Ohio State University
Department of Astronomy

Columbus, Ohio 43210–1106

Abstract

This annual report covers the period September 1998 through August 1999.

1 Personnel

During the period covered by this report, the regular academic staff of the Department of Astronomy included Richard Boyd, Darren DePoy, Jay Frogel, Andrew Gould, Eric Herbst, Gerald Newsom, Patrick Osmer (chairperson), Bradley Peterson, Marc Pinsonneault, Richard Pogge, Anil Pradhan, Barbara Ryden, Robert Scherrer, Kristen Sellgren, Gary Steigman, Donald Terndrup, Terrence Walker, David Weinberg, and Robert Wing. Michelle Kaufman held an appointment as Research Scientist and David Ennis as lecturer. Smita Mathur joined the department as a Research Scientist in October, 1999, and Jordi Miralda-Escudé will join the department as an Assistant Professor in January, 2000. Emeritus members of the Astronomy Department are Eugene Capriotti, George Collins II, Stanley Czyzak, Phillip Keenan, Geoffrey Keller, and William Protheroe.

We report with sadness the death of emeritus professor and former department chair Arne Slettebak.

The staff of the Imaging Sciences Laboratory (ISL) included Bruce Atwood (director), Ralph Belville, David Brewer, Paul Byard, Jerry Mason, Thomas O'Brien, Daniel Pappalardo, David Steinbrecher, and Edward Teiga. Michael Savage was manager of the Astronomy Department computer resources.

In Tucson AZ, Mark Wagner held the position of Research Scientist, while Ray Bertram was Research Associate.

Postdoctoral researchers in Astronomy during this period included Paul Eskridge, Eric Monier, Sultana Nahar, Alison Sills, and Keven Uchida. Uchida left in April, 1999 for a postdoctoral position at Cornell. Postdoctoral researchers joining the department in Autumn, 1999 are James Bullock, Stefan Collier, Andrey Kravtsov, and Marianne Vestergaard.

Graduate students in the Astronomy Department during the academic year included Jin An, Nikolay Andronov, Andreas Berlind, Guo-Xin Chen, Alberto Conti, Franck Delahaye, Scott Gaudi, Eric Himburg, Nathan Kraemer, Paul Martini, Vijay Narayanan, Solange Ramírez, Patrizia Romano, Samir Salim, Kenneth Sills, Adam Steed, Andrew Stephens, Ewan Todd, and Yongquan Yuan. Students arriving in summer 1999 were Shaikh Alam, Christopher Burke, Susan Kassin, James Pizagno, and Zheng Zheng. Narayanan completed the requirements for his Ph.D. and moved to a postdoctoral position at Princeton in October, 1999.

2 Facilities and Instrumentation

The Astronomy Department moved quarters from Smith Laboratory to the newly renovated McPherson Laboratory in September, 1999. The new quarters provide more office space for graduate students, postdocs, and visitors, and more laboratory space for the ISL.

OSU has a one-quarter share of the observing time on the 2.4-m and 1.3-m telescopes of MDM Observatory on Kitt Peak. The other MDM partners are Dartmouth University, Columbia University, and the University of Michigan. OSU also has a one-sixth share of observing time on the Large Binocular Telescope (LBT), which is under construction at the Mount Graham International Observatory in Arizona. Other partners in the project are the University of Arizona, astronomical consortia in Italy and Germany, and the Research Corporation. The LBT, with twin 8.4-m mirrors, will be the world's largest optical telescope on a single mount when it is completed in 2003 and will have a 23-m baseline for interferometric observations.

The OSU instrumentation group, which includes DePoy, Pogge, and the ISL staff headed by Atwood, has started to design an optical spectrograph for the LBT. This spectrograph should have high throughput from the atmospheric cut-off to the limit of CCD detectors in the red and be capable of observing faint targets. Plans call for cross-dispersion and a multi-object mode capable of observing roughly 50 objects simultaneously. In combination with the enormous light gathering power of the LBT, the spectrograph will be a valuable tool for a wide range of astronomical investigations. Its design is driven especially by plans for a comprehensive study of the evolution of galaxies, active galactic nuclei, and the intergalactic medium, from redshifts $z = 7$ to $z = 0$.

The past year has been a very active one for the instrumentation group. OSIRIS (the Ohio State InfraRed Imager/Spectrometer) was upgraded to a 1024×1024 HgCdTe detector and shipped to Cerro Tololo Inter-American Observatory. There it will be available for general community use for at least the next few years. The optics, mechanisms, and interface of a Boller & Chivens spectrograph were upgraded, and the improved instrument was installed on the telescopes at MDM. This instrument has excellent throughput at optical wavelengths and should allow increased operational flexibility and additional capability for spectroscopic observations at MDM. OSU continues to support the use of the MDM–Ohio State Active Infrared Camera (MOSAIC; also known as TIFKAM and ONIS) at Kitt Peak National Observatory. This is one of the few instruments in the world making routine observations with a large format

(512×1024) InSb detector array. This instrument was used extensively for a large survey of the sky at near-infrared wavelengths by KPNO personnel, and by MDM consortium members as a facility infrared imager and low-resolution spectrometer.

The group's major instrumentation activity involved the completion of an instrument capable of simultaneous imaging at one optical (UBVRI) and one near-infrared (JHK) wavelength. This instrument is equipped with a 2048×2048 CCD and a 1024×1024 HgCdTe array and is used every night on the CTIO/Yale 1-m telescope. The primary use is to image gravitational microlensing event fields to look for planets around the lenses (see §8 below), but the instrument is also used by others to monitor time-variable sources (black hole candidates, supernovae, etc.) and for general-purpose optical/infrared imaging. OSU anticipates completing a copy of this instrument for the South African Astronomical Observatory 1-m telescope in late 1999.

K. Sills and Pogge integrated a commercial thermo-electrically cooled SITe 512 × 512 CCD camera (acquired from Apogee Instruments, Inc.) into a Linux version of the OSU data-taking system for deployment at the 0.62-m telescope of the Perth Observatory in Western Australia. This camera is being used as part of the PLANET observing network. Sills traveled to Perth to install the camera and integrate it with the telescope and filter/guider module. The system has been in use since July, contributing to PLANET observations and to work by Perth Observatory astronomers. Sills is currently building a second system for the Lab, and upon refinement of this system plans to release the device drivers and user interface in the public domain.

