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, 1996 through August, 1997 inclusive.

1. INTRODUCTION

The Astronomy Faculty at Indiana University consisted of Professors: Haldan N. Cohn, Richard H. Durisen, R. Kent Honeycutt, Phyllis M. Lugger, and Stuart L. Mufson (Chair); Associate Professor: Martin S. Burkhead; Assistant Professor: Michael J. Pierce; and Professors Emeriti: Frank K. Edmondson and Hollis R. Johnson. Other department members included Postdoctoral Fellows: Gordon Drukier, Jeanette L. Miller, and Jeffrey W. Robertson; Visiting Research Associate: Craig Wood. Assistant Professor Constantine P. Deliyannis joined the faculty in August, 1997, and R. Kent Honeycutt became the Chairman effective July 1, 1997. Brice R. Adams, William R. Kopp, Richard LeBeau, and George W. Turner were members of our technical staff; Cathy N. Chamberlin and Brenda S. Records were the secretarial staff. Graduate Students in the Department during the year were: Robert C. Berrington, David H. Bush, Todd C. Hillwig, Thomas D. Hunt, John Jurcevic, Robert Link, Adam W. Rengstorf, Shawn D. Slavin, Aaron J.B. Steinhauer, Daniel J. Swearingen, and Robin M. Tripoli.

The High Energy Astrophysics group at Indiana University is an interdepartmental (Astronomy and Physics) research group with faculty: R.M. Heinz (Physics), J. Musser (Physics), S.L. Mufson (Astronomy); Senior Scientist: C. Bower; Postdoctoral Fellows: R. Hatcher and J.L. Miller; Graduate Students: A. Hawthorne and A. Bhattacharyya. M. Gebhard and G.W. Turner were staff members; C.N. Chamberlin, B.S. Records, and J. Williams provided secretarial support.

The Bachelor of Science Degree in Astronomy and Astrophysics was received by Jennifer J. Hoffman, Annie C. Mejia, Lynn D. Neakrase, Heather M. Pickett, and Michael S. Walworth. The Master of Arts Degree in Astronomy was received by Robert C. Berrington, Shawn D. Slavin, Daniel J. Swearingen, and Robin M. Tripoli.

2. RESEARCH

2.1 Instrumentation and Facilities

SpectraBot, a new 1.25m telescope at a site 16 miles north of campus, is nearing completion under the general direction of Honeycutt. The mirror mounts and the control system for this f/8 Cassegrain telescope are being constructed in-house. The control system is completed and undergoing tests and the mirror mounts are awaiting optics delivery, expected November, 1997. The primary and secondary mirrors are lightweight borosilicate honeycomb design, and the secondary mirror mount incorporates an active tip-tilt motion for optical alignment and for the eventual incorporation of image motion compensation. The telescope and observatory systems are being designed to support long-term synoptic spectroscopy and photometry of time-variable sources, using unattended automation techniques that have been developed and used on the companion 0.41m telescope, RoboScope, at this site. A radio modem was installed to support higher speed data communications between campus and the RoboScope/SpectraBot site. By placing the antennas on a tower at the obervatory and on a high building on campus, a near-line-of-sight link is available for this 900 Mhz spread spectrum signal, and 56KB data rates are now regularly available.

Through an interdisciplinary collaboration involving 15 co-investigators from seven departments with cost-sharing by various administrative units, Indiana University obtained a grant from the NSF Academic Research Infrastructure Program of the Computer and Information Science and Engineering Directorate to acquire an advanced multiple-processor computer and visualization facility. The collaboration is called the Scientific Applications on Arrays of Multiple Processors (SCAAMP) Project. The SCAAMP Co-I.'s include four members of the Department of Astronomy faculty (Cohn, Durisen, Lugger, and Pierce) representing three distinct research projects (star and galaxy cluster modeling, constraints on cosmological parameters from gravitational lenses, and gravitational instabilities in protostellar disks). An SGI Origin 2000 system with two 32 processor supermodules plus 4 developmental processors was purchased and delivered in Spring, 1997. The Origin system has a total shared memory of 16.5 Gigabytes and a peak collective speed of about 25 Gigaflops. In Fall, 1997, a Computer Automated Virtual Environment or CAVE was purchased for use in visualization of scientific results.

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. This experiment is a joint Italian-American collaboration designed to search for GUT monopoles and other fractionally charged superstring particles and for astrophysical sources of muons and high energy neutrinos. In addition, MACRO continues its search for the neutrino signal from Type II supernovae in our Galaxy and will alert observatories around the world if 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^2sr) is now complete. It is expected that the detector will operate until the year 2000.

