Indiana University
Department of Astronomy

Bloomington, Indiana 47405

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This report covers research activities in the Department of Astronomy and the High Energy Astrophysics group for the period September 1999 through August 2000 inclusive.

1. INTRODUCTION

The Astronomy Faculty at Indiana University consisted of Professors: Haldan N. Cohn, Richard H. Durisen, R. Kent Honeycutt (Chair), Phyllis M. Lugger, and Stuart L. Mufson; Assistant Professors: Constantine P. Deliyannis and Michael J. Pierce; and Professors Emeriti: Martin S. Burkhead, Frank K. Edmondson, and Hollis R. Johnson. Other department members included Visiting Research Scholar Patricia Rosenzwig and Research Associate Thomas Y. Steiman-Cameron. Brice R. Adams, William R. Kopp, Richard LeBeau, and Eric Ost were members of the technical staff; Christina M. Lirot and Brenda S. Records were the office staff. Graduate Students in the Department during the year were: Michael Baird, Robert C. Berrington, Kai Cai, David L. 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: R.M. Heinz (Physics), S.L. Mufson (Astronomy), J. Musser (Physics); Senior Scientist: C. Bower; Graduate Students: A. Bhattacharyya, Brian J. Rebel. M. Gebhard and E. Ost were staff members; C.M. Lirot, B.S. Records, and D. McKinney provided secretarial support.

The Bachelor of Science Degree in Astronomy and Astrophysics was received by Mieko Furuhashi, Rebecca Hilbrich, Joshua Masterson, and James Patterson. The Master of Arts Degree in Astronomy was received by Annie C. Mejia and Brian J. Rebel. The Doctor of Philosophy Degree in Astronomy was received by Robert C. Berrington. The Ph.D. in Physics was awarded to High Energy Astrophysics student A. Bhattacharyya.

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). These are among the best at any research university in the Nation. One of the most significant recent upgrades was the acquisition of IBM Power3 and Power3+ SP RS/6000 nodes – bringing the number of processors in IU's IBM SP research supercomputer to 139, with a peak computation rate of 147 GFLOPs. IU's SGI/Cray Origin 2000 was replaced by a 64-processor Sun E10000 symmetric multiprocessing supercomputer, with 64 GB of shared memory and a peak rate of computation of 51 GFLOPs. The E10000 is utilized heavily by Durisen's astrophysical hydrodynamics group (see section 2.3). Durisen is also making use of UITS-sponsored blocks of time on SGI/Cray Origin 2000 supercomputers at the National Center for Supercomputing Applications.

UITS hosts a GRAPE4a special-purpose supercomputer for doing astrophysical simulations of star clusters. The GRAPE family of computers are special-purpose N-body force engines which couple with a standard Unix workstation or server to perform direct integrations of the gravitational N-body problem. Cohn, Lugger, and Slavin are using the GRAPE4a to model globular star clusters with model sizes of roughly 10k particles (see section 2.5). In 2000 and 2001, Indiana University plans to acquire GRAPE6 and MD-GRAPE2 hardware, which will allow the extension of globular cluster models to 100k particles on the GRAPE6 and the initiation of work by Durisen and Slavin on colloidal plasmas using the MD-GRAPE2. The GRAPE6 runs at 500 GFLOPs per board and the MD-GRAPE2 at 64 GFLOPs per board.

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.

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 2.9). This experiment is a joint Italian-American collaboration designed to search for GUT monopoles and other fractionally charged superstring particles, and astrophysical sources of muons and high energy neutrinos. In addition, MACRO continues its search for the neutrino signal from Type II supernovae in our Galaxy and will alert observatories around the world if one is detected. Further, MACRO is investigating the composition of cosmic rays in the range of 10^{15}-10^{16} eV/nucleon. The full detector (10,000 m^2 sr) is now complete. The detector will be 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 1 eV^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 Soudan, MN was begun in 2000. The MINOS experiment will turn on in late 2002. 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 Antimatter 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 flight took place in May 1999 from Ft. Sumner, NM. The fourth flight took place in May 2000 from Ft. Sumner, NM. 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.

