# The Ohio State University
## Department of Astronomy
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### Abstract

This report covers the period September 1994 through August 1995.


## 1 Personnel

During the period covered by this report, the regular academic staff of the Department of Astronomy included Richard N. Boyd, Darren L. DePoy, Jay A. Frogel, Andrew P. Gould, Eric Herbst, Gerald H. Newsom, Patrick S. Osmer (chairman), Bradley M. Peterson, Marc Pinsonneault, Richard W. Pogge, Anil K. Pradhan, Barbara S. Ryden, Kristen Sellgren, Gary Steigman, Donald M. Terndrup, David H. Weinberg, and Robert F. Wing. Michelle Kaufman, Robert J. Scherrer, and Terrence P. Walker performed astronomical research while holding appointments in the Physics Department. Michael Savage was manager of the Astronomy Department computer resources. Thomas Burns was Director of the Perkins Observatory. Emeritus members of the Astronomy Department are Eugene R. Capriotti, George W. Collins II, Stanley J. Czyzak, Phillip C. Keenan, Geoffrey Keller, Walter E. Mitchell, Jr., William M. Protheroe, and Arne Slettebak.

The staff of the Astronomical Instrumentation Facility (AIF) 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, Robert Stonebreaker, and Edward J. Teiga. Byard retired from his full-time position in June 1995 and has been rehired into a half-time position.

In Flagstaff, R. Mark Wagner held the position of Research Scientist, while Ray C. Bertram was Research Associate.

Postdoctoral researchers in astronomy during this period included Suchitra Balachandran, John S. Carr, Sultana Nahar, Alice Quillen, João Santos, Ignaz Wanders, and Hong Lin Zhang.

Graduate students in the OSU astronomy department included Babar Ali, Manuel A. Bautista, Robert D. Blum, Mark E. Everett, Cheongho Han, Mark L. Houdashelt, Anita Krishnamurthi, Leslie E. Kuchinski, Nancy Jo Lame, Tina Mailloux, Vijay Krishna Narayanan, J. Michael Owen, Jianfang Peng, Piotr Popowski, Solange V. Ramírez, Ani R. Thakar, and Glenn P. Tiede. The Ph.D. degree was awarded to Blum, Houdashelt, and Lame.

## 2 Instrumentation

The infrared camera MOSAIC has had two successful runs at the Michigan-Dartmouth-MIT Observatory. Due to a delay in optical fabrication, both runs were with the provisional all-reflective modified Offner optics. All elements for the f/7 lens system have now been received and a run with the refractive collimator, all mechanisms, and the f/7 camera is scheduled for January 1996.

OSU-supplied hardware for the Lowell Observatory $2048 \times 2048$ CCD system has been completed; unfortunately Lowell has not as yet obtained a satisfactory detector. Pocket-pumping tests for their first "science grade" detector revealed of order 1000 traps; Lowell's second detector had a large light emitting defect in a central location.

Electronics for a new detector for the OSU Imaging Fabry-Perot Spectrometer and the CCD Spectrograph have been completed. One of the $1200 \times 800$ pixel detectors thinned and anti-reflection coated by M. Lesser (Steward Obs.) will be installed this fall for use on the Fabry-Perot with the UV transmitting optics. A new dewar for use with the folded Schmidt spectrograph camera will be completed in the spring of 1996.

## 3 Stars and Stellar Evolution

### 3.1 Be Stars

Slettebak is continuing his study of Be stars at high galactic latitude, in collaboration with Wagner and Bertram. CCD spectra of 10 program stars and 10 standard stars were obtained with the 1.8m Perkins telescope in Flagstaff in November 1994 and July 1995. Equivalent widths of prominent spectral lines and radial velocities are being measured to determine the spectral types and to ascertain whether these stars are "runaway" stars or are peculiar in any other way.

### 3.2 Young Stars and Star Formation

Pinsonneault, with Krishnamurthi and S. Barnes (Yale), has explored the sensitivity of the surface rotation of young stars to changes in initial conditions, angular momentum loss, and angular momentum transport. They find that slow rotators can naturally be produced if disks regulate T Tauri star rotation, and that the disk lifetimes can be modest (approximately a few million years) if solid body rotation is not enforced at young ages. A mass-dependent loss law or set of initial conditions is the most likely explanation of the mass dependence of the rapid rotator phenomenon seen in open cluster stars.

Infrared spectroscopy of MK spectral standards can provide a guide for spectral classification of young stars in molecular clouds. Ali, DePoy, Carr, Frogel, and Sellgren have obtained moderate resolution ($\lambda/\Delta\lambda \approx 1400$) spectra of 33 luminosity class V MK spectral standards in the 2.15 – 2.35 $\mu$m region. They found that the equivalent widths of H I, Na I, Ca I, and Mg I features, and the strength of $^{12}$CO molecular absorption, are useful effective temperature ($T_{\rm eff}$) diagnostics. Future work will expand on these results by exploring the effects of surface gravity and metallicity on the observed strengths of the features.

Hertzsprung-Russell diagrams of newly formed clusters can provide estimates of masses and ages of individual cluster members when combined with theoretical PMS evolutionary tracks. Ali, as the major part of his dissertation research, is collaborating with DePoy, Sellgren, Carr, I. Gatley (NOAO), and K. Merrill (NOAO) to determine $T_{\rm eff}$, luminosities, extinction, and excess emission for young stars in NGC 2024. They have combined infrared spectra with $J$, $H$, $K$, and $L'$ photometry to develop an iterative scheme for simultaneously deriving $T_{\rm eff}$, the $K$ band luminosity, extinction, and excess emission of individual stars. Results are near completion for the first sample of $\sim$ 30 stars in NGC 2024; more observations are planned for November 1995.

Terndrup, Pinsonneault, Krishnamurthi, J. Stauffer (CfA), and S. Wolff (NOAO) have completed the first half of an extensive theoretical and observational project to determine the rotational properties of low-mass stars in the Pleiades and Hyades star clusters. The goal of the investigation is to obtain rotation measures ($v \sin i$) and rotational periods for stars with $M < M_\odot$ to constrain new theoretical models of the mass and age dependence of angular momentum loss mechanisms such as winds, core-envelope interactions, and photosphere/disk locking. In the initial observational effort, completed in early 1995, they obtained time-series photometry for a large number of low-mass stars in the Pleiades, and $v \sin i$ for about 50 faint stars in the Hyades. Preliminary results indicate that the rotational properties do not show a break across the mass below which stars are expected to be fully convective.

Wagner, in collaboration with R. Wichman, J. Kautter (Landessternwarte, Königstuhl) and others, has completed a study of the Taurus-Auriga star-forming region based on the ROSAT All Sky Survey; the purpose of this study was to search for undiscovered T Tauri stars and to estimate their X-ray luminosity function and spatial distribution. The study area comprises about 280 square degrees; identification of the X-ray sources was accomplished at the Perkins telescope and at the 2.2m telescope at Calar Alto. Two new classical T Tauri stars and 66 new weak-line T Tauri stars were discovered in the initial survey; 8 additional T Tauri stars (6 WTTS, 2 CTTS) were found based on subsequent ROSAT pointed observations. The WTTS in the survey were found to be distributed over the whole survey area, with a decline in the surface density from south to north; no clustering toward the population of previously known T Tauri stars was observed. The WTTS/CTTS ratio is at least 6.5 within the survey area but is approximately unity near the central part of the Taurus-Auriga star-forming region.

In a related study, Wagner, J. M. Alcalá (MPE), and others have presented the results of spectroscopic and photometric follow-up of the ROSAT All Sky Survey in the direction of the Orion cloud complex. In all, 820 X-ray sources were discovered in a 450 square degree region. Approximately 5% of the sources were identified with previously known pre-main-sequence stars. Optical spectra were obtained for 181 of these X-ray sources with the Perkins telescope and the 2.2m telescope at Calar Alto. Based on the presence of strong Li I 6707 Å absorption, 112 of these objects have been classified as new weak-line T Tauri stars. In addition, 24 dKe-dMe stars were found in this direction on the basis of the ROSAT All-Sky data.

### 3.3 Late Type Stars

In collaboration with C. Barnbaum and R. Stone, Keenan is preparing an atlas and catalogue of standard spectral types for carbon stars on the revised MK system. It will be available in a data bank and will also be published as a set of flux plots.

