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This report covers research activities in the Department of Astronomy and the High Energy Astrophysics group for the period September 1998 through August 1999 inclusive.

1. INTRODUCTION

The Astronomy Faculty at Indiana University consisted of Professors: Haldan N. Cohn, Richard H. Durisen, R. Kent Honeycutt (Chair), Phyllis M. Lugger, and Stuart L. Mufson; Assistant Professors: Constantine P. Deliyannis and Michael J. Pierce; and Professors Emeriti: Martin S. Burkhead, Frank K. Edmondson, and Hollis R. Johnson. Other department members included Postdoctoral Fellows: Robert Link; Visiting Research Scholars: Patricia Rosenzweig, and Tae S. Yoon; and Research Associate: Thomas Y. Steiman-Cameron. Brice R. Adams, William R. Kopp, Richard LeBeau, and George W. Turner were members of the technical staff; Cathy N. Chamberlin and Brenda S. Records were the office staff. Graduate Students in the Department during the year were: Robert C. Berrington, Kai Cai, David L. Herrick, Todd C. Hillwig, John Jurcevic, Styliani K. Kafka, Robert Link, Steven J. Margheim, Annie C. Mejia, Brian J. Rebel, Adam W. Rengstorf, Allen B. Rogel, Shawn D. Slavin, and Aaron J.B. Steinhauer.

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

The Bachelor of Science Degree in Astronomy and Astrophysics was received by Dominic W. Holt. The Doctor of Philosophy Degree in Astronomy was received by Robert Link.

1.1 Instrumentation and Facilities

Work has continued by Honeycutt on the instrumentation for the new 1.25-m Indiana telescope, for which we are awaiting delivery of the re-figured optics. To avoid instrument changes on this automated telescope a number of functions have been incorporated in a single instrument, FIGS, which stands for Fiber-feed/Imager/Guider/Spectrograph. FIGS has a CCD imager, a CCD guider, a fiber feed to a bench-mounted echelle spectrograph, and a specialized high-thruput H-alpha spectrograph.

Honeycutt and Hillwig constructed and installed a Barlow lens assembly for the WIYN telescope to allow the WIYN DensePak to better sample WIYN images. This instrument is being used by Hillwig to study the kinematic structure of nova shells.

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 astrophysical sources of muons and high energy neutrinos. In addition, MACRO continues its search for the neutrino signal from Type II supernovae in our Galaxy and will alert observatories around the world if one is detected. Further, MACRO is investigating the composition of cosmic rays in the range of 10^{15}-10^{16} eV/nucleon. The full detector (10,000 m^2 sr) is now complete. It is expected that the detector will operate until the year 2000.

The High Energy Astrophysics group is now involved in an effort to expand the experimental reach of neutrino oscillation parameter space to include the region that best accounts for the peculiar atmospheric neutrino results obtained by the SuperK experiment in Japan. This experiment, called MINOS, will study muon neutrinos that have been directed to northern Minnesota from Fermilab. The experiment will explore the neutrino mass region below 1 eV^2. Neutrinos in this mass range would account for some fraction of the non-baryonic dark matter in the universe as well as hot dark matter postulated to explain large scale structure. This experiment is approved and construction is expected to begin in 1999. MINOS will turn on in late 2002.

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

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 and maintain an advanced multiple-processor computer and visualization facility. The collaboration is called Scientific Applications on Arrays of Multiple Processors (SCAAMP). The SCAAMP Co-I.'s include four members of the Department of Astronomy faculty representing three distinct research projects – star and galaxy cluster modeling (Cohn/Lugger), constraints on cosmological parameters from gravitational lenses (Pierce), and gravitational instabilities in protostellar disks (Durisen). The SCAAMP facility now consists of an SGI Origin 2000 system with two 32 processor supermodules plus 4 developmental processors with a total shared memory of 16.5 Gigabytes and a peak collective speed of about 25 Gigaflops. A Computer Automated Virtual Environment (or CAVE) is also available for visualization of scientific results.

1.2 Solar System

Durisen, B.K. Pickett (Valparaiso U.), and G.R. Stewart (U. Colorado) are studying the protolunar debris belt produced around the early Earth by an impact with another protoplanet. Nonaxisymmetric hydrodynamic instabilities in the belt may assist in making the Moon by transporting a lunar mass or more of material beyond the Roche limit. A. Cameron (Havard U.) has supplied Stewart with the endstate data from his giant impact simulations. Pickett and Durisen have constructed a fluid equilibrium model for the Earth with an equatorial belt which matches the mass and angular momentum distribution of Cameron's data. 3D hydrodynamics simulations with these initial conditions do show strong nonaxisymmetric instabilities. Some involve self-gravity, while others seem to be driven by the high shear between the Earth and the belt. The self-gravitating modes couple the debris belt to the deep Earth interior. Preliminary results were reported at the Monterey Workshop on the Origin of the Earth and the Moon in November, 1998. The group is currently assessing angular momentum transport rates. If these are promisingly large, more realistic treatments of the debris belt equation of state (EOS) will be pursued.