2.2 Solar System

Durisen, B.K. Pickett (Valparaiso U., now at Purdue U. Calumet), P. Cassen (NASA-Ames), and Mejia are testing the idea, recently revived by A. Boss (Cagnegie Inst. Washington), that gas giant planets might form directly by gravitational instabilities in protostellar disks. Using new Solar Nebula models generated by Mejia, they have completed a set of simulations that mimic conditions which, according to Boss, should produce bound clumps with the masses of Jovian planets. So far, even under the extreme assumption of isothermal disk behavior, clumps formed by dynamic instabilities in these simulations are transient and do not persist long enough to become independent entities. When the disk is treated as adiabatic rather than isothermal, clumps do not form at all. Instead, gravitational torques due to spiral arms cause rapid expansion of the outer disk. Further work on this problem is underway, including higher resolution simulations and a better equation of state (see Section 2.3).

Durisen and Herrick have made significant modifications to 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. Earlier papers by Durisen's group demonstrated that 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. Preliminary results suggest that combining effects of these ejecta goes a long way toward bringing the simulations into better agreement with observed ring structures. Future work will involve improvements in how other key elements of the input physics are treated, particularly ring opacity and kinematic viscosity.

2.3 Stars

Durisen, Pickett, J.N. Imamura (U. Oregon), M. Bate (Cambridge U.), A. Brandtl (MPE), and M.F. Sterzik (ESO) are completing a comprehensive multi-code study of the dynamically unstable barlike modes for polytropic stars. State-of-the-art grid-based and SPH hydrodynamic codes are being used at the highest practical resolution to determine the effects of different assumptions about shock dissipation and heating on the outcome of the instability. The purpose is two-fold: to learn more about the physics of this fundamental astrophysical instability and to learn more about the limitations of various numerical schemes when treating dynamic stability problems. Some researchers have suggested that binary stars could form through growth of such modes. At least for the idealized case of a polytropic equation of state, this seems unlikely. It is still not known for sure, however, whether the ultimate outcome is a ring (or disk) around a barlike structure or relaxation to complete axisymmetry. Long, high resolution calculations are currently underway.

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 hightened 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.

When Imamura and Durisen introduced a realistic equation of state for hot lepton-rich matter into the group's equilibrium and linear stability analysis codes for nonaxisymmetric modes, they found 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 and may precipitate rapid contraction to neutron star densities. This is quite different from the conventional idea that fizzler evolution would be dominated by the emission of gravitational radiation. Imamura, Durisen, and Pickett, in collaboration with M. Bate (U. Cambridge), are planning to follow dynamically unstable fizzler evolution with 3D hydro codes.

Pickett, Durisen, Mejia, Cai, P. Cassen (NASA-Ames), 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 massive, rotationally-supported disks around young stars using both linear analyses and 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 and Cassen), 3.) implementation of this equation of state in 2D and 3D hydro codes (Pickett, Cassen, and Durisen), 4.) creation of improved 2D equilibrium disk models (Mejia, Pickett, and Durisen), 5.) introduction of progressively more realistic treatments of energy loss and transport (Mejia and Durisen), 6.) linear analyses and wave propagation analyses (Imamura, Cai, and Durisen), 7.) 2D and 3D visualization of results (Rosheck, Pickett, and Durisen), 8.) increasingly parallelized and portable versions of the 3D hydro code (Berry and Pickett). A major advance for all these projects has been modification of the code used to produce initial equilibrium models by Mejia. 2D star/disk models can now be created with prescribed star/disk mass ratios (down to 10:1 so far), aspect ratios (up to 1:40 so far), surface density distributions, and, soon, temperature distributions.

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. The discovery since 1995 of many massive substellar companions orbiting close ($<$A.U.) to solar-type stars has increased interest in the stability of the massive protostellar disks which may exist during the earliest stages of star formation.

In the course of constructing few-body systems with realistic mass distributions for numerical studies of few-body system decay, Durisen and M.F. Sterzik (ESO) found that a two-step selection of stellar masses seemed to produce distributions of binary properties among the decay products which agree with observations. The two steps involve picking a total 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 cloud mass. Durisen, Pickett, and Sterzik have completed an extensive statistical analysis of this two-step initial mass function (IMF) process. They find that 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.