Wing and D. J. MacConnell (STScI) have obtained spectral classifications for approximately 160 low luminosity stars from narrow-band photometry of TiO and CN bands in the near infrared. The stars were selected for observation from Luyten's LHS catalog of proper-motion stars; most had no previous spectral information. Not surprisingly, most of these stars were found to be normal M-type main sequence stars. Some information on the spread in metallicity in this sample can be obtained from the TiO indices and continuum colors, since interstellar reddening should be negligible. No new dwarf carbon stars have been discovered in this program, but a few M dwarfs with enhanced CN have been found, which may be the result of moderate mass transfer from a former AGB companion.

Wing, MacConnell, and E. Costa (U. Chile) have continued their search for new late-type supergiants in the southern galactic plane. On a successful run at CTIO in April 1995, they obtained narrow-band photometry on Wing's eight color near-infrared system for 410 additional supergiant candidates, selected on the basis of their appearance on near-infrared objective prism plates. Of special interest is the region at galactic longitude

$\ell = 310 \rightarrow 330°$, where about 20 faint and extremely red stars have been found. Preliminary reductions indicate that they are heavily reddened M supergiants at distances of 4 to 5 kpc, much more distant than the optically visible spiral-arm features in this direction. These stars may help to define the structure of an arm of the Galaxy interior to the Sagittarius Arm.

Wing and K. Kelley (Ohio Wesleyan U.) have found that the two-micron source IRC–20062 is a Mira-type variable. Using narrow-band photometry collected during 6 observing runs at CTIO over a six year interval, they found a period in the range 420 – 460 days, an amplitude of 1.0 mag in I(104), and a spectral type range from M7.2 to M9.2. When earlier measurements of the K magnitude are taken into account, the most likely value for the mean period is 447 days.

### 3.4 Cataclysmic Variables, Binary Stars, and Novae

Wagner, S. Austin (ASU), S. Starrfield (ASU), S. Shore (Indiana U. South Bend), and G. Sonneborn (NASA) finished their analysis of an extensive set of UV and optical spectra of the classical nova V1974 Cygni 1992 from day 4 to day 540 after visual maximum. These data were obtained over a two year period with the IUE satellite and the Perkins telescope with CCD spectrograph; they comprised the dissertation research of Austin under the direction of Starrfield and Wagner. V1974 Cyg is classified as a neon nova, since forbidden emission lines arising from [Ne III] and [Ne V] are the strongest lines in the optical spectrum during the nebular stage of its evolution. To model the physical conditions and chemistry of the ejected envelope, the photoionization code CLOUDY was combined with multiparameter Monte Carlo fitting of the relative emission line strengths after correction for interstellar reddening. Enhancements in the abundances of He, N, O, Ne, and Fe with respect to the sun were found. In particular, the abundance of Ne derived from the data, $N_{Ne}/N_H = 250$, can only be explained by the mixing and ejection of core material from a massive $1.3M_\odot$ ONeMg white dwarf star.

Austin and Wagner have also finished the analysis and modeling of the emission line profiles in optical spectra of V1974 Cyg obtained at a resolution of 0.8 Å at the Perkins telescope. The castleated line profiles consisted of five primary components which were symmetric in velocity with respect to the line center, but with varying intensities. Permitted and forbidden lines as well as coronal lines exhibited nearly identical line profiles. The morphology of the profiles suggests that the line emission did not originate from a uniform spherical shell, but from filaments or blobs in a symmetric configuration around the central object. Early images of V1974 Cyg by the HST/FOC resembled those of DQ Her and suggested that the geometry of the ejected shell might consist of a combination of polar plumes, and equatorial torus, and tropical tori. Various combinations of these sources produced equally good fits to the line profiles. However, it was found that a configuration consisting of a polar cone and three rings at various latitudes viewed at an inclination angle of 85° reproduced the major features of the emission line profiles and simultaneously reproduced the major spatial features seen in the first HST/FOC images. The knots seen in the FOC image of the limb-brightened shell correspond in position to the limb-brightened equatorial and tropical rings, and the additional blob at the top of the image corresponds in position to the polar cone.

Wagner and DePoy analyzed the results of near-IR spectra of V1974 Cyg obtained with OSIRIS and the Perkins telescope on 1993 May 2, at a spectral resolution of 570. At that time, V1974 Cyg was well into its coronal emission-line phase. In agreement with previous IR spectra of V1974 Cyg, coronal lines arising from [Al IX], [Ca VII], [Ca VIII], [Ca IX], [Si VI], [Si VII], [Si IX], and [S IX] were present in the OSIRIS spectra. In addition, new coronal lines arising from other species were discovered. These included [P VII] and [P VIII] at 1.737 and 1.376 $\mu$m, [Si X] at 1.431 $\mu$m, and a blend of [S XI] and possibly [Cl XII] at 1.393 $\mu$m. The results also suggest that a coronal line at 3.08 $\mu$m may be due to [Cl X] in the strong OI isoelectronic sequence, rather than [Ca IX] as previously suggested. The enrichment in the ejecta of P and possibly Cl is consistent with recent hydrodynamic studies of accretion onto massive white dwarfs by Politano et al. and predicts that the mass of the white dwarf in V1974 Cyg should be near $1.3M_\odot$.

Everett and Wagner, during Everett's summer appointment in Flagstaff, finished the analysis and modeling of emission-line profiles obtained at high spectral resolution during the 1992 outburst of the X-ray nova black hole candidate GRO J0422+32. The optical spectra of most X-ray novae in outburst exhibit weak double-peaked emission lines superposed on broad absorption lines. Time series spectra obtained in October 1992 and January 1993, covering the 5.1 hour orbital period, show that He II 4686 Å exhibits a prominent S-wave component, with a semi-amplitude of 378 km/s superposed on a more symmetrical double-peaked profile. Radial velocity studies of the symmetrical profile give a semi-amplitude of about 56 km/s. Using these velocities and the results of line profile fitting to accretion disk models, they estimate that the mass of the compact object in GRO J0422+32 is $\sim 3 \pm 1M_\odot$, marginally consistent with a black hole.

### 3.5 Solar and Stellar Models

Pinsonneault, with S. Sofia (Yale), combined new experimental data on the measured solar oblateness with an exploration of the solar rotation as a function of depth and its sensitivity to theoretical uncertainties. Hydrodynamic mechanisms leave a degree of differential rotation with depth which is marginally consistent with the low observed oblateness, but which is not in accord with the rotation curve in the outer layers inferred from helioseismology. This implies that some other process (such as waves or magnetic fields) may be needed, but that the missing process probably operates over a relatively long time scale.

J. Bahcall (IAS) and Pinsonneault investigated the predicted solar neutrino fluxes of models which include both helium and heavy element diffusion. A series of improvements to the input physics was included, but the inclusion of metal diffusion is the single largest effect, producing a significant increase in the expected $^8$B neutrino flux. The effect of heavy element diffusion on helioseismology is currently being investigated in collaboration with D. Guenther (St. Mary's).

Pinsonneault, with C. Deliyannis (Yale), and L. Hobbs and J. Thorburn (Chicago), has been working on an observational reanalysis of the open cluster lithium data and a detailed study of the uncertainties in the predicted lithium depletion in standard stellar models. The main result is that the degree of PMS lithium depletion is constrained by observations in young open clusters, and that standard models cannot simultaneously fit young, middle-aged, and old systems. The deviations from the standard model predictions are less sensitive to errors in effective temperature than the absolute abundances are.

Pinsonneault and Narayanan investigated the range of primordial lithium abundances consistent with both the halo star and open cluster data. A new means of specifying the initial conditions was used (with a range of accretion disk lifetimes), and the sensitivity to the assumed solar initial angular momentum was explored. Most young stars are slow rotators, and if the distribution of initial conditions is similar in older systems, one expects to find a mean trend with modest internal dispersion (as seen in the Hyades) and a subpopulation with higher scatter. Old solar analogs will provide a crucial test of the primordial abundance, with typical abundances higher than the Sun indicating a relatively low initial abundance.

## 4 Interstellar Medium

In the last year, Herbst and collaborators have continued to investigate the effect of rapid neutral-neutral reactions on their chemical models of dense interstellar clouds. Although laboratory data for ion-molecule reactions at low temperatures are readily available, data for neutral-neutral reactions have only recently been taken for a small number of reactions. Rather than include only these systems, R. Bettens, H.-H. Lee (OSU Physics), and Herbst chose to add large classes of unstudied neutral-neutral reactions. They found that the addition of neutral-neutral reactions can dramatically change the calculated abundances of large molecules (with 5 – 10 atoms) but that this effect can be either negative or positive, depending on which classes of reaction are included. In general, the effects of reactions including atomic carbon are positive and those involving atomic oxygen negative. Since it is not currently understood why the rates of certain neutral-neutral reactions are large at low temperatures while others are quite small, Q. Liao (OSU Physics) and Herbst studied several reactions theoretically. They found that they could not reproduce the measured inverse temperature dependence of the rate of the reaction CN + $C_2H_2$ measured in the laboratory, although the discrepancy between theoretical and experimental rates is smallest at very low temperatures.