Work on a faster numerical algorithm to simulate ballistic transport in planetary rings has been completed by Durisen and coworkers. Ballistic transport is the net transport of mass and angular momentum due to exchanges of ejecta from hypervelocity meteoroid impacts onto ring particles. Earlier papers by his group have shown that this mechanism can explain the production and maintenance of features seen near the inner-edges of Saturn's A and B Rings, including the edges themselves. However, simulations published to date do not follow model inner-edge regions long enough to span a plausible ring system lifetime. Calculations with the new code that go ten times further than the published ones exhibit qualitatively new behaviors. Durisen and Herrick are beginning a collaboration to use the new code to study effects of ring opacity, an improved treatment of kinematic viscosity, and ejecta from disruptive meteoroid impacts.

As part of their larger collaboration to study protostellar disks (see the Stars section below), Durisen, B.K. Pickett (Valparaiso U.), P. Cassen (NASA-Ames), Mejia, and Link (now at U. Virginia) are conducting numerical experiments to test the idea, recently revived by A. Boss (Cagnegie Inst. Washington), that gas giant planets might form directly by gravitational instabilities in protostellar disks. Using the new star/disk models being generated by Mejia, this group is running simulations which mimic conditions studied by Boss for which he claims to see formation of bound clumps with Jovian masses. So far, under extreme conditions, dynamic instabilities do seem to form clumps, but they are transient and do not persist long enough to become independent entities.

1.3 Stars

Durisen, J.N. Imamura (U. Oregon), and B.K. Pickett (Valparaiso U.) extended their study of dynamic barlike instabilities in rotating polytropic stars to the nonlinear regime through comparison of torques computed using linear eigenfunctions and torques measured in nonlinear 3D hydro simulations. The analysis shows that dynamic growth of the barlike modes saturates when the torques become strong enough to transport angular momentum outward as fast as the mode is growing. For polytropic index $n = 5/2$, corresponding to isentropic molecular hydrogen, the models could be interpreted as ''first equilibrium cores'' formed during the protostellar collapse of a rotating interstellar cloud (ISC). For this n, the Imamura *et al.* analysis does confirm the large increase in central density due to the bar instability reported by M. Bate (Cambridge U.) in simulations of interstellar cloud collapses.

In a large collaboration, dubbed the ''Which Bar Project,'' this same group, in conjunction with M. Bate (Cambridge U.), A. Brandtl (MPE), and M.F. Sterzik (ESO), are completing a comprehensive multi-code study of a particular polytrope with a dynamically unstable barlike mode. State-of-the-art grid-based and SPH hydrodynamic codes are being used at the highest practical resolution to determine the effects of different assumptions about shock dissipation and heating on the outcome of the instability. The purpose is two-fold: to learn more about the physics of a fundamental astrophysical instability and to learn more about the limitations of various numerical schemes when treating dynamic stability problems.

Imamura, Durisen, Pickett, and Mejia are also extending the barlike mode studies to an entirely new regime – the equilibrium states called ''fizzlers'' that have densities between those of white dwarfs and neutron stars. At these intermediate densities, a spherical star would be unstable to collapse due to the softness of the equation of state. But, since the 70's, it has been known that rotation can stabilize these objects against collapse. They then become susceptible to secular (GRR time scale) and dynamic (free-fall time) instabilities of nonaxisymmetric modes. When the iron core of a massive star collapses with finite angular momentum, a supernova event caused by collapse to neutron star density can be substantially delayed or prevented altogether, hence the term ''fizzlers.'' Interest in these hypothetical states has been hightened by LIGO and by observational evidence that some black holes produced by massive stars have very high rotation rates. A realistic equation of state has been introduced into the group's linear codes and will, during the next year, be added to the nonlinear 3D hydro code in order to study the behavior of the barlike modes which are likely to determine the ultimate fate of a fizzler. Such events should produce unique gravitational radiation signatures, so their occurrence may be directly detected in the foreseeable future.

Pickett, Durisen, Mejia, Link, P. Cassen (NASA-Ames), Imamura, and D. Woolum (Cal State Fullerton) are continuing their research on gravitational instabilities in massive, rotationally-supported disks around young stars using both linear analyses and 3D hydrodynamic simulations. This work is multi-faceted. Its unique aspects are that a hydrodynamically active star can be and usually is included in our calculations, that artificial boundary conditions are avoided, and that the vertical structure of the disk is resolved in 3D. In addition to projects already mentioned in the Solar System section above, this work includes the following: 1.) comparisons of gravitational instabilities in star/disk systems using simple idealized assumptions about disk heating and cooling which span plausible physical extremes, 2.) simulations of externally forced spiral waves in disks to develop improved treatments of shock dissipation, 3.) implementation of a more realistic equation of state to determine the effects of major phase transitions on the behavior of instabilities in the nonlinear regime, 4.) introduction of progressively more realistic treatments of energy loss through cooling and transport. A major advance for all these projects has modification of the code used to produce initial equilibrium models by Mejia and Link. They are now able to create 2D, self-gravitating, equilibrium ''designer'' star/disk models with prescribed star/disk mass ratios (down to 10:1 so far), aspect ratios (up to 1:40 so far), surface density distributions, and temperature distributions. Mejia, Pickett, and Durisen are now working on ways to carve the star out of the model to improve the Courant time step in the 3D hydro code for studies where the star/disk interface and hydrodynamic response of the star are not considered important.

