1994 ANNUAL REPORT
ASTRONOMY DEPARTMENT
OHIO STATE UNIVERSITY

1 Personnel

During the period covered by this report (September 1993 – August 1994), the regular academic staff of the Department of Astronomy included Richard N. Boyd, Darren L. DePoy, Jay A. Frogel, Andrew P. Gould, Eric Herbst, Gerard H. Newsom, Patrick Osmer, Bradley M. Peterson, Marc Pinsonneault, Richard W. Pogge, Anil K. Pradhan, Barbara S. Ryden, Kristen Sellgren, Arne Slettebak, Gary Steigman, Donald M. Terndrup, Jens V. Villumsen, and Robert F. Wing. David J. Ennis held an appointment as Lecturer in the Department. Boyd was on quarter-time appointment, with the rest of his appointment in the Physics Department. Steigman and Herbst were members of the Astronomy Faculty while also holding regular appointments in Physics. Gould and Pinsonneault began at the rank of Assistant Professor during the 1993-4 academic year. Osmer began his appointment as Chairperson and Professor and Newsom as Vice Chair on October 1, 1993. Pradhan and Sellgren received reappointments as Professor and Associate Professor, respectively, to take place on October 1, 1994. David Weinberg has accepted a position as Assistant Professor, to commence in January 1995. Villumsen's appointment as Assistant Professor ended in June 1994. Slettebak retired on June 30, 1994, after 45 years on the faculty at OSU. Steigman was on sabbatical leave at the Institute of Astronomy in Cambridge from January 1, 1994.

Emeritus members of the Department included Eugene R. Capriotti, George W. Collins II, Stanley J. Czyzak, Phillip C. Keenan, Geoffrey Keller, Walter E. Mitchell, Jr., and William M. Protheroe.

Others engaged in astronomical research while holding appointments in the Physics Department were Michelle Kaufman, Robert J. Scherrer, and Terrence P. Walker.

The staff of Astronomical Instrumentation Facility (AIF) at Ohio State included Bruce Atwood (Director), S. Ralph Belville, David F. Brewer, Paul L. Byard, Kevin R. Duemmel, Jerry A. Mason, Thomas P. O'Brien, David Steinbrecher, and Robert Stonebreaker. Stonebreaker began as programmer and Steinbrecher as machinist during the report period.

In Flagstaff, R. Mark Wagner continued as Research Scientist, while Ray C. Bertram worked in the position of Research Associate. Locally, Thomas Burns continued as the Director of the Perkins Observatory, and Michael Savage was manager of the Department computer resources.

Postdoctoral researchers in the Astronomy Department included Suchitra Balachandran, John S. Carr, Sultana N. Nahar, Alice Quillen, and Honglin Zhang.

Graduate students at OSU included Babar Ali, Manuel Bautista, Robert D. Blum, Mark E. Everett, Cheongho Han, Mark Houdashelt, Anita Krishnamurthi, Leslie E. Kuchinski, Nancy J. Lame, J. Michael Owen, Jianfang Peng, Aniruddha R. Thakar, Glenn P. Tiede and Jun Zhao. William F. Welsh was awarded the Ph.D. degree. Krishnamurthi, Kuchinski, Peng, Thakar, and Zhao received the M.S. degree.

2 Instrumentation

The AIF at Ohio State continued as one of the world's premier groups for the design and construction of astronomical instrumentation. The Ohio State Infrared Imager and Spectrometer (OSIRIS) has now completed a fourteen-month tour of duty as a facility instrument at the Cerro Tololo Inter-American Observatory, and has returned to the northern hemisphere for use on the Perkins 1.8-m telescope. OSIRIS was essentially flawless during its southern tour, with less than 2% of scheduled observing time lost to problems with the instrument.

Construction drawings for the new AIF facility on the fifth floor of Smith Laboratory were completed in July. Just before the start of construction, however, the Dean of the College of Mathematical and Physical Sciences canceled the plan. The AIF now has plans to move with the Department to 1500 m^2 of renovated space in McPherson Laboratory, located adjacent to Smith Laboratory. In the interim the AIF will lease additional off-campus if space if large instrument programs are begun before the renovation of McPherson Laboratory.

Byard has completed a preliminary investigation of optical designs for combined beam interferometry with the Large Binocular Telescope. The results were presented as a poster paper at the Kona Hawaii meeting of the SPIE.

O'Brien has conducted preliminary experimental work on alternative aluminization methods for large astronomical mirrors. Areas of investigation included performance of activated charcoal cryopanels for high vacuum pumping, ceramic crucibles as aluminum evaporation sources, scattering of aluminum, and the effects of argon and hydrogen on aluminum coating quality.

A new infrared imager is being designed and built by the AIF to be used on the 2.4-m Hiltner telescope operated by the Michigan - Dartmouth - MIT consortium on Kitt Peak. The initial implementation will be very simple, providing only one plate scale, a single filter wheel, and a NICMOS III 256^2 HgCdTe detector. When fully funded, it will utilize a 1024^2 Aladdin InSb array, and will provide several plate scales and a more extensive set of filters. Byard has developed optical designs for infrared imaging and spectrometry in the 1 to 5 μm range, including those required for the consortium's planned MOSAIC camera and those that would be required for an IR spectrometer for an 8-m telescope.

To assess the tracking and guiding performance of the Perkins 1.8-m telescope, Wagner and Bertram obtained a series of guided and unguided CCD images at a grid of telescope positions with the Imaging Fabry Perot Spectrograph in its direct imaging mode. Approximately 1200 frames of bright field stars were obtained in a time-series fashion during a three night engineering run. For the initial analysis, the unguided and guided frames at a given telescope position were grouped together in a data cube and displayed as a movie using the IDL software package. The effectiveness of the autoguider was immediately obvious when presented in this fashion. Quantitative analysis of the frames indicated that the guiding precision of the Perkins telescope was $0.24''$ and $0.44''$ (2σ) in right ascension and declination, respectively. The tests also indicated some tracking problems in some extreme parts of the sky.

3 Solar System

Wagner in collaboration with B. L. Lutz and M. Womack (Northern Arizona U.) continued his analysis of spectra of comets P/Halley 1986 III and Bradfield 1987 XXIX. Spectra were obtained with the OSU Image Dissector Scanner on the Perkins 1.8-m telescope along the plasma tails of both comets. Ionic species due to CO^+, N_2^+, CH^+, and H_2O^+ were identified in these spectra and column densities for them were calculated from the measured integrated band fluxes. They find that the CO^+/H_2O^+ abundance ratios in these two comets are consistent with predictions of photochemical models provided that CO^+ and H_2O^+ are produced primarily from photoionization of CO and H_2O respectively. However, the observed N_2^+/H_2O^+ ratios are at least an order of magnitude lower and the observed CH^+/H_2O^+ ratios a factor of 100 higher than the theoretical predictions. The N_2/CO abundance ratio was found to be an order of magnitude higher in Bradfield than in Halley. The relative ion abundances in Halley were found to be consistent with *in situ* measurements obtained from the Giotto spacecraft.

In addition and as a prelude to the observational study, revised fluorescence efficiency factors for N_2^+, CO, C_2, CH^+, NH, OH^+, and CH were calculated based on more recent molecular data. Wagner, Lutz, and Womack also examined the spatial distribution of neutral gas and dust in the coma of P/Halley. These data indicate that Halley was $\sim 2-5$ times more abundant in gas and dust at post-perihelion than pre-perihelion. The gas-to-dust ratios appeared to be subject to changes as a result of short-term outbursts but did not exhibit any systematic dependence on heliocentric distance.

As part of the coordinated observing campaign to study the impact of Comet Shoemaker-Levy 9 (SL9) with Jupiter, Wagner and D. G. Schleicher (Lowell Observatory) obtained CCD images of SL9 and Jupiter with the OSU Imaging Fabry Perot Spectrograph in direct mode in the weeks before and during the impacts. Broad-band images of SL9 obtained one week before the impact monitored the brightness of the individual fragments on their approach to Jupiter. Images of Jupiter were obtained in narrow-band filters at 4050 Å, 6800 Å, and in the 8900 Å methane band. A full rotational sequence of images was obtained in the week preceding the impacts for comparison with post-impact images. On July 17, no impact of fragment B=20 was observed. However on the night of July 21 at 05:43 UT, a plume from impact R=6 was observed in the 8900 Å methane band. Reduction and analysis of all the images is continuing. In addition, Wagner and other Lowell Observatory staff members observed Jupiter visually with the Alvan Clark 24-in refractor at Lowell Observatory at 300×. Considerable detail was visible in the equatorial cloud structures and four impact sites were clearly visible in the Jovian southern hemisphere. Some fine structure was even seen visually surrounding the site of impact K=12.

4 Stars and Stellar Evolution

4.1 Cataclysmic Variables, Binary Stars, and Novae

Wagner, J. Glenn, G. D. Schmidt and J. Liebert (Steward Observatory), S. B. Howell (Planetary Science Institute), and A. D. Grauer (Arkansas) completed an analysis of extensive observations of the bright eclipsing magnetic cataclysmic variable RE 2107-053 using CCD and high-speed photoelectric photometry, low- and moderate-resolution phase-resolved optical spectroscopy, broad-band linear and circular polarimetry, and optical spectropolarimetry. The observations confirm that the system is a synchronized magnetic AM Herculis variable with a spin/orbit period of 125.02 minutes. Both broad and narrow emission-line components are seen with their origin arising in the accretion stream and the irradiated M4 V secondary star, respectively. High-resolution Hα spectra obtained at the Perkins telescope indicate that at some orbital phases individual coherent streamlines are visible and provides new information regarding the flow of accreting gas in AM Her systems. Analysis of broad-band polarimetry constrains the system inclination and accretion spot colatitude and longitude while optical spectra of the cyclotron emission harmonics suggest a magnetic field strength in the polar shock of 36 MG and a mean surface field strength of about 20 MG. Radial velocities of the broad and narrow emission-line components obtained at the Perkins telescope are consistent with a 0.3 $M_\odot$ M4 V secondary star and a 0.9 $M_\odot$ white dwarf star.

Wagner, C. R. Shrader (NASA/GSFC), R. M. Hjellming and X. H. Han (NRAO), and S. G. Starrfield (ASU) completed a detailed multiwavelength study of the X-ray nova and soft X-ray transient GRO J0422+32. J0422+32 was monitored at ultraviolet, optical, and radio wavelengths from two weeks post-discovery into its early decline phase. They found that its ultraviolet and optical spectra were similar to other recent X-ray novae such as A0620-00 and Nova Muscae 1991 but probably viewed at a much higher inclination angle than the other systems. The early-outburst optical-UV continuum energy distribution was well represented by a two power-law fit with a break at $\sim$ 4000 Å. Radio observations with the VLA reveal a flat spectrum source which decayed as t^{-1} in a manner similar to V404 Cyg.