A theoretical program in understanding nonthermal desorption of interstellar molecules from dust particles is continuing. 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 system is followed on a supercomputer by detailed quantum mechanical means. F. Dzegilenko (OSU Chemistry), Herbst, and T. Uzer (Georgia Tech) confirmed the results of earlier classical studies that small amounts of vibrational excitation cannot drive CO off dust particles. They also agreed with earlier studies in finding that rotational (librational) excitation of surface CO is much more efficient at inducing desorption at low excitation energies. To excite libration under interstellar conditions, Dzegilenko and Herbst considered an indirect process: vibrational excitation of a neighboring OH group by infrared radiation, followed by transfer of energy to the librational mode of a neighboring CO molecule. Detailed calculations show that such a mechanism is more efficient for CO adsorbed onto ice or hydrated silica than other proposed desorption mechanisms.

In the area of laboratory spectroscopy, J. Pearson (OSU Physics, currently JPL), K. Sastry (New Brunswick), F. De Lucia (OSU Physics), and Herbst have extended the rotational spectrum of the known interstellar molecule ethanol to millimeter and submillimeter wavelengths. The measured frequencies have been used by British radio astronomers to detect a large amount of ethanol in the hot molecular core associated with the ultracompact H II region G34.3+0.15. L. Oesterling (OSU Physics), D. Ferguson (OSU Physics), Herbst, and De Lucia measured the rotational spectrum of the symmetric mono-deuterated isotopomer of methyl formate, $DCOOCH_3$. Since methyl formate is abundant in molecular hot cores, and since deuterated molecules have surprisingly high abundances in such sources, it is expected that a secure interstellar detection of the deuterated isotopomer should be forthcoming now that spectral frequencies are available.

### 4.1 Reflection Nebulae

Sellgren, T. Brooke (JPL), R. Smith (U. New South Wales), and T. Geballe (JAC) have found that a new $3.2 - 3.5$ $\mu$m spectrum of the protostar Mon R2/IRS-3 confirms their previous tentative detection of a new absorption feature near 3.25 $\mu$m. The feature in their new spectrum has a central wavelength of 3.256 $\mu$m and has a full width at half maximum of 0.079 $\mu$m. The 3.25 $\mu$m feature has now also been detected by Brooke, Sellgren, and Smith toward NGC 7538/IRS-1 and S140/IRS-1. The feature may be due to aromatic hydrocarbons at low temperatures. If the feature is due to aromatics, the derived column density of C–H bonds is $\sim 1.8 \times 10^{18}$ cm$^{-2}$. If the absorbing aromatic molecules are of roughly the same size as those responsible for aromatic emission features in the interstellar medium, then $\sim 9\%$ of the cosmic abundance of carbon along this line of sight would be in aromatic hydrocarbons, in agreement with abundance estimates from emission features.

Sellgren, Brooke, and Smith have obtained new $3.3 - 3.6$ $\mu$m spectra of nine young stellar objects embedded in molecular clouds. An absorption feature at $\sim 3.47$ $\mu$m with FWHM $\sim 0.09$ $\mu$m was definitively detected toward seven objects, and marginally toward the other two. The 3.47 $\mu$m feature has been previously identified as being due to "diamond-like" carbon with $sp^3$ bonding. Brooke, Sellgren, and Smith, however, find that the 3.47 $\mu$m feature is better correlated with $H_2O$ ice than with the silicate dust optical depth in the data obtained to date. Assuming the feature is due to a C–H stretch absorption, the abundance of the C–H bonds averaged along the line of sight is closely related to that of $H_2O$ ice. We interpret this correlation as indicating that the C–H bonds form together with $H_2O$ ice on grain surfaces in the molecular clouds, though other formation mechanisms are not ruled out.

Sellgren, Martini, and J. Hora (U. Hawaii) have obtained infrared long-slit spectra of two filaments in the reflection nebula NGC 7023. Both filaments show $H_2$ emission; 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 narrow-band images at 3.3 $\mu$m, broad-band images at 2.2 $\mu$m, images of extended red emission at 0.67 $\mu$m, and photometry at $L'$. The strengths of $H_2$ emission lines in the $H$ and $K$ bands are currently being analyzed to derive the excitation and ortho-to-para ratio of the $H_2$ emission.

Sellgren and M. Werner (JPL) have been awarded time on the Infrared Space Observatory (ISO) to obtain images in aromatic hydrocarbon features at 6.2, 7.7, and 11.3 $\mu$m of reflection nebulae illuminated by central stars with a range of temperatures. Sellgren and Werner have also been awarded ISO time, in collaboration with A. Léger (IAS) and others, to obtain mid-infrared spectra of aromatic hydrocarbon features in reflection nebulae. These two projects will test specific identifications for the aromatic hydrocarbon features, such as polycyclic aromatic hydrocarbon molecules and hydrogenated amorphous carbon grains.

### 4.2 Emission Nebulae

Lame completed her dissertation research on the structure and ionization of bright planetary nebulae (PNs), under the supervision of Pogge and Peterson. Her work used imaging Fabry-Perot spectroscopy, long-slit spectroscopy, and interference filter imaging data for three PNs: NGC 6720 (the Ring nebula), NGC 7009, and NGC 7662. For the Ring nebula, there are three principal results: (1) The nebula is ionization-bounded and there is a clumpy ionization front around the entire outer edge. (2) There is no difference between the temperature and density of the O I filaments and the surrounding nebula. (3) The "ring" of the nebula is intrinsically oval, rather than being a tilted circular ring. The results for the filaments are surprising, since modeling of O I-bright microstructures suggested that the filaments should be cool and dense (as seen in other nebulae). The electron density map, which shows density enhancements along the minor axis, can be interpreted in the context of the "interacting stellar winds" paradigm of PN evolution to firmly establish the nebular geometry as a tilted oval seen in projection.

In NGC 7009 and NGC 7662 (unlike in the Ring) the low-ionization microstructures do follow the theoretical predictions. The O I-bright knots are dense structures (except for the FLIERs, which are known to be low-density regions from previous work of Lame and Pogge). The electron density maps show that the observed bright-rim structures are dense, as predicted by the current generation of radiative hydrodynamical models. In terms of the morphology, density structure, and ionization fronts, NGC 7009 and NGC 7662 fit the models well. However, the central stars are significantly older and lower in mass than is assumed in the models which fit the PNs most closely. This contradiction is not easily resolved.

### 4.3 ISM and Dust in Galaxies

Kuchinski and Terndrup have completed an initial survey of the properties of dust absorption in edge-on spiral galaxies, as part of a program to measure the kinematics of their (often boxy) bulges. Using the $J$–$H$ versus $H$–$K$ two-color diagram, they compared the color changes along the minor axis of each galaxy to the predictions of different models of radiative transfer. Models in which scattering effects are significant and those with a large fraction of light sources near the edge of the dust distribution do not produce enough extinction to explain the observed reddening. The optical depth in dust predicted by the color excess depends sensitively on the adopted dust geometry, ranging from depths of 4 to 15 in the visual band. This suggests that a realistic model of the dust distribution is required, even for infrared photometry, in order to correct for dust extinction in the nuclear regions of galaxies.

## 5 Our Galaxy

Gould, together with J. Bahcall, C. Flynn, and S. Kirhakos (IAS), used Hubble Space Telescope observations of a field at high galactic latitude to show that M dwarfs do not contribute significantly to the mass of the Galaxy or to microlensing statistics toward the Large Magellanic Cloud. Faint red stars in the halo or spheroid contribute less than 6% of the mass of the Galaxy; M dwarfs in the disk contribute less than 15% of the disk mass.