Baird, Slavin, and Durisen, in collaboration with B. Elmergreen (IBM), have begun a study to determine 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. N-body calculations will be made by the IU group using Starlab, while Elmergreen will generate initial conditions.

Durisen and Hillwig participated in a collaboration with E. Guenther and his colleagues at Tautenburg plus B. Stelzer, R. Neuhäuser, and K.M. Menten of Max Planck Institute to make simultaneous multi-wavelength observations of a field in Taurus containing several wTTS (weak-line T Tauri stars) and cTTS (classical T Tauri stars) known for their pronounced X-ray emission and/or variability. The hope was to observe an X-ray flare in several wavelengths regions at once and thereby determine the nature of the flaring mechanism. WIYN and several other ground-based telescopes were used for optical spectroscopy and photometry. Radio and X-ray observations were made by the VLA and ROSAT, respectively. No flare was detected simultaneously by any two facilities, due in part to difficulties operating the aging and now defunct ROSAT spacecraft. However, there were some simultaneous observations of variable behavior and observations in close temporal proximity. One unexpected result was that cTTS exhibit all the same X-ray and optical flare-like behaviors that wTTS do.

Durisen and Mejia, with J.M. Alcalá and E. Covino (Osservatorio Astronomica di Capodimonte), have made 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. If so, these represent a population of aging T Tauri stars and/or pre-main sequence stars which has otherwise proven difficult to identify. Mejia and Alcalá made the observations in January 1999, and data reduction is underway. At least one group near Orion seems confirmed.

Honeycutt and collborators continued to work on cataclysmic variables and related topics. The long-term photometric monitoring program of CVs and AGNs using the automated 0.41m telescope (RoboScope) has continued, as well as WIYN spectroscopy. Hillwig has completed the observing portion of a project using WIYN DensePak spectroscopy of nova shells. In collaboration with S. Shore (Indiana U. South Bend) and Honeycutt the data are being used to examine correlations of shell kinematics with abundances. In related work, Hillwig and Honeycutt are studying a number of post-common-envelope binaries both spectroscopically and photometically, the most recent being PG1114+187. Rosenzweig and other colloborators at Indiana and the AAVSO completed a study of the long-term light curve of the dwarf nova SU UMa. An interesting finding from RoboScope is the presence in significant numbers of ''stunted'' outbursts in old nova and nova-like CVs. These 0.5-1.0 mag events closely resemble dwarf nova outbursts in duration and spacing but are much smaller in amplitude. Various observational evidence suggests that these are thermal disk instability outbursts seen under unusual circumstances. Papers on various other CVs including DI Lac, V841 Oph, V446 Her, V1159 Ori, and AR UMA appeared with collaborators.

Deliyannis, King (UNLV), Kunha (Observatório Nacional, Brazil), and Boesgaard (U. Hawaii) have used red (S/N $\sim$ 1,000 per pixel) and ultraviolet (S/N $\gtrsim$ 100 per pixel) Keck/HIRES spectra (R $\sim$ 45,000 $=3$ pixels) to derive the iron (Fe) and beryllium (Be) abundances in each of the solar twins 16 Cyg A and B. Self-consistent spectroscopic solutions yield, for 16 Cyg A and B, respectively, $T_{\rm eff}=5795\pm20$ K and 5760 ± 20 K, log $g=4.30\pm0.06$ and 4.40 ± 0.06, $\xi=1.25\pm0.05$ km s^{-1} and 1.12 ± 0.05 km s^{-1}, and [Fe/H]$=+0.04\pm0.02$ and $+0.06\pm0.02$. If Fe is used as a surrogate for metallicity, this represents an average metallicity of $11\pm5\%$ above solar. These results are in excellent agreement with other recent studies of this (wide) binary. Whereas it can be argued that no single study is conclusive, the consistent findings of these various studies offer compelling evidence that these stars have just barely super-solar metallicity, that A is just hotter than the Sun, and that B is just cooler. These authors have previously reported (based on Keck/HIRES data) a difference in the Li abundances of these stars of at least a factor of 4.5; for A they detected a Li abundance a factor of $\sim$2 *above* solar, and for B they placed a conservative upper limit a factor of $\sim$3 *below* solar. They detect Be in both stars and find that, if there is any difference between them, it must be much smaller – conservatively no more than 0.2 dex. Evidence suggests that solar-type stars deplete their surface Li abundance during the main sequence, a feat that standard stellar evolution theory has, thus far, been unable to accomplish. Whatever physical mechanism depletes the surface Li abundance must create far less spread in the Be abundances than it does in the Li abundances. They find that their Li and Be results are consistent with the predictions of Yale models that include rotationally-induced mixing driven by angular momentum loss. The results provide no evidence for a small ($\sim$0.05 dex) enhancement in the ^{9}Be abundance of the A component relative to the B component expected if the stars' Li abundance difference was due to accretion of planetary material by the A component. Given the errors, however, neither are they able to firmly preclude such a signature.