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. These 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. In 1998, a redesigned experiment will be flown from Ft. Sumner to measure the abundance of low energy cosmic ray antiprotons.

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 Kamioka 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. This experiment is approved and construction is expected to begin in 1999.

The Fermilab experiment COSMOS is a search for the oscillation of muon neutrinos into tau neutrinos. This ‘appearance’ experiment will take place in the astrophysically interesting neutrino mass region of 1-30 eV. There is a great deal of evidence that a significant fraction (90%-99%) of the matter in the universe is ‘‘dark,’’ although the composition of this dark matter is unknown. A leading candidate for this hot dark matter is a neutrino with a nonzero mass. Cosmological arguments set the interesting neutrino mass scale at 1-30 eV. COSMOS is an approved Fermilab experiment designed to search for neutrinos in this mass range. Both MINOS and COSMOS share the same neutrino beam and will turn on at the turn of the century.

2.2 Solar System

With support from NASA’s Cassini Mission, Durisen coordinated a collaboration to observe the Sun’s crossing of Saturn’s ring plane in November, 1995 with the 3.5m WIYN telescope. Members of the team included Honeycutt, Jurcevic, and Tripoli from Indiana and L. Dones and M.R. Showalter from NASA-Ames Research Center. The five-night observing run produced about 200 images of Saturn’s rings and moons in B, V, R, I, and the 8900 Å methane absorption band. Many images recorded seeing of 0.6-0.7 arcseconds FWHM. A movie made from images taken in the methane band and other preliminary analyses and sample images can be viewed at http://www.astro.indiana.edu/personnel/durisen/. The dataset is unique in its combination of orbital coverage and sensitivity for detecting small moons in the outer satellite system. If one assumes that small moons have albedos similar to those of known Saturnian moons, no new moons with radii down to about 3 km, correponding to a limiting R magnitude of about 21.5, were detected over the orbital radius range of 3 to 23 Saturn radii. The orbit longitude completeness is about 80% over 4 to 15 Saturn radii. Preliminary studies also indicate that the data will be useful for E Ring photometry. Durisen and G.E. Morfill (Max Planck Institute for Extraterrestrial Physics) are continuing their collaboration to evaluate formation scenarios for chondritic meteorites based on constraints set by laboratory studies which have shown that the thicknesses of fine-grained chondrule accretion mantles are proportional to the chondrule core radii. Analytic models for chondrule growth show that a natural way to account for this trend is to have the chondrules deplete the dust over a localized volume in the time between chondrule formation and parent body formation. This presents some difficulties for scenarios in which chondrules are formed far from the site of parent body formation. To refine understanding of the chondrule rim/core relation, Durisen and Turner produced power-law fits to published data and confirmed that a nearly linear relation is favored.

Durisen is continuing his research on ballistic transport (BT) in planetary rings. BT is the net transport of mass and angular momentum due to exchanges of ejecta from hypervelocity meteoroid impacts onto ring particles. Earlier analytic and numerical work has shown that BT can explain the production and maintenance of features near the inner-edges of the A and B Rings, including the edges themselves. Simulations published to date follow model inner-edge regions for about 100 characteristic times, long enough to show that the features can be produced, but not long enough to span the ring system lifetime. A faster algorithm for BT simulations has been in development for several years. Durisen, Tripoli, and I.U. undergraduate major H. Pickett have now fine-tuned the fast algorithm to a considerable degree. For some parameter ranges, they can now obtain excellent agreement with the older, slower code in simulations of up to 500-1,000 characteristic times but with about 100 times fewer computations per time step. Qualitatively new behaviors have already been discovered which, through comparisons with observed ring features, increasingly constrain the uncertain input physics. Future work with the new code will include more realistic treatments of ring opacity, kinematic viscosity, and ejecta distribution functions for meteoroid impacts. Collaborations will continue with J.N. Cuzzi and E. Asphaug (NASA-Ames Research Center) on efforts to characterize the ejecta from both disruptive and nondisruptive hypervelocity impacts. The inclusion of disruptive impacts and of ring opacity is likely to be critical for understanding the effects of BT on Saturn’s rings.

Honeycutt participated in a study of Comet Hyakutake using the WIYN telescope for imaging with high time resolution and angular resolution near closest approach. Two arc-shaped molecular resonance emission features were found in these images. The morphology of these features suggests that an extended region of icy grains surrounds the nucleus and contributes significantly to the production of volatiles.