The most unusual aspect of the outburst of J0422+32 was the presence of mini-outbursts in 1993 August, 1993 December, and 1994 January during the decline phase. Wagner and colleagues fortuitously obtained near-simultaneous ROSAT X-ray observations and ground-based spectroscopy and photometry during the August mini-outburst. The ROSAT observations show a clear X-ray turnoff but photometry shows no change in the optical brightness associated with the X-ray turnoff until about one week later. Changes are evident in the lines profiles of He II 4686Å and the Balmer lines before and after the X-ray turnoff. Spectra obtained at the William Herschell Telescope during the December mini-outburst in collaboration with J. Casares, T. Marsh, and P. A. Charles (Oxford) and others show a strong modulation in radial velocities and the strengths of the emission lines with a period of 5.1 hours. The He II emission profiles exhibit an intense S-wave with a velocity semi-amplitude of about 755 km s^{-1}. If this emission originates on the X-ray heated face of the secondary star the implied mass function would be about 9.5 $M_\odot$ indicating a strong black hole candidate. These data will help to clarify the origin of the mini-outbursts as well as the accretion process in X-ray novae.

Between the August and December mini-outbursts and while the object was in a low brightness state (V = 19.9), Wagner, Charles, A. C. Martin (Oxford), and A. Henden (USNO) obtained I-band CCD photometry of J0422+32 over a period of two weeks at the USNO 1-m telescope. These data revealed a periodicity at 16.18 hours and no trace of the 5.1 hour period reported by other observers during the outburst and decline. The period is highly significant, but cannot be due to tidal distortion of the secondary star since recent photometry suggests that the quiescent magnitude of J0422+32 is about 22.4. The physical origin of this long period remains a mystery and photometry in the faint quiescent state will be required to differentiate between the two candidate orbital periods.

Wagner and colleagues reported the first unambiguous detection and measurement of the emergent X-ray spectrum of an X-ray nova black hole candidate in its quiescent state. V404 Cyg was detected with the ROSAT PSPC in a 16 ks observation 1265 days after the May 1989 outburst. They found that the observed X-ray spectrum is extremely soft and can be described equally well by either a blackbody, power-law, or thermal bremsstrahlung continuum. The best-fit blackbody is characterized by a temperature of 0.2 keV as well as significant absorption both along the line of sight and within the V404 Cyg system. Their observations show substantial variability on time scales of less than a day suggesting that significant accretion onto the compact object takes place even during quiescence. The X-ray luminosity of V404 Cyg is nearly two orders of magnitude larger than the upper limit for the X-ray nova and black hole candidate A0620-00 but comparable to neutron star X-ray novae such as Cen X-4. They conclude that the lack of a significant hard X-ray luminosity in quiescence, the presence of a large and cold neutral region in the accretion disk, and a low mass accretion rate suggest that an accretion disk instability might account for the outburst of V404 Cyg and possibly other X-ray novae as well.

Wagner, S. D. Vrtilek (CfA and U. Maryland), T. Mihara (Japan), F. A. Primini (CfA), P. Kahabka (MPE), H. Marshall (Eureka Scientific) and others presented the first results from a multiwavelength campaign in 1993 August to observe the binary pulsar system Hercules X-1/HZ Herculis. They found a substantial and unexpected drop in flux at X-ray energies as observed by both ROSAT and ASCA, but fits to the X-ray spectra indicated no change in absorbing column density. The X-ray pulse profile appears normal in the high intensity state but shows no pulsed emission above 1 keV in the low state. Optical and UV fluxes as measured at the Perkins 1.8-m telescope and elsewhere continued to show the 1.7 day modulation from X-ray heating of the companion star. However, the UV flux around eclipse was reduced from the value expected. The observations suggest the presence of an anomalous low state seen only once before in which the X-ray flux is obscured by the accretion disk during a transition from spinup to spindown as a result of a modulation in the mass accretion rate.

4.2 Late-type Stars

Wing has been searching the southern galactic plane for new late-type supergiants in collaboration with D. J. MacConnell (STScI) and E. Costa (U. Chile). These stars are recognized through two-dimensional spectral classifications, obtained from narrow-band photometry of TiO and CN bands in the near infrared, of candidate stars showing characteristic wedge-shaped spectra on MacConnell's near-infrared objective-prism plates. New red supergiants have been confirmed in all fields surveyed to date; many of these are heavily reddened and provide information about obscured regions that are difficult or impossible to study optically. A new calibration of the CN-based absolute magnitudes has been applied to a field in Carina, where the line of sight lies along a spiral arm and where several heavily-reddened supergiants have been found at distances in excess of 10 kpc. A comparison of luminosities based on CN bands and those based on the Ca II infrared triplet has been carried out with the help of eight-color photometry and CCD spectroscopy of MK standard stars. It is found that the two methods give consistent results for Iab and Ib supergiants earlier than about type M3; however, the measured Ca II line strengths appear to be unreliable in the case of class Ia supergiants (perhaps because of unresolved line emission) and in stars later than M3 (because of strong blanketing by TiO). In such cases the CN-based luminosities are in better accord with the MK luminosity classes.

Wing and MacConnell are attempting to find new examples of dwarf carbon stars by obtaining narrow-band classification photometry of faint, red stars known to have large proper motions. Two runs on the CTIO 1-m telescope have been devoted to this search and a third run has been scheduled. No new carbon stars have yet been discovered, but two stars (of about 120 classified) were found to have substantial CN strength; they must either be giants of enormously high velocity or dwarfs with mildly abnormal compositions. Most of the program stars are normal M dwarfs, for which the data provide accurate classifications.

Wing continues as Chair of the IAU Working Group on Peculiar Red Giant Stars. This WG publishes a Newsletter twice a year and is now working on the organization of IAU Symposium No. 177 on "The Carbon Star Phenomenon," to be held in Antalya, Turkey, in May 1996.

Frogel and E. Costa (U. de Chile) are completing what should be the last paper containing a large data base ($\sim$ 200 stars) of single channel infrared observations of LMC stars. These data are combined with *RI* photometry for a larger sample of $\sim$ 900 LMC carbon stars. What has been found so far from the near-IR and *RI* observations is a clear trend in stellar properties with distance from the bar rather than from the the center of the Cloud. The systematic change in the observed properties of the LMC field C stars suggests a strong dependence on age and metallicity with distance from the bar. Preliminary results suggest that the age of the carbon stars decreases with increasing distance from the bar. This may be the first time such clear evidence for this type of gradient has been detected within the main body of the LMC.

In order to simplify the classification of carbon stars on the Revised MK system introduced in 1993, Keenan is preparing an atlas of the spectra of standard stars, in collaboration with C. Barnbaum (NRAO) and R. Stone (Lick Observatory). The spectra in the atlas are to have a resolution of about 1 Å. Eventually the catalog will include all the major groups of carbon stars, as well as the closely related barium stars.

4.3 Lithium Studies

Balachandran has completed a study of the Li dip in the old cluster M67 in which the dip morphology is compared to the Hyades, Praesepe, and NGC 752 clusters. In M67, the Li dip stars have evolved off the main sequence and are now subgiants and giants which reveal the internal composition of the star. The absence of detectable Li in all except one subgiant argues strongly that Li is severely destroyed, not merely diffused from observable view. The comparison with the other open clusters required the adoption of a uniform temperature calibration. The standardization of the cluster data showed that the Li-$T_{\rm eff}$ distributions in the Praesepe and Hyades clusters are identical within the errors. Revised Yale isochrones were used to determine the masses and ZAMS temperatures of the individual stars in each cluster.

¿From the resulting Li versus mass and Li versus ZAMS $T_{\rm eff}$ plots, the following conclusions were drawn: a) the mass at the Li dip depends upon the metallicity of the star; b) the ZAMS temperatures of the dip stars are independent of metallicity; c) the morphology of the Li dip is characterized by a sharp drop at a blue edge and a more gradual rise at the red edge; d) no change is seen in the shape of the blue edge with age; and e) the red edge becomes shallower with age; this may either be due to the evolution of the Li dip, or it may be caused by a decrease in Li in stars cooler than the red edge and thus be unrelated to the Li dip phenomenon. None of the models so far proposed explains the Li dip results adequately. Microscopic diffusion and mass loss are contradicted by the observations. Models which incorporate rotation produce the Li dip through meridional circulation, turbulence or braking. All of these models would produce a larger scatter in Li abundances in the dip than is observed. Observations suggest that the stars in the dip may undergo spin-down on a much longer time-scale than the late-F and G dwarfs. Examination of the rotational velocity distribution in a cluster older than the Hyades may provide a clue to the origin of this anomalous Li depletion.

Balachandran and B. Carney (U. North Carolina) have acquired a complete set of OH and CO high-resolution infrared spectra of halo dwarfs using the cryogenic echelle spectrograph CSHELL at the IRTF. The data were taken in order to determine oxygen abundances as the numerous and strong OH infrared transitions offer a distinct advantage over the unreliable O I triplet. Analysis is in progress. A preliminary result for HD 103095 ([Fe/H] = -1.4) is [O/Fe] = $+0.15$.

In collaboration with C. F. Prosser and J. R. Stauffer (CfA), J.-P. Caillault (U. Georgia) and R. A. Stern (Lockheed), Balachandran is involved in a study of the open cluster NGC 6475 which at 200 Myr is intermediate in age between the Hyades and the Pleiades. Membership has been determined from a ROSAT PSPC observation and from BVI CCD photometry. Echelle spectra and time-series photometry will be obtained next in order to determine Li abundances and rotational velocities and thus understand their evolutionary pattern at this crucial age.

Balachandran is working with F. Spite and M. Spite (Meudon), and L. Pasquini (ESO) to determine Li abundances in halo binaries. This is an extension of the earlier study which led to their discovery of a high Li abundance in HD 89499. The goal is to determine if binarity (and thus the absence of or decrease in rotational spin-down) leads to less turbulence and thus decreased Li depletion compared to single stars at the same temperature, as suggested by recent models.

4.4 Young Stars and Star Formation

Carr is continuing his work on high-resolution spectroscopic observations and modeling of CO overtone emission in young stars, in collaboration with J. Najita and F. H. Shu (UC Berkeley), A. E. Glassgold (NYU), and A. Tokunaga (U. Hawaii). The velocity-resolved profiles are consistent with the emission originating in the inner regions of circumstellar disks. By fitting the spectra with Keplerian disk models, constraints can be placed on many of the gas properties, such as the radial temperature gradient. These results provide some of the best kinematic evidence for the existence of disks around young stars. A paper on the probable Herbig Ae/Be star 1548C27 is in preparation, and spectra of the T Tauri stars DG Tau, AS 353 A and V1331 Cyg are being analyzed.

Carr, Najita, and Tokunaga have acquired high-resolution profiles of Brγ emission in a number of T Tauri stars and low-luminosity obscured young stellar objects. The lines are broad, 400-700 km s^{-1} FWZI. None of the stars exhibit profiles predicted for winds by previous wind models. In particular, no blue-shifted absorption is seen, even in T Tauri stars with strong wind absorption features in the Balmer lines. In some objects, the velocity centroid of the line is blue-shifted with respect to the stellar velocity. Overall, the observed profiles may be in better agreement with emission from infalling gas in a magnetosphere than from an outflowing wind.

Balachandran and Carr have determined the Li abundance for two weak-lined T Tauri stars from echelle spectra containing both the 6708 Å and 6103 Å lithium features. Effective temperatures and microturbulent velocities were determined from analysis of Fe I lines. Analysis of the 6103 Å feature yields a Li abundance consistent with the maximum abundance observed in young clusters (3.2–3.3), while the 6708 Å line gives values around 3.6, similar to earlier studies. The highly saturated 6708 Å line systematically overestimates the Li abundance in many late-type T Tauri stars, and there is no evidence for an increase in the Li abundance in PMS stars over the meteoritic and Population I values.