Standard stellar evolution predicts that late F stars should have essentially retained their initial surface 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 on 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 survives. 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 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 to 10 and, yet it still contains detectable Li, which is in turn depleted by a factor of 100 to 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 on 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. King (STScI), S. Vogt (U. California/Santa Cruz), and M. Keane (CTIO) reported first results of this survey based on Li data from the University of Hawaii 2.2m telescope + Coude (R$\sim$80,000) and Keck I 10m telescope + HIRES (R$\sim$45,000; S/N$\sim$800 - 1500 per pixel), and Be data from the Canada-France-Hawaii 3.6m telescope + Gecko (R$\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 depletions 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.

Steiman-Cameron and J.N. Imamura (U. Oregon) continued their study of stellar X-ray sources. During the past year, they have concentrated on examining the temporal characteristics of the class of accreting magnetic white dwarfs known as Polars (also referred to as AM Herculis sources) which are known to experience eclipses by their main sequence companions. Their goal is to better understand the general problem of plasma flows in strongly magnetic environments and to determine the physical and geometrical characteristics of the Polars. The investigators are surveying the eclipsing Polars, using the facilities of the Rossi X-Ray Timing Explorer (RXTE) and the Cerro Tololo InterAmerican Observatory (CTIO). Papers discussing the system V2301 Ophiucus and the related noneclipsing system BL Hyi were published during the period of this report. Additional data on the sources WW Hor and EP Dra were obtained. This work has allowed the investigators to determine a wide array of physical information about these sources. During the term of this study, Steiman-Cameron and Imamura have examined all but two of the known eclipsing Polars. They are also conducting a study of the Intermediate Polars using RXTE and CTIO.

In a separate study, Steiman-Cameron and collaborators reported results of several years monitoring of Supernova 1987A. The authors studied SN1987A in optical/near-infrared bands using various high-speed photometers from a few weeks following its birth until early 1996 in order to search for a pulsar remnant. While they found no clear evidence of any pulsar of constant intensity and stable timing, they did find emission with a complex period modulation near the frequency of 467.5 Hz - a 2.14 ms pulsar candidate. The signal was first detected in data taken on the remnant at the Las Campanas Observatory (LCO) 2.5m Dupont telescope during 14-16 Feb. 1992 UT. Further signals near the 2.14 ms period were detected on numerous occasions over the next four years in data taken with a variety of telescopes, data systems and detectors, at a number of ground- and space-based observatories. Due to the nature of the 2.14 ms signature and its modulation, and the analysis techniques necessary for detection, it is difficult to determine the overall probability that all aspects of the signal are real, though it has remained consistent with an astrophysical origin throughout the several year timespan of the study.

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 as 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 (Wisconsin-Indiana-Yale-NOAO) 3.5m telescope at Kitt Peak, although other telescopes (such as the KPNO and CTIO 0.9m's) are used as supporting telescopes. WIYN's primary instruments are: 1) Hydra, a multi-object spectrograph that can observe up to 95 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-art research skills while studying fundamental astronomy with scientific goals that are within their intellectual grasp for that stage in their career. Deliyannis and IU students Steinhauer, Sarrazine, Hainline, Bavender, Raffauf, Blecksmith, Hilbrich, and Hall have been working with 0.9m 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. 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 Sun normal? 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