### 5.1 The Galactic Center

Blum, Sellgren, and DePoy used OSIRIS on the CTIO 4m telescope to acquire long-slit infrared spectra of Galactic center stars showing He I emission lines and of optically classified emission-line stars. Their goal was to determine which optical class of emission-line stars is most closely related to the Galactic center emission-line stars. Their sample of optically classified emission-line stars included a Luminous Blue Variable star, the only known WN9 star in our Galaxy, the two known WN9/Ofpe stars in our Galaxy, and five WN9/Ofpe stars in the Large Magellanic Cloud. They found that the Galactic center stars have many spectral similarities to WN9/Ofpe stars, but also some significant differences. Several Galactic center stars have much larger He I equivalent widths than the LMC stars which they observed, and most Galactic center stars have much higher He I velocity widths than any of the optically classified stars they observed. These differences may be due to the unique environment of the Galactic center. The spectra placed upper and lower limits on the effective temperatures of the Galactic center stars, confirming that the Galactic center stars are evolved massive stars, in transition between the main sequence and the Wolf-Rayet phase.

Blum, Sellgren, and DePoy also have discovered the first Galactic center star which could possibly be a true Wolf-Rayet star. Previous identifications of emission-line stars in the Galactic center have concentrated on searches for He I emission, which is strong in WN9/Ofpe stars. Wolf-Rayet stars, however, are too hot to have strong He I emission, and they are also fainter at $K$ than WN9/Ofpe stars; thus they have been missed by previous surveys. Blum et al. assign a preliminary classification of WC9 to their new Galactic center source, based on its He I, C IV, and C III emission. The relative numbers of WN9/Ofpe and WC9 stars will help to constrain starburst models for the young stellar population at the Galactic center and will have important consequences for understanding the sources of ionizing radiation in this region.

### 5.2 The Galactic Bulge

Blum, Carr, Sellgren, and Terndrup have measured radial velocities for approximately 40 stars in each of four optically obscured, off-axis fields toward the Galactic bulge. They present mean radial velocities and radial velocity dispersions in four fields toward the Galactic bulge at galactocentric radii of 150 – 300 pc. Their four fields lie nearly along an axis whose position angle from the major axis of the Galaxy is 55°. The observed kinematics generally match both axisymmetric and barred dynamical model predictions, but are marginally better described by the latter. The velocity dispersion in their innermost field is high; combined with data from previous studies at larger radii, this suggests that the stellar velocity dispersion is flat or still rising at projected radius $\lesssim 150$ pc.

Blum has also applied the tensor virial theorem to the mass distribution of the bulge. He shows that previous estimates of the bulge mass from the observed velocities have neglected the effect of the bar pattern speed, and as a consequence may have underestimated the mass of the bulge. He adopts a bar pattern speed from published interpretations of the observed gas kinematics, adopts a published barred mass distribution derived from near-infrared surface brightness measurements, and rederives the mass of the bulge. He finds a mass significantly higher than previous estimates; this higher mass brings the predicted microlensing event rate of barred mass models into better agreement with the observed microlensing rate.

In collaboration with B. Carney, J. Fulbright (U. North Carolina), N. Suntzeff (CTIO), and A. Walker (CTIO), Terndrup has completed a project to obtain $K$-band photometry of RR Lyrae variables toward the Galactic bulge which has yielded a precise measurement of the distance to the center: $R_0 = 7.8 \pm 0.4$ kpc. Although this is one of the more precise determinations yet, there are still systematic errors in the zero point, as evidenced by the difference between the RR Lyrae and Cepheid distance scales to the LMC. Including all systematic errors, Carney et al. derive $R_0 = 8.3 \pm 1.0$ kpc. This results suggests that the bulk of the stars in the bulge must be significantly younger than the Milky Way globular clusters.

Terndrup, E. Sadler (U. Sydney), and R. Rich (Columbia) have started publishing their ongoing work on the abundances and kinematics of K giants in the Galactic nuclear bulge. Their first two papers, presenting the observations and data analysis, have indicated that the abundance patterns in bulge stars are considerably different from those of similar stars in the nearby disk or in globular clusters. For metal-poor stars ([Fe/H] $\leq 0$), the CN strengths are similar to cluster stars, but Mg is elevated by an amount $\langle$[Mg/Fe]$\rangle \approx +0.3$. For metal-rich stars, there is no sign of a significant Mg overabundance, but the CN strengths are very weak. This may indicate that core-envelope mixing is strongly suppressed in metal-rich bulge giants.

Uncertainty in the values for the age and metallicity of stars in the Galactic bulge seems to be increasing with time. The most recent work by McWilliam & Rich suggests a younger age and a lower mean [Fe/H] than previously derived values. A comparison of near-infrared CMDs 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 change with look-back time. Frogel has obtained such data with IRCAM on the LCO 2.5m for about a dozen bulge fields; these provide the deepest, most accurate near-infrared CMD for Baade's Window and other bulge areas yet produced. The main sequence turnoff is visible at $K_0$ between 16 and 16.5, the RGB clump at 13.5, and the foreground field main sequence between $K = 16$ and 13 to the blue of the giant branch. With similar data for about a dozen other fields 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. Tiede, Frogel, and Terndrup have completed the analysis of the data for Baade's Window and a field at a Galactic longitude of $-6°$. They combine their data with previously published photometry and construct a luminosity function over the range $5.5 \leq K_0 \leq 16.5$. The slope of this luminosity function and the magnitude of the tip of the first ascent giant branch are consistent with theoretical values derived from isochrones with appropriate age and metallicity.

The mean metallicity is calculated for several bulge fields along the minor axis, using the relation between [Fe/H] and the giant branch slope found by Kuchinski and Frogel. For Baade's Window, this method yields $\langle$[Fe/H]$\rangle = -0.28 \pm 0.16$, consistent with the recent estimate of McWilliam & Rich. Between $b = -3°$ and $-12°$, the gradient in $\langle$[Fe/H]$\rangle$ is $-0.06 \pm 0.03$ dex/degree, or $-0.43 \pm 0.21$ dex/kpc for $R_0 = 8$ kpc, consistent with other independent derivations. The helium abundance for Baade's Window, using the R and R$'$ methods, is $Y = 0.27 \pm 0.03$, implying $\Delta Y/\Delta Z = 3.3 \pm 1.3$.

The bolometric corrections found for bulge K giants ($V - K \leq 2$) are in excellent agreement with empirical derivations based on observations of globular cluster and local field stars. However, for the redder M giants the bolometric corrections differ by several tenths of a magnitude from those derived for field giants and subsequently used in the Revised Yale Isochrones (a result in agreement with that of Frogel & Whitford). The difference most likely arises from the stronger molecular blanketing in the $V$ and $I$ bands of the bulge giants relative to that of field stars. The distance to the bulge is computed to be $(m - M)_0 = 14.43 \pm 0.35$ or $R_0 = 7.7 \pm 1.2$, based on the surface brightness fluctuation method of Tonry & Schneider, with the distance to M31 and M32 used for calibration.

Since most bulge fields are inaccessible to optical observations, Frogel has used the LCO CMDs to select a sample of stars to be observed spectroscopically with OSIRIS and the CTIO IRS on the CTIO 4m, with the objective of measuring metallic lines and blends in the $K$ band to get relative abundances. Frogel and DePoy have now had three observing runs and have observed most 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; Ramírez is working with DePoy and Frogel on the analysis of the data.

### 5.3 Globular Clusters

The third part of the study of bulge globular clusters by Frogel and Kuchinski has been completed. The data are primarily from the Las Campanas du Pont telescope, supplemented by observations from UKIRT and the Perkins 1.8m telescope. In this most recent part of their research they present new $JHK$ photometry for the disk globular clusters NGC 6440 and NGC 6624. These data were initially used to confirm and refine several important earlier results they derived earlier based on other disk globulars. First, they again demonstrated the ability to derive a reddening-independent estimate for the [Fe/H] of a cluster from the slope of its giant branch (GB) in a $K, J$–$K$ color-magnitude diagram (CMD). Second, the reddening corrected $J$–$K$ color and $K$ magnitude of the center of the horizontal branch (HB) and the $J$–$K$ color of its red edge are confirmed to be independent of [Fe/H] for these clusters. Thus, these parameters can be used to estimate E($J$–$K$) of metal-rich clusters with no knowledge of distance or [Fe/H], and to estimate $(m - M)$ if one can first estimate the reddening. They also confirm that the reddening-independent quantities, the half width of a cluster's HB and the color difference between the center of the HB and the GB at the level of the HB, both appear to be insensitive to metallicity. These results will be particularly applicable to bulge clusters that lie in very deeply obscured fields and to planned observations with the NICMOS camera on the Hubble Space Telescope.

