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This report covers research activities in the Department of Astronomy and the High Energy Astrophysics group for the period September 2001 through August 2002 inclusive.

1. INTRODUCTION

The Astronomy Faculty at Indiana University consisted of Professors: Haldan N. Cohn, Richard H. Durisen (Chair), R. Kent Honeycutt, Phyllis M. Lugger, Stuart L. Mufson, and Catherine A. Pilachowski; Assistant Professors: Constantine P. Deliyannis, and Liese van Zee; and Professors Emeriti: Martin S. Burkhead, Frank K. Edmondson, and Hollis R. Johnson. Adjunct Assistant Professor: Anurag Shankar. 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: Aaron Boley, Jeffrey Burkett, Kai Cai, Janet Casperson, David Herrick, Styliani Kafka, Steven J. Margheim, Scott Michael, Annie C. Mejia, Nicholas J. Mostek, Brian J. Rebel, Adam W. Rengstorf, Allen B. Rogel, Angela Sarrazine, Brian Sands, 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: Mark Messier (Physics), Stuart L. Mufson (Astronomy), and James Musser (Physics); Senior Scientist: Charles Bower; Graduate Students: Nicholas J. Mostek and Brian J. Rebel; Technical Staff: Art Cohee, Mark Gebhard, Richard LeBeau, James Lovell, Michael Simpson, and John Wildman; Support Staff: Christina Lirot, Debbie McKinney, and Brenda Records.

The Bachelor of Science Degree in Astronomy and Astrophysics was received by Emily Freeland and Kenneth Moody. The Masters of Arts Degree was received by Kai Cai, Styliani Kafka, and Steve J. Margheim. Ph.D. degree was received by Todd Hillwig.

2. RESEARCH

2.1 Instrumentation and Facilities

Honeycutt has completed the design and construction of the WIYN Universal Fiber Feed (WUFF). The unit provides acquisition and guiding functions the two fiber-fed integral field units at WIYN, DensePak and SparcePak. WUFF promises to be more stable and accurate than the device currently in use, and will allow DensePak and SparcePak to be used at either Nasmyth or Cassegrain focus.

The High Energy Astrophysics Group (HEAP) continues its participation in the MINOS experiment which is an effort to search for neutrino oscillations. The experiment studies muon neutrinos that are pointed toward northern Minnesota from Fermilab in Chicago. The experiment will explore the neutrino mass region below 1 eV^2 . Neutrinos in this mass

range can account for some fraction of the nonbaryonic dark matter in the universe as well as the hot dark matter postulated to explain large scale structure. Construction of the far detector in Soudan, MN is scheduled to be completed in early 2003; civil construction of the near detector hall is complete and near detector construction will start in 2003. At the present time the far MINOS detector is studying neutrino physics and muon physics initiated by cosmic rays in the atmosphere. The NuMI beam will turn on in 2005. The Indiana HEAP group is responsible for the far detector multiplexing boxes (MUX boxes) that route the fiber optic readout cables to the multipixel PMTs and the far detector fiber optic cables.

The balloon flight program of the HEAP group is currently participating in the HEAT (High Energy Antimatter Telescope) experiment. EARLY HEAT flights were launched in 1994, 1995, 1999, and 2000 from Ft. Sumner, NM and Lynn Lake, Alberta, Canada. The final HEAT flights took in April and September 2002 from Ft. Sumner. The purpose of this experiment is to study the antiproton spectrum and the positron spectrum in the cosmic rays.

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 600×2400 13-micron pixels. The camera controller uses the MFront interface board set with the control logic implemented in Xilinx field programmable gate arrays. The camera is complete and working in the lab and will soon be installed on the Palomar Schmidt Telescope.

2.2 Solar System

Durisen, Mejía, B.K. Pickett (Purdue U. Calumet), and P. Cassen (SETI Institute) are continuing their study of gravitational instabilities in protostellar disks as a mechanism for gas giant planet formation. The lifetimes of disks around young stars seem too short for the standard core-accretion mechanism to explain the common occurrence of super-Jupiter exosolar planets. This group has recently completed their analysis of 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 one particularly long calculation, which has been carried now beyond twenty outer disk rotations, long-lived dense rings develop. Within the rings, dense clumps tend to form, shear out, and reform. This may represent the formation of permanent dense structure which could be a precursor to protoplanet production. Contrary to expectations from the work by A. Boss (Carnegie Inst. Washington), the introduction of realistic radiative cooling

does not seem to facilitate clump formation. This important aspect of the problem is still under study as part of Mejia's Ph.D. dissertation.