Pinsonneault, Terndrup, Balachandran and Krishnamurthi, in collaboration with J. R. Stauffer (CfA) and S. Wolff (NOAO), have begun work on a project to study the evolution of angular momentum in low-mass stars. An observational program to measure the rotation periods of low-mass stars in the Pleiades will be combined with a theoretical effort to model the distribution of angular momenta in the relevant mass range. This is part of a large project to constrain models of angular momentum loss and the time scale for internal angular momentum transport. The other parts of the project will be to obtain rotation periods for stars covering a wide range in stellar masses in both the Pleiades and the Hyades. Investigating the behavior of the lower-mass stars makes up Krishnamurthi's thesis work.

Ali continued his near-infrared imaging and spectroscopic survey of the Orion star-forming region. He has also working to develop a K-band atlas of representative stellar spectra for MK-type classification in the infrared. Infrared spectra were obtained of several sources in the young cluster in NGC 2024 in attempts to classify these stars on the basis of their spectral signatures. Ultimately, the masses of these stars will be assessed by finding their locations on the H-R diagram and overlaying pre-main-sequence evolutionary tracks.

4.5 Other studies

Slettebak has begun a study of Be stars at high galactic latitudes. Optical spectra will be obtained with the 1.8-m Perkins Telescope in Flagstaff to determine whether these differ spectroscopically from Be stars in the plane and normal B stars, and radial velocities will be measured to ascertain whether they are "runaway" stars.

5 Globular Clusters

Frogel and Kuchinski have completed the majority of their study of bulge globular clusters and have submitted two papers to the Astronomical Journal. The data are primarily from the Las Campanas duPont telescope supplemented by observations from UKIRT and the Perkins 1.8-m telescope.

As a first step in investigating the properties of these heavily reddened, metal-rich globular clusters, Kuchinski, Frogel, Terndrup, and S. E. Persson (OCIW) present JHK colors and magnitudes for four objects: NGC 5927, NGC 6712, NGC 6838 (M71), and Terzan 2. These data begin near the top of the giant branch (GB) and extend to stars six magnitudes fainter, reaching below the horizontal branch (HB). With these data and previously published photometry for 47 Tucanae and M69, they develop techniques for deriving basic properties such as metallicity and distance modulus from observable parameters of cluster color-magnitude diagrams (CMDs) in the near-infrared. They also analyze the horizontal branches of the clusters in an attempt to set constraints on mass loss for first-ascent giants.

The slope of the linear fit to GB stars brighter than the HB can be used to predict metallicity to an accuracy of ±0.25 dex for clusters with [Fe/H] between -1.0 and $+0.3$. There appears to be no significant dependence on [Fe/H] for other reddening-free indices measured from the CMD, including the width of the HB and the separation between the GB and HB at the level of the HB. Using the clusters in the sample that have known distances, they derive a value of $\langle M_{K,0}(\mathrm{HB})\rangle = +1.15\pm0.10$ for the extinction-corrected absolute K magnitude of the HB. This provides a means of determining the distance to clusters for which only infrared CMDs are available.

They derive a distance modulus to Terzan 2 of 14.37 ± 0.2 which places it within a few hundred parsecs of the galactic center. In the $J-H$, $H-K$ diagram, Terzan 2 giants are located near the Baade's Window giants rather than in the region populated by nearly all other globular cluster stars. The GB of stars in the field around Terzan 2 has a slope that implies [Fe/H] = +0.1, comparable to that in Baade's Window.

Frogel, Kuchinski, and Tiede then apply these results to Liller 1, a globular cluster with an angular separation of only 5° from the Galactic center and a latitude of 0.2°. From their near-IR photometry they are able to form the first color-magnitude diagram for Liller 1. The cluster has a metallicity of [Fe/H] = $+0.30\pm0.3$ based on the slope of the giant branch. This implies that Liller 1 is the most metal rich Galactic globular cluster known. No reasonable uncertainty in the age of the cluster will affect the method for deriving the metallicity. On the basis of the near-infrared data for Liller 1, they conclude that $E(J-K) = 1.75\pm0.06$ (or $A(V)\approx10$) and $(m-M)_0 = 14.65\pm0.23$. The atypical JHK colors of the Liller 1 stars, the extreme slope of its giant branch, and its physical closeness to the Galactic center raise the question of whether it is a normal globular cluster or if its formation and evolution have been strongly influenced by its proximity to the Galactic center.

Terndrup has completed a JHK imaging survey of 12 globular clusters in the LMC, in collaboration with F. R. Ferraro, F. Fusi Pecci, V. Testa and L. Greggio (Bologna), R. Buonanno and C. E. Corsi (Monte Mario), and H. Zinnecker (U. Würzburg). They explored the effects of age and metallicity on the integrated light of these clusters and find that $J-K$ is primarily determined by AGB stars, $V-K$ by AGB and RGB stars, and $B-V$ by age and by the whole population of stars brighter than the red giant clump. Such explorations of simple stellar populations are necessary for the interpretation of the colors of galaxies at large redshift. Their results have been submitted to MNRAS.

6 Interstellar Medium and Nebulae

Carr, N. J. Evans (U. Texas), J. Lacy (U. Texas), and S. Zhou (U. Illinois) have submitted a paper on molecular abundances toward GL 2591 based on observations of mid-infrared and radio lines of molecules. The abundances of C_2H_2 and HCN derived from the infrared lines are high in the warm (200 K) and hot (1000 K) gas components, but absorption from the cold gas (38 K) component is not observed. The abundances of molecules derived from the radio data, which sample the extended cloud, show depletions compared to models of gas-phase chemistry. The abundances in the hot and cold gas can be explained if depletion onto grains occurred at early times in the cloud history when the abundances of C_2H_2 and HCN were high, and these molecules were later released into the gas phase when heating due to star formation evaporated the grain mantles. The observed abundances are consistent with passive storage of molecules on grains with little or no grain chemistry.

In the last year, Herbst, who won the Max Planck Research Prize for his work in molecular astrophysics, has worked with collaborators to improve their gas phase chemical model for dense interstellar clouds and utilizing it for different physical environments. The major improvement has been the addition of a wide variety of neutral-neutral reactions. Until recently, the model was dominated by ion-molecule reactions, because these processes are known to occur rapidly at the very low temperatures prevalent in dense interstellar clouds. Recent laboratory work on some classes of neutral-neutral reactions indicates that such reactions are also rapid at low temperatures. Rather than include only the small number of reactions measured to date, Herbst, H.-H. Lee (OSU Physics), D. A. Howe (UMIST), and T. J. Millar (UMIST) extrapolated the measurements to include a large number of reactions. Their results show that the gas phase production of complex molecules in dense interstellar clouds appears to be hindered by inclusion of neutral-neutral processes. Unlike the situation for interstellar clouds, the inclusion of neutral-neutral reactions appears to help molecular synthesis in the carbon-rich circumstellar source IRC+10216. Millar and Herbst have published a new chemical model of the envelope in this source, in which they account for both the fractional abundances and spatial extents of the various complex molecules detected there. Finally, P. Farquhar (UMIST), Millar, and Herbst have studied how the gas phase chemistry of dense clouds varies with the ionization rate. Since the major cause of ionization is cosmic ray bombardment, the ionization rate in external galaxies is likely to be different from what it is for clouds in the Milky Way.

P. Caselli (CfA), T. I. Hasegawa (St. Mary's U.), and Herbst have utilized a chemical code which includes both gas phase and dust-surface reactions to attempt to understand the high abundance of solid phase CO in the interstellar medium. They found that the predicted abundance of CO on grain mantles is highly dependent on the elemental abundances chosen for the gas and condensed phases.

A theoretical program to understand the non-thermal desorption of interstellar molecules from dust particles has been started. The ubiquitous interstellar molecule CO has been chosen for detailed study. Energy is placed in a mode of the CO molecule, and the time dependence of the CO-dust particle system is followed on a supercomputer by both classical and quantum mechanical means. In the initial paper, E. T. Galloway (OSU Physics) and Herbst used the classical trajectory treatment to show that small amounts of vibrational excitation cannot drive CO off dust particles and that even large amounts of energy are efficient only on certain types of lattices. In a second paper, E. Dzegilenko (OSU Physics) and Herbst realized that rotational ("librational") excitation of surface CO is much more efficient at inducing desorption at low excitation energies. The authors are now studying how the librational mode can be efficiently excited under interstellar conditions.

S. A. Maluendes and A. D. McLean (IBM), and Herbst have made progress in understanding some gas phase reactions important in interstellar chemistry. In particular, Herbst has shown that a class of reactions involving molecular hydrogen, the dominant molecule in the gas, which have previously been thought to be slow at low temperatures, may occur at appreciable rates because of quantum-mechanical tunneling.

In the area of laboratory spectroscopy, J. Pearson (OSU Physics), K. Sastry (New Brunswick), F. De Lucia (OSU Physics), and Herbst have extended the rotational spectrum of the known interstellar molecule ethyl cyanide (propionitrile, CH_3CH_2CN) to submillimeter wavelengths and have studied the rotational spectrum of propylene (CH_3CHCH_2), a molecule which should be present in interstellar clouds. Work is currently being undertaken on extending the measured high-resolution rotational spectra of methanol and methyl formate, two well-known interstellar weeds, to frequencies of 1 THz and higher.

Sellgren, A. N. Witt (U. Toledo), Carr, J. L. Hora (U. Hawaii), Krishnamurthi, and Blum have obtained infrared long-slit spectra, images, and photometry of two filaments in the reflection nebula NGC 7023. Both filaments show H_2 emission, and the H_2 emission appears to coincide with emission from 10 Å sized aromatic hydrocarbon grains and/or polycyclic aromatic hydrocarbon molecules, as seen in narrowband images at 3.3 μm, broadband images at 2.2 μm, images of extended red emission (ERE) at 0.67 μm, and photometry at L'. Many lines of H_2 were detected in the K band, and their relative strengths will provide information on the excitation of the H_2 emission. Sellgren and M. W. Werner (JPL) hope to extend this study to longer wavelengths and have submitted a proposal to the Infrared Space Observatory (ISO) to obtain images in other aromatic hydrocarbon features at 6.2, 7.7, and 11.3 μm of this and other reflection nebulae.

Sellgren, Werner, and L. J. Allamandola (NASA Ames) are working on a study of the excitation of near-infrared continuum emission and 3.3 μm feature emission in reflection nebulae. This feature and continuum emission is attributed to either thermal emission from stochastically heated tiny grains or to vibrational or electronic fluorescence from polycyclic aromatic hydrocarbon (PAH) molecules. They have searched for extended 2.2 μm emission in 20 new visual reflection nebulae illuminated by stars with spectral types ranging from O9.5 V to M1 IIIe and have detected extended 2.2 μm emission in 12 new nebulae. For most of these 12 nebulae they have obtained $J-H$, $H-K$, and $K-L'$ colors as well as surface brightness measurements of the 3.3 μm emission feature. These results are currently being analyzed to constrain tiny grain and PAH models. Sellgren and Werner are also collaborating with A. Léger (U. Paris) and others on an ISO proposal to continue this infrared survey of reflection nebulae to more sensitive levels using the spectroscopic and photometric capabilities of the satellite.