The *JHK* colors of NGC 6440 are similar to those of Liller 1 and unlike those seen for other globular clusters, field giants, or bulge giants. Frogel and Kuchinski have not been able to identify any other cluster parameter that would help to explain these anomalous colors. Finally, they have assembled *V* photometry from the literature for the clusters in their sample and for two additional disk globular clusters from Davidge et al. (1992). They conclude that *K,J–K* CMDs are preferable to *K,V–K* CMDs as tools to study basic cluster properties. Finally, they compared their data with theoretical isochrones for metal-rich clusters and presented evidence that the dependence of the *V–K* color of the GB on [Fe/H] may be different for halo and disk globular clusters. This difference may be related to differences in the [O/Fe] values for the two cluster systems.

## 6 Extragalactic Astronomy

### 6.1 Structure and Evolution of Galaxies

VLA radio continuum observations by Kaufman, F. Bash (U. Texas), P. Crane (Interferometrics), and G. Jacoby (KPNO) reveal complex structure near the center of M81. The most striking feature is a highly polarized, nonthermal arc connected by three bridges to the extended emission surrounding the mini-Seyfert nucleus. The arc is without optical counterpart and is probably highly inclined to the disk of M81. It resembles the minor-axis, nuclear radio lobes seen in certain edge-on Seyferts or the arc in the center of the Milky Way. In the radio continuum images, they also find an oval of ionized gas that coincides with the near-infrared mini-bar. There is filamentary H-alpha emission, suggestive of shock heating, throughout the mini-bar and beyond.

Kaufman, E. Brinks (NRAO), B. Elmegreen (IBM), D. Elmegreen (Vassar), C. Struck (Iowa State), M. Thomasson (Onsala), and M. Klarić (Midlands Tech) have made VLA H I observations of the interacting galaxy pair NGC 2535/36. NGC 2535 has an eye-shaped structure similar to that in IC 2163, which they studied previously. In NGC 2535, they find widespread high velocity dispersion in the gas and, on the tidal arms, five unusually massive clouds, comparable in mass to H I-rich dwarf galaxies, but without strong stellar counterparts. Elmegreen et al. found similar clouds and widespread high turbulence in the interacting pair IC 2163/NGC 2206. This suggests that enhanced turbulence and unusually massive gas clouds produced by gravitational instabilities in the gaseous disk may be a general feature of interacting spiral galaxies during the early phases of post-encounter evolution.

Santos and Frogel have been collaborating on a study of stellar populations of galaxies. Their study involves the construction of photometric evolution models of galaxies based on star cluster *UBVJHK* integrated colors. For this purpose, a data base was created by grouping star clusters of the Large Magellanic Cloud (LMC) according to their photometric and spectroscopic similarities. Overall, twenty average clusters, with ages between 2 Myr and 10 Gyr, were used in the computation of the models. Galaxies of different ages and star formation rates were then characterized by mixtures of the average cluster colors. Santos and Frogel have compared the models to integrated observations of three dwarf galaxies (NGC 1705, NGC 1800, and NGC 7764) with metallicities similar to the LMC. All three galaxies are compatible with stellar systems formed 10 Gyr ago, with slightly decreasing star formation rates.

Ryden, using nonparametric methods for estimating the distribution of apparent axis ratios, has displayed still more evidence for the ubiquity of triaxiality. Stellar systems as small as dwarf elliptical galaxies and as large as clusters of galaxies have apparent axis ratios which cannot be explained by their being randomly oriented axisymmetric systems. Only old, dense stellar systems, such as the globular clusters associated with our Galaxy, have undergone two-body relaxation to become rotationally supported oblate bodies. For other stellar systems, the oblate hypothesis can be rejected at the 99% confidence level.

Pogge, Ryden, and Terndrup are continuing their investigation of the surface photometry of dwarf galaxies in the Virgo cluster. Those galaxies which have been labeled "dwarf elliptical" are not systematically different in their properties from the galaxies which have been labeled "dwarf S0". If there do exist separate classes of rotationally flattened dwarf S0 galaxies and triaxial dwarf elliptical galaxies, they cannot be distinguished without kinematic information.

Thakar and Ryden have continued their numerical simulations of the formation of counterrotating disks. Preliminary simulations, using a sticky-particle gas dissipation scheme, indicate that both episodic and continuous gas infall are able to form a counterrotating gas disk without drastically upsetting the stability of the stellar disk. The initial angular momentum of the infalling gas is crucial in determining the scale length of the counterrotating disk, as well as the time it takes to form. A merger with a gas-rich dwarf is not a viable mechanism for creating a massive counterrotating disk; only a very tiny dwarf can produce a counterrotating disk without excessively thickening the stellar disk. Thakar's future work will replace the sticky particle scheme with an SPH code, in order to more accurately simulate the properties of the infalling gas and the resulting counterrotating disk.

### 6.2 Digital Atlas of Galaxies

Three years ago Frogel, DePoy, Pogge, Sellgren, Terndrup, and Davies (U. Durham) received a multi-year 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. The survey will produce a photometrically calibrated library of images of late-type galaxies from 0.4 to 2.2 $\mu$m. Data are being taken with OSIRIS, with the CTIO infrared imager, and with CCD detectors at Lowell Observatory and CTIO. 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 $\mu$m will be sensitive to the ages of such structures and will be valuable tests for theories of their formation. 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.

Several new papers based on data from the Galaxy Atlas have been accepted or submitted for publication. The first is a *BVRJHK* imaging survey of the barred galaxy NGC 1097 carried out by Quillen, Frogel, Kuchinski, and Terndrup. The optical and infrared color maps trace the major dust features. The dust lanes are relatively free of star formation and have low opacity. The depth of the dust lanes decreases as a function of wavelength; they are deepest at $B$ and shallower at $H$ and $K$ where they are difficult to detect. The dust lane on the northwest side of the galaxy has colors consistent with those of a dust screen with opacity derived from the galactic extinction law. Thus, it must be located on the near side of the galaxy. The colors in the dust lane on the southeast side of the galaxy, on the other hand, suggest that there are stars both in front of and behind the dust, consistent with this dust lane being on the far side of the galaxy.

Near the inner spiral ring (at $\sim$17$''$, or $\sim$1.4 kpc, from the nucleus) of NGC 1097, the dust lane becomes double peaked with a peak-to-valley extinction ratio similar to that observed in radio continuum by Ondrechen & van der Hulst. This suggests that if the cold diffuse component of the interstellar medium (traced by the dust) moves with the cosmic ray electron component, then the magnetic field pressure is not a significant force in the shocks. If the two phases do not move together, a more detailed comparison may show differences in the shock shapes. From the $K$ images, we estimate that the total stellar mass of the star-forming spiral ring at a radius of $\sim$1 kpc from the nucleus is comparable to the molecular gas mass in the ring. The infrared images show a short bar inside the inner spiral ring. In the principal plane of the galaxy, the short bar is not perpendicular to the prominent outer bar. This suggests that there are torques between the inner bar and the spiral ring, and that the inner bar may have a pattern speed different from that of the outer bar.

A second paper by Quillen, Ramírez, and Frogel presents visible and near-infrared images of the amorphous dwarf galaxy NGC 1705 in the *B, V, R, J, H,* and *K* bands. Optical and near-infrared colors in the galaxy are consistent with a composite population with colors similar to those of the bluest Sc nuclei. The contribution of young stars to the disk population of the galaxy decreases outward from the center. In the near-infrared images they detect three unresolved point sources, two of which have colors and luminosities comparable to intermediate-age LMC clusters.

In a third paper recently submitted for publication, Quillen, Ramírez, and Frogel show how radial color gradients in disk galaxies can be used to detect the presence of non-circular motion. In a galaxy with both a radial color gradient and non-circular motion, isocolor contours should follow the shape of closed stellar orbits, and the ellipticity of the isophotes should vary as a function of wavelength. A difference in the ellipticity of isocolor contours and the isophotes can be used to detect non-circular motion. This phenomenon was searched for in the dwarf galaxies NGC 1800 and NGC 7764. A bar was detected in NGC 1800 which previously has only been suggested from the H I velocity field. In NGC 7764 there is no color gradient along its bar, so non-circular motion cannot be detected in this region; however, ellipticities observed in a star-forming ring at the end of the bar are consistent with the ring being located near the corotation radius.

## 7 AGNs and Quasars

Pogge and M. DeRobertis (York U.) are continuing their imaging spectrophotometric study of extended emission-line regions in Seyfert galaxies. In addition to ground-based images, they are including measurements of archival HST images and have begun a program of integral-field spectroscopy using the CFHT. Morphologically, there are strong indications of shocked features in a few of the systems with combined HST and CFHT narrow-band imaging, but the spectrophotometric diagnostics are somewhat ambiguous. The main problem is that the models suggest that the traditional diagnostics, keyed to interpreting either "pure shock" or "pure ionization," are inadequate. Pogge and DeRobertis are exploring comparisons of the observations with composite shock and photoionization models (for example, shocks emerging into a pre-ionized medium), and models which include fast autoionizing shocks.