One particular star/disk model with Toomre $Q \approx 1.5$ over the disk has been studied extensively by this group with 3D hydrodynamic simulations. The disk is small (with an outer radius smaller than Mercury's orbital semimajor axis) and massive (disk mass about 40 to 50% of the total system mass $\sim 0.5 M_{\odot}$). The recent discovery of massive substellar companions orbiting close ($x \lesssim$ A.U.) to solar-type stars has increased interest in the stability of such small, massive protostellar disks which may exist during the earliest stages of star formation. The nonlinear behavior of instabilities depends critically on the thermal energetics of the disk. With assumptions equivalent to rapid energy loss through cooling, the disk fragments into dense arclets with substantial transport of mass and angular momentum. On the other extreme, with shock heating and no cooling, the instablities are weak. The disk heats up after only modest restructuring, and the instabilities die out. The long-term goals for all star/disk projects are 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/.

In the course of constructing few-body systems with realistic mass distributions for numerical studies of few-body system decay, Durisen and M.F. Sterzik (ESO) found that a two-step selection of stellar masses seemed capable of matching the observed IMF while simultaneously giving distributions of binary properties among the decay products which agree with observations. The two steps involve picking a total mass based on some protostellar cloud mass spectrum and then constraining the sum of the component masses, chosen from another spectrum, to be equal to the selected cloud mass. Durisen, Pickett, and Sterzik are completing a further statistical analysis of this process and find that the two-step process improves the binary characteristics by as much as does dissipation due to disk collisions, as proposed by other researchers.

X-ray selected wTTS (weak-line T Tauri stars) show coronal emission which is several orders of magnitude greater than that of the Sun. Some of these objects are highly variable and exhibit X-ray outbursts which resemble solar flares but are of much larger scale. In August, 1998, simultaneous multi-wavelength observations were made of a field in Taurus containing several wTTS and also cTTS (classical T Tauri stars) known for their pronounced X-ray emission and/or variability. WIYN and several other ground-based telescopes were used for optical spectroscopy and photometry. Radio and X-ray observations were made by the VLA and ROSAT, respectively. The collaboration included Durisen and Hillwig from IU and E. Guenther (Tautenburg), R. Neuhäuser (MPE), and B. Stelzer (MPE). No flare was detected simultaneously by any two facilities, due in part to difficulties operating the aging ROSAT spacecraft. However, there were some simultaneous observations of variable behavior and observations in close temporal proximity. One unexpected result was that cTTS exhibit all the same X-ray and optical flare-like behaviors that wTTS do. Analyses are almost complete and being prepared for publication.

Honeycutt and collaborators continued to work on cataclysmic variable stars and related topics. The long-term photometric monitoring program of CVs and AGNs using the automated 0.41-cm telescope (RoboScope) has continued, but at a lower level than in previous years. Kafka and Honeycutt are analyzing the 8-year RoboScope light curve of QQ Vul, a polar that whose transitions between one-pole and two-pole accretion can be characterized from this photometry. Yoon and Honeycutt have studied the long-term RoboScope light curve of the symbiotic variable PU Vul, paying particular attention to recent 200-day oscillations likely due to the Mira component. Rosenzweig, Mattei (AAVSO), Kafka, and Honeycutt are analyzing the normal and super outbursts in SU UMa, using AAVSO and RoboScope data. Hillwig is doing WIYN DensePak spectroscopy of nova shells for a kinematic study of shell morphology and also doing a photometric period search in certain old novae and central stars of planetary nebulae, seeking to understand better the effect of stellar duplicity in shaping ejection shells.

Deliyannis, King (UNLV), Kunha (Observatório Nacional, Brazil), and Boesgaard (U. Hawaii) have used red (S/N $\sim$ 1,000 per pixel) and ultraviolet (S/N$\gtrsim$ 100 per pixel) Keck/HIRES spectra ($R \sim 45{,}000 = 3$ pixels) to derive the iron (Fe) and beryllium (Be) abundances in each of the solar twins 16 Cyg A and B. Self-consistent spectroscopic solutions yield, for 16 Cyg A and B, respectively, $T_{\rm eff} = 5795 \pm 20$ K and 5760 ± 20 K, $\log g = 4.30 \pm 0.06$ and 4.40 ± 0.06, $\xi = 1.25 \pm 0.05$ km s^{-1} and 1.12 ± 0.05 km s^{-1}, and [Fe/H]$= +0.04 \pm 0.02$ and $+ 0.06 \pm 0.02$. If Fe is used as a surrogate for metallicity, this represents an average metallicity of $11 \pm 5\%$ above solar. These are in excellent agreement with other recent studies of this (wide) binary. Whereas it can be argued that no single study is conclusive, the consistent findings of these various studies offer compelling evidence that these stars have just barely super-solar metallicity, that A is just hotter than the Sun, and that B is just cooler. These authors have previously reported (based on Keck/HIRES data) a difference in the Li abundances of these stars of at least a factor of 4.5; for A they detected a Li abundance a factor of $\sim$ 2 *above* solar, and for B they placed a conservative upper limit a factor of $\sim$ 3 *below* solar. They detect Be in both stars and find that, if there is any difference between them, it must be much smaller– conservatively no more than 0.2 dex. Evidence suggests that solar-type stars deplete their surface Li abundance during the main sequence, a feat that the standard stellar evolution theory has, thus far, been unable to accomplish. Whatever physical mechanism depletes the surface Li abundance must create far less of a spread in the Be abundances than it does in the Li abundances. They find that their Li and Be results are consistent with the predictions of Yale models that include rotationally-induced mixing driven by angular momentum loss. The results provide no evidence for a small ($\sim$ 0.05 dex) enhancement in the ^{9}Be abundance of the A component relative to the B component expected if the stars' Li abundance difference was due to accretion of planetary material by the A component. Given the errors, however, neither are they able to firmly preclude such a signature.