2.3 Stars

Durisen and B.K. Pickett (NASA-Ames Research Center), together with J.N. Imamura and J. Toman (U. Oregon), have completed linear analyses of rotating polytropic equilibrium objects identical to the protostars studied earlier with a nonlinear 3D hydrodynamics code. A variety of linear techniques were used, including the tensor virial equations, a Lagrangian Variational Principle (LVP), and an initial value problem (IVP) approach utilizing hydrodynamic equations linearized about the equilibrium state. The best linear regime results for dynamic instabilities are obtained with the IVP; and, for secular instabilities, with the LVP. For a range of fluid compressibilities and rotation laws (angular momentum distributions), the linear and nonlinear results for dynamic two and three-armed Kelvin mode instabilities are in remarkable quantitative agreement. The two-armed barlike instability sets in for $T/|W| \gtrsim 0.26$, where T is the total rotational K.E. and W is the total gravitational P.E., a remarkably general result. However, for extreme flattening and angular momentum distributions, the agreement between the linear and nonlinear calculations is not as good. In particular, the IVP does not seem to confirm a one-armed instability detected in the nonlinear calculations. Work is continuing on efforts to treat the more extreme cases at higher resolution. Visit http://cosmic.arc.nasa.gov:8082/~pickett/ for diagrams, images, animations, and other information. Durisen and co-workers are continuing research on the structure and stability of rapidly rotating protostellar cores and protostellar disks. Pickett, Durisen, and Link have extended earlier work by Durisen and S. Yang (JPL) on equilibrium models for protostellar cores that would form from the collapse of centrally condensed initial clouds. In particular, the equilibrium objects that form from the collapse of singular isothermal spheres are star/disk systems with massive rotationally-supported disks and with distinct pressure-supported central stars. The disk vertical structure and the star/disk boundary are fully resolved. Numerical models of these objects can be computed for disks up to several Astronomical Units (A.U.'s) in size. Sequences of the star/disk systems with increasing size represent an evolutionary sequence and can readily be connected to realistic initial cloud conditions. The self-consistent-field equilibrium code used by Pickett, Durisen, and Link effectively forces the assumption that these star/disk models consist of isentropic ideal gas, with an adiabat representative of the starlike regions. As a result, the disks tend to be unrealistically hot and thick. Pickett, P. Cassen (NASA-Ames Research Center), and Durisen have developed a technique for cooling the disks of these models in an axisymmetric version of Pickett's hydrodynamics code. The specific entropy along cylinders about the rotation axis is kept uniform but is decreased quasistatically until some target Toomre Q stability parameter is attained. One particular star/disk model with $Q \approx 1.5$ has been used as a starting condition for 3D hydrodynamic stability studies. The disk is small (outer radius smaller than Mercury's orbital semimajor axis) and massive (disk mass about 40 to 50% of the total system mass $\sim 0.5 M_{\odot}$) and, with $Q \approx 1.5$, has realistic temperatures. The recent discovery of massive substellar companions orbiting close ($\lesssim$ A.U.) to solar-type stars has increased interest in the stability of such small, massive protostellar disks.

Several 3D simulations have been completed using different assumptions about thermal equilibium in the disk, including locally isentropic and locally isothermal behavior, in order to test the sensitivity of gravitational instabilities to thermal energetics. In both cases, the instabilities begin in the star/disk boundary region and stimulate the growth of three and four-armed Kelvin modes in the star and inner disk. A global two-armed mode grows more slowly in the disk region but eventually dominates the system evolution. The combined action of these instabilities is that a nonlinear pulse of mass and angular momentum transport works outward through the disk. In the isentropic case, the growth of all modes eventually saturates at modest amplitude leading to steady-state transport; in the isothermal case, the disk structure is radically altered, with the development of extremely slender, dense spiral arms and arclets. Indiana's new SGI Origin 2000 is now being used to study these systems at higher resolution over longer times. The long-term goals are to introduce more realistic treatments of thermal equilibrium, to probe the conditions, if any, under which disks will fragment, and to characterize the long-term effects of gravitational instabilities. To view some animations of results to date and for links to related Web sites, visit http://www.astro.indiana.edu/scaamp/projects/.