Peterson, Pogge, Wanders, 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 (AGNs). Spectroscopic observations of these galaxies are obtained with the CCD spectrograph on the Perkins 1.8m telescope on an approximately weekly basis. Much of this monitoring is carried out in support of multiwavelength monitoring campaigns undertaken by the International AGN Watch, a large, informal consortium of AGN observers; Peterson is one of the organizers of AGN Watch activities. Last year, the AGN Watch carried out major multiwavelength monitoring programs on Fairall 9 and 3C 390.3; a new program on the Seyfert 1 galaxy Mrk 335, including 30 days of virtually continuous coverage with the International Ultraviolet Explorer and the X-ray Timing Explorer, is scheduled for summer 1996.

Wanders, Peterson, and Pogge, working with M. Goad and A. Koratkar (STScI), K. Korista and G. Ferland (U. Kentucky), K. Horne (St. Andrews), and J. Shields (U. Arizona), have begun an in-depth analysis of the Hubble Space Telescope spectral monitoring observations that were made of the Seyfert 1 galaxy NGC 5548 in 1993. They find that the response of the broad C IV 1549 emission line to continuum variations can be modeled by line-emitting clouds on randomly inclined Keplerian orbits around an anisotropically emitting central source of mass $10^8 M_\odot$. The continuum emission from the central source is assumed to be emitted in a wide ($35-60°$ semi-opening angle) conical beam that is directed approximately toward the observer.

Wanders and Peterson are completing an analysis of H$\beta$ line profile variability in NGC 5548, based on five years of well-sampled monitoring data from the International AGN Watch. Unlike the emission-line flux variations, which are closely coupled to the continuum variations with only a small delay due to light travel-time effects, the changes in emission-line profile do not appear to be tied to continuum changes. Profile changes appear to occur on broad-line region dynamical time scales, suggesting that they are attributable to actual changes in the distribution and responsivity of the gas rather than to light travel-time effects. This further suggests that the number of broad-line clouds must be small enough that stochastic variations are detectable. Finally, certain profile features appear to remain stationary in velocity over many years. This can be understood in terms of an isotropically emitting continuum source, as was postulated to explain the C IV response observed during the HST experiment.

As part of the data selection process preceding the profile study, Peterson, Pogge, and Wanders, in collaboration with W. Romanishin (U. Oklahoma) and OSU student Sean M. Smith, investigated the origin and magnitude of aperture effects on optical spectrophotometry of AGNs. The basic problem is that an AGN consists of several different components which have different surface brightness distributions. The relative amount of light detected from each component is a function of both aperture geometry and seeing. In the case of nearby Seyfert galaxies, the small spectroscopic apertures ($2''$ or less) that are typically used in faint-object spectroscopy can lead to large systematic errors in flux calibration based on the non-variable narrow-line fluxes. To minimize aperture effects in AGN monitoring programs, spectroscopic entrance apertures larger than the worst seeing that is expected to be encountered are recommended.

Peterson has continued to work on analysis of multiwavelength data that have been obtained as part of AGN Watch monitoring projects. Work with R. Edelson (U. Iowa) and others shows that the continuum variations in the Seyfert galaxy NGC 4151 from the X-ray to the optical apparently vary with time delays between the various bands no longer than $\sim 0.1$ day. Similar comparisons of ultraviolet and extreme ultraviolet variations in NGC 5548, undertaken with H. Marshall (MIT & Eureka Scientific) and others, are yielding similar results; the UV and EUV variations are simultaneous to within $\sim 0.25$ day.

In anticipation of next year's major multiwavelength campaign on the Seyfert 1 galaxy Mrk 335, Mailloux, Peterson, Pogge, and Wanders are analyzing six years of data on optical continuum and emission-line variability in this galaxy. The H$\beta$ emission-line response time is about the same as for other AGNs of similar luminosity – approximately 17 days.

Wanders and F. Pijpers (Aarhus) have continued to work on the SOLA method for time-series analysis inversion. This technique, based on the Backus-Gilbert method developed in seismology, was modified to handle discrete, noisy time series. This is important for reverberation mapping in AGNs, where the geometry and kinematics of the broad-line region can be inferred from the transfer function.

Wanders continued the study of quasar host galaxies at intermediate redshifts, in collaboration with J. Rönnback (ESO Garching), E. van Groningen, and E. Örndahl (Uppsala). Deep CCD images of 14 radio-loud and 9 radio-quiet quasars were obtained under excellent atmospheric conditions at the ESO 3.6m NTT in the $R$ band and, for a subset of these, in the $V$ and $I$ bands. The quasar redshifts were between 0.3 and 0.8, a range largely unexplored in other surveys. For 9 radio-loud and 8 radio-quiet quasars, the host galaxy is detected. The luminosity profiles are satisfactorily fitted by either an exponential or an $r^{1/4}$ profile. The $V$–$I$ colors are consistent with a stellar population typical for late-type spirals and irregular galaxies. The mean value of the absolute $R$ magnitude is $-22.2 \pm 0.4$ for the radio-loud sample and $-22.0 \pm 0.4$ for the radio-quiet sample.

Osmer, P. Hall (U. Arizona), R. Green (NOAO), A. Porter (deceased), and S. Warren (Imperial College) continued work on their deep multicolor survey with the KPNO 4m telescope. They have covered 0.83 square degrees in six filters with wavelengths ranging from 0.35 to 0.86 $\mu$m. They have compiled a catalog of 21,375 stellar objects with positions, magnitudes, and error estimates in the six bands. They obtained spectra of 350 quasar candidates with the Hydra multifiber instrument at the KPNO 4m. To date, they have discovered 46 quasars with $0.6 < z < 4.3$ and 39 compact emission-line galaxies with $0.1 < z < 0.8$. To estimate the quasar luminosity function, they have carried out extensive simulations to determine their selection efficiency for quasars as a function of redshift, magnitude, and spectral type. Preliminary results indicate that the number of quasars in their sample with $z \leq 2.3$ is consistent with the predictions of the Koo & Kron (1988) luminosity function. However, the new survey contains more candidates predicted to have $z > 3$ than are expected from the results at brighter magnitudes of Warren, Hewett, & Osmer (1994) and of Schmidt, Schneider, & Gunn (1995). Osmer et al. are planning spectroscopic observation of these candidates with the KPNO 4m telescope to confirm the predictions.

## 8 Atomic Processes

Pradhan, Nahar, Zhang, Bautista, and Peng are involved in theoretical studies of physical processes in astrophysical plasmas. With the aim of defining accurate spectral diagnostics of gaseous nebulae, supernovae, white dwarfs, AGNs, and quasars, a comprehensive program is underway to compute the basic atomic parameters required in the models. The processes studied include electron collisions, photoionization, and recombination. The data are then employed in diagnostic models to determine the physical conditions in the sources. Particular applications include spectral analysis of ground- and space-based observations. The research program involves components of atomic physics, plasma physics, and astrophysics. The group is also involved in two international collaborations: the Opacity Project and the Iron Project. The large-scale quantum mechanical calculations are being done on the Cray YMP 8/64 and the massively parallel Cray T3D at the Ohio Supercomputer Center.

The opacity is the fundamental quantity that determines radiation flow through a plasma. The calculation of stellar models, and models of other types of objects, requires the calculation of opacities that depend on the constituent elements in the source. The Opacity Project has calculated new opacities that are now being applied to a variety of astrophysical applications such as stellar pulsations, white dwarf atmospheres, and determination of chemical abundances.

Heavy elements of the iron-peak group, such as iron, cobalt, and nickel, are of great importance as endproducts of stellar nucleosynthesis. The analysis of the observations of these elements in supernova remnants, for example, yields valuable information on the abundances and energy sources in the ejecta of supernovae. Recent work by the group includes the determination of iron and nickel abundances in the Orion nebula and other gaseous nebulae.

Analogous to the Opacity Project, which dealt with radiative processes, 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 – VI. In addition, the Iron Project team at Ohio State has initiated work on other iron-peak elements: nickel, cobalt, manganese, chromium, and titanium.