The chemically peculiar stars which inhabit the upper main sequence exhibit very extreme enhancements and deficiencies of several, seemingly unrelated, elements. Radiatively-driven diffusion is, most likely, the primary cause of these anomalies, although other mechanisms may also be important, such as mass loss and various kinds of mixing. Only by examining as many elements as possible will a cohesive theory explaining these abundance oddities materialize. To this end, A. Stephens (U. Hawaii) and Deliyannis studied high resolution (R 62,5000 2.5 pixels) low noise (S/N 120 per pixel) spectra of the region containing the Li I 6708 resonance doublet, taken at the University of Hawaii 2.2m telescope and Coude spectrograph, of two Hg-Mn stars (HR 6158 & HR 8915) whose atmospheres contain an inordinate amount of beryllium (Be). While the LTE concentration of Be is several thousand times larger than cosmic (A(Be) 1.27) in both stars, lithium (Li) is detected in neither HR 6158 nor HR 8915 at the 3 sigma (99upper limits place the maximum Li enhancements at 50 times and 80$\times$ cosmic (A(Li) 3.23) for HR 6158 and HR 8915, respectively, or at least 100 times smaller than the Be overabundances. These novel observations of a hitherto unobserved nuclide, a) argue against a nuclear origin for the Be overabundance since that would create an observable Li abundance as well, and b) provide yet another means of constraining the internal stellar physical process (or processes) responsible for the Hg-Mn phenomenon in hot, A stars.

A. Boesgaard (U. Hawaii), J. King (STScI), Deliyannis, and S. Vogt (U. California/Santa Cruz) studied the evolution of oxygen (the third most abundant element after hydrogen and helium) in our Galaxy. The determination of the abundance of oxygen (O) is important in our understanding of mass-spectrum of previous generations of stars, the evolution of the Galaxy, stellar evolution, and the age-metallicity relation. O was measured in 24 unevolved stars with Keck I HIRES observations of the OH lines in the ultraviolet spectral region at a resolution of 45,000 (=3 pixels) and typical S/N = 60 - 110 per pixel. Very special care was taken in determining the stellar parameters in a consistent way, using two different (plausible) temperature scales. The O abundance from OH was computed by spectrum synthesis techniques for all 24 stars plus the Sun, for which a Keck spectrum of the daytime sky was used. In addition, O abundances from the O I triplet were determined with the same stellar parameters and the published equivalent widths of the three O I lines from six sources. The comparison of data analyzed with the same, consistently-determined, parameter sets show generally excellent agreement in the O abundances; differences in the origin of the models (not the parameters) may result in abundance differences of 0.07 to 0.11 dex. It was shown that the O abundances from OH and O I are reliable and independent. Averaging the two has the great benefit of neutralizing uncertainties in the parameters since OH and O I strengths depend on Teff and log g in opposite directions. For these cool, unevolved stars it was found that O is enhanced relative to Fe with a completely linear relation between [O/H] and [Fe/H] over three orders of magnitude, with very little scatter. Taking the errors into account, the following relation is found: [O/H] = 0.66 (+/- 0.02) [Fe/H] + 0.05 (+/- 0.04). The O abundances from 76 disk stars of Edvardsson *et al.* (1993) have a measured slope of 0.66 (identical to our halo dwarf stars) and fit this relationship smoothly. The relation between [O/Fe] and [Fe/H] is robustly linear and shows no sign of a break at metallicities between -1.0 and -2.0, as has been discussed by others. At low metallicities, [Fe/H] $<$ -3.0, [O/Fe] $>$ +1.0. This fit is [O/Fe] = -0.35 (+/-0.03) [Fe/H] + 0.03 (+/-0.05). The enrichment of O is probably still from massive stars and Type II supernovae; however, the absence of a break in [O/Fe] vs [Fe/H] runs counter to traditional galactic evolution models, and the interplay of supernovae Type II's and Type Ia's in the production of O and Fe should be re-examined. It appears that either Fe or O can be used as a chronometer.