Durisen, Jurcevic, Honeycutt, M.F. Sterzik (Max Planck Institute for Extraterrestrial Physics), and W. Brandner (U. Illinois & U. Würzburg) completed their binary frequency study of ROSAT-selected X-ray sources south of the Taurus star forming region (SFR). R-band images for 99 optical counterparts of ROSAT All-Sky Survey sources were obtained under excellent seeing conditions (0.5 to 0.6 arcseconds) with the WIYN 3.5m telescope. The binary frequency for the young stars in the sample over the detectable separation range is consistent with that for solar-type main sequence stars placed at the Taurus distance. Durisen and Sterzik are continuing their systematic study of the decay of nonhierarchical few-body systems. The primary application of this work is to the young stellar object few-body systems which are likely to form through the collapse and fragmentation of interstellar clouds. This research is motivated in part by modern hydrodynamical collapse and fragmentation calculations and in part by the observations of some X-ray selected T Tauri stars quite far from known SFR's. One possibility is that these are ''runaway'' T Tauri stars (RATTS) ejected dynamically with large speeds ($\gtrsim$ 5 km/s) from decaying few-body systems of young stars. Durisen and Sterzik have now produced N-body simulations which follow the complete decay of such systems and where the effects of a realistic initial mass function (IMF) are included. Initial conditions are constrained according to known properties of molecular cloud cores and to available results of hydrodynamic collapses. For $N = 3D5$, about 2/3 of the systems decay fully into binaries, and the number of high-speed ($\gtrsim$ 5 km/s) ejections is quite large ($\sim$ 20-25% of the stars). However, dynamical biasing causes preferential ejection of the lowest mass stars included in the IMF. So the vast majority of RATTS are likely to be low-mass stars or brown dwarfs. At the same time, the heavier remnants (mostly binaries and stable triples) receive a substantial recoil $\sim$ 2 km/s which adds stochastically to the random motions of their parental clouds, enhancing their diffusion rate out of their SFR. With collaborator Pickett, Durisen and Sterzik are also using their few-body decay results to produce kinematic models of SFR's dominated by few-body fragmentation. The RoboScope long-term photometry of cataclysmic variables (CV's) is being used by Honeycutt, Robertson, and Turner to perform observational tests of the predicted dependence of accretion disk structure on mean mass transfer rate from the secondary star. High $\dot{M}$ systems such as old nova and nova-like CV's are expected to be stable against thermal instabilities in the accretion disk, such as those seen in dwarf novae outbursts. Nevertheless, the RoboScope data shows that significant numbers of nova-likes have outbursts that resemble those in dwarf novae, except that the amplitudes are smaller. VY Scl CV's undergo low states in which the accretion turns off for a period of time. During slow transitions between states these systems may be subject to dwarf nova outbursts. RoboScope has been monitoring a number of VY Scl stars to search for such effects, with mixed results. Outbursting-like events are seen during some slow transitions, but the data are too sparce at present to attribute these to thermal instabilities in the disk. Z Cam stars have intervals of steady disk brightness interleaved with intervals of dwarf nova outbursts. These systems should have a larger mean brightness when steady, reflecting the higher $\dot{M}$ needed for disk stability. Using both RoboScope and AAVSO data, Honeycutt and J. Mattei (AAVSO) have found that, in general, these expections are confirmed for 5 Z Cam systems. If we assume that the outbursts seen in nova-likes are mass transfer events, then the overall conclusion is that long-term CV photometry generally supports accretion disk limit cycle theory.

Robertson, Honeycutt, and Hillwig have used the WIYN telescope for both photometric and spectroscopic studies of specific CV's. Orbit-resolved spectroscopy of V794 Aql, SS UMi, V630 Cas, and PG 1000+667 has been obtained to find the orbital period and to study the structure (kinematics and excitation) of the accretion disks. PG 1000+667 was found by RoboScope to be a new VY Scl star. WIYN spectroscopy gives a period of 3^h 28^m, placing the system just above the period gap where all other VY Scl stars reside.

WIYN multiple-object spectroscopy and multi-color imaging by Robertson, Honeycutt, Hillwig, and Jurcevic has been used to recover 7 old novae whose identifications were missing or uncertain. Determining the rate of brightness decline long past nova outburst bears on the relationship among CV variability types and the possible transformation from nova-like to dwarf nova as $\dot{M}$ declines after the nova explosion. Some of these new recoveries are quite old nova and therefore important for such studies. V446 Her (Nova Her 1960) has been recently found to have regular dwarf nova outbursts, so that at least one recent nova now has an $\dot{M}$ low enough for the accretion disk instability to operate.