Sellgren, R. G. Smith (U. New South Wales), and T. Y. Brooke (JPL) have completed their study of the 3 μm spectra of two stars whose extinction is due to dust in molecular clouds, obtained at a resolution $\lambda/\Delta\lambda = 800$. These two stars, the protostar Mon R2/IRS-3 and the K giant Elias 16 behind the Taurus molecular cloud, show no evidence of the hydrocarbon features seen toward stars extinguished by similar column densities of dust in the diffuse interstellar medium. Mon R2/IRS-3 does show an absorption feature around 3.49 μm, which is likely to be related to the feature at 3.47–3.48 μm recently detected in four protostars by Allamandola et al. (1992; ApJ, 399, 134) and attributed by them to interstellar "diamonds." Mon R2/IRS-3 also shows tentative evidence for an absorption feature near 3.25 μm, which if confirmed may provide the first evidence for absorption in molecular clouds by polycyclic aromatic hydrocarbons. Neither Mon R2/IRS-3 nor Elias 16 shows evidence for methanol ice absorption. Theoretical models of gas-grain chemistry in quiescent dark clouds predict substantially more methanol ice toward Elias 16 than their upper limit, which provides a puzzle for modelers to solve.

M. Shure (U. Hawaii), Sellgren, T. J. Jones (U. Minn.), and D. Klebe (U. Denver) have completed their study of polarization measurements of the bipolar nebula OH0739−14 at 1.2, 1.6, 2.2, and 3.6 μm. Previous work had concluded that the infrared color of the bipolar lobes of this nebula is too red to be due to light scattered from the central M giant star, and that it might therefore include a contribution from thermal emission from dust in the lobes. However, the new polarization results show the polarization at 1.2–3.6 μm to be around 50%, independent of wavelength. This shows that the nebular light is certainly due to scattered light with no significant thermal emission component. The redness of the nebula must therefore be due to the central star being redder than normal, perhaps due to a circumstellar disk or shell of warm dust. Even with such a model of the central star surrounded by a warm dust shell, however, the nebula is brighter and redder in color than predicted by simple grain models. Their results point to a higher albedo for grains in the near infrared than predicted by standard grain models. There is also a contradiction between the high levels of polarization they observe (∼50%), which suggests Rayleigh-like scattering from small grains, and the red nebular colors, which suggests scattering from large grains whose scattering cross-section is relatively flat with wavelength.

DePoy, Pogge, Bautista, and Everett are using long-slit, cross-dispersed IR spectra to study selected regions in the Orion Nebula. The spectra cover all of the J, H, and K atmospheric windows at a resolution of 570. They are pursuing two parallel lines of inquiry. The first, led by Bautista, combines JHK spectra and $0.4-1\mu$m spectra of a set of nebular regions (the latter spectra are from Osterbrock, Tran, & Veilleux). The combined data set covers most of the H I Balmer, Paschen, and Brackett emission-line series and includes many lines of helium and iron. Comparing the H I line strengths to their theoretical values, they find that in order to account for dust extinction along the line of sight, they must use a more sophisticated treatment than the classic dust-screen approach. Using the stellar extinction law derived for the Trapezium stars and a first-order treatment of radiative transfer that includes effects of dust mixed in with the nebula, they can derive a good "nebular" extinction law for this region of the nebula, which can be applied in general to any nebula for which adequate multiwavelength data are available. The NIR emission lines of helium and iron (Fe II and Fe III), along with their improved extinction estimates, will allow them to better estimate the helium and iron ionic abundances in the Nebula.

The second line of inquiry is led by Everett. This work is revisiting the Becklin-Neugebauer object, using cross-dispersed IR spectra to study the H_2 emission peak (BN "Pk1"). Because they sample the $1-2.5\mu$m region simultaneously with the same effective beam, they can eliminate many of the beam matching problems of earlier studies and measure very precise emission-line ratios. This region covers a number of S– and Q–branch lines of H_2 spanning a wide range of vibrational and rotational levels. From these they can derive an accurate estimate of the extinction towards Pk1. Comparing the strengths of the H_2 lines with thermal and fluorescent excitation models, they find that the absence of high-v emission lines rules out any significant contribution from fluorescent excitation in this region. They confirm that the excitation is thermal, but not consistent with a single excitation temperature as the data are better fit by a simple two-temperature model. Further work to refine their models is in progress.

Pogge and J. A. Morse (STScI) have begun a Fabry-Perot spectrophotometric study of a shocked interstellar cloud in the southwest portion of the Cygnus Loop supernova remnant. The goal is to map physical conditions (temperature, density, and excitation) and kinematics across this interstellar cloud which was "run over" by the supernova blastwave that created the Cygnus Loop nebula a few$\times 10^3$ years ago. Results will be compared with models being developed by P. M. Hartigan (U. Mass.) and C. F. McKee (Berkeley), who are collaborators on this project.

Lame is completing her thesis project of imaging spectrophotometry of planetary nebulae under the supervision of Pogge and Peterson. Analysis of the Ring Nebula has been completed, and the observations show an ionization front covering the entire outer edge of the nebula. The [O I]-bright filaments are not cool and dense as predicted, and the density structure suggests an oval-shaped toroid model for the nebula. Work is continuing on the PNs NGC 7662 and NGC 7009.

DePoy finished a project with J. Shields (Arizona) in which the integrated He I 2.06 μm to Brγ ratio was measured in planetary nebulae. The observations confirmed the predictions of a photoionization model and showed that the ratio is sensitive to many physical parameters.

DePoy and Pogge have made a spectrophotometric study of the central regions of the Orion Nebula at $2.0-2.4$ μm using OSIRIS. The first phase of the study was to make a complete map of the inner $4' \times 6'$ of the nebula by scanning the region with a long-slit. One of the surprising results was that the strongest emission lines in the nebula after the H I, He I, and H_2 lines are the $^3H_J - ^3G_{J'}$ lines of [Fe III]. With improved atomic calculations underway by Pradhan and collaborators, two of these lines will provide an important IR density diagnostic. In addition, the two strongest of these [Fe III] lines are closely blended with two H_2 emission lines, $v = 1-0$ $S(0)$ and $v = 2-1$ $S(1)$. These two H_2 lines are important as diagnostics of molecular excitation, and in low-resolution spectra, one must beware of possible [Fe III] contamination of these lines.

7 Supernovae

Bautista, DePoy, and Pradhan in collaboration with J. H. Elias, B. Gregory, and N. B. Suntzeff (CTIO) have completed a study of near infrared spectra of SN 1987A taken between days 936 and 1145 after the core collapse. The spectra, obtained at CTIO using the 4-m telescope with the infrared spectrometer IRS, show many lines from neutral and singly ionized species of which the most notable are Si and Fe. Another species tentatively detected was Co II. By using the strength of the [Fe II] lines, the electron density and temperature of the emitting region were diagnosed. The total mass of Fe was estimated and found to be lower than many theoretical expectations. Also, the intensities of the H I and He I lines were analyzed in relation to the physical conditions in the [Fe II] emitting region. They concluded that the observed emission from these species may come from disjunctive zones in the ejecta of the supernova.

Bautista and DePoy have continued the study of late-time spectra of SN 1987A by taking near-infrared spectra of the supernova beyond day 2000 after the explosion of its progenitor. These new spectra are expected to provide more information about the heating source of the ejecta as well as the depletion of Fe observed in many spectroscopic studies of this supernova.

Wagner, E. Baron and D. Branch (U. Oklahoma), P. H. Hauschildt and S. J. Austin (ASU), and A. Filippenko and T. Matheson (UCB) reported analysis of early optical spectra of SN 1993J in M81 using NLTE synthetic spectrum fits to the observations. They found that these early spectra were characterized by photospheric velocities of 10,000–11,000 km s^{-1} and photospheric temperatures between 8000 K and 6500 K and a radius of $1-2 \times 10^{15}$ cm. Most of the spectral features could be fitted assuming a solar composition. In a related study, these authors, with P. Garvavich and H. B. Ann (DAO) and J. Liebert (Steward Observatory), presented NLTE synthetic spectra fits to a more extensive series of optical spectra of SN 1993J. Based on these spectra, they find that while the early spectra are well represented by a solar composition, an enhanced abundance of helium is required in order to fit the neutral helium lines. They derive a distance modulus of 28.0 ± 0.3 mag which is consistent with the recent Cepheid distance.

8 Milky Way

8.1 The Galactic Center

Progress continues on a project by Carr, Sellgren, Balachandran, and Terndrup to determine stellar abundances of late-type giants in the Galactic Center using high-resolution near-infrared spectra. This program will yield the first measurements of metallicities in Galactic Center stars. Spectra have been obtained at the IRTF for the M2 supergiant IRS 7 and three late M giants. The spectra, which include transitions of CO, CN, OH and various transitions of Fe and other metals, will permit the determination of stellar effective temperatures, microturbulent velocities and elemental abundances. The analysis of IRS 7 is nearing completion.

Blum, DePoy, and Sellgren obtained K band spectra of seven Galactic Center He I emission-line stars and compared them to spectra of massive post-main-sequence stars from the LMC. The data were taken on the CTIO 4-m using OSIRIS. The comparison indicates that the Galactic Center (GC) objects are similar to the LMC objects, and lends strong support to the proposition that there has been recent star formation ($< 10^7$

yr) in the GC. The observations significantly extend the wavelength coverage over previous work, achieve much improved background subtraction of unresolved stellar light and diffuse gas, and allow for the GC objects to be approximately placed in the H–R diagram. The latter point suggests that several of the GC He I emission-line stars could be among the most luminous objects in the Galaxy. This project is part of Blum's Ph.D. dissertation.

DePoy and Pogge continued their work on [Fe II] and [Fe III] emission in the Galactic Center. The line ratios suggest that much of the filamentary gas in the Galactic Center is in high density clumps.

8.2 The Galactic Bulge

Blum, Carr, Sellgren, and Terndrup have obtained radial velocities for stars in three optically obscured fields toward the Galactic bulge between 150 and 300 pc from the Galactic Center. The radial velocities are derived from spectra of the 2.3 μm CO bandhead which is prominent in late-type giants. Comparison to axisymmetric mass models shows rough agreement with the predicted velocity dispersions for the three fields, but there is some evidence that the dispersion may be larger for $R < 180$ pc than in the axisymmetric models. This project is part of Blum's Ph.D. thesis.

Uncertainties in the values for the age and metallicity of stars in the Galactic bulge seem to be increasing with time. The most recent work by McWilliam and Rich suggests both a younger age and lower mean [Fe/H] than values derived previously. A comparison of near-IR CMDs that reach to near the main sequence turnoff with theoretical isochrones has the potential of yielding better estimates for stellar ages than other techniques such as CMDs at shorter wavelengths. In addition, such data will be valuable for the construction of stellar synthesis models and the prediction of how the luminosity and color of old, metal rich stellar populations will change with look-back time. Frogel has obtained such data with IRCAM on the LCO 2.5-m for about a dozen bulge fields. These are the deepest, most accurate near-IR CMDs for Baade's Window and other areas of the bulge yet produced. The MS turnoff is visible at $K_0 = 16 - 16.5$; the RGB clump at $K_0 = 13.5$, and the foreground field sequence between $K_0 = 16$ and 13 to the blue of the GB. With similar data for about one dozen other fields down to only 0.5° from the Galactic Center and at a variety of longitudes it should be possible to delineate the disk from the bulge population and determine the age and [Fe/H] for the stars. Frogel, Tiede, and Terndrup are presently analyzing the results for Baade's Window.

