

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 1997 through August 1998 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: Gordon Drukier, Jeanette L. Miller, and Jeffrey W. Robertson; Visiting Research Scholar: 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, Todd C. Hillwig, Thomas D. Hunt, John Jurcevic, Robert Link, Steven J. Margheim, Annie C. Mejia, John Pescott, Brian J. Rebel, Adam W. Rengstorf, Shawn D. Slavin, Aaron J.B. Steinhauer, 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), S.L. Mufson (Astronomy), J. Musser (Physics); Senior Scientist: C. Bower; Postdoctoral Fellows: R. Hatcher and J.L. Miller; Graduate Students: A. Bhattacharyya and A. Hawthorne. 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 Katharine H. Brewer, Marcus A. Christie, and Anthony W. Foster. The Doctor of Philosophy Degree in Astronomy was received by Thomas D. Hunt.

2. RESEARCH

2.1 Instrumentation and Facilities

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 (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).

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.

SpectraBot, a new 1.25-m telescope at a site 16 miles north of campus, was completed in the spring of 1998 under the general direction of Honeycutt. The facility is to be used for unattended synoptic imaging and spectroscopy, in order to sample long-time-scale phenomena whose study is impractical using conventional telescope scheduling. In the summer of 1998, SpectraBot was used for photometry of cataclysmic variable stars during the evaluation and commissioning of the telescope. It was concluded that the optics must be re-figured, and they have been recently removed for that work. Parks and Honeycutt (1998) described the novel mirror supports for SpectraBot, and Honeycutt, Robertson, & Pier (1998) discussed the echelle spectrograph for the new telescope. This spectrograph was originally installed on the WIYN telescope using a fiber-feed head designed for that purpose. This fiber-feed head is now devoted to DensePak, an integral field spectroscopy unit on WIYN described by Barden, Sawyer, & Honeycutt (1998).

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 m² sr) 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 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. 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 1999, 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 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. This experiment is approved and construction is expected to begin in 1999. MINOS will turn on in late 2002.

2.2 Solar System

Durisen, B.K. Pickett (NASA-Ames), and G.R. Stewart (U. Colorado) have begun a collaboration to study whether gravitational instabilities could have facilitated the formation of the Earth's Moon. Such instabilities are likely to occur in the circumterrestrial debris belt produced around the proto-Earth by a giant impact. Hydrodynamic simulations of giant impacts do not follow the material ejected into Earth orbit long enough to resolve the fate of the debris. Work by Durisen and Pickett on protostellar gas disks (see Section 2.3 below) shows that gravitational instabilities can transport angular momentum plus some mass outward. In the circumterrestrial debris belt, this may assist in placing enough material beyond the Roche limit to make the Moon. A. Cameron (Harvard U.) has supplied Stewart with the endstate data from his most recent giant impact simulations. Pickett and Durisen are now developing techniques to construct fluid equilibrium models which match their mass and angular momentum distributions. With such initial conditions for their 3D hydrodynamics code, Durisen and Pickett hope to determine under what conditions the debris belt might become unstable and what the consequences might be. If preliminary tests are promising, more realistic treatments of the debris belt equation of state (EOS) will be pursued.

Chondrules, which are millimeter-sized inclusions found in many meteorites, were flash heated by energetic events of unknown origin during the planetesimal building phase of Solar Nebula evolution. Laboratory studies by other researchers show that the thicknesses of the fine-grained mantles around chondrules in chondritic meteorites are proportional to the chondrule core radii. Durisen, Turner, and G.E. Morfill (Max Planck Institute for Extraterrestrial Physics [MPE]) evaluated formation scenarios for chondritic meteorites based on constraints set by the mantle-thickness systematics, under the assumption that the fine-grained rims are accretionary. A natural way to account for the trend is to have chondrules deplete the available dust over a localized volume in the time between chondrule formation and parent body formation. This favors local chondrule formation mechanisms, such as nebular shocks and lightening, with subsequent confinement to a limited volume of the Solar Nebula, rather than other popular scenarios which require formation of chondrules near the Sun followed by transport over large distances to the parent body formation region.

Durisen is completing work on a faster numerical algorithm to simulate ballistic transport in planetary rings. 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. For some parameter ranges, excellent agreement is obtained with the older, slower code, but with about 100 times fewer computations per time step. Recent calculations that go ten times further than the published ones exhibit qualitatively new behaviors. Comparisons with the observed ring features increasingly constrain 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.