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 affected estimates for the primordial Big Bang abundance. Together with A. Boesgaard (U. Hawaii), A. Stephens (U. Hawaii), and J. King (STScI), results in M92 were previously published, 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 10m 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 4m 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 $T_{\rm eff}$. 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 factor of 10 – 20 near $T_{\rm eff} = 5400$ K, c) establish a diluted plateau from $T_{\rm eff} = 5300$ 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 GRAPE4 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 undertaken a major expansion of the local GRAPE program that will add GRAPE6 and MD-GRAPE2 capability and a powerful new host machine. S. McMillan (Drexel) and Slavin exchanged visits to plan further development of the Starlab software suite for GRAPE simulations. In the past year, the Indiana GRAPE work has concentrated on the effect of hard binaries on the global evolution of clusters through core collapse. A striking result is that even in the absence of external tidal influences, the ejection of stars from the cluster, via strong gravitational interactions in and near the core, produces an increasing velocity dispersion profile in the halo as is observed in the WIYN/Hydra studies of M15 and M92 described below. A study of the evolution of the cataclysmic variable population in clusters is underway.

Lugger, Cohn, Slavin, Drukier (Yale), 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. A highly successful Hydra run in June 2000 brought the sample of radial velocities determined for M13 members to 540, with half of these stars observed multiple times. Analysis of these data indicates: (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), P. Edmonds (Harvard), A. Cool (San Francisco State), and C. Bailyn (Yale) to search for cataclysmic variables (CVs) 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. Results from this program in the past year include two HST-NICMOS infrared photometric studies of the high-density, metal-rich, obscured globular cluster Terzan 5, which contains a low-mass X-ray binary (LMXB). A study of stellar varability in the core 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. A study of the infrared color-magnitude diagram of Terzan 5 has resulted in new determinations for the reddening, distance, and metallicity of Terzan 5. 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.

2.6 Galactic Astronomy

Cohn and Lugger have joined the ChaMPlane survey that is being carried out by a consortium led by J. 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 4m telescopes. WIYN/Hydra will be used to do followup spectroscopy of Hα-excess and blue objects in the northern Chandra fields.

2.7 Interstellar Medium

Steiman-Cameron, M. Wolfire (U. Maryland), and D. Hollenbach (NASA-Ames) continued a study of the physical properties of the Galaxy's interstellar medium (ISM) through analyses of data obtained with the Cosmic Background Explorer (COBE) satellite. This effort combines detailed theoretical models of the interstellar medium (ISM) of the Milky Way Galaxy with the satellite data to develop a global model for many of the important physical characteristics of the ISM (*e.g.*, thermal pressure of the diffuse ISM, heating/cooling rates, volume filling factors). Intensities and line ratios in several atomic fine-structure transitions and CO rotational transitions observed by COBE's Far Infrared Absolute Spectrophotometer (FIRAS) along with measures of the far infrared continuum radiation from COBE's Diffuse Infrared Background Experiment (DIRBE) are being used used in this study.

The researchers completed a reevaulation of the intensities of eighteen far-infrared emission lines observed by FIRAS. These include the most important coolants of the ISM. Utilizing an interpolation approach to evaluating line intensities along the Galactic midplane, they determined that line intensities at the midplane are typically 20 – 40% greater than suggested in previous works. Based upon the reanalysis of the [C II] 128 micron and [N II] 205 micron line intensities observed by COBE in and near the Galactic plane, Steiman-Cameron and collaborators constructed a model for the spiral structure of the Milky Way Galaxy. These lines are tracers of spiral structure. Intensity maps of these lines were derived and used to construct models for the volume emissivity of [C II] and [N II] as a function of position within the Galaxy. Emissivity models with two, three, and four arms were explored. Only a four-arm model was found to fit the COBE data. This model, with arms defined by logarithmic spiral forms, reproduces the observations extremely well.

2.8 Galaxies and Cosmology

Durisen, T. Toniazzo, and T. Hartquist (U. Leeds) have completed an 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 old 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. A sufficiently strong magnetic field, however, can remove angular momentum from the inflowing gas and permit the accretion flow to extend all the way to the black hole. A significant finding was that the introduction of a magnetic field and rotation eliminates the possibility of steady trans-fast solutions for most parameters, although trans-slow solutions are still allowed. In this context, ''fast'' and ''slow'' refer to the fast and slow magnetosonic wave propagation speeds. The group recognizes that their treatment of this problem as 1D is a drastic oversimplification. Even so, 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.