3 Stars and Stellar Evolution

A. Sills and C. Bailyn (Yale) are continuing their investigations into the formation and evolution of blue straggler (BS) stars, and into the use of blue stragglers to study the dynamical history of globular clusters. They explored the effects of significant changes in the BS formation rate on the observed distribution of BSs in the color-magnitude diagram and found that the currently observed BS populations should vary significantly depending on the past formation rate. These models were applied to the observations of blue stragglers in 47 Tuc. The results suggest that this cluster may have undergone a burst of blue straggler formation that ended some 3 Gyr in the past.

Sills, J. Lombardi (Vassar), and F. Rasio (MIT) are combining smoothed particle hydrodynamics simulations of stellar collisions with detailed stellar evolution calculations to study the formation of blue stragglers. Of particular interest are the off-axis collisions which produce a rotating blue straggler. Since off-axis collisions are much more likely to occur than head-on collisions, this is the expected starting model for a blue straggler formed by stellar collisions. It appears that these stars have very high angular momenta and reach their breakup velocities shortly after the collisions. Only the outer $\sim 1\%$ of the mass reaches this critical velocity, and it is probably lost from the star. The subsequent evolution of the blue straggler is still affected by the remaining angular momentum, and is different from that of a non-rotating star.

Sills and C. Deliyannis (Indiana) are using evolutionary models to look at the light element transport mechanisms in low-mass stars. By comparing models that include diffusion, rotation, or mass loss to observations of lithium in subgiants in M67, they have determined that both diffusion and mass loss are unlikely candidates for light element transport, and stellar rotation seems the best choice for understanding the destruction of lithium in stars.

Pinsonneault, Narayanan, Steigman, and Walker investigated the agreement between recent halo Li data sets and the predictions of stellar evolution models that include rotational mixing. A small intrinsic dispersion, implying stellar evolution-induced Li depletion at the lower end of the range in Pinsonneault et al.'s recent investigation, was found for the recent Ryan et al. sample. However, a much larger intrinsic dispersion for the same stars and the same assumed effective temperatures was found by Thorburn (1994), indicating that a difference in the reported equivalent widths and not simply a reduction in observational uncertainties is responsible for the different result.

Pinsonneault, with J. King (STScI) and A. Krishnamurthi (JILA), examined the correlation between Li abundance, rotation, and activity in the young cool stars of the Pleiades. A de-trending technique was used to remove the strong decline in Li abundance with effective temperature, and stellar abundances relative to that mean trend were used to search for a correlation between Li excess or deficit and other stellar properties. Although rapid rotation has been proposed as strongly correlated with high Li abundance, Pinsonneault et al. found that there are bona fide slow rotators with measured rotation periods that have Li excess. However, there was a strong correlation between chromospheric activity and Li excess; furthermore, there was also a strong correlation between unusually strong potassium and unusually strong Li at the same temperature. They concluded that at least some component of the Li dispersion in these young, cool stars arises from atmospheric effects (the mapping from equivalent width to abundance) rather than interiors effects.

Pinsonneault, with S. Basu and J. Bahcall (IAS), investigated the sensitivity of helioseismic inversion to the assumed solar reference model. They found that the inferred "true" solar sound speed was relatively insensitive to the reference model that was used; only in cases where the reference model was far from the real Sun were the errors found to be significant. They also found that models that include rotational mixing have an improved agreement with helioseismic data. In other solar model studies, Pinsonneault and C. Watson (OSU physics student) studied the structural effect of an increased (^{3}He,p) cross-section on the helioseismic properties of solar models. The effect was found to be small, indicating that — similar to the (^{7}Be,p) reaction — nuclear physics rather than helioseismology is the most important constraint on some of the rare nuclear reactions that could be important neutrino sources for the Sun.

Pinsonneault, Yuan, Terndrup, and J. Stauffer (CfA) compared the open cluster distance scale derived from main sequence fitting to that inferred from the Hipparcos mission. The focus of this work was primarily on developing a good distance and metallicity scale for less well studied open clusters. In addition, a technique was developed that uses the boundary between young stars on the main sequence and lower mass stars still above the main sequence as an age diagnostic. An age of 55 ± 5 Myr was derived for the Alpha Per cluster using this method; this is consistent with ages determined using the upper main sequence but inconsistent with recent age determinations found from Li-age dating in the brown dwarf regime.

Pinsonneault, Terndrup, and A. Sills continued their work on the angular momentum evolution of stars in young open clusters. In a recently submitted paper, they presented the results of an extensive study of rotation and chromospheric activity of nearly 90 low mass ($M \leq 0.4 M_{\odot}$) stars in the Pleiades and Hyades, in collaboration with Stauffer and several other authors. The main results are an estimate of the time scale for rotational spindown at the bottom of the main sequence and new observational support for the current theoretical paradigm of saturation of the angular momentum loss rate at high rotational velocities.

Terndrup and Pinsonneault, in collaboration with Stauffer and Krishnamurthi, have also been exploring the frequency of rotational photometric modulation by starspots in M dwarfs and substellar objects in the Pleiades. They detected spots in two of four M dwarfs and estimated spot coverage for one of them, but found no modulation in any of the substellar objects in the Pleiades. This is consistent with other recent studies which show a rapid decline of chromospheric and coronal activity near the mass limit for hydrogen burning. This collaboration plans an extensive survey of modulation in field L-type dwarfs in the Spring of 2000.

Stauffer, Terndrup, and several other authors recently submitted a paper that provides a new estimate for the age of the Alpha Persei star cluster using the lithium edge method. This method makes use of the fact that fully convective pre-main sequence stars below an age-dependent luminosity do not have central core temperatures high enough for Li destruction. Their age estimate, 85 ± 8 Myr, is considerably older than previous values from the morphology of the main-sequence turnoff, but it is in line with other recent studies which suggest that the estimated ages of most young clusters need to be increased.

Terndrup, R. Peterson (UCO/Lick), E. Sadler (U. Sydney), and A. Walker (CTIO) are extending their survey of hot horizontal-branch stars in the nuclear bulge. These stars are believed to be responsible for the copious ultraviolet flux that arises from elliptical galaxies and the bulges of other spirals, but few of these stars are known in the Galaxy. In a recent conference proceeding, Terndrup and Peterson reported the discovery of dozens of hot horizontal branch stars in the bulge, and they are preparing a paper on their metallicity and kinematics.