Using the same Keck I HIRES spectra just described, A. Boesgaard (U. Hawaii), Deliyannis, J. King (STScI), S. Ryan (AAO,RGO), S. Vogt (U. California/Santa Cruz) and T. Beers (Michigan State) studied the evolution of beryllium (Be) in the Galaxy, to enhance our understanding of the chemical evolution of the Galaxy, cosmic ray theory, and cosmology. The Be abundances were found, a) from the measured equivalent width of the relatively unblended Be II line at 3131.065 A with an analysis that included 11 weak atomic and molecular lines near that wavelength, and b) from spectrum synthesis which included newly-derived enhanced O (relative to Fe), as discussed above, in the synthesis calculations. The two methods are in excellent agreement. The following straight-line fits were found: logN(Be/H) =0.96(+/-0.04)[Fe/H] - 10.59(+/-0.03), and logN(Be/H) =1.45(+/-0.04)[O/H] - 10.69(+/-0.04). While it would seem that Fe and Be increase at the same rate, Be increases faster than does O. Traditional models where energetic cosmic rays interact with ambient CNO nuclei in the interstellar medium to produce Be, are consistent with this finding, as long as certain chemical evolution effects (such as mass outflow from the halo) are taken into account. However, models predicting a linear relationship between Be and O, such as those producing Be in the vicinity of Type II supernovae, are less consistent with this result. There is still no evidence of a primordial Be plateau down to logN(Be/H) = -13.5.

Using Keck I HIRES spectra in the ultraviolet spectral region at a resolution of 45,000 (=3 pixels) and typical S/N = 60 - 110 per pixel, J. Crawford (U. Texas), C. Sneden (U. Texas), J. King (STScI), A. Boesgaard (U. Hawaii), and Deliyannis studied the evolution of silver (Ag) in the Galaxy. Very special care was taken in determining the stellar parameters in a consistent way, using two different (plausible) temperature scales. The resonance lines of neutral Ag near 3280 and 3382 A were identified in halo stars with metallicities -1.3 >= [Fe/H] ⟩= -2.3. This represents the first detection in metal-poor stars of an element in the atomic number range 41 <= Z <= 55. The mean relative silver abundance is ⟨[Ag/Fe]⟩ +0.2, with little star-to-star variation. Silver abundance upper limits in other metal-poor stars are consistent with this mean value. The modest overabundance of silver is similar to the overabundances in this metallicity range exhibited by other neutron-capture elements whose primary nucleosynthesis origin is the r-process (such as europium and dysprosium).

Standard stellar evolution predicts that late F stars should have essentially retained their initial surface lithium (Li) abundance because their convection zones are too shallow to destroy it at their base. Yet observations reveal Li depletions, sometimes quite severe (the ‘‘Li gap’’). Several physical mechanisms, which are not usually included in stellar evolution calculations, have been proposed to account for the Li depletions. These mechanisms include mass loss, microscopic diffusion, and various types of slow mixing driven by either waves or rotation. Identifying which of these (if any) might really be at work not only is of vital interest to advancing our knowledge of stellar interiors but also may have serious implications in other contexts, such as in evaluating the big bang Li abundance, and its implications for testing models of big bang nucleosynthesis (BBN) and cosmology. Deliyannis and M. Pinsonneault (Ohio State) followed up on a suggestion they made earlier, and brought attention to Be observations in late F stars, proposing that such observations are crucial for discriminating between scenarios. (Be survives to about twice the depth that Li survives in.) It was argued that, while all proposed mechanisms can produce a Li gap, each leaves a different Be signature. In the case of mass loss, all the Li must be depleted before any measurable Be gets depleted. In the case of diffusion (for the cool side of the Li gap), Li and Be depletion occurs at similar rates. In the case of slow mixing, both Li and Be are depleted simultaneously, at a rate that depends on how the mixing is done. For example, in the models with wave-driven mixing, mixing is confined fairly close to the surface, so Li goes down much faster than Be. In the models with rotationally-induced mixing, the mixing is more extensive, so Li goes down more slowly compared to Be, though though still faster than Be. It was pointed out that the star 110 Her might be especially important: this star is depleted in Be by a factor of 5 - 10 and, yet its still contains detected Li, which is in turn depleted by a factor of 100 - 200. Such a depletion pattern requires specific circumstances; this star could very well be the smoking gun of the responsible mechanism. If 110 Her is representative, then both mass loss and diffusion are argued against, and slow mixing is strongly favored.

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

Deliyannis participated in a study led by B. E. McArthur (U. Texas) involving 15 authors to determine a parallax distance to the 13th magnitude Nova-like cataclysmic variable star RW Triangulum. This star’s period is 5.56 hours and has a K7 secondary. Past analysis of the disk and spot eclipses in B and V, together with the semiamplitude of the radial velocity curve (K1) place the star at 270 pc. Recently completed Hubble Space Telescope Fine guidance Sensor interferometric observations allow determination of the first trigonometric parallax to RW Tri. This puts the distance of RW Tri at 341.5 +38 -31, one of the most distant objects with a direct parallax measurement. This result has been compared with those from previous methods employed to estimate distances to CV’s.