Musser, Mufson, Honeycutt, and Rengstorf, in collaboration with astronomers at Yale and Venezuela, are members of the QUEST collaboration. A major focus of this collaboration is to collect a sample of gravitationally lensed quasars one to two orders of magnitude larger than the present world sample with uniform and carefully controlled experimental efficiencies. Rengstorf is currently testing whether quasars and quasar lensing candidates can be efficiently found by searching for aperiodic brightness fluctuations in high galactic latitude objects.

Berrington completed a Ph.D. dissertation on the dynamical evolution of galaxy clusters, under the supervision of Lugger and Cohn, and began a postdoctoral appointment at the Naval Research Laboratory. The theoretical component of this work produced high-resolution, N-body simulations of evolving galaxy clusters. These were performed on the Indiana University SGI/Cray Origin 2000 system, using a parallelized tree code. The simulations followed the mergers of poor clusters of galaxies that are believed to result in the development of rich clusters. This study investigated statistical tests for the presence of cluster substructure that is generated by the merger event.

Berrington, Lugger, and Cohn completed a program to use the WIYN telescope to obtain photometric and spectroscopic data sets for galaxy clusters that have been noted to have complex structure in X-ray or previous optical studies. These data are used to test the results of the N-body cluster simulations. Deep R-band image mosaics have been obtained for A2256, A399, and A401. The Hydra multi-object spectrograph has been used to obtain velocities for 320 galaxies in A2256 and a extensive analysis of these velocities has been reported. This analysis indicates that in addition to the two merging subclusters that have previously been identified, there is a third subcluster that is just now colliding with the A2256 system.

Pierce and R.B. Tully (U. Hawaii) are nearing completion of their survey of the distances to nearby spiral galaxies using the correlation between luminosity and rotational velocity. This involves high quality, multi-color surface photometry and rotational velocities measured using the 21-cm HI line for about 800 galaxies within several clusters and the field. The primary goals of this survey are to measure the Hubble Constant within a velocity of about 8,000 km/sec and to characterize the peculiar (non-Hubble) velocity field within the Local Supercluster ($V < 3000$ km/sec).

Recent HST-based and ground-based Cepheid surveys have produced distances to 30 galaxies suitable for calibrating this technique for measuring distances (a.k.a. the Tully-Fisher relation). The rms scatter of the calibrating systems is found to be only 0.2 mag, or 10% in distance. This means that the only significant sources of error remaining in the calibration are in the absolute calibration of Cepheids. A template relation was constructed using spirals within the Ursa Major, Pisces, and Coma clusters.

The template relation has been used to constrain the metallicity-dependence of the Cepheid period-luminosity relation. The fact that there is a strong correlation between the luminosity and metallicity of late-type galaxies means that any significant variation in the Cepheid zero point with metallicity will result in systematically biased Cepheid distances with luminosity for the calibration sample. The result will be a systematic deviation of the calibration sample with luminosity when compared with the template luminosity–line-width relation. A simple, first-order parameterization of the metalicity dependence ($\delta M = \alpha \times$ [Fe/H]) was examined through a χ^2 minimization of deviations of the calibration sample with respect to the template relation. This analysis suggests that α is less than 0.1 (or 5% in distances and the value of H_o) with 95% confidence.

Additional, though less complete, data is available from the literature for more distant clusters but the measured distances for these clusters allow the Hubble flow to be sampled over a volume extending to 8,000 km/sec where any peculiar motions are negligible. Applying the local calibration to these more distant samples yields a value of the Hubble constant of $H_o = 77 \pm 8$ km/s/Mpc. This result agrees well with other studies but is inconsistent with the current age estimates for globular clusters assuming an inflationary cosmology unless the cosmological constant is nonzero.

Pierce and Rogel are continuing the surface photometry of the field spiral sample. The rms scatter of the luminosity–line-width relations was found to be only 0.25 mag, or 12% in distance, for the template and calibration samples. As a result, it should be feasible to measure peculiar velocities as small as 350 km/sec at the limit of the sample (3,000 km/sec). The primary advantages of this survey are high intrinsic precision and relatively dense sampling. This should enable a detailed comparison of the peculiar velocity field with that predicted from the distribution of luminosity (*i.e.*, the distribution of galaxies) and thereby allow the ''luminosity bias'' to be characterized.