Keenan and Newsom extended the Revised Catalog of Standard MK Spectral Types for the Cooler Stars through 13 hrs. of right ascension. The purpose of this catalog is to provide a network of type stars covering all parts of the sky at a resolution of about 2500 (2 to 3 Å in the blue). This extensive revision of the Perkins Catalog was made necessary by the Hipparcos parallaxes, which have led to a slight modification of the MK luminosity classes for giants of types G5 to K3. Class IIIb now identifies most stars belonging to the clump. As the zones of the catalog are completed they are made available on the web at `http://www.astronomy.ohio-state.edu/MKCool/`.

Wing has continued his search for distant red supergiants along the southern galactic plane in collaboration with D. MacConnell (CSC/STScI) and E. Costa (U. de Chile). To date approximately 5000 candidate stars, selected on the basis of near-infrared objective-prism plates, have been classified by narrow-band photometry, and more than 1000 of them have been confirmed as supergiants (luminosity class Ib and higher). Most of these are heavily reddened and quite faint visually, and they are providing new information about distant spiral arms of the Galaxy.

As a by-product of their search for red supergiants, Wing and his collaborators have discovered four new stars of type S. Their colors on Wing's eight-color system of narrow-band classification photometry were noted as peculiar, and CCD spectrograms in the 6800–8800 Å region showed both the ZrO bandhead at 6474 Å and broad LaO features near 7400 and 7900 Å. Stars of type S have frequently been mistaken for reddened M supergiants (and vice versa) in previous survey work, since both show enhanced CN absorption (relative to normal M giants) and weak TiO for their colors. Wing and MacConnell are therefore studying their photometry of known S stars to develop ways of making this distinction.

4 Interstellar Medium (ISM)

Herbst, in collaboration with F. De Lucia (OSU Physics) and G. Winnewisser (U. of Cologne), has for many years directed a program in laboratory spectroscopy of molecules of interstellar interest. In the last year, the millimeter-wave spectra of the molecules methyl mercaptan (CH_3SH), dimethyl ether (CH_3OCH_3), methyl formate ($HCOOCH_3$), ethylene oxide (c-C_2H_4O), and phosphorus hydride (PH) have been investigated. Spectra have been taken at frequencies up to and surpassing 1 THz. Millimeter-wave spectra are also being utilized to measure cross sections for rotationally inelastic collisions at low temperatures involving molecular hydrogen and collision partners such as CO and the ion HCO^+; such cross sections are needed to convert interstellar emission spectra into column densities under non-LTE conditions.

Herbst's program of research into the gas-phase and grain surface chemistry of interstellar clouds has recently encompassed the study of protoplanetary disks. With postdoctoral associate Y. Aikawa (OSU Physics), Herbst has studied the chemistry and deuterium fractionation occurring in both inner and outer regions of the disks. In collaboration with B. Turner (NRAO), Herbst and graduate student R. Terzieva (OSU Physics) have continued their research into the chemistry of high-latitude translucent clouds in our Galaxy. Herbst and postdoctoral associate D. Ruffle (OSU Physics) have looked at the formation of large negatively-charged organic molecules in diffuse interstellar clouds to determine if such species can be the carriers of some of the well-known diffuse interstellar bands (DIBs).

Herbst, D. Talbi (Ecole Normale, Paris), and Terzieva have shown that the high abundance of the metastable isomer HNC in dark interstellar clouds is very surprising from a chemical point of view since most gas-phase reactions produce not this species but the more stable HCN isomer. With Terzieva and Japanese collaborators Y. Osamura and K. Fukuzawa (Rikkyo U.), Herbst has studied the formation of the well-known species HC_3N and three of its metastable isomers in interstellar clouds. Herbst and Terzieva, along with collaborators from assorted laboratories, showed that gas-phase chemical reactions can produce aromatic molecules in cold interstellar clouds.

Although the formation of molecular hydrogen from precursor hydrogen atoms is thought to occur on the surfaces of interstellar dust particles, the details of this process are not well understood. Herbst and collaborator V. Le Page (Paris) have shown that it is unlikely that the reaction can occur on small interstellar dust particles such as polycylic aromatic hydrocarbons if they possess positive charge, since the hydrogen atoms sticking to these grains are strongly bound and immobile. The outcome of collisions between the positively-charged molecular ion HCO^+ and negatively-charged grains has been investigated by Herbst, Aikawa, and F. Dzegilenko (NASA Ames). The granular chemistry leading to the major components of molecular ices in cold interstellar clouds has been studied with P. Caselli (Arcetri) and Ruffle.

Martini, Sellgren, and DePoy completed their study of molecular hydrogen in NGC 1333, NGC 2023, NGC 2068, and NGC 7023. They found that NGC 1333 has a lower density and weaker UV field than NGC 2023 and NGC 7023, consistent with its later B-type central star. NGC 2068, the other previously unstudied reflection nebula in this sample, has similar physical conditions to NGC 2023 and NGC 7023. They also found that the near-infrared continuum in NGC 2023 and NGC 7023 peaks closer to the central star than the molecular hydrogen emission, implying that the carrier for this emission can survive in a stronger UV field than the molecular gas.

Martini, Sellgren, and DePoy obtained (remote) observations of a sample of 20 galactic nebulae in the L–band with a 3.3 μm narrow-band filter with ABU/SPIREX at the South Pole. These nebulae were selected on the basis of bright aromatic emission features in IRAS spectra and include reflection nebulae, H II regions, and planetary nebulae. As these nebulae span a wide range in ionization field, temperature, and density, they will form a useful data set for probing the spatial distribution of dust emission and the physical conditions in which the dust emits strongly and is destroyed.