Since most of the bulge fields are inaccessible at optical wavelengths, Frogel has used the LCO CMDs to select a sample of stars to be observed spectroscopically with OSIRIS on the CTIO 4-meter with the objective of measuring metallic lines and blends in the K band to get relative abundances. Frogel and DePoy have now had two observing runs and observed about two-thirds of the sample of stars. Differences in atomic line strengths between globular clusters being used for calibration are obvious. Additional data demonstrate that this technique is sensitive enough to detect [Fe/H] differences of the size expected along the minor axis of the Galaxy for the inner bulge.

Terndrup, E. M. Sadler (U. Sydney), and R. M. Rich (Columbia U.) will shortly submit a series of papers on their extensive survey of metallicities and radial velocities of bulge stars. Their first three papers are on a sample of over 400 stars in Baade's Window which have proper motions from Lick Observatory. They confirm the recent result from McWilliam and Rich that the mean metallicity of the bulge is about $[Fe/H] = -0.2$, about 0.2 dex lower than previously estimated. There is also a strong indication that the bulge stars are enhanced in magnesium; if the bulge is older than 7 Gyr in age, the majority of bulge stars must have $[Mg/Fe] \approx +0.2$. They also find that after a correction for the presence of foreground stars, the three-dimensional kinematics of the Baade's Window stars is very close to those predicted by isotropic rotator models for the bulge. There do not appear to be strong signatures of strong bar-induced streaming motions in the Baade Window data.

Terndrup and A. Walker (CTIO) have completed a study of the globular cluster NGC 6522 in Baade's Window. Their photometry yields significantly improved estimates for the extinction towards the bulge and the distance to the cluster. They also find that most of the hot horizontal-branch stars in Baade's Window belong to NGC 6522 and not to the bulge. They conclude that the UV flux from such stars contributes no more than $\sim 20\%$ of the far-UV light ($\lambda = 1750$Å) of the bulge, if the bulge has the same UV emission as the bulge of M31. To extend this study, Terndrup, Walker, Sadler, and R. C. Peterson (Lick Observatory) have begun an extensive survey to detect and classify hot stars in the bulge. These objects – hot horizontal-branch stars, post-AGB stars, and other exotics – have been postulated to explain the copious UV emission from elliptical galaxies and the bulges of other spirals. This survey will use the facilities at CTIO and AAO.

Terndrup, Rich, Peterson, and A. McWilliam (OCIW) have obtained high-quality optical spectra of two faint ($V = 17.3$) K giants in Baade's Window at a resolution of $\approx 40,000$. These spectra were obtained at CTIO in 1994 May and represented over 13 hr of integration for each star. A first comparison to local metal-rich stars such as μ Leo shows that the two bulge stars are indeed extremely metal-rich, with [Fe/H] values at least as high as μ Leo. Spectrum synthesis is currently underway.

9 Extragalactic Astronomy

9.1 Digital Atlas of Galaxies

Two years ago Frogel, DePoy, Pogge, Sellgren, Terndrup, and R. Davies (U. Durham) were given a multiyear NSF grant to assemble a digital atlas of galaxies. Since coming to OSU as a Columbus Fellow, Quillen has assumed a major role in this undertaking as well. Multiwavelength surveys of galaxies are of great importance for investigations of structure and stellar content. The OSU program will conduct a new, extensive survey of spiral galaxies using wide-field infrared and optical imaging systems developed at The Ohio State University. This survey will produce a photometrically calibrated library of images of late-type galaxies from 0.4 to 2.2 μm. Infrared observations are key to this survey because infrared light is a better tracer of the stellar mass distribution than optical light which is strongly affected by dust absorption and has a large contribution from young stars. Photometry and infrared long-slit spectroscopy will be used to study the dependence of stellar content on position, including the identification of regions of active star formation. The variation in appearance of structures such as spiral arms, bars, and disks as they are viewed from 0.4 to 2.2 μm will be sensitive to the ages of such structures (since young stars dominate the blue light whereas old stars dominate the near-IR) and be valuable tests for theories of the formation of these structures. The effects of scattering and absorption by dust on the observed luminosity and color of a galaxy will be investigated. Finally, these data will be of value in predicting the colors of galaxies at large redshift.

Although the program got off to a slow start, it is now picking up steam. Three papers have already been accepted for publication and several more are in preparation. The first paper by Terndrup, Davies, Frogel, DePoy, and L. Wells (NOAO) presents the most extensive and most accurate examination of the infrared surface brightness profiles of spiral galaxies to date. In this paper surface photometry of 43 S0 and spiral galaxies in the K band with a subset also observed in J is presented. Most of the data are photometrically calibrated. These new data are combined with published optical major-axis profiles to construct a set of galaxies with rJK colors, to divide the major-axis profiles into bulge-dominated and disk-dominated regions, and to compute mean colors and color gradients for bulges and disks. Typically the disk colors are measured from 0.8 to 1.8 scale lengths.

The colors of the bulge and disk components are strongly correlated, indicating that both components have a red stellar content that is similar in both age and metallicity. In the mean the disks are 0.1 mag bluer in $r-K$ than bulges; this color difference would arise if the disks are $2-4\times10^9$ yr younger or have lower metallicities by [Fe/H] ≈ -0.1 to -0.2. Many of the bulges exhibit negative color gradients (bluer outwards), which indicate that metallicity gradients of order [Fe/H] ≈ -0.2 may be common in bulges. Bulges of late-type galaxies are bluer on average than those of early types, probably a consequence of lower metallicity. About 25% of the galaxies have especially red bulge and disk colors, which is interpreted as arising from large internal extinction rather than from an enhanced star formation rate.

Quillen, Frogel, and R. González (UCB) have studied the gravitational potential of the bar in NGC 4314, based on JHK images from Lowell Observatory. Colors in these bands are constant across the bar of NGC 4314 indicating that the mass-to-light ratio is constant over much of the galaxy. They have developed an efficient procedure for mapping the gravitational potential of a non-axisymmetric galaxy based on its appearance in the near-infrared using a Fourier Transform method. They account for the thickness of the galaxy's stellar disk by convolving its K image with a function that depends upon the vertical stellar scale height. They apply this procedure to NGC 4314 and find that prograde stellar orbits integrated in the potential are consistent with the shape of the bar for a disk vertical scale height of $h = 350 \pm 100$ pc and a corotation radius of $r = 3.5 \pm 0.5$ kpc. The inner $m = 4$ Lindblad resonance is approximately at the location of knob-like features seen near the end of the bar. The shape of nearly closed orbits at this radius are lozenge or diamond shaped and have low speeds along the major axis of the bar. The low speeds imply an increase in density along the major axis of the bar. The angle of the major axis of the $m = 4$ component of the surface density begins to twist at the location of its resonance, and the angle of the $m = 2$ component begins to twist at a larger radius near the corotation radius.

Quillen, Frogel, J. Kenney (Yale), Pogge, and DePoy have published images of the barred galaxy NGC 7479 in the B, V, R, J, H and K bands, and images in Hα + N II, and in CO(J=1$\rightarrow$0) emission. The Hα and CO emission in the bar are coincident and confined to narrow linear features that are offset from the center of the bar as observed in the near infrared. From the techniques developed in the first paper, Quillen et al. estimate the gravitational potential from the K image, which provides an estimate of the torque on the gas at the position of the CO emission in the bar. They find that the implied gas inflow velocity derived from the torque is $10-20$ km s^{-1}. This inflow velocity is independent of the large streaming motions which can be observed in CO and H I.

Quillen and Frogel are analyzing data on the dwarf galaxy NGC 1705 which is thought to have a mini-starburst near its center. Significant studies of NGC 1097 and 1365 are also being completed by Quillen, Frogel, and Pogge. Particular emphasis is being placed on attempting to model the effects of the dust on the optical appearance of these galaxies.

9.2 Structure of Galaxies

Thakar has begun a numerical investigation into the formation of extensive counterrotating disks (of the type discovered in NGC 4550, among others) in spiral galaxies for his Ph.D. dissertation, supervised by Ryden. The coexistence of two comparably-sized populations of stars with anti-parallel angular momenta in a relatively cold spiral disk configuration poses a special problem for prospective models for the formation of these two-way disks. Thakar has adapted a C version of the TREE code to study this problem, and he has added sticky-particle gas dynamics to conduct simulations aimed at determining the likelihood of formation of cold, counterrotating disks by slow infall of ambient gas onto a pre-existing spiral disk surrounded by a dark halo. The code has been optimized for execution on the vector processors of the Cray Y-MP at the Ohio Supercomputer Center. Preliminary results of the sticky-particle simulations are encouraging and indicate that gaseous infall may indeed produce counterrotating disks without serious disruption of the pre-existing disk. The simple sticky-particle scheme for dissipation of the gas kinetic energy in the form of inelastic collisions will be replaced by Smoothed Particle Hydrodynamics in the next phase.

Han and Ryden have studied the apparent shapes of globular clusters associated with our own Galaxy and with the Large Magellanic Cloud. The apparent shapes of globular clusters in the Galaxy are consistent with the hypothesis that they are all intrinsically oblate, with a peak in the distribution of intrinsic axis ratios at $\gamma \approx 0.95$. The apparent shapes of the LMC globular clusters, however, are inconsistent with the hypothesis that they are intrinsically oblate; there are too few apparently circular clusters. The shapes of the LMC clusters are consistent with their being triaxial ellipsoids, with the most probable axis ratios being $1 : 0.86 : 0.74$.

9.3 ISM and Dust in Galaxies

Kuchinski and Terndrup have continued a study of the photometric properties of boxy-peanut bulges in spiral galaxies to test various theoretical predictions about bulge formation. Optical and infrared images of several galaxies with boxy, peanut-shaped, and round bulges were obtained in December 1993 with the CTIO 0.9-m + CCD and 1.5-m + OSIRIS, respectively. Initial results show that the central regions of nearly edge-on spirals are dimmed by up to 5 mag of extinction at visible wavelengths. Analysis is underway to look for relations between colors or color gradients and bulge morphology, which are predicted by some bulge formation models. Spectroscopic observations of these galaxies are scheduled for early 1995 to study kinematics and population indicators in different types of spiral bulges. This work is part of Kuchinski's Ph.D. dissertation.

Kaufman, D. Elmegreen (Vassar), E. Brinks (NRAO), B. Elmegreen (IBM), and M. Sundin (Chalmers, Goteburg) have completed their study of the interacting galaxy pair IC 2163/NGC 2207, which provides a view of tidal disturbances during a recent close flyby encounter between galaxies of comparable mass. They find that the observed morphological structures and velocity anomalies in the ocular galaxy IC 2163 match in detail the predictions of the in-plane, prograde encounter simulation. Also, NGC 2207 is in the process of being warped, with present z-velocities as large as 100 km s^{-1}, as a result of strong out-of-plane tidal forces. Both galaxies contain several clouds with masses in excess of $10^8 M_\odot$, but neither is currently undergoing a burst of star formation. As a follow-up to this work, Kaufman, Brinks, Elmegreen, Elmegreen, and C. Struck-Marcell (Iowa State) have made VLA observations of H I in several other pairs of galaxies containing ocular or swallow-tail structures. In computer simulations of galaxy collisions, such structures occur only during the early stages of post-encounter evolution and involve unusual kinematic features such as discrete orbit streams.

Kaufman, W. Wall (GSFC), F. Bash (U. Texas), and R. Rand (U. Maryland) have made ^{13}CO and ^{12}CO $J = 1 \rightarrow 0$ observations at Owens Valley Radio Observatory to place limits on the variation of the kinetic temperature of the molecular gas across a spiral arm in M 51.