2.3 Stars

Durisen, Pickett, and J.N. Imamura (U. Oregon) completed linear analyses of rotating polytropic equilibrium objects which correspond to the first and second equilibrium cores expected during protostellar collapse. For a range of plausible fluid states (such as adiabatic gases dominated by molecular or atomic hydrogen) and plausible rotation laws (e.g., collapse from a uniformly rotating, uniform density cloud), the linear and nonlinear results for dynamic two and three-armed Kelvin mode instabilities are in remarkable quantitative agreement. It is known from nonlinear calculations that the spiral character of the two-armed modes leads to outward transport of angular momentum through gravitational torques. As an extension of the published linear work, the group is using the linear eigenfunctions to predict the effects of the gravitational torques. This could be important for understanding how collapse of the "first" (molecular hydrogen) core is initiated under some conditions and may also elucidate the nature of nonaxisymmetric states possible in rotating compressible fluids.

This same group, in conjunction with M. Bate (Cambridge U.), A. Burkert (Max Planck Institute for Astronomy), A. Brandtl (MPE), and M.F. Sterzik (ESO), has embarked on a comprehensive multi-code study of one particular Kelvin-mode-unstable polytrope. 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.

Pickett, Durisen, Link, and collaborators P. Cassen (NASA-Ames) and D. Woolum (Cal Tech) are continuing their research on gravitational instabilities in massive, rotationally-supported disks around stars using both an approximate analytic treatment and 3D hydrodynamic simulations. The disk vertical structure and the star/disk boundary are fully resolved in the simulations. It is now possible for them to create numerical star/disk models with a particular targeted Toomre Q stability parameter distribution and to evolve the system under a variety of assumptions about heating, cooling, and the equation of state. 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 (with an outer radius smaller than Mercury's orbital semimajor axis) and massive (disk mass about 40 to 50% of the total system mass $\sim 0.5M_{\odot}$) 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 already been completed using different assumptions about thermal equilibrium in the disk. These calculations demonstrate that the nonlinear behavior of instabilities depends critically on thermal physics and energetics. With assumptions equivalent to rapid energy loss through cooling, the disks fragment into dense arclets with substantial transport of mass and angular momentum. With shock heating and no cooling, on the other hand, the instabilities are weak; the disk heats after only modest restructuring, and the instabilities die out. Future plans include the introduction of more realistic physics, including the molecular to atomic phase transition of hydrogen and optically thick radiative cooling. Indiana's SGI Origin 2000 will be used to study these systems at higher resolution over longer times and with this additional physics. The long-term goals 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/>.

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 few-body systems which form through the collapse and fragmentation of interstellar clouds. This research is motivated in part by the observation that many X-ray selected T Tauri stars are 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 cold spherical systems 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. Dynamical biasing causes preferential ejection of the lowest mass stars included in the IMF. So the vast majority of true RATTS are likely to be very low-mass stars or brown dwarfs. Nevertheless, the heavier remnants (mostly binaries and stable triples) and the heavy stars that are ejected as singles can have substantial mean speeds ~ 3 km/s which add stochastically to the random motions of their parental clouds, enhancing the diffusion rate out of SFR's. Sterzik and Durisen are currently extending their calculations to include systematic velocities and elongation or flattening of the initial fragment systems. With P. Kroupa (U. Heidelberg) and B. Elmegreen (TJ Watson Research Center), they will consider how few-body decay might differ in a clustered star formation environment and how the dynamics of clustered star formation might be affected by fractal distributions of the initial positions and velocities of the stars.

In the course of constructing few-body systems with realistic mass distributions, Durisen and Sterzik found that a two-step selection of stellar masses seemed to match the observed IMF rather easily. The two steps involve picking a

total system mass based on a protostellar cloud mass spectrum and then constraining the sum of the component masses, selected from another spectrum, to be equal to the selected cloud mass. The binary fractions and the mass ratio distributions for the decay products as a function of stellar mass group look promisingly realistic. Together with Pickett, they are presently exploring this further in the hopes of defining realistic choices for the mass spectra in the two-step process.

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 of much larger scale. Simultaneous multi-wavelength observations are critical for determining the location and mechanism producing the flares. Durisen and Hillwig in collaboration with R. Neuhäuser and B. Stelzer (MPE) recently completed a five night run on the WIYN telescope where MOS Hydra was used to monitor the $H\alpha$ spectral region of several known wTTS and flare stars during times when ROSAT was performing pointed observations of X-ray emission. On one night there was also some overlap with radio observations. A preliminary look suggests that several flares were detected in both the MOS Hydra and ROSAT data. A full analysis of the data will be made during the coming year.