Uchida, Sellgren, and M. Werner (JPL) have been using ISO's mid-infrared camera and its circular variable filter to obtain imaging spectroscopy of photodissociation regions, where stellar radiation interacts with a nearby molecular cloud. They have obtained spectra of six reflection nebulae whose central stars have temperatures between 3,600 and 19,000 K. They detect the interstellar infrared emission features (IEFs) at 6.2, 7.7, 8.6, 11.3, and 12.7 μm in three nebulae with stellar temperatures of 6,800 to 19,000 K. Current models which identify the IEFs with polycyclic aromatic hydrocarbons (PAHs) predict that PAHs should be neutral in low UV fields and ionized in high UV fields. Laboratory data on PAHs show distinct spectroscopic differences between neutral and ionized PAHs, which can be quantified by the relative strengths of different IEFs. Uchida et al. observe, however, that the relative strengths of the IEFs show little or no dependence on the intensity or hardness of the incident UV field over a very wide range in UV field strength. This observation suggests that ionization balance models for PAHs may be in error, or that another substance may be responsible for the IEFs.

Pizagno, Sellgren, and Uchida are currently convolving laboratory absorption spectra at UV and visible wavelengths with the energy distributions of the stars illuminating different reflection nebulae, to make quantitative tests of laboratory analogs for the materials which emit the IEFs. These laboratory analogs include neutral and ionized PAHs as well as several varieties of hydrogenated amorphous carbon.

Sellgren has used ISO's short-wavelength spectrometer to obtain a 2 – 45 μm spectrum of the bright reflection nebula NGC 7023, in collaboration with C. Moutou (ESO), and A. Léger and L. Verstraete (Institut d'Astrophysique Spatiale). The results to date include (a) a sensitive upper limit on the C_{60}^+ abundance in the ISM; (b) detections of pure rotational transitions of H_2, which are good measures of the gas temperature in the photodissociation region; (c) the discovery that the "7.7" μm IEF in fact breaks up into three distinct features at 7.4, 7.6, and 7.8 μm; and (d) a discovery of a new IEF at 16.4 μm which may be evidence for interstellar PAHs containing pentagonal ring structures.

Sellgren and An are comparing the spatial distribution of different molecular and grain components in NGC 7023. They are analyzing images of emission from H_2, the 2 μm continuum, and the 3.3 μm IEF. The H_2 emission arises in narrow, dense filaments at the edge of the photodissociation region. The 2 μm continuum peaks considerably closer to the star than the H_2 emission, suggesting that it is predominantly associated with neutral rather than molecular gas. The 3.3 μm IEF, believed due to tiny aromatic grains and/or large aromatic molecules, is found in association with both the 2 μm continuum peak and the H_2 peak. This suggests, surprisingly, that the 3.3 μm IEF emitter is distinct from the 2.2 μm continuum emitter, and that the 3.3 μm IEF emitter can survive in both neutral and molecular gas.

5 Our Galaxy

J. Carr (NRL), Sellgren, and S. Balachandran (U. Maryland) have completed a paper on the first stellar abundance determinations in the Galactic Center (GC), based on observations of the M supergiant IRS 7. They perform a detailed abundance analysis of high-resolution ($\lambda/\Delta\lambda = 40{,}000$) K–band spectra obtained with CSHELL at the NASA Infrared Telescope Facility. Surprisingly, they find that [Fe/H] in IRS 7 has a solar value, rather than the super-solar value expected from models and observations of external galaxies. They also find evidence from the CNO abundances in IRS 7 for surprisingly strong mixing processes at work in this star.

Ramírez, for her Ph.D. thesis, is using the techniques established by Carr et al. to measure the stellar abundances in a much larger sample of stars in the central 100 pc of the Galaxy. She is collaborating with Sellgren, Carr, Balachandran, R. Blum (CTIO), and Terndrup to perform a detailed abundance analysis based on high-resolution K–band spectra of ten GC stars. Her sample consists of seven M supergiants and three AGB stars, each with $K < 9$ and low water absorption. Nine of these stars, including the three AGB stars, are located in the central cluster within 2.5 pc of the GC. The remaining M supergiant belongs to the Quintuplet cluster, located 30 pc away from the central cluster. Ramírez et al. have found that *all* the [Fe/H] values for the ten GC stars are consistent with the solar Fe abundance, confirming the Fe abundance found by Carr et al. for IRS 7. Furthermore, the narrow spread of [Fe/H] values in the GC is in agreement with the narrow spread of [Fe/H] values for disk supergiants measured in the solar neighborhood, and in stark contrast to the wide spread of [Fe/H] measured for the bulge of the Milky Way. This suggests that the GC stellar population is more closely linked to the disk stellar population than to the bulge stellar population, although many have considered the GC simply to be the high-density core of the bulge. Ramírez and her collaborators plan next to measure stellar abundances of α–elements (Ca, Si, Ti) to address the issue of selective enrichment in the GC.

Ramírez, Blum, and Sellgren are using low-resolution 1.4 – 2.3 μm spectra of ~ 50 GC stars to measure the strengths of CO and H_2O bands in these stars. These two spectral features, considered together, can provide a measure of effective temperature for the GC stars. These data, combined with photometry from which the bolometric luminosity can be derived, place each GC star on the Hertzsprung-Russell diagram. The mass and age of each GC star can then be estimated by comparison with published stellar evolutionary tracks. Initial results suggest that the most luminous stars in the GC at infrared wavelengths are primarily asymptotic giant branch stars, with ages of hundreds of millions of years, rather than luminous M supergiants and hot emission-line stars with ages of a few million years. This confirms that star formation has been an on-going process in the GC, but further work is needed to determine whether the star formation history of the GC has been continuous over time or whether stars form there in bursts of star formation.

Frogel, Gould, and Stephens, together with a team of astronomers from the European Southern Observatory and several Italian universities, analyzed deep HST NICMOS images of one field in the bulge of the Milky Way. They were able to derive a main sequence luminosity function down to an absolute J (1.2 μm) magnitude of 9.3. This is the faintest luminosity function derived to date for the bulge; the equivalent mass function reaches down to 0.15 $M_\odot$ with a power-law slope of -1.33. Although shallower than the Salpeter mass function (-2.35 on this scale), it agrees with some recent determinations of the local disk mass function and is also similar to mass functions derived for a sample of globular clusters that are believed to have experienced little or no dynamical evolution. These HST/NICMOS data are well fit by new low-mass stellar models that include opacity sources due to water and molecular hydrogen. When the luminosity functions derived earlier by Frogel and his collaborators for brighter stars in the bulge are combined with the new HST/NICMOS data, the resulting luminosity function spans about 15 magnitudes — the most extensive luminosity function ever derived with such precision. Finally, the mass-to-luminosity (at 1.2 μm) ratio for the bulge is found to be 0.9 ± 0.1 in solar units.