Pogge and P. Sackett (IAS) are nearing completion of their imaging Fabry-Perot kinematical study of the polar-ring galaxy A0136−0801. The largest hurdle was not the F-P data, but working out a methodology for comparing the observed 2-D radial velocity field to model orbits with a range of parameters for the system's gravitational potential. The observed radial velocity field shows a twist in the isovelocity contours along the major axis that is characteristic of the projection of intrinsically oval orbits onto the plane of the sky. By determining the true shape of the orbits, it is possible to estimate the flattening of the dark matter halo in the host galaxy. They are working to refine the analysis to better constrain the range of halo flattening allowed by the observed velocities. They also have imaging F-P observations of the polar-ring galaxy ESO415-G26, which by contrast to the ring in A0136–0801 is very faint and narrow, and will require a slightly different treatment.

Pogge has continued his collaboration with C. L. Taylor and E. D. Skillman (U. Minnesota) on a project of deep Hα imaging of dwarf irregular galaxies with H I companions. The first imaging set has been reduced and published. A larger imaging set was obtained in May 1993. Taylor is presently working to complete the analysis of these data as part of his dissertation research.

10 Active Galaxies and QSOs

10.1 Seyfert Galaxies

Pogge and M. M. DeRobertis (York University, Toronto) completed their multi-line imaging spectrophotometric study of the Seyfert 2 galaxy Mrk 573. Images in the emission lines of [O I], [O II], [O III], [Si II], and Hα+[N II] were used to measure the structure and excitation in the extended emission regions surrounding the active nucleus. A weak bar and two short spiral arms were detected in the galaxy itself, and no evidence of enhanced star formation was found in the circumnuclear region. The two-sided ionization cone region contains a variety of complex features, including two arc-like structures within $\sim 2''$ of the nucleus that appear to be associated with the extended radio continuum emission in the sense that the radio lobes lie just inside the centroids of the emission-line arcs. They interpret these arc-like features as kiloparsec-scale bowshocks analogous to what is seen in the nearby Sy2 galaxy NGC 1068. They also find multiple emission-line components at regular intervals on either side of the nucleus that are suggestive of episodic ejection of radio plasma from the nucleus. Work on other Seyfert galaxies in this study is proceeding.

Peterson, Pogge, Wagner, and Bertram are continuing a long-term program of spectroscopic monitoring of selected Seyfert galaxies. These data are being used in "reverberation mapping" studies of the broad-line region in active galactic nuclei. Spectroscopic observations of these galaxies are obtained with the CCD spectrograph on the Perkins 1.8-m telescope on an approximately weekly basis. Much of this monitoring is carried out in support of multiwavelength monitoring campaigns undertaken as part of the AGN Watch Project.

10.2 The International AGN Watch

The International AGN Watch is a large, informal consortium of AGN observers; Peterson is one of the organizers of AGN Watch activities. During the last year, the AGN Watch has carried out major multiwavelength monitoring programs on NGC 4151 and Fairall 9. A new program on the broad-line radio galaxy 3C 390.3 is scheduled for 1995.

Peterson served as principal investigator on an International AGN Watch campaign to monitor the Seyfert 1 galaxy NGC 5548 intensively with HST, IUE, and ground-based telescopes during the spring of 1993. The preliminary results of this program have now been submitted for publication. This program, a follow-up study to the 1988 – 89 IUE/ground-based program, was undertaken in order to address questions that require both higher temporal resolution and higher signal-to-noise ratios than were obtained in the first campaign. IUE spectra were obtained once every two days for a period of 74 days beginning on 1993 March 14, and during the last 39 days of this period observations were also made with the HST Faint Object Spectrograph (FOS) on a daily basis. Ground-based observations were obtained during the period 1992 October to 1993 September, although much of the data are concentrated around the time of the satellite-based program. These data constitute a fifth year of intensive optical monitoring of this galaxy by the AGN Watch. During the HST portion of the monitoring campaign, the 1350 Å continuum flux varied by nearly a factor of two. In other wavebands, the continuum showed nearly identical behavior, except that the amplitude of variability is larger at shorter wavelengths, and the continuum light curves appear to show more short time-scale variability at shorter wavelengths. The broad emission lines also varied, with amplitudes that are slightly smaller than the UV continuum variations and with a small time delay relative to the UV continuum. It is found (1) that the ultraviolet and optical continuum variations are virtually simultaneous, with any lag between the 1350 Å continuum and the 5100 Å continuum amounting to less than about one day, (2) that the variations in the highest ionization lines observed, He II λ1640 and N V λ1240, lag behind the continuum variations by somewhat less than 2 days, and (3) that the velocity field of the C IV-emitting region is not dominated by radial motion. The results on the C IV velocity field are preliminary and quite uncertain, but there are some weak indications that the emission-line wings ($|\Delta v| \geq 3000$ km s^{-1}) respond to continuum variations slightly more rapidly than does the core. The optical observations show that the variations in the broad Hβ line flux follow the continuum variations with a time lag of around two weeks, about twice the lag for Lyα and C IV, as in the 1988 – 89 program. However, the lags measured for Lyα, C IV, and Hβ are each slightly smaller than previously determined.

10.3 QSO Surveys

Everett and Wagner completed the classification and measurements of spectra of 124 objects selected from the Case Low Dispersion Northern Sky Survey. The spectra were obtained at the Steward Observatory 2.3-m telescope with the pulse counting Reticon system. The objects were selected from the Case Stellar Objects and consist of unresolved point sources having either a featureless blue continuum or emission features in their objective prism discovery spectra. Forty-six of the objects are confirmed QSOs with redshifts ranging from 0.20 to 2.97. Several QSOs exhibit absorption features arising from intervening material. Three of the objects are LINERS or H II region galaxies. Most of the remaining objects are galactic stars.

Osmer completed his work with S. Warren (Imperial College) and P. Hewett (Cambridge) on a wide-field multicolor survey for high-redshift quasars. They used UK Schmidt plates in six bands from U through I to cover an effective area of 43 sq. deg. With subsequent spectroscopy at the AAT and CTIO, they compiled a complete, well-defined sample of 86 new quasars with $2.2 < z < 4.5$. Extensive modeling of the selection process for quasars combined with simulations of quasar spectra to allow for both hydrogen absorption along the line of sight and differences in the continuum slope and emission-line strengths allowed them to derive the luminosity function and its dependence on redshift. They found that positive evolution of the luminosity function (which is very strong for $z < 2$) continues from $z = 2$ to approximately $z = 3.3$. However, at redshifts larger than 3.3 there is a marked decline in the space density of quasars, consistent with Osmer's estimate in 1982.

Osmer, A. Porter (deceased) and R. Green (NOAO) completed a study of the luminosity effects and emission-line properties of radio- and optically-selected quasars with $0 < z < 3.8$ based on new ground-based data and the IUE archives. Their sample covered a factor of 40 in emitted luminosity for $z > 3$, a range of 10^3 in luminosity for $z < 1$, and a slice of constant luminosity in the luminosity-redshift plane for $0 < z < 3.8$. They found a pronounced Baldwin effect (weakening of emission lines with increasing luminosity) in the line of C IV 1549 Å and other principal UV lines except for N V 1240 Å and the Si IV+O IV] feature at 1400 Å. Furthermore, the component that varies with luminosity has a narrower FWHM than the average line width and is similar in several respects to the first component in the principal component analysis carried out by Francis et al. on the Large Bright Quasar Survey. At constant luminosity, however, there is no evidence for redshift-dependent spectral changes, Baldwin or otherwise, for $1.8 < z < 3.8$. They note that the large N V to Lyα ratio and the behavior of the He II 1640 Å line are consistent with the arguments of Hamann and Ferland for the N/C ratio being enhanced in high-luminosity quasars with $z > 3$.

Osmer, P. Hall (Arizona), Green, Porter, and Warren are working on a new, deep multicolor survey carried out with a 2048×2048 pixel CCD at the KPNO 4-m telescope. They covered 0.83 sq. deg. with six filters in the spectral range 0.34 to 0.86 μm to a 5σ limit per exposure of $B = 23.8$. Application of FOCAS to the images yields a catalog of 21,375 stellar objects, for which they have positions, magnitudes, and error estimates in the six bands. Multifiber spectra with the Hydra instrument at KPNO have been obtained for 350 candidates. To date approximately 40 quasars with $0.6 < z < 4.3$ and 40 compact, narrow emission-line galaxies with $0.1 < z < 0.8$ have been identified, along with a variety of unusual stars at high galactic latitude. They are working to estimate the luminosity function of quasars at higher redshift and lower luminosity than has been done previously to investigate whether luminosity evolution is the proper characterization for $z < 2$ and whether the decline in space density for high-luminosity quasars at $z > 3$ also holds for fainter ones.

11 Astrophysical Theory

11.1 Stellar Evolution

Pinsonneault, in collaboration with B. C. Chaboyer (CITA) and P. Demarque (Yale), investigated the behavior of stellar models which include both rotation and microscopic diffusion. This work was done as part of Chaboyer's Ph.D. thesis. Rotational mixing tends to reduce composition gradients, while microscopic diffusion produces a significant helium gradient below the surface convection zone of solar-type stars. The degree to which mixing is inhibited by gradients in the mean molecular weight (μ) is a significant theoretical uncertainty; in standard stellar models such gradients occur only in the deep interior and surface diagnostics are insensitive to the model assumptions. This is no longer true in models which include both diffusion and rotation. They found that rotational mixing was not able to completely remove envelope composition gradients caused by diffusion, i.e., that a helium composition gradient is present below the surface convection zone in solar analogues. At the same time, there is clear evidence for progressive lithium depletion in solar analogues on the main sequence, which indicates that mixing is occurring in the presence of such μ gradients. This class of models shows promise for providing an empirical determination of a model property which is difficult to constrain from first principles.

The angular momentum evolution and light-element depletion patterns of low mass stars were also examined; good agreement with the overall lithium depletion pattern in open clusters was found. Neither the dispersion in lithium seen in cool Pleiades stars, nor the mass dependence of the spindown of rapid rotators, is explained by these models; further work on the angular momentum evolution of young stars is in progress.

Pinsonneault and C. Bailyn (Yale) examined the luminosity functions of blue stragglers produced by collisions and binary mergers. They concluded that collisions tend to produce relatively more bright than faint stragglers relative to binary mergers, and that these distributions can be distinguished with moderate sample sizes. The 47 Tuc luminosity function and formation rate were found to be consistent with the collision scenario. In M3 the inner stragglers and outer stragglers have different luminosity functions; the inner straggler luminosity function is consistent with collisions while the outer straggler luminosity function is consistent with that expected from binary mergers. The large number of stragglers in the inner regions of M3 probably requires an enhancement of the collision rate by interactions involving primordial binaries.

Pinsonneault and J. N. Bahcall (IAS) examined the impact of the diffusion of heavy elements on the solar neutrino fluxes. A significant increase in the neutrino fluxes for the ^{37}Cl and Kamiokande detectors was found, further worsening agreement between experiment and the predictions of the standard solar model. The impact of recent changes in opacity tables, the assumed solar mixture of heavy element abundances, and nuclear reaction cross-sections was also examined, and different prescriptions for the diffusion coefficients were compared.