Honeycutt, Hillwig, and Steinhauer, along with J.W. Robertson (now at Arkansas Tech), continued to work on cataclysmic variable stars (CV's) and related topics. The long-term photometric monitoring program of the automated 0.41-cm telescope (RoboScope) at Indiana University was sustained, and several kinds of interesting and unexpected photometric behaviors revealed by RoboScope were studied spectroscopically. Examples include spectroscopic studies at the WIYN Observatory for PG1000+667 (Hillwig, Robertson, & Honeycutt 1998), V794 Aql (Honeycutt & Robertson 1998), PG1114+187, X Ser, V630 Cas, and others. Other CV work included studies of high-state/low-state photometric behavior in V Sge (Robertson & Honeycutt 1997), a (negative) search for collimated jets in bright CV's (Hillwig, Livio, & Honeycutt 1998), recovery of several historical novae using WIYN spectroscopy and imaging (Robertson & Honeycutt 1998), multi-wavelength studies of short-outburst-cycle SU UMa systems (Szkody *et al.* 1997), and collaborative studies of SX LMi (Wagner *et al.* 1998) and blazars (Sillanpaa *et al.* 1997, Dietrich *et al.* 1998). Also, the best (and perhaps only) example of a historical nova that now has dwarf nova outbursts, Nova Her 1960 = V446 Her, was discovered and studied (Honeycutt *et al.* 1998).

One of the underpinnings of the limit cycle theory for dwarf nova (DN) outbursts (OB's) is the dependence of the outburst behavior on \dot{M} , the mass transfer rate from the red dwarf. Several observational tests of the \dot{M} dependence have been made using long-term CV photometry. First, do old novae and nova-likes (NL's) ever have outbursts, and if so do the OB's occur when the system is faint? Yes, OB's are sometimes present (Honeycutt, Robertson, & Turner 1998). They resemble the OB's of DN's in width and spacing, but the amplitudes are only about 0.7 mag. The occurrence of

these “stunted” OB’s is not correlated with system brightness. Second, do VY Scl stars have DN OB’s during high-state/low-state transitions? The tentative answer is yes (Honeycutt *et al.* 1998), but more and better data are needed to be sure. Third, are Z Cam stars brighter at standstill than during outbursting intervals? By fitting splines to outbursting intervals in both RoboScope and AAVSO data for five Z Cam stars, we find (with the exception of SY Cnc) that the standstills in Z Cam’s are as bright or brighter in V than the mean brightness during outbursting intervals (Honeycutt *et al.* 1998). The situation with the “stunted” OB’s in the old novae and NL’s is complicated and yet to be resolved with regard to outburst mechanism. If we assume that these “stunted” OB’s are mass transfer events, then the overall conclusion from these studies is that long-term CV photometry supports the limit cycle theory.

Steiman-Cameron continued his study of the role of gravitational instabilities in controlling the early evolution of the Solar Nebula. This work is examining in detail how gravitational instabilities manifest themselves in protostellar disks and how spiral density waves, produced by these instabilities, affect the disk’s physical and thermal structure. The goals of the research are to understand how the interactions between gravitational, rotational, and other forces determine the time-dependent configuration of the Solar Nebula and to analyze the mechanisms by which spiral density waves in the nebula lose energy and redistribute angular momentum.

Currently, Steiman-Cameron, Cassen, and G. Laughlin (UC Berkeley) are involved in a systematic study of the properties of excited low-order spiral density waves, including their propagation and dissipation, and an examination of the coupling between low and high-order modes. These results will lay the groundwork for a study of dissipation by high-order modes and an analysis of mode saturation of low-order modes mediated by high-order mode dissipation. This work will provide critical information required to solve the set of equations governing the evolution of gravitationally unstable disks.