Frogel and Ramírez are completing the analysis of K–band (2.2 μm) spectra of more than 100 M giants along the minor axis of the Galactic bulge, extending from 0.5 to 8 degrees. The main objective is to derive the metallicity gradient along the minor axis by measuring the strengths of atomic absorption features due to calcium and sodium and molecular features due to carbon monoxide. Globular cluster giants are used for calibration purposes. The initial results indicate only a small inward increase in metallicity as the center of the Galaxy is approached. Frogel and Ramírez find, from a small extrapolation, that the abundance at the center itself should be near solar. These results are consistent with the findings of Frogel, Tiede, and Kuchinski described in last year's annual report, which were based solely on photometric observations in the same fields.

Frogel and Stephens are completing their analysis of K–band spectra of globular cluster giants. They have observed more than 100 stars in 15 clusters from CTIO and MDM. Their objective is to set up a metallicity calibration that will be applicable to metal-rich clusters and to clusters that are heavily reddened. Eventually, the system can be extended to extragalactic clusters via observations with NGST. Metal-rich clusters are difficult to study optically for several reasons. They are often heavily reddened, and it is often difficult to separate foreground dwarfs from giant cluster members because they lie in crowded, low-latitude fields. Furthermore, strong molecular absorption throughout the optical region of the spectrum reduces the observed optical light from the giants in a cluster by up to several magnitudes, making them appear significantly fainter, optically, than stars that are much further down the giant branch. Since many available optical abundance rankings are based on integrated light measurements, the combined effects of reddening, field contamination, and molecular blanketing cause the relative contributions of stars in different evolutionary stages to be skewed towards (bolometrically) fainter and hotter stars. This skewing can cause underestimates of the true cluster abundance. In the K band, the giants are the brightest and reddest stars in a metal-rich cluster. There is enhanced contrast between them and foreground stars, and they are relatively easy to identify even on short-exposure, non-photometric images. Also, because they are bright in the K band, the necessary spectroscopic observations are easy to obtain. From their preliminary results Frogel and Stephens find that with $3-8$ stars per cluster they can reproduce the best high resolution optical metallicity scale to better than 0.15 dex and, in some cases, to 0.10 dex. They do not see evidence for α–process abundance enhancement. These initial results point to the great usefulness of this technique in the analysis of many of the metal-rich globular clusters in the central part of the Milky Way and in external systems. Frogel and Stephens have already determined that the optical abundances of two clusters are in error by as much as a factor of 10.

6 Other Galaxies

Frogel, Stephens, and a small international team of astronomers are studying the stellar content of M31, the nearest large spiral galaxy to the Milky Way, with observations from two HST programs. The first program consists of HST/NICMOS observations of several fields in the bulge of M31. The primary objective is to settle the long-standing controversy about the luminosity of the stars in M31's bulge. This luminosity in turn has important implications for the determination of the age, and hence the formation history, of M31's bulge. In another HST NICMOS project, Frogel and Stephens have obtained images of five M31 globular clusters that appear to be extremely metal-rich. Again, determination of the luminosity function of the bright stars on the red giant branches of these clusters will have important implications for the determination of their ages and history. The data will be compared with similar observations of galactic globular clusters that Frogel, Stephens, and other OSU graduate students have been obtaining at the MDM observatory. These programs will add to our knowledge of the early history of M31.

Eskridge is working with Frogel on analysis of the OSU Spiral Galaxy Survey. The ~ 200 galaxies in the survey are a complete, magnitude-limited sample drawn from the RC3. With the exception of about one dozen galaxies whose deep BVR images need photometric calibration, all of the observations for the survey have now been completed. The first results on the full survey database show that 56% of the sample is strongly barred in the H–band (1.6 μm), compared with 30% in the B–band. Roughly three-quarters of the sample have detectable bars. This is the first large, statistically well-defined sample that has been used to determine the frequency of bars in the near-IR. Eskridge and Frogel are also working on a general spiral galaxy morphological classification in the near-IR. Since the H light is a much closer tracer of the stellar mass distribution of the galaxy than is optical light, this work will result in a more fundamental classification of the galaxies that should be closely related to the galaxy dynamics rather than being primarily determined by the presence of dust and young stars. A collaboration with D. Block (U. Witwatersrand) and I. Puerari (INAOE) is using a subsample of the OSU Survey sample to make a quantitative comparison between the optical and near-IR arm structure of spirals.

Frogel and Eskridge continue their collaboration with R. Windhorst's galaxy group at Arizona State University. From their deep U band images of many of the galaxies in the OSU survey, they expect to learn much about star formation and to be able to predict the appearances of galaxies at large redshift. With this collaboration, there are more than 400 galaxies in the sample. The combined $UBVRIJHK$ sample will allow them to quantify local galaxy parameters in the range 3000 Å – 2.2 μm. They have submitted a proposal to HST to obtain even deeper images in the UV.

Kaufman, E. Brinks (U. Guanajuato), B. Elmegreen (IBM), D. Elmegreen (Vassar), M. Klarić (Columbia SC), C. Struck (Iowa State), and M. Thomasson (Onsala) have continued their detailed studies of galaxy pairs undergoing close, non-merging encounters. They have made HST WFPC2 observations in $UVBI$ of the ocular (eye-shaped) galaxy IC 2163 interacting with its spiral companion NGC 2207 and are comparing the HST images with their previous VLA H I and radio continuum data. They find no super star clusters in this galaxy pair, which suggests that the 40 Myr since perigalacticon is too short a time for their development. In the region where rapidly streaming gas in IC 2163 meets its tidal tail, the HST images reveal an impressive array of nearly parallel dust filaments, which will be analyzed. In collaboration with S. Vogel (U. Maryland), this group has completed an extensive study of the interacting spiral galaxies NGC 5394/95. NGC 5394 is in an immediate post-ocular phase, with a central starburst, an intrinsically oval disk, two long tidal arms, and very bright inner spiral arms, disjoint from the outer tidal arms. They find that most of the gas in NGC 5394 is in molecular form and concentrated near the center, and so is suitable for fueling the starburst. NGC 5394 and the two ocular galaxies IC 2163 and NGC 2535, studied earlier by this group, form an evolutionary sequence of structures resulting from prograde encounters and thus confirm the generic models of such collisions.