Clump formation in 3D disk simulations is a difficult numerical problem, requiring high resolution and algorithmic accuracy. It is premature to conclude on the basis of any published calculations whether gravitational instabilities do or do not work as a planet formation mechanism in the real world. Simulations with more physics and more refined numerical techniques are required. Even for a simple isothermal equation of state, it is not clear that permanent clumps form. 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 protostellar disks is 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. Herrick is completing his Master's research by running a suite of simulations for the B Ring inner edge under different assumptions about the nature of the two ejecta distributions. Future work will involve the inclusion of a more realistic treatment of ring opacity and kinematic viscosity.

2.3 Stars

Pilachowski, in collaboration with V. Smith (UTEP) and numerous other authors, participated in the Gemini Observatory Demonstration Science Program for the Phoenix spectrometer on Gemini South. High-resolution infrared spectra were obtained for twelve red-giant members of the Large Magellanic Cloud (LMC) with the Gemini South 8.3m telescope plus Phoenix spectrometer. Two wavelength regions, at 15540Å and 23400Å, were observed. Quantitative chemical abundances of carbon (both ^{12}C and ^{13}C), nitrogen, and oxygen were derived from molecular lines of CO, CN, and OH, while sodium, scandium, titanium, and iron abundances were obtained from neutral atomic lines. The twelve LMC red giants span a metallicity range from $[\text{Fe}/\text{H}] = -1.1$ to -0.3 . Values for both $[\text{Na}/\text{Fe}]$ and $[\text{Ti}/\text{Fe}]$ in the LMC giants fall below their corresponding Galactic values (at these same $[\text{Fe}/\text{H}]$ abundances) by about ~ 0.1 to 0.5 dex; this effect is similar to abundance patterns found in the few dwarf spheroidal galaxies with published abundances. The program red giants all show evidence of first dredge-up mixing of material exposed to the CN-cycle, i.e. low $^{12}\text{C}/^{13}\text{C}$ ratios, and lower ^{12}C - with higher ^{14}N -abundances. The carbon and nitrogen trends are similar to what is observed in samples of

Galactic red giants, although the LMC red giants seem to show smaller $^{12}\text{C}/^{13}\text{C}$ ratios for a given stellar mass. This relatively small difference in the carbon isotope ratios between LMC and Galactic red giants could be due to increased extra mixing in stars of lower metallicity, as suggested previously in the literature. Comparisons of the oxygen to iron ratios in the LMC and the Galaxy indicate that the trend of $[\text{O}/\text{Fe}]$ versus $[\text{Fe}/\text{H}]$ in the LMC falls about 0.2 dex below the Galactic trend. Such an offset can be modeled as due to an overall lower rate of supernovae per unit mass in the LMC relative to the Galaxy, as well as a slightly lower ratio of supernovae of type II to supernovae of type Ia.

J. Truran (U. Chicago), J. Cowan (U. Oklahoma), Pilachowski, and C. Sneden (UT Austin) continued their work on heavy metals in the early galaxy with a review paper in the P.A.S.P. The heavy elements formed by neutron capture processes have an interesting history from which we can extract useful clues to and constraints upon both the characteristics of the processes themselves and the star formation and nucleosynthesis history of Galactic matter. Of particular interest in this regard are the heavy element compositions of extremely metal-deficient stars. At metallicities $[\text{Fe}/\text{H}] \leq -2.5$, the elements in the mass region past barium ($A = 130-140$) have been found (in non carbon-rich stars) to be pure r -process products. The identification of an environment provided by massive stars and associated Type II supernovae as an r -process site seems compelling. Increasing levels of heavy s -process (e.g., barium) enrichment with increasing metallicity, evident in the abundances of more metal-rich halo stars and disk stars, reflect the delayed contributions from the low- and intermediate-mass ($M \sim 1-3 M_{\odot}$) stars that provide the site for the main s -process nucleosynthesis component during the AGB phase of their evolution. New abundance data in the mass region $60 \leq A \leq 130$ is providing insight into the identity of possible alternative r -process sites. The paper reviewed recent observational studies of heavy element abundances both in low metallicity halo stars and in disk stars, discussed the observed trends in light of nucleosynthesis theory, and explored some implications of these results for Galactic chemical evolution, nucleosynthesis, and nucleocosmochronology.

