Zee, Salzer, and Skillman are also obtaining stellar rotation curves for many of the dwarf galaxies in the VLA sample. Observations for this project are ongoing. At this time, a total of 11 starbursting dwarf galaxies have been observed with the CTIO 4-meter, and time has been allocated in Fall 2001 to observe 4 additional starbursting dwarf galaxies with GMOS on Gemini North. These observations will provide an independent measure of the galaxy kinematics and will be used to determine if the stars and gas are kinematically coupled.

In a related project, van Zee, M.P. Haynes (Cornell U.), and Skillman are analyzing stellar rotation curves for dwarf elliptical galaxies in the Local Group and the Virgo Cluster. Previous observations of dwarf elliptical galaxies indicated that dwarf elliptical galaxies had little to no rotational component. Since almost all gas-rich dwarf galaxies appear to have significant rotational support, this result suggests that dwarf elliptical galaxies cannot form via passive evolution of gas-rich dwarf galaxies due to angular momentum conservation. However, the published kinematic data for dwarf elliptical galaxies is sparse. We are now in the process of observing a statistically significant sample of dwarf elliptical galaxies in a variety of environments. Observations of 7 dwarf elliptical galaxies were obtained with the Palomar 5-meter in 2000/2001; additional observations are scheduled with the Palomar 5-meter in 2001/2002.

L. van Zee is continuing her gas-phase abundance studies of oxygen and nitrogen in gas-rich dwarf irregular galaxies. In collaboration with Haynes, she has recently completed observations of over 50 HII regions in 19 dwarf irregular galaxies. This extensive data set will be analyzed to investigate the chemical evolution of quiescent dwarf galaxies.

In collaboration with E. Gillespie (U. Arizona), van Zee has begun a study of the morphological evolution of spiral galaxies at intermediate and high redshift. Observations are underway with the CFHT 3.6-meter and the WIYN 3.5-meter for this project. The superb image quality of these two telescopes will enable accurate morphological measurements of galaxies at high and intermediate redshift. This project will focus on the bulge formation process in spiral galaxies.

L. van Zee, S. Côté (HIA), and D. Schade (HIA) are obtaining deep Hα images of nearby spiral galaxies to search for evidence of star formation at large radii. The observations are underway with the CFHT 3.6-meter and WIYN 3.5-meter telescopes. The optical data will be compared with HI synthesis images (VLA) of the neutral gas to investigate the star formation process at low density and low metallicity.

Durisen, T. Toniazzo (U. Leeds), and Hartquist have published their investigation of how rotation and magnetic fields affect steady-state, mass-loaded accretion flows in active galactic nuclei. The approach is analogous to that used by Weber and Davis to model a steady-state equatorial flow for the solar wind. Confining the solution to the equatorial plane reduces the 2D steady-state equations to 1D ODE's. The spherically symmetric, nonrotating, and nonmagnetized Durisen-Burns solutions, both with and without multiple sonic points, have been reproduced. Rotation with a weak magnetic field introduces an inner centrifugal barrier, at the size-scale where one would expect a central disk around the black hole to form. On the other hand, the introduction of a strong magnetic field plus rotation eliminates the possibility of steady trans-fast solutions for most parameters, although trans-slow solutions are still allowed. The solution space is surprisingly rich and complex. Time-dependent calculations will be needed to determine which of several alternative solutions actually occur under realistic conditions.

2.8 High Energy Astrophysics

Mufson, J.L. Miller (James Madison U.), and A. Habig (Boston U.) have continued their studies of the arrival directions of muons observed by MACRO. Presently, they have analyzed all the muons collected from the turn-on of MACRO in February 1989 through May 2000. They have made an all-sky survey to search for point sources of astrophysical muons. The search for muons from point sources is essentially a search for exotic processes. This survey used the entire muon sample of approximately 60 million muons. In addition, a search was performed for muon excesses modulated by the orbital period of the X-ray source Cygnus X3. Further, a search was made for bursting activity from the sources Cygnus X3, Hercules X1, Mrk421, and 3C273. No sources were found in any of these searches. The MACRO data are also being searched for astrophysical point sources of high energy neutrinos using all-sky survey techniques. These neutrinos are detected as upgoing muons that result from neutrino interactions in the rock below MACRO. No neutrino sources have been found. No coincidences of upward muons with X-ray bursts have been found.

The MACRO muon data are also being anayzed for the ''sidereal wave'' that would result from the solar system motion through a sea of extragalactic cosmic rays, an effect first predicted by Compton and Getting in 1935. Our results show a sidereal wave in the direction of the solar rotation about the Galaxy is present with an amplitude of $>0.08\%$. This suggests the presence of halo cosmic rays as predicted by the leaky box model.

2.9 Miscellaneous

Johnson taught a noncredit class for adults, ''Look at the Stars,'' to 24 people in Fall 2000. The paper ''Calculating Lunar Retreat Rates Using Tidal Rhythmites,'' by Erik P. Kvale, Hollis R. Johnson, Charles P. Sonett, Allen W. Archer, and Ann Zawistoski, Journal of Sedimentary Research, Vol. 69, No. 6, November 1999, pp.1154-1168, was chosen by the SEPM (Society for Sedimentary Geology) as the best paper of 1999. Handsome plaques were awarded to the authors at the annual meeting of the society in June 2001.

Edmondson looked into the genealogical connection between Daniel Kirkwood (1814-1895) and Robert Jamison Kirkwood (1854-1892). Robert graduated from Indiana University in 1877 and was a lawyer in Chattanooga TN at the time of his death. He was the grandfather of the anonymous donor whose contribution in June 2000 raised the Daniel Kirkwood Professorship to a Chair. His descendents thought he was Daniel Kirkwood's brother. This was not the case. His family came form Scotland in 1817, and Daniel's family came from Ireland in 1781.

Dr. Catherine ''Caty'' Pilachowski became the Department's first Kirkwood Professor in August 2001.

Edmondson received a certificate at the January 2001 meeting of the American Astronomical Society ''In Recongition of Attendence at AAS Meetings over a Span of Seventy Years, 1931-2001.'' He has been appointed to the Executive Committee of the Friends of the Center for the History of Physics for a three year term. He continued to serve as AURA Consultant/Historian, a position he has held since his retirement in 1983.

During Summer 2001, Durisen spent his last month and a half as a Alexander von Humboldt Awardee at the Max-Planck-Institute for Extraterrestrial Physics in Garching, Germany.

Pilachowski began her term as President-elect of the American Astronomical Society. She also chairs the Nominating Committee of the Astronomical Society of the Pacific and is a member of the Nominating Committee of the American Association for the Advancement of Science.

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