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 ($R \approx 62,500 \approx 2.5$ pixels) low noise ($S/N \approx 120$ per pixel) spectra of the region containing the Li I 6708 resonance doublet, taken at the University of Hawaii 2.2-m 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 ($A(\text{Be}) \approx 1.27$) in both stars, lithium (Li) is detected in neither HR 6158 nor HR 8915 at the 3 sigma (99%) confidence level. The calculated upper limits place the maximum Li enhancements at 50 and 80 times cosmic ($A(\text{Li}) \approx 3.23$) 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 (UC 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 $S/N \approx 60$ -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 T_{eff} 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 $[\text{O}/\text{H}]$ and $[\text{Fe}/\text{H}]$ over three orders of magnitude, with very little scatter. Taking the errors into account, the following relation is found: $[\text{O}/\text{H}] = 0.66(\pm 0.02)[\text{Fe}/\text{H}] + 0.05(\pm 0.04)$. 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 $[\text{O}/\text{Fe}]$ and $[\text{Fe}/\text{H}]$ 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, $[\text{Fe}/\text{H}] < -3.0$, $[\text{O}/\text{Fe}] > +1.0$. This fit is $[\text{O}/\text{Fe}] = -0.35(\pm 0.03)[\text{Fe}/\text{H}] + 0.03(\pm 0.05)$. The enrichment of O is probably still from massive stars and Type II supernovae; however, the absence of a break in $[\text{O}/\text{Fe}]$ vs $[\text{Fe}/\text{H}]$ runs counter to traditional galactic evolution models, and the interplay of supernovae of Type II and Type Ia 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, Boesgaard, Deliyannis, King, S. Ryan (AAO, RGO), Vogt, 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 mea-

sured equivalent width of the relatively unblended Be II line at 3131 Angstroms 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: $\log N(\text{Be}/\text{H}) = 0.96 (\pm 0.04)[\text{Fe}/\text{H}] - 10.59 (\pm 0.03)$, and $\log N(\text{Be}/\text{H}) = 1.45 (\pm 0.04)[\text{O}/\text{H}] - 10.69 (\pm 0.04)$. 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 $\log N(\text{Be}/\text{H}) = -13.5$.

Once again using the Keck I HIRES spectra described above, J. Crawford (U. Texas), C. Sneden (U. Texas), King, Boesgaard, and Deliyannis studied the evolution of silver (Ag) in the Galaxy. The resonance lines of neutral Ag near 3280 and 3382 Angstroms were identified in halo stars with metallicities $-1.3 \geq [\text{Fe}/\text{H}] \geq -2.3$. This represents the first detection in metal-poor stars of an element in the atomic number range $41 \leq Z \leq 55$. The mean relative silver abundance $[\text{Ag}/\text{Fe}]$ is $\sim +0.2$, 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 Li abundance because their convection zones are too shallow to destroy it at their base. Yet observations reveal Li depletions, sometimes quite severe (the ‘Li gap’). Several physical mechanisms, which are not usually included in stellar evolution calculations, have been proposed to account for the Li depletions. These mechanisms include mass loss, microscopic diffusion, and various types of slow mixing driven by either waves or rotation. Identifying which of these (if any) might really be at work not only is of vital interest to advancing our knowledge of stellar interiors but also may have serious implications in other contexts, such as in evaluating the big bang Li abundance, and its implications for testing models of big bang nucleosynthesis (BBN) and cosmology. Deliyannis and M. Pinsonneault (Ohio State) followed up on a suggestion they made earlier and brought attention to Be observations in late F stars, proposing that such observations are crucial for discriminating between scenarios. Be survives to about twice the depth that Li survives. It was argued that, while all proposed mechanisms can produce a Li gap, each leaves a different Be signature. In the case of mass loss, all the Li must be depleted before any measurable Be gets depleted. In the case of diffusion (for the cool side of the Li gap), Li and Be depletion occurs at similar rates. In the case

of slow mixing, both Li and Be are depleted simultaneously, at a rate that depends on how the mixing is done. For example, in the models with wave-driven mixing, mixing is confined fairly close to the surface, so Li goes down much faster than Be. In the models with rotationally-induced mixing, the mixing is more extensive, so Li goes down more slowly compared to Be, though still faster than Be. It was pointed out that the star 110 Her might be especially important. This star is depleted in Be by a factor of 5-10 and, yet it still contains detected Li, which is in turn depleted by a factor of 100-200. Such a depletion pattern requires specific circumstances; this star could very well be the smoking gun of the responsible mechanism. If 110 Her is representative, then both mass loss and diffusion are argued against, and slow mixing is strongly favored.

Following up the original suggestion of Deliyannis and Pinsonneault, a survey was undertaken to study Li and Be abundances in solar-type stars, to ascertain how common the 110 Her phenomenon might be. Deliyannis, together with Boesgaard, A. Stephens (U. Hawaii), King, Vogt, and M. Keane (CTIO) reported first results of this survey based on Li data from the University of Hawaii 2.2-m telescope + Coude ($R \approx 80,000$) and Keck I 10-m telescope + HIRES ($R \approx 45,000$; $S/N \approx 800-1500$ per pixel), and Be data from the Canada-France-Hawaii 3.6-m telescope + Gecko ($R \approx 120,000$) 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.