1.4 WIYN Open Cluster Study (WOCS)

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

WIYN collaboration have initiated WOCS, a project dedicated to comprehensive photometric, astrometric, andspectroscopic studies of a select set of open clusters spanning the range in age and metallicity. There are two main WOCS goals: 1) comprehensive and definitive photometric, spectroscopic, and astrometric databases for new fundamental clusters, and 2) a body of investigations which address critical astrophysical problems through study of open clusters. Some subjects under active investigation within WOCS include: detailed testing of core convective overshoot and implications for stellar lifetimes; photometric monitoring of periods for study of surface angular momentum evolution; delineation of faint main sequences to test stellar evolution theory of very low mass stars; discovery of white dwarf sequences as independent dating mechanisms; abundance analyses for studies of galactic chemical evolution and primordial abundances; binary populations; stellar evolution in close binary environments; initial and present-day mass functions. The centerpiece of WOCS is the WIYN (Wisconsin-Indiana-Yale-NOAO) 3.5m telescope at Kitt Peak, although other telescopes (such as the KPNO and CTIO 09.m's) are used as supporting telescopes. WIYN's primary instruments are, 1) Hydra, a multi-object spectrograph that can observe up to 95 objects in low, medium, or even high (R 30,000) resolution mode, over a 1-degree field and 2) an imager, that takes advantage of the best seeing at Kitt Peak.

The primary WOCS interests at Indiana are photometry and spectroscopy. Open cluster photometry provides an ideal research experience for undergraduates, since they can obtain state-of-art research skills while studying fundamental astronomy with scientific goals that are within their intellectual grasp for that stage in their career. Deliyannis and students Steinhauer, Sarrazine, Hilbrich, Hall, Hainline, and Bleck-smith have been working with 0.9m (and, soon, WIYN data) of the open clusters NGC 188 (one of the oldest Galactic clusters), NGC 2420 (the nearest significantly metal-poor cluster), M35 (a very rich, nearby, Pleiades-like cluster), NGC 3532 (a very rich, nearby, cluster with age intermediate to that of the Pleiades and the Hyades), NGC 1817 (a rich, Hyades-age cluster), and NGC 6819 (a very rich cluster 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, with students 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 occuring 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 Sun normal? (is the solar Li depletion normal), 3) do cool solar-type stars deplete their Li during the main sequence, and if so, what is the physical cause?, 4) does the decline of Li with age in the Li plateau region represent Li depletion in stars, Galactic Li enrichment, or both – and how does this relate to the halo Li plateau, the Big Bang Li abundance, and Big Bang cosmology?

1.5 Globular 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. Together with A. Boesgaard (U. Hawaii), A. Stephens (U. Hawaii), and J. King), results in M92 were previously published, and observations in M13, M71 and M5 have been obtained and are being analyzed. All of the data for these clusters were taken with the Keck I 10m telescope. As was the case in M92, preliminary indications in M13 are that there exist otherwise apparently identical stars that have Li content differing by at least a factor of 2 – 3. Together with J. Thorburn (Yerkes Obs.), M. Rich (Columbia U.), E. Rubinstein (Yale U.) and J. Orocz (Penn State), data were taken at the CTIO 4m telescope + Argus multi-object spectrograph in echelle mode of about 40 stars in NGC 6397. Analysis is ongoing, and will include other southern clusters in the future. Like the previous clusters, NGC 6397 also shows a scatter in Li at the same Teff. Furthermore, stars past the turnoff agree remarkably well with field halo stars in that both sets of stars, a) establish a Li plateau near the turnoff, b) experience subgiant Li dilution by about a fcator of 10 – 20 near Teff = 5400 K, c) establish a diluted plateau from Teff = 5300 to 5000 K, and d) experience sudden and severe Li depletion with giant branch evolution past 5000 K, which is probably related to in situ giant branch mixing.

Cohn and Lugger added a GRAPE4 N-body supercomputer to the computational facilities of their research group. The GRAPE4 computation board was kindly provided by J. Makino (Tokyo Univ.) and was installed by K. Takahashi during a visit to Indiana University in Oct. 1998. The host for the GRAPE system is a DEC/Compaq Alpha 500-MHz workstation which was provided by the IU Center for Innovative Computing Applications. Work with the GRAPE system has so far concentrated on simulations of isolated clusters, with $N = 8$k stars, evolving well beyond core collapse and generating hard binaries by three-body interactions. Results from the simulations include predictions for the evolving spatial distribution of the binary population and the evolving behavior of the cluster velocity dispersion profile. Escape rates for both single stars and binaries are found to correlate with the behavior of the core. Plans for subsequent work include treatments of a primordial binary population and tidal heating of the halo.

G. Drukier (Tel Aviv Univ.), Cohn, and Lugger reported results from a benchmark anisotropic Fokker-Planck simulation of an isolated globular cluster (Drukier *et al.* 1999). Their code follows the stellar orbital angular momentum distribution, as well as the stellar orbital energy distribution, thus allowing the development of velocity-space anisotropy. An investigation of long-term, post-collapse evolution indicates that strong anisotropy develops in the outer halos of isolated clusters and that this results in much faster halo expansion than is seen in more approximate isotropic simulations. There is a strong acceleration of the halo expansion at the time of the first core collapse, indicating a close connection between the evolution of the core and outer halo. Frequent stellar encounters in the dense core rapidly boost stars to large orbital apocenter distances on highly elongated orbits. These orbits provide an efficient energy and mass transport conduit between the inner and outer regions.