Pilachowski is collaborating with Deliyannis, S. Barden (NOAO), D. Harmer (NOAO), and R. Mathieu (U. Wisconsin) to search for planets in open clusters of a variety of ages using the Hydra fiber spectrograph on the 3.5-m WIYN telescope. Radial velocities for cluster members are determined relative the average velocity of the ensemble of stars observed. Velocity precision of at 100 m s^{-1} or better has been demonstrated. Observations of NGC 752 and Praesepe have been obtained and additional clusters will be included in the program. Pilachowski, A. Quillen (U. Rochester), and C. Grady (GSFC) are using the Hydra multi-fiber spectrograph on the 3.5-m WIYN telescope to survey A and late B stars in several young star clusters to search for stars which display the spectral signature of infalling debris. Preliminary observations of NGC 2264 suggest that about a third of the A stars show such signatures, and followup observations are underway. Similar observations of A stars in the older (100 Myr) cluster IC 4665 show no such signatures. E. Friel (NSF), H.

Jacobson (UT Austin), and Pilachowski are investigating the composition of giant stars, including oxygen abundances, in the very old open cluster Cr 261. The data were obtained with the echelle spectrograph at the Blanco 4-m telescope at the Cerro Tololo Interamerican Observatory.

Rotational fission was the first theory of binary star formation to be proposed by astrophysicists. The idea is that, if a star rotates fast enough, instabilities or bifurcations of non-axisymmetric surface distortions ultimately lead to splitting of the star into two or more objects. Using 3D hydrodynamics codes, Durisen and coworkers in the 1980's demonstrated that rotating polytropic stars which are dynamically unstable to barlike modes develop strong two-armed spirals. Gravitational torques in the spiral arms transport angular momentum outward and abort the nascent fissioning of the central regions. Until recently, however, there have been few calculations which tested the case where an object evolves quasistatically from stable to unstable conditions. N. Lebovitz (U. Chicago) has maintained for several decades that fission will occur under these conditions. As a follow up to detailed studies of finitely unstable polytropes, J.N. Imamura (U. Oregon), Pickett, and Durisen have been using their 3D hydrodynamics code to simulate polytropes in which the entropy per gram is slowly decreased. The polytropic stars are started with slow enough rotation that they are dynamically stable. As they contract due to decreasing entropy, they spin up and surpass the stability limit. This work is in progress, but preliminary results indicate that the instability proceeds in the same way as calculated earlier, and binary fission is avoided.

Imamura, Durisen, and Pickett have extended their barlike mode studies to "fizzlers," equilibrium objects with densities between those of white dwarfs and neutron stars. In this density regime, a nonrotating star would collapse due to the softness of its equation of state; but rapid rotation can stabilize the radial collapse modes. So, 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 term "fizzler," for "fizzled supernova."

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. By incorporating a hot, lepton-rich, high-density equation of state into their 3D hydrodynamics code, Imamura, Pickett, and Durisen have shown that dynamic rather than secular instabilities dominate the evolution of a fizzler and that these instabilities are reached on a deleptonization time scale of a few seconds or less. The gravitational waves emitted during the dynamic instability are, in principle, detectable by LIGO I at Virgo Cluster distances provided that the resultant bar is long-lived. Further work will be necessary to determine whether or not it is. The longevity of the bar is sensitive to the treatment of the thermodynamics and deleptonization of the fizzler. Longer evolutions are also needed in order to determine the ultimate fate of the fizzler.

Durisen, Mejía, Pickett, Cai, Cassen, Sands, D. Berry (IU's UITS), and J. Rosheck (free-lance software engineer) are continuing their research on gravitational instabilities

(GI's) in disks around young stars using 3D hydrodynamics 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) introduction of progressively more realistic treatments of heating and cooling, energy transport, and shear viscosity (Mejía and Durisen), (3) analysis of the asymptotic steady-state equilibrium between heating and cooling (Cai, Mejía, and Durisen), (4) adaptive mesh treatment of isothermal disks (Pickett, Falle, and Hartquist; see Section 2.2), (5) studying maser conditions in disks around massive protostars (Rosheck, Sands, Mejía, and Durisen), (6) 2D and 3D visualization of results (Rosheck, Sands, Mejía, and Durisen), (7) increasingly parallelized and portable versions of the 3D hydro code (Berry), and (8) an improved Poisson solver (Berry).