Deliyannis together with A. Boesgaard (U. Hawaii), A. Stephens (U. Hawaii), J. King (STScI), S. Vogt (Lick Obs.), and M. Keane (CTIO) presented lithium and beryllium observations in field F stars that clearly identify the physical mechanism responsible for creating the Boesgaard Li gap. It has been known for over a decade that Hyades F stars have severely depleted their Li abundances (the ''Li gap''), in sharp contrast to the predictions of the standard stellar evolution theory. Several alternate explanations for this Li gap have been proposed, including mass loss, diffusion, and different forms of slow mixing such as wave-driven mixing and rotationally-induced mixing of various kinds. Following the suggestion by Deliyannis & Pinsonneault that the surface Be abundance leaves a different signature for each class of mechanism, and particularly that stars like 110 Her (below) may be the smoking gun of the responsible mechanism, a Li and Be survey was begun aimed at identifying the physical mechanism that creates the Li gap. The first results of that survey were presented, which includes high resolution (R =3D 48,000 – 120,000) and high S/N observations in 24 stars of the Li I 6707.8 Å and/or the Be II 3131 Å doublets taken at UH 2.2m, CFH 3.6m, and Keck I 10m telescopes. The Li and Be depletion pattern in the star 110 Her is not unique; the program stars with detections in both Li and Be define a clear trend which suggests (1) the surface Li and Be abundances are depleted simultaneously and (2) surface Li diminishes more rapidly than surface Be. The remaining program stars (with upper limits in Li or in both Li and Be) are fully consistent with this trend. The results suggest that simultaneous Li and Be depletion is a normal process that F 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 surface light element deficiencies. Moreover, models with rotationally-induced mixing are in better agreement with the data than models with wave-driven mixing. These conclusions also support the idea that rotationally-induced mixing has depleted the Li abundances in halo dwarfs from a higher primordial Li abundance, with implications for testing and interpreting models of big bang nucleosynthesis. Work is ongoing to present results from the remainder of the survey.

Deliyannis, in collaboration with King, Boesgaard, Stephens, and others, continues to obtain Li, Fe, and O data in several open clusters using the WIYN 3.5m telescope with the Hydra multi-fiber spectrograph in echelle mode. This combination allows unprecedented efficiency in studying sufficiently large numbers of stars in enough open clusters to address interesting astrophysical problems. The purposes of this program include using Li as a probe of stellar structure and studying the chemical history of the Galaxy. Li has been observed in over 120 stars in the old open cluster M67, which has a similar age and metallicity as the Sun. Preliminary analysis of Li near the turnoff in this cluster argues against both diffusion and mass loss as the mechanism responsible for the Boesgaard Li gap and supports slow mixing. This is in agreement with the completely independent Li-Be data described above. Cooler dwarfs suggest that the Sun is not extremely abnormal (and may be entirely normal) in its Li depletion; in any case, these dwarfs are much more depleted than those in younger (and more metal-rich) clusters such as the Hyades, suggesting that Li depletion occurs during the main sequence. This is in sharp contrast to the expectations of standard stellar evolution theory and suggests that additional mechanisms are required, such as rotationally-induced mixing. A similar result is obtained from observations in NGC 752. To address these and other issues, a key goal is to map out the evolution of the morphology of the Li-T_{eff} relation in clusters of different ages and metallicity. Additional issues include the following. The timing of when the Boesgaard gap forms and its dependence on metallicity will yield further clues as to its origin. The evolution of the open cluster Li plateau will yield insights into whether or not Galactic Li production has occurred, with implications for the primordial big bang Li abundance.

2.4 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 estimates for the primordial big bang abundance. In collaboration with Boesgaard, Stephens, and King, results in M92 have been published and observations in M13 and M71 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 with the Argus multi-object spectrograph in echelle mode for about 40 stars in NGC 6397. Analysis is ongoing and will include other southern clusters in the future. Like the previous clusters, NGC 6397 also shows a scatter in Li at the same T_{eff}. Furthermore, stars past the turnoff agree remarkably well with field halo stars in that both sets of stars: a) establish a Li plateau near the turnoff, b) experience subgiant Li dilution by about a factor of 10 – 20 near T_{eff} =3D 5400 K, c) establish a diluted plateau from T_{eff} =3D 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.