Lugger, Cohn, Slavin, Drukier, and B. Murphy (Butler Univ.) continued a program to use the WIYN telescope to study the global dynamics of globular clusters. Their cluster sample now includes M13, M15, M56, and M92. The Hydra multi-object spectrograph is used to obtain several hundred high-accuracy stellar velocities, per cluster, over a radial range extending from the inner arc minute to the tidal radius. Likely cluster members are selected for spectroscopy by use of 3-color Washington photometry from large mosaics obtained with the WIYN imager. The velocity dispersion profiles of M15 and M92 show a flattening and possible upturn in the outer halos of these clusters that may provide evidence for heating by the galactic tidal field. A highly successful Hydra run in June 1999 netted velocities for 364 probable members of M13. Preliminary analysis of these data indicates: (1) a continuously decreasing velocity dispersion profile, suggesting little tidal heating and (2) evidence for radial anisotropy in the halo, consistent with results from previous proper motion studies. Thus, M13 appears to provide a reasonable approximation to an isolated cluster.

Lugger and Cohn continued their participation in a collaboration with J. Grindlay (Harvard), P. Edmonds (Harvard), A. Cool (San Francisco State), and C. Bailyn (Yale) to search for cataclysmic variables (CVs) and other X-ray binaries in globular clusters using HST and Chandra. HST WFPC2 and NICMOS images of collapsed-core globular clusters are used to identify candidate CVs based on photometric measures of hydrogen-line emission. Results from this program in the past year include: (1) analysis of HST WFPC2 photometry of the central region of the nearby collapsed-core globular cluster NGC 6397, resulting in the discovery of two more CVs and three members of a new class of non-flickering UV-excess stars (Cool *et al.* 1998), (2) analysis of HST FOS spectroscopy of two CVs in NGC 6397, supporting the conclusion that the four brightest of the CVs discovered in NGC 6397 are magnetic systems (Edmonds *et al.* 1999), (3) analysis of HST FOS spectroscopy of a non-flickering UV-excess star in NGC 6397, indicating that the star is a 0.25 $M_\odot$ helium white dwarf with a possible binary companion (Edmonds *et al.* 1999), and (4) a photometric analysis of NICMOS imaging of the very high density, obscured cluster Terzan 5, which reaches the main-sequence turnoff in a NIC1 field offset by 0.5 arcmin from the cluster center and reaches below the horizontal branch in the central NIC2 field.

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. Centrally concentrated blue straggler populations are detected 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 underway to assess completeness and photometric accuracy.

1.6 Galaxies and Cosmology

In a collaboration lead by T. Toniazzo and T. Hartquist (U. Leeds), Durisen is revisiting research on staedy-state mass-loaded accretion flows in active galactic nuclei. Earlier spherically symmetric solutions are being generalized by using the Weber-Davis model for treating the equatorial flow of a rotating magnetized wind. By reversing the sign of the radial velocity, the wind becomes an accretion flow. Confining the solution to the equatorial plane reduces the steady-state equations to ODE's. The old Durisen-Burns solutions, both with and without multiple sonic points, have been reproduced. Rotation with a weak magnetic field introduces an inner centrifugal barrier, at the size-scale where one would expect a central disk around the black hole to form. A sufficently strong magnetic field, however, can remove angular momentum from the inflowing gas and permit the accretion flow to extend all the way to the black hole. The group recognizes that treatment of this problem as 1D is a drastic oversimplification. However, it provides a quantitative measure of the magnetic field strengths necessary to affect the inflow and the size of the central accretion disk.

Pierce has continued investigating the fundamental plane of elliptical galaxies (FP) as a means for measuring distances to clusters of galaxies. The primary goal is to extend the ''local'' measures of distance out to z $\sim$ 0.1 and measure the Hubble Constant ($H_\bigcirc$) over these scales. The multiplex advantage offered by the multi-fiber spectrograph at WIYN (Hydra) allows data to be obtained for up to 60 galaxies at a time. The spectroscopic data have a signal-to-noise ratio of about 50 and a velocity resolution of 50 km/sec, enabling velocity dispersions to be measured to a precision of 10 km/sec. New I-band surface photometry has been acquired using WIYN. To date, data have been obtained for about 100 galaxies within *each* of the Coma, Perseus, and Abell 2199 clusters. The rms scatter in the FP is found to be only about 10% in distance. This is about a factor of two smaller than that found in most previous investigations and implies that much of the scatter in the FP was due to observational uncertainties in the velocity dispersions. At larger distances (z $\sim$ 0.1), data have been acquired for about 50-80 galaxies in *each* of three clusters (Abell 98, 2065, 2670). Cumulative exposures of 10-14 hours were obtained to reach a signal-to-noise comparable to that obtained in the nearby clusters. Analysis of these data is currently underway but the rms scatter in the FP of these higher redshift clusters also appears to be only about 10% in distance.

Integral-field spectroscopy of nearby elliptical galaxies has also been obtained at WIYN using ''DensePak.'' DensePak consists of a 7x14 array of closely-packed fibers which are 3 arcsec in diameter and sample a $30'' \times 45''$ region on the sky. 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. To date, data have been acquired for about 30 members of Coma Cluster and 20 members in each of the

Virgo and Fornax clusters. Analysis of this data set is currently in progress. One unexpected result has been the discovery of significant stellar streaming within the cores of luminous ellipticals. The central few arcsec of these galaxies show significant, and in some cases dramatic, deviations from the gaussian velocity fields which characterizes the larger scales in these galaxies. These deviations are essentially absent in systems with $M_B > -20.5$ and increase in both amplitude and number for more luminous systems. These stellar streaming motions are thought to be a relic signature of the growth of luminous elliptical galaxies through mergers.