11.2 Structure of the Milky Way

Gould continued his work in several areas of cosmology and galactic structure with current emphasis focused on gravitational lensing. He is developing new methods to extract additional information from the microlensing events that are being detected in three ongoing experiments with the aim of measuring the masses, positions, and velocities of the lenses. He is also developing new applications of lensing studies including a method to measure the transverse velocities of galaxies at 100 Mpc.

Gould is also working on the interpretation of galactic star counts. New data from HST make star counts possible to $I \sim 25$, about 5 magnitudes fainter than was possible a few years ago. Gould is currently using data from the repaired HST to study galactic structure in this regime.

Another of Gould's interests is statistical methods in astronomy. He has developed a method for estimating errors analytically and has applied this method to diverse astrophysical problems.

11.3 Atomic Processes

Pradhan, Nahar, Zhang, Bautista, and Peng are involved in extensive calculations of atomic processes in astrophysical sources such as electron collisions, photoionization, and recombination. Two major international projects, the Opacity Project and the Iron Project, are in progress. Also in progress are several applications of the new atomic data to the spectral analysis of ground-based and space-based observations (IUE, HST, EUVE etc.). The large-scale quantum mechanical calculations are being done on the Cray Y-MP 8/64 and the massively parallel Cray T3D at the Ohio Supercomputer Center.

A group of approximately 25 atomic physicists and astrophysicists launched the Opacity Project about a decade ago with the aim of calculating accurate astrophysical opacities – a task which requires new atomic physics and computational techniques. The resulting opacities are up to factors of 2-5 higher than the opacities previously available from Los Alamos, and in broad agreement with another recent calculation by a group at Livermore. Several outstanding problems in astronomy have now been solved as a result of the new data. Most notable is the determination of Cepheid pulsation properties and period ratios upon which rests a crucial link in the cosmological distance ladder. The seminal paper on the Opacity Project is currently in press. Further significant refinements of the atomic physics and opacities are being carried out by Pradhan collaborators in the Opacity Project.

The new opacities will not only be useful in the modeling of stellar interiors, but also in the modeling of emitted spectra of astrophysical sources where thermal equilibrium may prevail. One such example is the analysis of white dwarf spectra observed with the Extreme Ultraviolet Explorer.

Analogous to the Opacity Project that deals with radiative processes, a new project called the Iron Project has been initiated to deal with collisional processes that determine emission spectra in most wavelength ranges, from the far infrared to the hard X-ray. In the initial phase the emphasis is on all ions of iron. Nahar, Zhang, Bautista, Peng, and Pradhan are currently carrying out calculations for Fe I–Fe VI. In addition, the Iron Project work by the Ohio State team has initiated work on other iron-peak elements, including nickel, cobalt, manganese, chromium, titanium.

Eventually the Iron Project aims to obtain definitive atomic parameters for all the iron-group elements. A crucial application of this work will be in the accurate determination of stellar and non-stellar abundances of heavy elements. These calculations require the development of new theoretical methods and codes, particularly for the relativistic effects considered in the Breit-Pauli and the Dirac R-matrix formulations. Collision strengths, rates, and line intensities for spectral excitation are being calculated, including fine structure, and are applied to astrophysical plasmas under non-LTE conditions. Examples of work recently completed are B-like ions (IR and UV lines); S II (optical and UV lines); and Fe II (IR, optical, and UV lines). Zhang and Pradhan are currently engaged in extensive relativistic and non-relativistic calculations for Fe III, Fe XXII, and Fe XXV.

Determination of abundance and ionization structure in astrophysical sources may depend on the knowledge of electron-ion recombination rates, for example in the interstellar medium. At the present time in order to obtain total effective recombination rates one needs to consider three different types of atomic processes: (i) radiative recombination, (ii) low-temperature dielectronic recombination, and (iii) high-temperature dielectronic recombination. Nahar and Pradhan have now developed a computationally unified theoretical treatment that yields total electron-ion recombination rates, at all temperatures, incorporating all three processes.

R-matrix calculations are continuing on new cross sections for photoionization and transition probabilities that, as has recently been shown by Nahar and Pradhan, differ considerably from presently available data usually calculated in simpler approximations such as in the central field model. The most recent work is on Fe II and Fe V under the Iron Project where they find that the ground-state photoionization cross sections differ from earlier ones by up to two orders of magnitude. Partial cross sections for ionization into excited states of the residual ion are also being calculated. These are important in non-LTE modeling of astrophysical sources.

Bautista has initiated calculations on Fe I and Fe V, with particular emphasis on the important radiative transition probabilities for Fe I that are required to determine the iron abundance in the Sun.

Nahar has completed accurate calculations for the oscillator strengths of Fe II including fine structure. The results indicate significantly higher accuracy, when compared with experimental values, than the data by Kurucz.

In collaboration with S. Vennes (Center for EUV Astrophysics), Pradhan is calculating new monochromatic opacities to model the observed spectra of H-rich DA white dwarfs. It is found that iron dominates the spectrum. Apparently the gravitational dispersion on the surface of the hot white dwarf is affected by radiation pressure due to the extensive atomic structure of iron (a fact that also emerged from the dominant role of iron in the pulsation of Cepheids). Radiation pressure holds up iron against gravitational settling in the early atmospheres of white dwarfs, while lighter elements with less atomic structure sink in. This should be an important first application of the monochromatic opacities from the Opacity Project (as opposed to the Rosseland mean opacities used in stellar models).

Peng and Pradhan recently showed that the ground state fine-structure transition $^2P^o_{1/2} - ^2P^o_{3/2}$ in the boron-like ions C II, N III, O IV, Ne VI and Mg VIII at 157 μm, 58 μm, 26 μm, 7.6 μm and 3.0 μm should undergo stimulated emission at temperatures and densities prevalent in novae shells, AGNs and hotter H II regions ($T > 2 \times 10^4$ K).

Using the new atomic data for boron-like ions calculated by Zhang et al., Peng and Pradhan have calculated line ratios for prominent UV lines in the spectra of C II, N III, O IV, Ne VI, Mg VIII, Al IX, Si X, and S XII. Cooling functions were also calculated for the IR transitions in these ions.

The new atomic data base from the Opacity Project is being interfaced with the photoionization modeling code CLOUDY by G. Ferland and D. A. Verner (U. Kentucky), Nahar and Pradhan as part of a Long Term Space Astrophysics program supported by NASA. Future work will involve the interpretation of observations being carried out by Peterson and collaborators. Owing to the extent and structure of the new data it is required that accurate numerical methods be developed in order to compute photoionization models without loss of precision. The theoretical work should set a precedent for future applications of atomic physics into astronomy on a large scale.

It is of considerable interest to determine the iron abundance in supernova 1987A and to correlate it with the other intermediaries in the nuclear chain, i.e. nickel and cobalt. Ground-based IR observations from days 936 to 1445 have been analyzed by Bautista et al., employing accurate new Fe II excitation rates by Pradhan and Zhang. The total Fe mass in the ejecta is estimated to be 0.04 $M_\odot$, considerably lower than that predicted by nucleosynthesis models and suggested by optical light curves. Fe concentration in thick clumps and grain depletion are possible explanations. Further work is in progress to calculate accurate atomic data for Ni II and Co II to estimate or constrain the nickel and cobalt abundances in the supernova.

Bautista, D. E. Osterbrock (Lick Observatory), and Pradhan have recently analyzed the optical and near IR spectra of Fe II from the Orion nebula using the Pradhan and Zhang data. It is found that the electron densities in the Fe II emitting regions, perhaps close to the ionization front, are considerably higher, $N_e \approx 10^5 - 10^7$

cm^{-3}, than determined previously from O II and S II observations. Further work is in progress on the analysis of Fe III observations in collaboration with Pogge and DePoy.

12 Nuclear Astrophysics

12.1 Abundances of Light Elements

During his visit to the Institute of Astronomy, Steigman concentrated on analysis of the abundances and evolution of the light elements (D, ^{3}He, ^{4}He, and ^{7}Li). The goal of this research has been to infer from current observations the primordial abundances of these elements produced during Big Bang Nucleosynthesis (BBN). This research tests the consistency of the standard hot Big Bang model, places bounds on the present density of nucleons (baryons), and constrains extensions of the standard model of particle physics.

The light elements D, ^{3}He, and ^{7}Li serve as "baryometers" in that their primordial abundances may be used to bound the present ratio (η) of nucleons to photons. Steigman responded to the announcement of a possible detection of D in the absorption spectrum of a high-redshift QSO by noting that the high abundance inferred was entirely consistent with BBN (for a low value of η), but inconsistent with the presently observed abundances of D and ^{3}He in the context of stellar and Galactic chemical evolution. He then suggested that the putative D absorption feature might be a weak hydrogen absorber at the "wrong" velocity.

Steigman has continued his work with M. Tosi (Bologna) which follows the evolution of D and ^{3}He in the context of galactic evolution. The goal of this study is to achieve results which are robust in the sense of having minimal reliance on unconstrained model parameters. This approach has permitted them to bound η from above and below using solar system and interstellar data. However, a problem looms on the horizon in that the models which incorporate ^{3}He production in $\sim 1-3M_\odot$ stars all lead to production of more ^{3}He than is observed, and a ^{3}He gradient with galactocentric distance opposite to that observed.

Since ^{7}Li is observed in the oldest, most metal-poor stars in the Galaxy, corrections for evolution are negligible. However, during their long lifetimes these Population II stars may have destroyed or diluted their surface abundance of lithium so that the prestellar abundance may exceed that observed. To probe this possibility, Steigman utilized the results of the search for lithium in the LMC which relied on SN 1987 A to provide the bright background source against which ^{7}Li absorption was sought. None was found, and Steigman used the resulting upper limit, along with the observed absorption due to LMC potassium, to bound the LMC (and hence primordial) abundance of lithium. This computation was done in a manner which avoids highly uncertain ionization and gas-phase depletion corrections. Steigman's results are that the LMC lithium abundance is no more than 50% of solar, and that the primordial value is likely to be that inferred from the surfaces of the warmest, most metal-poor stars.

The abundance of ^{4}He provides the keystone for testing the internal consistency of the BBN. Since the inferred primordial abundance is relatively small, it places an interesting upper bound on η and significant constraints on physics beyond the standard model. K. A. Olive (U. Minnesota) and Steigman analyzed the recent observational data on ^{4}He in metal-poor giant extragalactic H II regions to derive bounds to the primordial abundance (mass fraction) of helium. They find $Y_P \leq 0.243$. From this bound they confirm the consistency of BBN provided that $\eta \leq 2.5-3.9\times10^{-10}$. For the number of equivalent light neutrino species, they find $N_\nu \leq 2.7-3.1$ which, for $N_\nu < 3.0$, may suggest a massive unstable tau neutrino. The bound $N_\nu \leq 3.1$ is consistent with the standard model of particle physics but severely constrains possible extensions.

In the Inhomogeneous Models (IMs) of Big Bang Nucleosynthesis, reactions through the short-lived nucleus ^{8}Li can be extremely important in synthesizing the nuclides heaver than ^{9}Be. In particular, ^{8}Li$(\alpha,$n$)^{11}$B is thought be on the dominant pathway that produces nuclides heaver than ^{11}B, so its cross section is crucial to accurate abundance predictions in this model. Boyd and collaborators have measured this cross section down to energies in the middle of the energy range relevant to BBN. This measurement was performed with the radioactive beam facility at the University of Notre Dame. The ^{8}Li beam from this facility was directed into an unusual heavy ion detector that used He as the detector gas, thereby allowing observation of reaction events as they occurred in the detector. This experiment will constitute the Ph.D. dissertation work of OSU student Xinyang Gu.