Pogge, Ryden, Terndrup, and T. Statler (Ohio U.) are continuing their study of the surface photometry of dwarf ellipticals in the Virgo cluster. They obtained B and R photometry for a sample of approximately 20 dwarf ellipticals in 1999 March. Additional observations in the V and I bands, planned for the future, will place constraints on the stellar populations and star formation histories of these dwarfs. Measurement of surface brightness fluctuations will also permit a calculation of the upper end of the stellar luminosity function and may permit accurate distance determinations to the dwarf ellipticals.

Berlind and Conti have been studying the evolution of galaxy sizes in the Hubble Deep Field (HDF). They have adopted as their angular size estimator the Petrosian metric radius, which is defined by a threshold value of ratio of the average surface brightness within a radius r to the surface brightness at that radius. This definition is relatively insensitive to redshift, making it a good probe of evolutionary changes in the galaxy size. Preliminary results show little change in the galaxy size distribution from a redshift of 3 to a redshift of 0, for galaxies with published photometric redshifts in the HDF.

7 Active Galactic Nuclei and Quasars

Martini and Pogge obtained the data for their NICMOS program of imaging the CfA Seyfert 2 galaxies. They found spiral structure in the circumnuclear regions (100 – 1000 pc) of nearly all of these AGN that is distinct from the main spiral structure in these galaxies. Their study showed that these spiral arms reside in a non-self-gravitating disk and are therefore likely due to shocks. If this is the case, these spirals may be the dynamical signature of the fueling process in these low-luminosity AGN.

Pogge and D. Maoz (Tel Aviv), M. Eracleous (Penn State), and L. Ho (OCIW) have examined HST narrow-band Hα and [O III] λ5007 images of the central regions of 14 galaxies with LINER nuclei (both from their observations and the HST Archives). This is the first such study of a sizable sample of LINERs at HST resolution. The compact, $\sim 1''$–scale, unresolved emission which dominates the line flux in ground-based observations of these LINERs is mostly resolved in the HST images. Most of the Hα and [O III] emission arises, on 10–100 pc scales, as a combination of knots, filaments, and diffuse gas. Most of the galaxies do not show clear linear structures or ionization cones analogous to those often seen in Seyfert galaxies, with the possible exception of NGC 1052, the prototypical LINER, in which a $3''$–long ($\sim$ 250 pc) biconical structure is oriented on the sky along the galaxy's radio jet axis. The 14 galaxies are divided into 7 UV-bright and 7 UV-dark objects ("UV-dark" meaning undetected at 2200 Å by either the HST FOC or WFPC2). They find a dusty environment in the nuclear regions of all 14 galaxies, but only in most of the "UV-dark" cases is the nucleus itself fully obscured. Overall, their data suggest that the line-emitting gas in most LINERs is photoionized by a central source (which may be stellar, nonstellar, or a combination thereof) but that this source is often hidden from direct view in the UV by dust in the host galaxy.

Peterson, Pogge, Wagner, and Bertram are continuing their study of long-term optical continuum and broad emission-line variability in Seyfert 1 galaxies with the telescopes of the MDM Observatory. The goals of this program are to understand broad-line profile variations and to determine the variability power spectrum of the continuum with the specific aim of identifying the low-frequency turnover, which is expected to be related to the mass of the central black hole.

Peterson, A. Wandel (UCLA and Hebrew U.), and M. Malkan (UCLA) are investigating the mass–luminosity relationship for AGNs. Masses are virial estimates based on broad emission-line gas within a few light-days of the central source. The sizes of the line-emitting region are determined from reverberation mapping, i.e., by measurement of the time delay between continuum variations and the response of the emission line. Virial masses are obtained by combining these measurements with measurements of the width of the variable part of the emission lines. In a few cases, notably the well-studied galaxy NGC 5548, the time lags for multiple emission lines have been measured, and these show the expected $V \propto r^{-1/2}$ virial relationship, adding credence to these determinations. For the Seyfert galaxies studied thus far, the AGN masses typically lie in the range $10^{6-8}\,M_{\odot}$.

Peterson is continuing to analyze the results of a multiwavelength monitoring experiment on the Seyfert 1 galaxy NGC 7469 undertaken in 1996 with IUE, RXTE, HST, and ground-based telescopes. G. Kriss (STScI), Peterson, D. M. Crenshaw (Catholic U.) and W. Zheng (JHU) have carried out a re-analysis of the IUE data by modeling the spectra with a template based on a single high-quality spectrum obtained with HST. This work seems to confirm the existence of wavelength-dependent time delays between continuum variations in various bands. With K. Nandra (GSFC) and others, Peterson is also in the early stages of a more complete spectral analysis of the RXTE data on this source.

Peterson continues his involvement in several multiwavelength monitoring programs. With R. Edelson (U. Leicester) and others, the Seyfert 1 galaxy NGC 3516 was monitored continuously for approximately three days by HST while it was in the continuous viewing zone. Simultaneous X-ray observations were made by ASCA and RXTE. The hard (2–10 keV) and soft (0.5–2 keV) X-ray variations were found to be strongly correlated without any evidence for an interband lag. Similarly, while statistically significant variations were detected in the optical, there is no evidence either for interband lags or for any correlation with the X-ray variations. M.

Santos-Lleó (LAEFF, Spain), J. Clavel (ISO Operation Center, Spain), Peterson, and others, are analyzing observations of the Seyfert 1 galaxy Mrk 279 obtained with the Infrared Space Observatory (ISO) and ground-based telescopes. Low-level variations in the optical were significant enough to yield a reverberation lag for the broad Hβ line, but were not strong enough to yield detectable IR variations due to dust reprocessing.

In collaboration with various members of the International AGN Watch, including Bertram, Pogge, Romano, and Wagner, Peterson is completing a reverberation-mapping study of the narrow-line Seyfert 1 galaxy NGC 4051. The Hβ emission-line lag has been measured to be $5.9^{+3.1}_{-2.1}$ days, leading to a virial mass estimate of $1.1 \times 10^6\,M_\odot$ for the central source.