The Goddard High Resolution Spectrograph on HST has been used to observe the boron (B) I region at 2497 Angstroms in a subset of the stars discussed above that are severely depleted in Li and/or Be. Boron is sturdier than either Li or Be, and thus provides complementary information. Boesgaard, Deliyannis, King, and D. Lambert (U. Texas) found a nearly constant B abundance in F and G stars. This argues against diffusion and is consistent with the above arguments against mass loss and in favor of slow mixing. Furthermore, constraints are placed on the effectiveness of mixing in layers below the Be preservation region. Six stars with $[\text{Fe}/\text{H}]$ from -0.75 to $+0.15$ have Be abundances ranging from the maximum of the sample to a factor of 4 below the maximum, yet these stars have a B/Be ratio that is constant to within ± 0.10 dex and that is close to the predictions of Galactic cosmic ray spallation of 10-15. The Be range for four stars with solar metallicity is still a factor of 2, and yet the B/Be ratio is constant to within ± 0.03 dex. These re-

sults imply that the Galactic cosmic ray production of B and Be is not uniform relative to the production of elements such as Fe by stellar nucleosynthesis.

2.4 Star Clusters

Lugger, Cohn, Drukier, Slavin, and B.W. Murphy (Butler U.) 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. Drukier *et al.* (1998) report a new determination of the outer velocity dispersion profile of M15. They observe a striking flattening and possible upturn in the outer halo ($r > 7'$). This finding provides evidence for tidal heating of the cluster halo by the galactic tidal field and is consistent with recent simulations of tidal mass loss by galactic satellites. Over 300 velocities have been obtained for M92 and 120 velocities have been obtained for M56. The analysis of the M92 data is complete and indicates that the outer velocity dispersion profile behavior is similar to that in M15. The next target for this program is M13, and a large 3-color Washington photometry mosaic of this cluster has been obtained in order to select candidate members in the halo for Hydra spectroscopy.

Lugger and Cohn 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) and other X-ray binaries in globular clusters using HST and AXAF. HST WFPC2 and NICMOS images of collapsed-core globular clusters are used to identify candidate CV's 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 a fourth CV 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 CV's in NGC 6397, supporting the conclusion that all four of the CV's discovered in NGC 6397 are magnetic systems (Edmonds *et al.* 1998), and (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.* 1998).

Cohn, Lugger, Slavin, and Grindlay have continued the analysis of their WFPC2 UB_v 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.

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 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. Murphy, 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 outer velocity dispersion profile determined from WIYN observations.

Drukier, Cohn, and Lugger reported results from a benchmark anisotropic Fokker-Planck simulation of an isolated globular cluster (Drukier *et al.* 1998). 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.

Deliyannis participated in a study led by W. van Altena (Yale U.), involving 26 authors, to determine the distance to the Hyades cluster using the Fine Guidance Sensor (FGS) 3 of the Hubble Space Telescope. Trigonometric parallax observations of seven Hyades members in six fields of view were analyzed along with their proper motions to determine the distance to the cluster. Knowledge of the convergent point and mean proper motion of the Hyades is critical to the derivation of the distance to the center of the cluster. Depending on the choice of the proper-motion system, the derived cluster center distance varies by 9%. Adopting a reference distance of 46.1 pc or $m-M = 3.32$, which is derived from the ground-based parallaxes in the General Catalogue of Trigonometric Parallaxes (1995 edition), the FK5/PPM proper-motion system yields a distance 4% larger, while the Hanson system yields a distance 2% smaller. The HST FGS parallaxes reported in this study yield either a 14% or 5% larger distance, depending on the choice of the proper-motion system. Orbital parallaxes (Torres *et al.*) yield an average distance 4% larger than the reference distance. The variation in the distance derived from the HST data illustrates the importance of the proper-motion system and the individual proper motions to the derivation of the distance to the Hyades center; therefore, a full utilization of the HST FGS parallaxes awaits the establishment of an accurate and consistent proper-motion system.

Deliyannis continues programs to study lithium Li 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 10-m 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. Oroc (Penn State), data were taken at the CTIO 4-m 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 $T_{eff} = 5400$ K, c) establish a diluted plateau from $T_{eff} = 5300$ to 5000 K, and d) experience sudden and severe Li depletion with giant branch evolution past 5000 K, which is probably related to *in situ* giant branch mixing.