Dull completed a Ph.D. dissertation on modeling globular clusters under the direction of Cohn and Lugger. As part of this work, they presented a new determination of the central velocity dispersion profile of the collapsed-core cluster M15 based on high-resolution, long-slit spectroscopy. They also developed a new set of Fokker-Planck models to fit these data. The models predict the presence of a few times 10^4 degenerate remnants with masses exceeding about 1 $M_\odot$, of which a few times 10^3 are likely to be neutron stars. B. Murphy (Butler Univ.), Cohn, Lugger, and Drukier have developed a refined set of 20-mass-group Fokker-Planck models to fit the most current data sets for M15, including HST Faint Object Camera star counts from Sosin & King and the newly determined velocity dispersion profile from WIYN observations. Lugger, Cohn, Drukier, Slavin, and Murphy continued a program to use the WIYN telescope to study the global dynamics of globular clusters. The Hydra multi-object spectrograph is used to obtain high-accuracy stellar velocities over a radial range extending from the inner arc minute to the tidal radius. During the past year, an efficient method was developed for selecting likely cluster members using Washington system photometry. A large, 4-color mosaic was obtained for M92 in May, 1997. Follow-up WIYN-Hydra spectroscopy in June, 1997 indicated that 75% of the stars selected from the color-color diagram are cluster members. To date, velocities have been determined with a median accuracy of 0.3 km/s for 230 members of the collapsed-core cluster M15 and 300 members of the normal-core cluster M92. This group developed a new Bayesian technique for determining cluster velocity dispersion profiles from stellar velocity data sets and reported results for M15. These indicate a striking flattening and possible upturn of the velocity dispersion profile in the outer region of the cluster ($r > 5'$). This finding provides evidence for tidal heating of the cluster halo by the galactic tidal field. Lugger, Cohn, and Slavin continued their participation in a collaboration with J. Grindlay (Harvard), C. Bailyn (Yale), and A. Cool (San Francisco State) to search for cataclysmic variables (CV's) in globular clusters using HST. Planetary Camera images of collapsed-core globular clusters in UBVRI and Hα are used to identify candidate CV's. They discovered two Hα excess CV candidates in the relatively nearby cluster NGC 6752. HST Faint Object Spectrograph observations of the nearby cluster NGC 6397 have yielded a fourth CV and another interesting blue star that lies between the main sequence and the white dwarf cooling curve. Cohn, Lugger, Slavin, and Grindlay have continued the analysis of their WFPC2 UBV imaging of the centers of the collapsed-core clusters NGC 6284 and NGC 6293. A striking finding of this work is the detection of substantial, centrally concentrated blue straggler populations in both clusters. The typical blue straggler mass, estimated from the spatial distribution of these stars relative to that of giants, is about twice the turnoff mass, *i.e.*, about 1.5 $M_\odot$. Artificial star experiments are now underway to assess completeness and photometric accuracy. Cohn and Lugger continued their participation in a collaboration with I. King & C. Sosin (UC Berkeley), Cool, Bailyn, and Grindlay to study the distribution of stars in the central region of NGC 6397. Cohn and Lugger have recently developed 20-group Fokker-Planck models for this cluster that reasonably reproduce the behavior of the observed mass functions, surface density profile, and velocity dispersion profile. The quality of the fit substantially exceeds that of standard multi-mass King models. The Fokker-Planck model fits suggest that significant tidal mass loss has occurred in the outer regions of NGC 6397. Drukier, Cohn, and Lugger carried out a program to refine and extend a two-dimensional Fokker-Planck code for simulating star cluster evolution. This code follows the stellar orbital angular momentum distribution as well as the stellar orbital energy distribution. Thus, it is possible to observe the development of velocity-space anisotropy in both the expanding halo of a cluster and in the inner region during core collapse. An investigation of long-term, post-collapse evolution has been carried out with this new code. An important goal of this work is to produce an accurate simulation of an *isolated* cluster, in order to provide a benchmark against which to compare simulations of clusters subject to the perturbative effects of the galactic tidal field. Drukier has continued the development of a non-parametric method for correcting observed luminosity functions for incompleteness and photometric uncertainties.