Peterson is also leading a multiwavelength program to measure a virial mass for the narrow-line Seyfert 1 galaxy Akn 564 and to determine the relationship between continuum variations in the X-ray and those at longer wavelengths. This program involves HST, RXTE, the Chandra X-ray Observatory, and several ground-based telescopes. It will be undertaken in two epochs, in 1999 October and November and in 2000 May and June.

Peterson and Collier are carrying out a program of numerical simulations to determine requirements for future reverberation-mapping experiments. The goal of the program is to determine efficient strategies, in terms of total duration, time resolution, and duty cycle, for multiwavelength monitoring programs.

Osmer, Monier, and Conti are involved in two multicolor searches for quasars intended to investigate the evolution of quasars and to determine the quasar luminosity function at high redshifts. These optical surveys are designed to detect the presence of Lyα emission and continuum flux in one filter and the fainter, depressed continuum shortward of Lyα in another. As the redshift region of interest increases, the filters needed to perform the search become progressively redder. This color differential (e.g. V–I), the quasar signature, is readily apparent when the magnitudes are compared. By using color–color diagrams (e.g. V–I vs. I–Z), possible quasars can be distinguished from stars and suitable candidates can be selected for follow-up spectroscopy. The Z data are particularly necessary in the search for $z > 5$ quasars to eliminate late-type M stars that would contaminate a sample selected solely on the basis of V–I colors.

The BTC40 wide-field survey for quasars at $z > 5$ is is being led by J. Kennefick (Oxford) and includes R. Green (NOAO), P. Hall (U. Toronto) and M. Smith (CTIO). The BTC40 has imaging data at high galactic latitude for 40 deg^2 in the B, V, I, and Z bands and reaches to $\sim$ 25th magnitude at its deepest limit. Catalogs of the data reduced to date have been generated using the SKICAT catalog management software. To prepare candidate lists for follow-up spectroscopy, Kennefick and Monier are currently performing photometric calibrations and removing astrometric distortions from the field to produce accurate coordinates. Further spectroscopic observations are planned for Spring 2000.

The BFQS is a collaboration of the same group and is being led by Hall. It also uses the BTC camera and reaches to $m_{\rm lim} = 26.7$ over 7 deg^2. It uses the B, R, I bands and is aimed at quasars with $3.3 < z < 5$ down to luminosities near the break in the luminosity function.

Conti, Monier, and Osmer are using Z–band data of the HDF-South, taken by Conti and M. Smith (CTIO) at the CTIO 4-m in November 1998, to investigate the presence of high-redshift quasar candidates. This work is a logical extension of Conti et al.'s similar search in the HDF-North, described in last year's annual report.

Monier is working with D. Turnshek, S. Rao, and D. Nestor (U. Pittsburgh), and F. Briggs and W. Lane (Kapteyn Institute) to investigate the properties of galaxies responsible for damped Lyα absorption lines at low redshifts. These features are produced when a background quasar is viewed through a large column of neutral hydrogen. The low-redshift sample resulted from an HST survey of quasars with previously identified low-redshift Mg II absorbers, and it includes the lowest-redshift ($z \approx 0.09$) damped Lyα system known, toward the quasar OI 363. A large amount of ground-based imaging and spectroscopic data obtained in the past year at WIYN, the KPNO 4-m, the MDM 2.4-m, and NASA's Infrared Telescope Facility is currently being reduced and analyzed.

Martini and Weinberg are investigating the possibility that measurements of quasar clustering can constrain the typical quasar lifetime, a quantity currently uncertain by more than an order of magnitude. In their theoretical modeling they assume that the most luminous quasars form in the most massive dark matter halos, and they determine the minimum halo mass by matching the observed space density of quasars at a given redshift. For long quasar lifetimes, the minimum mass is large; the corresponding halos are highly biased tracers of the underlying mass distribution and therefore exhibit strong clustering. For shorter quasar lifetimes, the host halos are less massive and more weakly clustered.

8 Gravitational Lensing and Its Applications

Gould is currently focusing his work on applications of gravitational microlensing and on the local distance scale. Microlensing studies include detection of planets, microlensing observations toward M31, developing new methods to extract additional information about individual microlensing events, investigation of the relation between star counts and microlensing, and measurement of the masses of nearby stars using astrometric microlensing. Local distance-scale work includes measuring the Galactocentric distance R_0 using kinematics and measuring the absolute magnitude of RR Lyrae stars using the FAME satellite. Gould serves on the science team of FAME, which has just been approved as a NASA MIDEX mission.

DePoy, Gould, Pogge, An, and Gaudi work with the PLANET collaboration to search for extra-solar planets by intensive follow-up observations of on-going microlensing events. PLANET has substantial observing time on four telescopes, the Yale–CTIO 1-m, the SAAO 1-m, the Canopus 1-m in Hobart, Tasmania, and the Perth 0.6-m in Western Australia, and over the past year has made nearly ten thousand CCD images of microlensing events. As noted in §2, OSU has installed an instrument for simultaneous optical and near-IR imaging on the Yale–CTIO 1-m and expects to install an identical instrument in South Africa in late 1999, in support of the PLANET project.

During the past year, the PLANET collaboration developed a general method for extracting the frequency of extrasolar planets from microlensing observations and began applying this method to 25 events with good sensitivity to planets. This will soon yield the first limits on Jovian mass planets in Jupiter-like orbits to date. It also measured the limb darkening of two stars, a K giant and a metal-poor A star, and showed (in collaboration with several other microlensing groups) that one of the two lenses detected toward the SMC is in the SMC itself and not in the Galactic halo.

9 Cosmology

9.1 Large-Scale Structure

Berlind, Narayanan, and Weinberg have used a combination of large volume N-body simulations and simple but varied prescriptions for biased galaxy formation to examine what can be learned from measurements of the parameter $\beta = \Omega^{0.6}/b$, where the linear bias parameter b is the ratio of density contrasts in the galaxy and mass distributions. Given that the one-parameter model for bias is most likely oversimplified, it is not clear what is actually being measured by the different techniques. This study has focused on two techniques for measuring β: the anisotropy of the redshift-space power spectrum and the POTENT method. In most cases, the bias factor $b = \Omega^{0.6}/\beta$ derived from redshift-space anisotropy or POTENT is similar to the large-scale value of $b_\sigma(R)$ defined by the ratio of rms fluctuation amplitudes of the galaxy and mass distributions. However, non-linearity of bias and residual effects of non-linear gravitational evolution both influence estimates of β at the 10–20% level.