Pierce, P. Stetson (HIA/NRC), D. Welch (McMaster Univ.), and S. van den Bergh (HIA/NRC) are nearing completion of their HST-based Cepheid survey in the Virgo cluster galaxy NGC 4571. The position and velocity of NGC 4571 and the fact that it is one of the more HI-deficient late-type galaxies within Virgo suggests that this system is located within the compact core of the cluster. The analysis is based upon observations using the Wide Field and Planetary Camera 2 (WFPC2) of the Hubble Space Telescope. The DAOPHOT/ALLFRAME package was used to derive photometry from 11 visits acquired with the F814W filter and 4 with the F555W filter. These data were transformed to the Johnson and Cousins V and I systems, respectively, and periods and mean magnitudes derived by fitting template Cepheid light curves to the data. We identify 19 probable Cepheids in the period range 15–62 days. A comparison of the resulting period-luminosity relations with those of the Large Magellanic Cloud yields an extinction-corrected distance modulus of 30.81 ± 0.16 mag, or a distance of 14.5 ± 1.1 Mpc for NGC 4571. These results are in good agreement with the majority of Cepheid and red giant branch tip distances presently available for galaxies within the Virgo region, implying that the distance to the Virgo Cluster is now reasonably well established.

Pierce and Berrington have continued their survey of the large-scale peculiar velocity field using distances for a complete sample of Abell clusters measured using the fundamental plane of elliptical galaxies (FP). The primary goal is to extend the range over which peculiar velocities have been sampled in order to better constrain the flow field within a velocity of 15,000 km/sec, roughly three times the distance of the ''Great Attractor.'' The multiplex advantage offered by the multi-fiber spectrograph at WIYN/Hydra allows data to be obtained for up to 60 galaxies at a time. The spectroscopic data have a signal-to-noise ratio of about 50 and a velocity resolution of 50 km/sec, enabling velocity dispersions to be measured with a precision of 10 km/sec.

To date, spectroscopy has been obtained for about 2/3 of the sample, 60 clusters in total. I-band surface photometry is also being acquired using WIYN. To date, surface photometry have been obtained for about 100 galaxies within *each* of the Coma, Perseus, and Abell 2199 clusters. The rms scatter in the FP is found to be only about 10% in distance. This is about a factor of two smaller than that found in most previous investigations and implies that much of the scatter found in previous studies of the FP was due to observational uncertainties. The high precision of the FP and the large samples of ellipticals available within these clusters should allow peculiar velocities to be measured to a precision of about 2%, the level at which systematic errors are likely to begin to dominate the measurements. These data should allow the large-scale peculiar velocity field to be sufficiently characterized that it is no longer a significant source of uncertainty in the characterization of the local peculiar velocity field.

2.9 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 (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 $>0.1\%$. This suggests the presence of halo cosmic rays as predicted by the leaky box model. In addition, the muons are modulated with a wave that is anticorrelated with the pressure as measured by the EAS-TOP air shower experiment on the top of the Gran Sasso.

2.10 Miscellaneous

During this period, Johnson and his wife, Grete, enjoyed the fascinating experience of serving as missionaries for The Church of Jesus Christ of Latter-day Saints in Ghana. Serving in the capital, Accra, as missionaries of the church educational system, they worked to train the (volunteer) local teachers for church classes and to compile reports of church activties from all of West Africa. On the side, Johnson gave several lectures on astronomy at the University of Ghana at Legon.

Edmondson's invited paper about Daniel Kirkwood was published in the May - June, 2000 issue of Mercury. Kirkwood was appointed Professor of Mathematics at Indiana University in 1856 and retired in 1886. In 1857 he predicted there would be gaps in the orbits of astroids at distances where the period would be commensurate with the period of Jupiter. In 1866, when the number of known asteroids had increased to 88, he was able to call attention to gaps at 7/2, 3/1, 5/2. In 1877, using data for 146 asteroids, he called attention to gaps at 2/1, 7/2, 4/6, 9/4, and 7/3. Edmondson continued to serve as AURA Consultant/Historian, a position he has held since his retirement in 1983.

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