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? Recent progress has been made in developing realistic treatments of radiative cooling and in performing very long simulations with idealized heating and cooling. The latter are useful for testing the asymptotic behavior of disks evolving under the influence of GI's. As predicted in earlier work, the disk seems to settle into a state of roughly constant Toomre Q after a strong dynamic transient as the GI's first kick in. One surprise in these long calculations is the build up of large ring-like density enhancements in the inner disk.

The work on radiative cooling is progressing quickly. Large differences in cooling time are found depending on how the optically thick to thin boundary conditions are handled. Greater care seems required than has been exercised by others in their 3D calculations. Claims of very short radiative cooling times in the literature are probably incorrect. A major effort is being made now by Mejía and Durisen to include irradiation by the central star. This has a dramatic effect on the temperature structure and appearance of the disk. The goal is to determine whether it affects the development and evolution of GI's.

Durisen, M.F. Sterzik (ESO-Chile), and Pickett are continuing their investigations of binary formation by small cluster decay, particularly the effects of a two-step initial mass function (IMF). 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 than one-step stellar mass selection. This work has now been extended by including objects with brown dwarf masses in the clusters. The rather high fraction of brown dwarf binaries claimed by some observers seems to require some dissipation in the cluster dynamics or a very

large number of brown dwarfs. Slavin and Durisen, in collaboration with B. Elmergreen (IBM), are planning a related study of the binary characteristics which result from the dynamics of clustered star formation 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 was involved with two observational projects concerning young stars. For the first effort, led by J. Alcalá (Osservatorio Astronomico de Capodimonte), a region in Orion near NGC 1788 was selected for study because it contained a high density of X-ray selected ROSAT young star candidates. WIYN Hydra observations combined with photometric data confirm that this is indeed an association of young stars. The other project was a coordinated effort, led by B. Stelzer (La Palma) to obtain simultaneous observations in the optical and X-rays for V410 Tau, a strongly flaring T Tauri star. Although no simultaneous observations were obtained due to scheduling problems with Chandra, many flare events were captured over days of monitoring.

Kafka and Honeycutt have completed a study of the long-term RoboScope light curve of the polar QQ Vul. The secondary dip in the orbital light curve is found to quite variable with time. Unlike optical light curves in the literature, the secondary dip is found to be completely missing in about half the data acquired 1991-2002. The depth of the secondary dip is strongest when the system is faintest, a correlation that also holds for optical light curves from the literature acquired 1982-86. The fact that the secondary dip in the optical disappears at times presents problems when attempting to form a coherent picture for the both the x-ray and optical data. It is proposed that an x-ray corona on the secondary star contributes to the observed soft x-ray light curves, an idea consistent with an observed x-ray flare in QQ Vul and the high rotation of the secondary star.

2.4 WIYN Open Cluster Study (WOCS)

Star clusters are superb astrophysical laboratories containing copatial 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; and initial and present-day mass functions.

The centerpieces of WOCS are the WIYN 3.5-meter and WIYN 0.9-meter telescopes at Kitt Peak, although other telescopes (such as the CTIO 0.9-meter telescope) 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) the wide-field images on the WIYN telescopes.

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, Jacobson, Cummings, Hilbrich, and Hall have been working with 0.9-meter and 3.5-meter data of the open clusters NGC 188 (one of the oldest Galactic clusters), NGC 2420 (the nearest significantly metal-poor cluster), M34 (a nearby cluster with age intermediate to that of the Pleiades and the Hyades), M35 (a very rich, nearby, Pleiades-like cluster), M36, M37, and M38 (three anticenter clusters about 1kpc away, of very young, intermediate, and intermediate ages, respectively) 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), 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?