The determination of abundances and ionization structure in astrophysical sources depends on knowledge of electron-ion recombination rates. A unified theoretical method has been developed by Nahar and Pradhan that subsumes both the radiative and di-electronic recombination processes, leading to the computation of total electron-ion recombination rates. Work is in progress to apply the new data to models of the interstellar medium, AGNs, and gaseous nebulae.

Large-scale calculations are continuing on new cross sections for photoionization and transition probabilities employing state-of-the-art methods from atomic physics (primarily the R-matrix method). Recent work on photoionization shows that current astrophysical models may be in error by large amounts, particularly for low ionization stages of iron and other heavy elements; for instance, Bautista has found that the new ground-state photoionization cross sections for Fe I are up to three orders of magnitude higher than those employed in current astrophysical models. The new cross sections may provide an explanation for the dominance of singly ionized iron in the spectra of many astrophysical sources.

Peng is developing a code to analyze Fe II emission from quasars and AGNs, employing the atomic data calculated by members of the group. This work should lead to an understanding of the presence of heavy elements observed in the spectra of high-redshift quasars.

## 9 Nuclear Astrophysics

The network calculations by Boyd, M. Hencheck (Chadron State), and B. Meyer (Clemson U.) of the rp-process have suggested that the p-process nuclides from $^{78}$Kr to $^{98}$Ru could be produced in a high-temperature hydrogen burning environment such as that expected in a Thorne-Zytkow object (TZO). Since TZOs result from the capture by a red giant of a companion neutron star, the material that gets processed near the surface of the neutron star will have been subjected to s-processing. Thus, the network calculations assumed s-process seeds and conditions that have been shown to be appropriate near the surface of the neutron star: temperatures of 1 – 2 billion K and densities around $10^4$ g/cm$^3$. These conditions persist for several seconds. Under these conditions, the p-process nuclides from $^{78}$Kr to $^{98}$Ru are all produced with about the same overproduction factor (relative to their solar abundance); furthermore, this abundance is about what is required to explain their origin. This high-temperature hydrogen burning scenario drives the seeds, the s-process nuclides, to the most proton-rich nuclides, the "proton drip-line nuclides", in this mass region. Since little is known about the properties of many of these nuclides, the calculations require the use of nuclear mass formulae, and the results are necessarily uncertain. In some cases, the nuclei in question not only have uncertain masses, but might decay either by emission of a positron or of both a positron and a proton. To measure decay properties of some of the critical nuclei, Boyd and collaborators have begun measurements at an accelerator facility in Darmstadt, Germany; the first experiment, in May 1995, studied $^{98}$Ag and $^{98}$Cd.

It has been suggested that the ground state of nuclear matter may not be nuclei consisting of protons and neutrons, but may rather be strange quark matter nuggets consisting of up, down, and strange quarks. Such nuggets would be characterized by an anomalously low charge to mass ratio, since equal numbers of the three quark flavors would produce a zero charge. A subsequent theoretical study by Takahashi & Boyd (1988) that included shell effects in the "strangelets" suggested that light strangelets might exist, and that they could have an enormous effect on stellar evolution, even at very low abundances. This would be due to their extremely low coulomb barriers. The most interesting strangelet candidate, at least for stellar evolution, was one with a charge of 2 and a baryon number of 65: $^{65}$He. Thus, J. Vandegriff (OSU Physics), G. Raimann (OSU Physics), Boyd, M. Caffee (LLNL), and B. Ruiz (LLNL) have done a mass spectrometric search for such an entity. The mass of these objects is quite uncertain, so the experiment spanned the mass region from 40 to 80 amu. Terrestrial helium would be greatly enhanced in this anomalously heavy "isotope", compared to cosmic helium, by the evaporation from earth of the light helium contained in the gas from which the earth was formed. Thus a relatively modest abundance limit from such a search is greatly amplified. Abundance limits of about 1 part in $10^{12}$ normal nuclei were found for strangelets. Although several anomalous peaks were seen in the spectra, none stood out as being particularly identifiable as having resulted from a strangelet. Further work is in progress.

Recent observations have suggested that even very distant quasars have solar abundances, or higher, of elements like carbon, nitrogen, and oxygen. This rather surprising result has been explained in terms of an early epoch of massive star formation, but the persistence of these high metallicities even to the most distant objects observed strains the credibility of this explanation. Thus, Vandegriff, Raimann, Boyd, and Osmer have begun a study to see if those elements can be generated in the interactions of jets with clouds near the central engine. Their calculations at present involve all the nuclides from hydrogen to mass 20 amu nuclides. They find that at suitably high temperatures it is possible to produce huge abundances of the CNO nuclides in rather short times, even at typical cloud densities. A crucial feature of the network is that $^7$Be is virtually stable in such environments. If the temperature is sufficiently high it is ionized and, in the low density environment of a cloud, it is unable to capture the electron necessary for it to decay to $^7$Li. Thus an abundance equilibrium is established between $^7$Be and $^{10}$B that allows $^{10}$B to be promoted to the CNO nuclides at a steady rate. Preliminary results show that carbon, nitrogen, and oxygen become the dominant nuclear species in this environment; further study is in progress.

### 9.1 Big Bang Nucleosynthesis

The focus of Steigman's research program is the confrontation between the predictions of primordial nucleosynthesis in the context of the standard hot big bang cosmology and the primordial abundances of light elements (D, $^3$He, $^4$He, $^7$Li) inferred from observational data. In the last year, Steigman and collaborators have vigorously pursued a multi-pronged program aimed (on the one hand) at exploiting observational data to derive better, less uncertain, primordial abundances of cosmologically interesting light elements and (on the other hand) at using these data to challenge and test the standard hot big bang model.

The predicted primordial abundances of D and $^3$He depend sensitively on $\eta$, the universal ratio of baryons to photons, providing, as a result, an ideal 'baryometer'. Unfortunately, these light elements are for the most part observed here and now (in the solar system and local ISM). As a result, it is necessary to employ a chemical evolution model to infer the primordial abundances of D and $^3$He which, as a consequence, have model-dependent uncertainties. To finesse this obstacle to the extent possible, Steigman and M. Tosi (Bologna) have developed a generic approach to D and $^3$He evolution which avoids an evolution model by incorporating all the model dependence in one parameter, $g_3$, the $^3$He survival fraction. Steigman and Tosi argue that $g_3 \gtrsim 1/4$ is reasonable and, neglecting stellar production of $^3$He, derive upper and lower bounds to primordial D which lead to significant constraints on $\eta$. Building on the Steigman & Tosi work, Scherrer, Steigman, Walker, N. Hata, and D. Thomas (OSU Physics) have extended the generic analysis in a statistical study. This work, which utilizes both solar system and interstellar data, provides a new upper bound to primordial $^3$He and tightens the noose on the universal density of baryons.

In a long-term collaboration with M. Tosi (Bologna) and D. Dearborn (Lawrence Livermore), Steigman and colleagues have used a new, extensive grid of stellar models by Dearborn in concert with Tosi's chemical evolution models to follow the galactic evolution of D and $^3$He as a function of time and location in the Galaxy. The stellar models allow for the production of $^3$He which is dominant in low-mass stars. This work finds that stellar $^3$He production is so overwhelming that even in the absence of primordial D or $^3$He all evolution models predict $^3$He abundances in excess of those observed in the solar system and in galactic H II regions. To reconcile this contradiction, Dearborn, Steigman, and Tosi have explored a series of nonstandard models in which the $^3$He yields are modified.

As the second most abundant nuclide in the universe, $^4$He plays a key role in testing the standard hot big bang cosmology and in probing for new physics beyond the standard model. Steigman and K. Olive (Minnesota) have used the extant data on $^4$He in $\sim 50$ low-metallicity H II regions to infer the primordial mass fraction of helium, $Y_P = 0.232 \pm 0.003$. The large number of independent measurements of high statistical accuracy is responsible for the small uncertainty in $Y_P$. This, along with the relatively low central value for $Y_P$, challenges standard big bang nucleosynthesis; Olive and Steigman find for the equivalent number of light neutrinos $N_\nu^{\rm BBN} = 2.17 \pm 0.27 \pm 0.42$, in contrast to the LEP result $N_\nu^{\rm LEP} = 2.99 \pm 0.02$. This could be a hint that the tau-neutrino may be massive ($\sim 5 - 24$ MeV) and unstable. If, indeed, $N_\nu^{\rm BBN}$ should be greater than or equal to 3, the usual upper bound to $N_\nu^{\rm BBN}$ must be reconsidered; Olive and Steigman have done this, concluding that $N_\nu^{\rm BBN} \leq 3.2 - 3.6$ at the 95% confidence level.