2.5 Galaxies and Cosmology

S. Ryan (R. Greenwich O.) and Deliyannis continued their study of Li depletion in halo stars cooler than the Spite Li plateau. Understanding whether or not the plateau itself is depleted (from a higher primordial big bang value) requires that we first understand how these cooler stars are depleted (see also sections on Stars and on Globular Clusters, above). 26 stars were observed with the CTIO 4m, AAT 3.6m, and Keck I 10m telescopes. These metal-poor stars are generally cooler than the Spite plateau, where Li destruction (in dwarfs) and dilution (in subgiants) is expected. Iron abundances were also measured from the spectra. The dwarfs show steep depletion of Li by about 0.27 dex per 100 K over the interval 5000 K $< T_{eff} <$ 5500 K. Even stars at 5700 K show systematically lower abundances than hotter plateau stars. Depletion is slightly greater than predicted by a subset of 16.5 Gyr Yale ‘‘standard’’ (nondiffusive, nonrotating, nonmagnetic, no–mass–loss) models at 5400 K, by perhaps 0.3 dex, but is in reasonable agreement with those models at 5000 K. A more quantitative comparison requires that age and metallicity effects be considered. Despite the shallower slope of the observations over this temperature range, depletion becomes a much steeper function of temperature cooler than this, as judged by the nondetection of Li in stars cooler than 4800 K, consistent with the models. Other models may also be acceptable. The subgiants conform to dilution patterns previously revealed for this class, with the exception of two stars cooler than 5000 K for which other mechanisms are believed responsible.

As part of his Ph.D. dissertation, under the supervision of Lugger and Cohn, Berrington continued an investigation of the dynamical evolution of galaxy clusters. High-resolution, *N*-body simulations have been carried out on the Indiana University Intel Paragon massively parallel supercomputer. These simulations are now being ported to the new Indiana University SCAAMP facility. The focus of this work is the simulation of the mergers of poor clusters of galaxies that are believed to result in the development of rich clusters. Berrington, Lugger, and Cohn have continued 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 being 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 approximately 200 galaxies in A2256. A71, A104, A154, and A2271 have also been observed. Musser, Mufson, Honeycutt, and Rengstorff, in collaboration with Yale, are involved with the QUEST project. A major goal of this project is to collect a sample of gravitationally lensed quasars between one and two orders of magnitude larger than the present world sample, and to do this with uniform and carefully controlled experimental efficiencies. With this sample of gravitational lenses we plan to make a sensitive search for Einstein’s Cosmological Constant. =09 Pierce has continued investigating the intrinsic dispersion in the fundamental plane of elliptical galaxies and the precision of $D_n - \sigma$ relations for measuring distances. The multiplex advantage offered by the multi-fiber spectrograph at WIYN (Hydra) allows data to be obtained on as many as 60 galaxies at a time. The spectroscopic data are taken at 0.5 Å/pix and have a velocity resolution of 50 km/sec. A signal-to-noise ratio of about 50 can be achieved in nearby clusters within 4 hours, enabling velocity dispersions to be measured to a precision of 10 km/sec. Dispersions have been obtained for over 100 galaxies within both the Coma Cluster and Abell 2199. Data for about 50 members of the Perseus Cluster have also been acquired. The $D_n - \sigma$ and distance-velocity relations for Coma show a ‘‘ridge-line’’ with a scatter of only 6% in distance with strong evidence for a foreground group superimposed upon the core of the cluster. The group appears located at the ‘‘turn-around’’ radius of the cluster. This interpretation would imply that the intrinsic precision of the $D_n - \sigma$ relation is considerably higher than has been generally believed. Efforts are underway to test this interpretation by observing additional nearby clusters as well as more distant samples where ‘‘line-of-sight depth’’ should be minimal. Data have been acquired for about 40 galaxies in Abell 98 (z =3D 0.105). Cumulative exposures of 14 hours were required to reach a signal-to-noise comparable to that in the nearby clusters. Imaging data was acquired is sub-arcsec seeing (some of the images have FWHM =3D 0.4−0.5 arcsec). The r.m.s. scatter in the $D_n - \sigma$ relation is found to be only 6% in distance implying that the precision is indeed high and that the Coma sample probably suffers from contamination. With such a precise distance indicator it becomes possible to determine redshift-independent distances for clusters to very high precision. Efforts are underway to use this technique to establish the local distance scale and provide a high-precision measure of the Hubble Constant. The feasibility of using this technique to constrain Ω is also being investigated. Integral-field spectroscopy of a subset of about 25 members of Coma and about 15 members of the Virgo Cluster have also been obtained at WIYN using ‘‘Dense-Pak.’’ Dense-Pak consists of a 7x14 array of closely-packed fibers which are 3 arcsec in diameter. By spatial resampling, the velocity dispersions of nearby galaxies can be measured over comparable spatial scales as more distant systems and thereby avoid any systematic errors which might arise from the use of a fixed-sized slit/fiber. The data are currently being reduced, and we hope to make this database available to the community in the coming year.