Cai, Deliyannis, and Durisen developed a method to detect binaries in clusters by photometric means only. With

accurate enough photometry and a good fit of the color-magnitude diagram to a theoretical Yale isochrone, comparison of the observed U-I and B-I versus V with binaries constructed from stars in the isochrone main sequence can, in principle, be used to determine the primary mass (M_1) and mass ratio (q) of a system. So far, over 200 proper motion members of the WOCS open cluster M35 have been analyzed in this way. For most stars, we can reliably place them into three bins $q < 0.4$, $0.4 < q < 0.7$, and $q > 0.7$ for M_1 between one and three solar masses. The distribution tends to be more peaked at middle q -values than the distribution observed for nearby solar-type stars. At higher masses in the cluster, the method fails. This suggests that some additional parameter, like stellar rotation, significantly alters the main sequence UBVR magnitudes from the Yale values. Despite the limitations, the method does allow some measure of the binary fractions and q -distributions in clusters without time-consuming spectroscopy, which picks up only close binaries. The method will be refined and extended to other WOCS clusters to examine possible trends with cluster age and metallicity.

Kafka and Honeycutt are using WIYN Mini-Mo Imaging to search for new variable stars in NGC 6791 and NGC 188. The goal is to find and study cataclysmic variables in old galactic clusters. No new CVs have been found, but a number of new variables have been identified in this monitoring program, which reaches about magnitude 23.

2.5 Globular Clusters

Pilachowski, J. Casperson, and undergraduate student E. Freeland, with C. Sneden (UT Austin), have determined carbon isotope ratios in three giants in the globular cluster M3 from high dispersion infrared spectra obtained at the Keck Observatory, and in a fourth M3 giant observed with the Phoenix infrared spectrometer on NOAO's Mayall 4-m Telescope at Kitt Peak National Observatory. Abundances of iron, silicon, and titanium were also derived for the three stars with NIRSPEC data. The derived atomic abundances are consistent with values in the literature for these stars. While three of the giants have isotope ratios of approximately 6, typical of globular cluster giants, the carbon isotope ratio in the lithium-rich giant IV-101 is approximately 11, higher than what is found in most other globular cluster giants of similar temperature. The Li and carbon isotope ratio of IV-101 is consistent with a recent suggestion of anomalously energetic hydrogen shell fusion and mixing events in low mass, low metallicity stars on the first-ascent red giant branch.

A. Saha (NOAO) and Pilachowski are conducting a Baade-Wesselink analysis of 29 RR Lyrae variables in the globular cluster M3 with velocities from moderate resolution spectra taken with the Hydra multi-fiber spectrograph on the 3.5-meter WIYN telescope. Light curves in the Gunn *uvgr* system were obtained with the Kitt Peak 0.9-meter telescope.

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 Pilachowski's 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), Pilachowski 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, Pilachowski has accumulated spectra of more than 700 giants in more than a dozen globular clusters to survey lithium, H α 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 $\log(\text{Li}) = 2.3$. 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 ^7Be , which decays to ^7Li , through mixing induced by differential internal rotation.

Cohn, Lugger, and Slavin continued a program to study globular cluster dynamical evolution using the Indiana University GRAPE-4 and GRAPE-6 N-body supercomputers. Indiana University's Information Technology Services has provided strong support for this program through the acquisition and maintenance of GRAPE-6 and MD-GRAPE2 systems. The Indiana GRAPE work has concentrated on the effect of hard binaries on the global evolution of clusters through core collapse.

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. Recent results from this program include the following.

(1) 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 (Cohn, Lugger, *et al.* 2002). 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.

(2) A study of the population of ≥ 100 Chandra X-ray sources in the luminous, high-metallicity globular cluster 47 Tuc (Grindlay et al. 2002). Analysis of the spatial distribution of the 44 soft-spectrum sources indicates that these are consistent with having a typical mass in the range $1.1 - 1.4M_{\odot}$, which includes the canonical neutron star mass. The distribution of 16 radio millisecond pulsars, which are also identified as Chandra sources, is entirely consistent with that of the soft-spectrum sources. Substantial allocations of Chandra time (300 ksec) and HST time (9 orbits) have been made for follow-up observations to constrain the complete CV and millisecond pulsar populations in 47 Tuc.

(3) A 50 ksec Cycle 3 Chandra ACIS-S observation has been obtained of the collapsed-core globular cluster M30 (=NGC 7099). Analysis of this imaging indicates the presence of at least four discrete low-luminosity ($L_x < 10^{33} \text{ erg s}^{-1}$) sources, all located within $12''$ of the dynamical center of the cluster (Cohn, Lugger, et al. 2002, BAAS, 200, 10.02). The innermost two of these sources lie within 1.4 of the cluster center, which places them within the very small upper limit on the core radius that has been established by HST-based studies. Candidate optical identifications have been obtained for the outermost two sources, using archival HST imaging. These objects appear consistent with being cataclysmic variables. The soft X-ray spectrum of the brightest central source and its luminosity, which is higher than that of most cataclysmic variables, suggest that it may instead be a quiescent low-mass X-ray binary.