Pierce and Tully (U. Hawaii) have continued their investigation of using the correlation between luminosity and rotational velocity to measure the distances to spiral galaxies. Recent HST-based and ground-based Cepheid surveys have produced distances to almost 30 galaxies suitable for calibrating the technique (aka the Tully-Fisher relation). The rms scatter of the calibrating systems is found to be only 0.2 mag, or 10% in distance. This means that the only significant sources of error remaining in the calibration are in the absolute calibration of Cepheids. A template relation was constructed from the calibrators and nearby clusters such as Ursa Major and Fornax. Less complete data is available for more distant clusters in the literature but these sample the volume out to 10,000 km/sec where the Hubble flow is much more uniform. Applying the local calibration to these more distant samples yields a value of the Hubble constant of $H_0 = 77 \pm 8$ km/s/Mpc. This result agrees well with others studies and is inconsistent with current age estimates for globular clusters assuming an inflationary cosmology with zero cosmological constant.

Jurcevic (under direction of Pierce) has completed his dissertation research of Long-Period Variables (LPVs) in nearby galaxies. These stars are significantly more luminous and more common that Cepheids and also follow a period-luminosity relation at near-infrared wavelengths. The goal of the study was to compare the distances which result from LPVs with those of Cepheids for late-type galaxies which span a broad range in luminosity and metal abundance in order to test for any systematic effects which might significantly affect either technique. The survey was based upon imaging data acquired over several years using WIYN and the KPNO 2-m telescope. The survey was restricted to 3 galaxies in the M81 group (NGCs 2366, 2403, 3031) and M101 (NGC 5457) but periods were found for well over 100 newly discovered LPVs. These data were combined with photometry of known LPVs in the Galaxy, LMC and M33 (NGC 598). The distances to these galaxies derived from LPVs agrees with those of Cepheids to within the observational uncertainties. This in turn implies that that the period-luminosity relation of LPVs is a promising new tool for measuring extragalactic distances and is comparable to Cepheids in precision.

Link (under direction of Pierce) has completed his dissertation research involving the use of gravitational lens systems with multiple giant arcs as a means of determining cosmological parameters. Simulations using a 64-processor SGI Origin 2000 machine obtained through the SCAAMP collaboration 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 imply that peculiar velocities of the background sources are the dominant source of intrinsic uncertainty in the method. The simulations suggest that Ω and λ can be measured simultaneously to within about 10% using this approach. 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. Recently redshifts have become available for a number of arcs within these lensing systems. Work is now in progress to apply this technique to real systems in order to constrain the large-scale geometry of the universe.

Musser, Mufson, Honeycutt, and Rengstorff, in collaboration with researchers at Yale U., 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, they plan to make a sensitive search for evidence of Einstein's Cosmological Constant.

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 SGI Origin 2000 system, using a parallelized tree code kindly provided by J. Dubinski (Univ. Toronto). 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 320 galaxies in A2256 and an extensive analysis of these velocities has been reported by Berrington, Lugger, and Cohn (1999). This analysis indicates that in addition to the two merging subclusters that have previously been identified, there is a third subcluster that is just now colliding with the A2256 system.

1.7 High Energy Astrophysics

Mufson, J.L. Miller (James Madison U.), and A. Habig (Boston U.) have continued their studies of the arrival directions of muons observed by MACRO. Presently they have analyzed all the muons collected from the turn-on of MACRO in February 1989 through June 1999. They have made an all-sky survey to search for point sources of astrophysical muons. The search for muons from point sources is essentially a search for exotic processes. This survey used the entire muon sample (approximately 55 million muons). In addition, a search was performed for muon excesses modulated by the orbital period of the X-ray source Cygnus X3. Further, a search was made for bursting activity from the sources Cygnus X3, Hercules X1, Mrk421, and 3C273. No sources were found in any of these searches. The MACRO data are also being searched for astrophysical point sources of high energy neutrinos using all-sky survey techniques. These neutrinos are detected as upgoing muons that result from neutrino interactions in the rock below MACRO.

The MACRO muon is being anayzed 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.

1.8 Miscellaneous

Durisen spent June through August, 1999 as an Alexander von Humboldt Senior Scientist at the Max Planck Institute for Extraterrestrial Physics in Munich, Germany. His visit was hosted by MPI Director Dr. Gregor E. Morfill.

Edmondson has written the first part of an invited paper about Daniel Kirkwood for Mercury, bringing him to Indiana University in 1856. Progress is being made in filling several archival gaps during Kirkwood's 30 years on the Indiana University Faculty and retirement years (1886-1895). Edmondson continued to serve as AURA Consultant/Historian.

Hollis R. Johnson spent the period of this report in Accra, Ghana, where he and his wife are serving as missionaries for The Church of Jesus Christ of Latter-day Saints.

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