2.5 Interstellar Medium

Steiman-Cameron, M. Wolfire (U. Maryland), and D. Hollenbach (NASA-Ames) are continuing a study of the physical properties of the Galaxy's interstellar medium (ISM) through analyzes of data obtained with the Cosmic Background Explorer (COBE) satellite. This effort combines detailed theoretical models of the interstellar medium (ISM) of the Milky Way Galaxy with the satellite data to develop a global model for many of the important physical characteristics of the ISM (e.g., thermal pressure of the diffuse ISM, heating/cooling rates, volume filling factors). The emphasis here is on the cold neutral, warm neutral, and warm ionized components of the ISM. Intensities and line ratios in several atomic fine-structure transitions and CO rotational transitions observed by COBE's Far Infrared Absolute Spectrophotometer (FIRAS) along with measures of the far infrared continuum radiation from COBE's Diffuse Infrared Background Experiment (DIRBE) will constrain the model. Currently, the researchers are concentrated on determining the volume emissivity of [C II] (158 μm) and [N II] (205 μm) as a function of position within the Milky Way. A side product of this work has been the development of a model for the three-dimensional geometry of the spiral structure of the Galaxy. A paper dealing with this topic is near submission.

2.6 Galaxies and Cosmology

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_0) 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" x 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 arcseconds of these galaxies show significant, and in some cases dramatic, deviations from the Gaussian velocity fields which characterizes the larger scales in these galaxies. Interestingly, these deviations appear to be much less prevalent in lower luminosity systems.

Tying the high-precision relative distances produced via this technique to the nearest clusters 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 have recently obtained 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 $[\text{Fe}/\text{H}] < -0.7$. This is essentially a modern version of Baade's now classic result for M31. Multi-color surface photometry (U,B,V,R,I) from WIYN is used to constrain $[\text{Fe}/\text{H}]$ using the calibration provided by the Galactic globular clusters. The HST data (12 full-orbit exposures) easily reaches the TRGB, and maximum likelihood fits to the luminosity function yield a distance of 15.7 ± 1.5 Mpc. This distance agrees well with recent HST Key Project results using Cepheids but is completely independent. Ultimately, the TRGB method should provide the most precise distance to the cores of the Virgo and Fornax clusters given that the dE's are more strongly concentrated than are the spirals. Efforts are currently underway to obtain similar data for additional dE's in these clusters.

Jurcevic completed his dissertation research, under the direction of Pierce, on Long-Period Variables (LPV's) in nearby galaxies. These stars are significantly more luminous and more common than 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 LPV's 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 (NGC 2366, 2403, 3031) and M101 (NGC 5457), but periods were found for well over 100 newly discovered LPV's. These data were combined with photometry of known LPV's in the Galaxy, LMC, and M33 (NGC 598). The distances to these galaxies derived from LPV's agrees with those of Cepheids to within the observational uncertainties. This in turn implies that the period-luminosity relation of LPV's is a promising new tool for measuring extragalactic distances and is comparable to Cepheids in precision.

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. 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.

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 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. 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 also continued a program to use the WIYN telescope to obtain photometric and spectro-

scopic 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. A71, A104, A154, and A2271 have also been observed.

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 2.3 Stars and 2.4 Star Clusters above). 26 stars were observed with the CTIO 4-m, AAT 3.6-m, and Keck I 10-m 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 $5000 \text{ K} < T_{eff} < 5500 \text{ K}$. 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.

2.7 High Energy Astrophysics

Mufson, Miller, 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 1998. 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 through 1995 (approximately 45 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 data have 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 ac-

curacy of MACRO's absolute pointing and the determination of its angular resolution. With a sample of 31 million moons, the Moon shadow was detected a significance level of 4.1σ ; the angular resolution is 0.9 degrees.

The MACRO moon 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 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. Data analysis is currently underway. The second flight occurred in the summer of 1995 from Canada. Future flights in this series are planned to measure the abundance of low energy cosmic ray antiprotons.

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

2.8 Miscellaneous

Durisen spent January through July 1998 on a research leave 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.

In January 1998, during an AAS Meeting, Edmondson was invited to write an article about Daniel Kirkwood for Mercury, the popular journal of the Astronomical Society of the Pacific.

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Richard H. Durisen
Cathy N. Chamberlin