Since it is the abundance of ^{8}Li during BBN that determines how much nucleosynthesis can occur through it, reactions which might destroy ^{8}Li are also important to accurate predictions. Thus reactions between ^{2}H, which is relatively abundant during BBN, and ^{8}Li were also studied at the University of Notre Dame by Boyd and collaborators. The heavy reaction products from these reactions were detected with conventional particle detector telescopes. It was found that the ^{8}Li(d,t)^{7}Li reaction had a considerably larger cross section than had been anticipated, and that the inclusion of this reaction into the BBN codes is essential. The ^{8}Li(d,n)^{9}Be reaction was found to have an observable, but fairly small, cross section, and thus it can produce some ^{9}Be in BBN. This work will constitute the Ph.D. dissertation of OSU student Margaret Farrell.

However, the ^{8}Li(d,n) reaction to ^{9}Be excited states would not have been observed in the experiment done to the ^{9}Be ground state, and it could be significant in the destruction of ^{8}Li. Since all ^{9}Be excited states decay into a neutron and two alpha particles, a study of these latter cross sections was performed by detecting the two alpha particles in coincidence. The data for ^{8}Li(d,n)^{9}Be (excited states) do indeed suggest a considerably larger ^{8}Li destruction cross section than observed for any other reaction. This experiment will comprise the Ph.D. dissertation of a University of Notre Dame student.

12.2 Beta-Neutron decays of ^{17}B and ^{19}C

The IMs of BBN have the capability of producing much larger abundances of the nuclides heavier than ^{12}C than are produced in the Standard Model. However, since the reactions that would synthesize those nuclei operate just beyond the neutron-rich edge of stability, reactions such as ^{18}N(n,γ)^{19}N and ^{16}C(n,γ)^{17}C can be important to the predictions of these models. While the study of interactions between neutrons and short-lived nuclei such as ^{18}N or ^{16}C are experimentally intractable, one can learn something about the cross sections for these reactions by observing states in the final nuclei just above their neutron emission thresholds. Boyd and collaborators have used the radioactive beam facility of RIKEN (Japan) to produce beams of ^{19}C and ^{17}B. These nuclides were stopped in a scintillator which then observed their subsequent beta-decay. This produced a start signal for a time-of-flight system with a flight path of about 1.25 m to "neutron walls," large detectors that observed neutrons emitted following the beta-decays. Several neutron groups were observed from decays of both nuclides, indicating states within 3 MeV of the threshold for neutron emission. Unfortunately, these states are probably too high in energy to have much influence on the cross sections at energies appropriate to BBN. However, the nonexistence of lower lying states suggests that a direct reaction mechanism dominates the low energy cross section, also useful information. The analysis for these experiments is being performed jointly by Gerhard Raimann, an OSU postdoctoral fellow, and A. Ozawa, a postdoctoral research associate at RIKEN.

12.3 The p-Process Nuclides ^{92,94}Mo and ^{96,98}Ru

In a combined theoretical-experimental effort, Boyd and his collaborators studied the stellar conditions required to synthesize these p-process nuclides. The abundances of the two molybdenum isotopes are anomalous in that p-process nuclides, typically produced either by rapid proton captures on lighter nuclides or by photonuclear reactions on heavy nuclides, are quite rare except for these two nuclides. Thus far their production has evaded explanation. They concluded that their abundances become plausible if they are produced by rapid proton captures in a very hot ($t > 1 \times 10^9$ K) environment that contains H. Such environments have been suggested as existing either in the periphery of accreting neutron stars, or in Thorne-Zytkow objects.

Their reaction network produced the correct abundance ratios for the two molybdenum isotopoes over a broad range of time and temperature, and the resulting abundances were about 50 times solar. If the site is assumed to be a Thorne-Zytkow object, the matter being processed would have already undergone s-processing, so would be enriched by an additional factor of 50 or so in the seed nuclides for synthesizing the light Mo isotopes. Thus resulting overabundances are quite plausible.

However it was found that the network calculations gave the correct abundance ratios only if the nucleus ^{95}Ag was stable to proton decay. Boyd and collaborators performed an experiment with the radioactive beam facility at Michigan State University to search for this nuclide; it was observed. The flight time through the radioactive beam facility is sufficiently long that any nuclei observed must undergo β-decay rather than baryon emission. Thus this point seems to be satisfied. Further tests are planned to study lifetimes and decay modes of the precursors of the light ruthenium isotopes, ^{96}Cd and ^{98}Cd, which also provide important tests for this model. This work comprised the Ph.D. dissertation of OSU student Michael Hencheck.

13 Cosmology

Scherrer continued his research on the large-scale structure of the universe. He and J. Fry (Florida) have examined the evolution of the skewness of the density field in non-Gaussian models. The skewness measures the lowest-order deviation from linear behavior. Using second-order perturbation theory, they have derived an expression for the skewness evolution in arbitrary non-Gaussian models. This work is important because recent observations have given an indication of the skewness of the distribution of galaxies, and their work can help to clarify whether the observations are consistent with non-Gaussian initial conditions. Scherrer is beginning work with J. Frieman (Fermilab) to use these results and Frieman's analysis of the APM data to see which non-Gaussian models can be ruled out by the observations. This work is still in its preliminary stages.

Scherrer has completed work with P. Catelan (Oxford) on a study of velocity fields in non-Gaussian models. Scherrer's earlier work indicated that the velocity distribution tends to be Gaussian even when the underlying density field is non-Gaussian. The new work with Catelan indicates that the difference in velocities measured at two points provides a better tracer of non-Gaussian behavior than does the one-point velocity distribution.

OSU student A. de Laix and Scherrer have been examining the self-interacting dark matter model of Carlson et al. Previous investigations of this model ignored the importance of free-streaming of the dark matter particles. They have included this effect in a calculation of the density perturbation spectrum produced in this model. Their results indicate that the model has too little small-scale power and is unlikely to produce an acceptable distribution of galaxies. de Laix has also begun work on his dissertation project, a study of isocurvature hot dark matter models, using the computer code he developed for the self-interacting dark matter project.

With OSU student A. Protogeros, Scherrer has been examining a simplified model for the evolution of non-Gaussian density fields. Very little is known about the general differences between gravitational clustering in non-Gaussian versus Gaussian models. This is an extremely difficult problem, so they have been examining a special case: the evolution of density fields in one dimension. In this case, an exact solution to the equations of motion exists, called the Zel'dovich approximation. They have applied the Zel'dovich approximation to examine how the distribution of densities evolves in time for a variety of non-Gaussian models. In addition to providing a clue to the general behavior of three-dimensional models, their results would be applicable to cases where the growth of gravitational perturbations is dominated by one-dimensional collapse into sheet-like structures, a type of collapse which is known to occur in some models.

R. Schaefer (Bartol Institute) and Scherrer have finished their investigation of the conditions necessary to produce a Gaussian Sachs-Wolfe effect (the Sachs-Wolfe effect is the source of the fluctuations observed by COBE). Using the central limit theorem, they were able to show that a wide class of non-Gaussian density fields will produce a Gaussian Sachs-Wolfe effect. This result limits the usefulness of the COBE observations in determining whether the initial density field was Gaussian or not.

Scherrer has continued his research on the applications of particle physics to cosmology, including both the evolution of the early universe and the formation of large-scale structure. Much of his early work was concentrated on non-standard models for primordial nucleosynthesis. J. Applegate (Columbia U.), C. Hogan (U. Washington), and Scherrer provided the first investigation of the effects of the QCD phase transition on primordial nucleosynthesis; this work led to a great deal of interest in the subject. Scherrer has also investigated primordial nucleosynthesis with neutrino degeneracy and light-element production from massive neutrino decay. In collaboration with J. Cline (McGill U.), S. Raby (OSU), and D. Seckel (Bartol Institute), Scherrer has examined primordial nucleosynthesis in a model in which baryogenesis from gravitino decay occurs at very low temperatures.

Scherrer has also examined a number of topics related to cosmic strings. He and W. Press (Harvard) have produced a numerical code to simulate the dynamical evolution of cosmic string loops in order to investigate loop fragmentation. J. M. Quashnock (U. Chicago), D. Spergel (Princeton U.), Press, and Scherrer used the loop fragmentation code as a cosmic string "laboratory" to study the properties of realistic loop trajectories, in particular, their angular momentum, gravitational radiation, and electromagnetic self-interaction; they discovered that the final string trajectory properties were independent of the initial conditions, and they derived an expression for the gravitational radiation rate from such strings, a number which is crucial in limiting the cosmic string energy scale from observations of the gravitational radiation background.

White-noise Gaussian density perturbations arise in a variety of models. Scherrer has investigated some of the consequences of such fluctuations with T. Vachaspati (Case Western Reserve U.). They have also examined the formation of pregalactic objects from white-noise perturbations. Since white-noise initial conditions cannot lead to acceptable large-scale structure through gravitational evolution alone, Scherrer has investigated the explosion model with generic initial conditions for the power spectrum, in which the explosion seeds are produced gravitationally by the dark matter perturbations.

Scherrer has also been examining non-Gaussian models for the formation of large-scale structure. Villumsen, E. Bertschinger (MIT), and Scherrer have investigated hot dark matter models with generic primordial "seeds." Their results indicate that such models can give a distribution of galaxies in good agreement with the observations, allowing them to resurrect massive neutrinos as an acceptable dark matter candidate. Scherrer and M. Beaky (OSU) have examined the topology of the isodensity surfaces in this model and plan to subject this model to more exhaustive testing, including a study of the formation of dwarf galaxies in the void regions and an examination of the distribution of Abell clusters. A great deal is known about the statistical properties of Gaussian density perturbations, but almost no work has been done on non-Gaussian perturbations such as those from seed masses.

Bertschinger and Scherrer have developed a general treatment of the statistical properties of density perturbations in seed mass models, including the power spectrum, the n-point mass correlation functions, and the (non-Gaussian) single-point distribution of densities. Many different seed mass models have been developed recently, and this work will provide a base of information for other workers to build on when new models are proposed in the future. Scherrer is presently investigating peculiar velocity fields in a number of non-Gaussian models, including both seed models and "local" non-Gaussian fields produced by a local transformation on a Gaussian field. With A. Melott and S. Shandarin (U. Kansas), Scherrer has developed a quantitative measure for phase correlations in density fields. Such correlations exist in any non-Gaussian set of initial conditions, but they also develop as Gaussian fields evolve gravitationally.

Ryden has investigated the possibility of using the cosmological distortion of voids in redshift space to estimate the value of the deceleration parameter q_0. If $q_0 > -1$, then voids in redshift maps will become larger and more elongated along the line of sight as the redshift increases. After devising a method for estimating the axis ratios of voids by fitting ellipsoids (or ellipses, in the two-dimensional case), Ryden measured void distortions in synthetic universes with no peculiar velocities. In the absence of peculiar velocities, a 360 degree redshift slice would have to reach a depth of $z \approx 0.15$ in order to distinguish between a universe with $q_0 = -1$ and one with $q_0 = 1/2$. Further investigations of n-body simulations will reveal whether distortions in redshift space which result from peculiar velocities are large enough to mask the cosmological distortions.

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