Tying the high-precision relative distances produced via this technique to the Virgo Cluster will enable these results to be placed upon an absolute scale and hence enable a high-precision measurement of the Hubble Constant. Pierce and collaborators are using deep, I-band HST imaging of a nucleated dwarf elliptical (dE) in the Virgo Cluster. The tip of the red giant branch (TRGB) is a standard candle in the I-band, provided that [Fe/H] $<$ -0.7. This is essentially a modern version of Baade’s now classic result for M31. Multi-color surface photometry (U,B,V,R,I) obtained at WIYN imply an [Fe/H] =3D -1.2 for the dE using the calibration of Galactic globular clusters. The co-added HST data (12 full-orbit exposures) easily reaches the TRGB, and a luminosity function has been obtained using ALLFRAME/DAOPHOT. Maximum likelihood fits are in progress, and we expect to soon have a distance to Virgo that is independent of the Cepheid distance scale. In addition to simply being a check of the Key Project results, this technique should provide a higher-precision distance to Virgo given that the dE’s in Virgo are more strongly concentrated to the core of the cluster than are the spirals. That is, the line-of-sight depth within the dE population should be minimal. Link and Pierce have completed the initial phase of their investigation into the use of gravitational lens systems with multiple giant arcs as a means of determining cosmological parameters. The recent purchase of a 68-processor SGI Origin 2000 machine by the SCAAMP collaboration has enabled extensive testing of the methodology using simulated lens systems constructed from galaxy images in the Hubble Deep Field. The method works by exploiting the fact that sources over a considerable range of redshift can be imaged by the same potential. This allows the effects of the lensing mass distribution and the cosmology to be separated, and the parameters used to simulate the data can be recovered. The only input data required are an image of the system at HST resolution and the redshifts for about 4 arcs. Monte-Carlo simulations have been completed which imply that redshift errors are the dominant source of uncertainty in the method and suggest that Ω can be measured to within about 10% using this approach. Simulations using more complicated (*i.e.*, nonanalytic) lensing potentials computed from N-body simulations are currently under investigation. Although the method has yet to be applied to a real gravitational lens system, it shows strong promise for constraining cosmological parameters, provided that a sufficient number of arc redshifts can be determined (about 4 or 5) and sufficient care is taken in modeling the details of the lensing potential.

2.6 High Energy Astrophysics

Mufson, Miller, and A. Habig (Boston University) 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 June, 1997. 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. 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 at the 95% C.L.

A high quality subset of the muon data was searched for evidence of seasonal variations in muon rate. This effect was found to be present in the data over a period of 4 years and to be correlated with atmospheric temperature. Essentially, a higher underground muon rate is observed during the warmer summer months and a lower rate is observed during the cooler winter months. The MACRO muon data have also been searched for a deficit of muons in the direction of the moon. The detection of the ''moon shadow'' is important for the verification of the accuracy of MACRO's absolute pointing and the determination of its angular resolution. With a sample of 31 million muons, the moon shadow was detected at a significance level of 4.1 σ with an angular resolution of 0.9 degrees.

The MACRO muon data is being analyzed for the ''sidereal anisotropy'' that would result from the solar system motion through a sea of extragalactic cosmic rays, an effect first predicted by Compton and Getting. Preliminary results suggest a sidereal anisotropy is present with an amplitude of approximately 0.1%, although the direction of the anisotropy is uncertain. If the direction is not toward the solar apex, then alternative explanations for the effect must be developed.

The MACRO data are currently 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.

The balloon flight program of the High Energy Astrophysics group is currently involved with the HEAT (High Energy Antimatter Telescope) experiment. This experiment was designed to analyze the cosmic ray positron spectrum in the range 5-50 Gev. The first HEAT flight took place in May, 1994 from Ft. Sumner, NM, and the second in August, 1995 from Alberta. Future flights in this series are planned to measure the abundance of low energy cosmic ray antiprotons.

2.7 Miscellaneous

In October, 1996, Durisen received an Alexander von Humboldt Research Award for Senior U.S. Scientists to pursue research at Max Planck Institute for Extraterrestrial Phyiscs in Munich, Germany. The award will permit visits totaling twelve months over the next five years.

After an unexpected delay by the printer, Edmondson's book *AURA and its US National Observatories* was published by the Cambridge University Press on March 6, 1997. The total number of pages is 385 (xviii + 367), of which 83 are the References are two Appendices, and 14 are the Index. He autographed 15 copies at the Winston-Salem Meeting and 125 for AURA at the Corporate Office in May. His future plans include revision of a 1989 draft of a paper, ''The Ford Foundation and the European Southern Observatory,'' for the Journal for the History of Astronomy and continuing work on Daniel Kirkwood and the history of the Indiana University Department of Astronomy.

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