Lithium is observed in $\sim 100$ low metallicity halo stars, so in principle the primordial abundance may be determined accurately. The problem is that the surface abundance of lithium may have been modified during the long lifetimes of these oldest stars in the Galaxy. In an attempt to provide an alternate path to primordial lithium, Steigman has considered observations of interstellar lithium. The problem here is that most interstellar lithium is Li II but Li I is observed, so that a large ionization correction (involving an uncertain electron density) is required. To avoid this complication, Steigman noticed that potassium and lithium would have similar ionization corrections and similar corrections for depletion onto grains. Using data for 10 lines of sight, Steigman found a constant Li I/K I ratio which, when corrected for ionization to Li/K, is in excellent agreement with the solar system (meteoritic) ratio, suggesting similar depletions. If lithium is on its way down from a high primordial value, then in the less chemically evolved Large Magellanic Cloud, lithium should be higher and potassium lower than in the Galaxy. Using observations of SN1987A, Steigman noted that the LMC Li/K ratio is smaller than the Galactic value by at least a factor of two (K I is observed, Li I is not), suggesting that lithium is on its way up from a small primordial abundance consistent with that derived from the Pop II halo stars.

Over the last few years, newer, more accurate observational data have led to bounds on the primordial abundances of D, $^3$He, $^4$He, and $^7$Li which have begun to challenge the consistency of the standard ($N_\nu = 3$) hot big bang predictions of nucleosynthesis. To explore this problem, the OSU group of Hata, Scherrer, Steigman, Thomas, and Walker has embarked on a statistical analysis of the comparison between theory and data. Deuterium and $^3$He provide the lower bound to $\eta$; $^4$He, $^7$Li, and deuterium provide the upper bound. Provided that the $^3$He stellar survival fraction is $g_3 \geq 1/4$ and the systematic uncertainty in the primordial $^4$He mass fraction is $\Delta Y_{\rm sys} \leq 0.005$, Hata et al. conclude that standard ($N_\nu = 3$) big bang nucleosynthesis is inconsistent with the inferred primordial abundances at the 99% confidence level. If the tau neutrino were massive and unstable, $N_\nu^{\rm BBN} < 3$ would be possible (and consistent with $N_\nu^{\rm LEP} = 3$). Hata et al. find that $N_\nu^{\rm BBN} = 2.1 \pm 0.3$. Alternatively, if $N_\nu^{\rm BBN} = 3$, consistency may be found if $g_3 \lesssim 0.10$ or $\Delta Y_{\rm sys} = 0.014 \pm 0.004$.

## 10 Cosmology & Large Scale Structure

Weinberg has been using cosmological simulations with gas dynamics to study the formation and clustering of galaxies and the evolution of the intergalactic medium. He investigated the influence of photoionizing background radiation on the formation of low mass galaxies both using high resolution, spherically symmetric calculations (with A. Thoul, IAS) and using lower resolution, large volume, three-dimensional simulations (with N. Katz, U. Washington, and L. Hernquist, UC Santa Cruz). These studies show that a photoionizing background suppresses the formation of galaxies with circular velocities $v_c < 30$ km/sec but does not affect the formation of systems with $v_c > 60$ km/sec. Katz, Weinberg, and Hernquist completed a paper describing the smoothed particle hydrodynamics (SPH) code used in these simulations, and illustrating its application to cosmological models. Most recently, they have used SPH simulations to investigate properties of Lyman-alpha absorption systems at high redshift (in collaboration with J. Miralda-Escudé, IAS). Simulations of the cold dark matter (CDM) model reproduce the observed properties of the Lyman-alpha forest remarkably well, for systems covering more than eight orders of magnitude in neutral hydrogen column density.

Weinberg and Z. Protogeros (OSU Physics) are analyzing the topology of isodensity surfaces in the 1.2 Jy survey of IRAS galaxies. As part of this analysis, they are applying identical techniques to a large ensemble of artificial 1.2 Jy catalogs drawn from cosmological N-body simulations; these will yield a good measure of statistical and systematic uncertainties in the observational analysis. The results of this study will test the hypothesis that primordial density fluctuations were Gaussian and will place constraints on the effective index of the galaxy power spectrum.

L. Teodoro, C. Frenk (Durham U.), and Weinberg are applying Weinberg's "Gaussianization" reconstruction method to the recently completed redshift survey of 12,000 IRAS galaxies brighter than 0.6 Jy in the point source catalog. The method recovers a model set of initial conditions from the observed galaxy distribution under the assumption that the primordial fluctuations were Gaussian. Forward evolution of these initial conditions with an N-body simulation yields a model that can be compared to the input data to test the Gaussian hypothesis and constrain models of biased galaxy formation. Weinberg and Narayanan are attempting to improve the accuracy of the reconstruction method by including corrections for large-scale displacements during dynamical evolution.

Weinberg continues participation in the Sloan Digital Sky Survey, a multi-institution project that will produce a five-band photometric survey of the North Galactic Cap and a redshift survey of $10^6$ galaxies and $10^5$ quasars. He has created simulated data that are being used to test the survey's data reduction software and has investigated criteria for the selection of targets for the galaxy redshift survey. With R. Gott (Princeton) and C. Park (Seoul National U.), he is working on a detailed simulation of the Sloan redshift catalog, drawn from a large N-body simulation of a low density cold dark matter model. He is also working with Frenk and S. Cole (Durham U.) on a series of simulations that will be used to create artificial Sloan catalogs for models with different values of the density parameter $\Omega$ and cosmological constant $\Lambda$. Using these simulations, Cole, Weinberg, Frenk, and B. Rhatra (MIT) are examining the viability of low density CDM models normalized to the level of microwave background fluctuations seen by the COBE satellite. Preliminary results indicate that open universes require $\Omega \geq 0.4$ to reproduce the observed abundance of massive galaxy clusters, while flat models with a cosmological constant require $\Omega \geq 0.3$.

Popowski, Weinberg, and Ryden are investigating the use of the quasar two-point correlation function as a tool for constraining the cosmological constant. At high redshifts, an intrinsically isotropic correlation function appears anisotropic in naïve Euclidean coordinates because of the cosmology-dependent transformation from angular and redshift separations to physical distances. This anisotropy depends on both $\Omega$ and $\Lambda$, but it is more sensitive to $\Lambda$. The goal of the current study is to find what limits on $\Lambda$ can be obtained from the quasar redshift samples expected from the Sloan survey and the Anglo-Australian survey planned for the AAT.

Han, Gould, and P. Sackett (IAS) obtained photometry and spectroscopy for 60 galaxies toward the Ursa Major filament, using the Imaging Fabry-Perot Spectrograph on the 1.8m Perkins telescope. With these data, they showed that the alignments of galaxy spin vectors within the filament are random to within the Poisson noise.

The work of Gould continued to focus primarily on applications of gravitational microlensing. He devised a technique for measuring "microlensing parallaxes" using a single satellite, as compared to the two satellites that were previously thought to be necessary. He developed a number of new types of microlensing observations and experiments. The microlensing effects examined by Gould include the effects of self-lensing by stellar disks and binary stars. Gould and Han together developed several new methods for analyzing microlensing events, including a method of deriving the mass spectrum of MACHOs from parallax measurements.

Ryden and A. Melott (U. Kansas) are measuring the distortions caused in redshift maps by peculiar velocities in the gravitational clustering scenario. For a wide range of initial power spectra, peculiar velocity distortions increase the size of the biggest voids in a simulation. This amplification of the largest voids is most noticeable when the initial power spectrum is weighted toward power on large scales rather than small scales. The voids in redshift space do not show a tendency at high confidence levels ($> 95\%$) to be elongated or squashed along the line of sight from the observer.

X-ray observations of rich clusters of galaxies reveal that baryons in the hot intracluster gas dominate those in the optically visible galaxies. For $H_0 = 50$ km/s/Mpc, the fraction of the total mass in hot gas is $\sim$20% (scaling inversely with the 3/2 power of $H_0$). If such clusters provide a fair sample of the universal fraction of baryons ($\Omega_{\rm Bar}/\Omega_{\rm Tot}$), then the X-ray cluster 'baryon crisis' suggests a low density universe, with $\Omega_{\rm Tot} \leq 0.3(50/H_0)^{1/2}$. Steigman and J. Felten (NASA/GSFC) are studying ways to mitigate this crisis, as well as exploring the cosmological options: an open, low density universe or a cosmological constant dominated universe.

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