2.6 Galactic Astronomy

Lugger and Cohn with graduate students Rogel and Slavin are participating in the ChaMPlane survey, which is being carried out by a group 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 $H\alpha$, R , V , and I using the mosaic cameras on the CTIO and KPNO 4m telescopes. Objects are selected for spectroscopic follow-up based on Chandra detection and/or $H\alpha$ excess. WIYN/Hydra spectroscopy was obtained for 8 northern hemisphere ChaMPlane fields during the past two years, producing spectra for $\sim 50 - 70$ objects per field (Lugger, Cohn, et al. 2002, BAAS, 200, 58.03). It is generally possible to classify objects to a limiting magnitude of $R \sim 21 - 22$. The classified objects in-

clude two CVs (detected through $H\alpha$ excess), a large number of M stars (about half of which are dMe type), and about 30 quasars with redshift z ranging up to 4.2.

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. HI synthesis maps have been obtained with the Very Large Array for 4 blue compact dwarf galaxies and 5 quiescent dwarf galaxies in order 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.

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. In the last year, stellar rotation curves were obtained for 3 starbursting dwarf galaxies with the Gemini North 8-meter telescope; when combined with a sample previously observed with the CTIO 4-meter, the total data set consists of 13 spatially resolved stellar rotation curves. These observations 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. In the last year, observations of 8 dwarf elliptical galaxies were obtained with the Palomar 5-meter telescope. In contrast to the previously published results for dwarf elliptical galaxies, at least half of the 16 galaxies in our total sample have clear evidence of rotational support throughout the stellar component.

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.

van Zee, Caspersen, and D. Schade (HIA) have initiated a large imaging survey with the WIYN 0.9m telescope. The primary goal of the SMUDGES (Systematic Multiwavelength Unbiased catalog of Dwarf Galaxies and Evolution of Structure) survey is to determine the fraction of dwarf galaxies that undergo a starburst phase. Imaging surveys, with appropriate spectroscopic follow-up, are an efficient method to identify and catalog galaxies with a range of star formation properties. The SMUDGES survey will be the first with both the depth and volume to identify a statistically significant sample of dwarf galaxies that is unbiased by the current star formation activity in each galaxy. The large, complete catalog of galaxies will provide an excellent resource for both the planned dwarf galaxy studies and other statistical analyses of galaxy evolution.

R. Berrington (Naval Research Labs), Lugger, and Cohn (2002) presented an analysis of the dynamics of the galaxy cluster A2256, based on photometric and spectroscopic observations with the WIYN Telescope. This cluster has been noted to have complex structure in the X-ray which correlates with optical evidence for an ongoing merger event. A deep R-band WIYN image mosaic was used for the photometry and the Hydra multi-object spectrograph was used to obtain velocities for 236 galaxies, bringing the total sample to 319 with the addition of previously determined velocities. An extensive statistical analysis provides strong support for the finding that two major galaxy groups are undergoing a merger in A2256. In addition, the greatly increased sample size provides evidence for the existence of a third subcluster, on the outer reaches of the system, that is just now beginning to merge into A2256.

2.8 High Energy Astrophysics

Mufson, J.L. Miller (James Madison U.), and A. Habig (U.MN, Duluth) have finished their studies using MACRO. Their final results appear in papers on the Compton-Getting Effect (Sidereal and Solar Diurnal Waves), point sources of astrophysical muons, and the diffuse neutrino flux from AGN.

The Indiana HEAP group has joined the SNAP experiment (SuperNova Acceleration Probe), a satellite experiment that seeks to confirm the acceleration of the universal expansion and to explore the nature of the dark energy that is driving this acceleration. The launch is currently scheduled for 2008.

2.9 Miscellaneous

Edmondson was appointed for a three year term, starting July 2001, on the Executive Committee of The Friends of the Center for the History of Physics. Much of the work of the Committee is done by telephone, e-mail, and FedEx. The Committee met at the AIP Headquarters on April 5, 2002 to discuss the start of a campaign to raise an endowment (“His-

tory that Matters”) for the Center. Edmondson’s AAS Treasurer archives had recently been transferred to the Center. They had been organized into 47 manuscript boxes, 23.5 linear feet of shelf space, and were described in a 16 page finding list. The AIP Governing Board and the Officers of AIP Member Societies were also meeting that day. Indiana University was well represented in the latter meeting by Caty Pilachowski, Arlo Landolt, and Bob Milkey. A reception celebrating the 40th anniversary of the Niels Bohr Library and dinner with the AIP Governing Board ended the day.

During this year, the Department initiated a new NSF-funded Research Experience for Undergraduates (REU) site program in Astronomy, bringing six undergraduate students participants from around the country. Students spent 10 weeks on campus over the summer, carrying out research projects with faculty members Honeycutt, Deliyannis, and Pilachowski. The IU program offered the students a special emphasis on stellar astronomy. Indiana University’s program is one of more than a dozen programs nation-wide, and one of the first such programs in the Midwest. All of the students visited Kitt Peak in June or July to participate in observing runs on the WIYN 3.5-m and 0.9-m telescopes. These visits to Tucson also included additional activities such as a visit to the University of Arizona to learn about graduate school or to visit the Steward Observatory Mirror Lab.

Mark Pitts, a senior from Ohio State University, and Luis Mercado, a junior from Indiana University Bloomington, worked with Honeycutt to derive light curves of cataclysmic variables from Roboscope data obtained from the department’s 16” telescope at the Morgan-Monroe Station of the Goethe Link Observatories. After deriving the light curves, the students worked to interpret the data to understand the nature of the light variations.

Heather Jacobson, a senior from the University of Texas at Austin, and Jeffrey Cummings, a junior from the University of Rochester, worked with Deliyannis to derive distances, ages, reddenings, and metallicities for open star clusters in the direction of the Galactic anti-center using data obtained on the WIYN 0.9-m telescope on Kitt Peak. Students reduced UBVR images of three clusters, M36, M37, and M38, to obtain precise magnitudes and colors, and then compared the resulting color-color and color-magnitude diagrams to theoretical isochrones to derive the stellar parameters.

TalaWanda Monroe, a senior from Western Kentucky University, and Stacy Sidle, a junior from Rhodes College in Tennessee, worked with Pilachowski to study the chemical compositions of stars with planets. The students used very high resolution, high S/N spectra obtained with the coude-feed telescope at Kitt Peak to measure the strengths of spectral lines of various atomic species. The measurements were combined with atomic line data and model atmospheres to obtain chemical abundances. The students were also able to measure lithium abundances in the stars using spectral synthesis.

During July 10-11, Site Directors from REU programs in astronomy around the country met in Bloomington for two days of discussion. The meeting was hosted by the Indiana University Astronomy Department, and sponsored by the

National Science Foundation through a grant. In addition to the Site Directors from 15 programs, the meeting was attended by NSF/REU Program Officer Dr. Kathy DeGioia-Eastwood and by Dr. Eileen Friel of the NSF Astronomy Division. Each site presented a brief summary of its program and discussed the unique aspects of each program. Common elements include a focus on the research experience of the students, observatory visits, written or web-based project reports, and student presentations. All sites also shared a desire to reach underserved populations, especially underrepresented minority students. During the meeting, the Site Directors agreed on a common date for offers to be made, and to request that students reply to offers. Student stipends and housing costs were also compared among programs with the goal of equalizing student “take-home pay.”

A series of graduate seminars on the activities of professional astronomers in the astronomical community was held during the Spring 2002 semester. The seminars covered such topics as the role of professional societies, scholarly publishing, teaching, public outreach, the NSF and NASA, and the federal research budget. The goal of the series was first to inform our students about the many aspects of being a professional astronomer that are not covered in their normal course work, and second to foster in our students an appreciation of the value of service to the community. Seminars by visiting astronomers included presentations by Dr. Eileen Friel of the National Science Foundation, on the topic of NSF support of astronomy and opportunities for students; Dr. Brian Pickett of Purdue University Calumet, on public outreach and his experience with the ASP’s Project Astro; Dr. Steven Shore of Indiana University South Bend, on scholarly publishing and the refereeing process for the astronomical literature; Dr. Kevin Marvel of the American Astronomical Society, on federal science funding and the federal budget cycle; and Dr. Guenter Riegler of NASA, on the role of astronomers in government. The seminar series was reported in a paper in *Astronomy Education Review* (<http://aer.noao.edu>).

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