Narayanan and Weinberg, in collaboration with E. Branchini (Kapteyn) and C. Frenk (Durham U.) have reconstructed the galaxy distribution in the Point Source Catalog Redshift Survey (PSCz), using their hybrid reconstruction technique. They find that unbiased models in which IRAS galaxies trace mass fail to reconstruct the PSCz catalog accurately, for different values of the cosmological density parameter Ω_m. They also find that low Ω_m models in which IRAS galaxies are antibiased with respect to the mass distribution are the most successful in reconstructing the PSCz catalog.

Weinberg continues his participation in the Sloan Digital Sky Survey (SDSS). In the last year he has concentrated on issues related to galaxy spectroscopic target selection. He serves on the SDSS Collaboration Council and is the project's Scientific Publications Coordinator. Although the SDSS is still in its commissioning phases, it has produced its first important scientific results, including discovery of the first $z = 5$ quasars and discovery of the first free-floating methane dwarfs. Weinberg and Berlind, in collaboration with W. Colley (Harvard), J. R. Gott (Princeton), and C. Park (Seoul National U.), completed a paper analyzing the topology of large-scale structure in a simulated SDSS catalog drawn from a large N–body simulation.

Ryden and J. Schmidt (OSU physics) are conducting a study of voids in the large-scale distribution of galaxies. They are investigating how the statistical properties of voids depend on the algorithm used to define voids. In addition, they are determining how the size and shape of voids are affected by peculiar velocities and cosmological distortions in different cosmologies. Currently, they are applying void-defining algorithms to three-dimensional numerical simulations of large-scale structure.

With E. Gaztañaga (Barcelona), Scherrer is investigating how redshift distortions alter the probability distribution of the density of galaxies. Scherrer has developed a theoretical model of this distortion and is testing it with Gaztañaga's numerical simulations. This work is still in progress, but early results indicate that the theoretical model works quite well at predicting the galaxy density distribution in redshift space. This project is motivated by the large galaxy redshift surveys underway or planned for the immediate future.

9.2 Galaxy Formation and High-Redshift Structure

As part of his thesis work, Conti is developing a theoretical framework for interpreting observations of disk galaxy properties with the aid of Principal Component Analysis (PCA). PCA has already yielded important insights about elliptical galaxies, but it has been more difficult to apply to disk galaxies because of the complex selection biases that affect existing observational samples. These biases will be much better controlled in the SDSS, and the sample of data suitable for PCA will be orders of magnitude larger than those that exist today, thereby providing an ideal test bed for Conti's work. This work takes as its starting point the semi-analytic model of disk galaxy formation developed by Mo, Mao & White; however, while Mo et al. focused on the predictions of specific cosmological models, Conti will instead consider a broad range of input assumptions and examine the relation between the observable properties of galaxies (luminosities, scale lengths, colors, morphologies, velocity widths, spectroscopic signatures of star formation, etc.) and the physical parameters that describe galaxies in the theoretical framework (e.g., halo masses, halo density profiles, baryon fractions, initial angular momenta, collapse redshifts, star formation histories, merger histories).

Weinberg, in collaboration with R. Davé (Princeton), J. Gardner (U. Washington), L. Hernquist (Harvard), and N. Katz (U. Massachusetts), is using hydrodynamic cosmological simulations to investigate various theoretical aspects of galaxy formation. These include the predicted star formation properties and clustering of galaxies from $z = 8$ to $z = 0$, the properties of damped Lyα and Lyman Limit absorbers at $z = 2 - 4$, and (in collaboration with M. Fardal of U. Massachusetts) the contribution of cooling radiation to the ultraviolet and Lyα-line luminosities of high redshift galaxies.

Weinberg, Steed, Todd, and OSU physics students A. Linn and J. Phillips carried out a variety of investigations related to high-redshift Lyα forest absorption, in collaboration with Hernquist, Katz, and R. Croft (Harvard). Steed and Todd used a numerical approximation tested against full hydrodynamic simulations to investigate the sensitivity of statistical properties of the forest to numerical and physical parameters, focusing on statistics like the flux distribution function and flux power spectrum that treat the absorption spectrum as a continuous field rather than a collection of discrete lines. Linn investigated the distribution of line shapes in spectra drawn from hydrodynamic simulations and from models in which the Lyα forest consists of discrete clouds, finding that the hydrodynamic models predict more irregular line shapes because of departures of the absorbing systems from dynamical equilibrium. Phillips derived constraints on the parameters of cold dark matter cosmological models by combining the results of a measurement of the mass power spectrum from Lyα forest data with COBE measurements of cosmic microwave background anisotropies and other cosmological measurements. Croft is now analyzing a larger data set that should substantially improve the precision of the power spectrum measurements.

9.3 Big Bang Nucleosynthesis and Cosmological Parameter Constraints

Steigman's research program focuses on the confrontation between the predictions of primordial nucleosynthesis and the primordial abundances of the light elements inferred from observational data. As in the past, Steigman and his collaborators pursued a vigorous, multi-pronged program aimed at exploiting observational data to derive better estimates of the primordial abundances with the goal of using such data to challenge and test the standard hot, big bang model. This effort continued with several independent projects aimed at constraining the abundances of ^{4}He and Li.

S. Viegas and R. Gruenwald (U. de São Paulo) and Steigman are continuing their program of investigating sources of potential systematic errors in using emission-line observations of extragalactic H II regions to zero-in on the primordial abundance of ^{4}He. In a recently submitted paper they revisited the question of ionization corrections for unseen neutral helium (or hydrogen) for H II regions ionized by clusters of young, hot, metal-poor stars. Their key result is that for the H II regions used in the determination of Y_P there is a "reverse" ionization correction, i.e., the "ionization correction factor" (ICF) is less than unity. They further explored the effect on the ICF of more realistic inhomogeneous H II region models, finding that for regions ionized by young stars with "hard" radiation spectra the ICF is reduced further below unity. In Monte Carlo simulations using H II region data from the literature they estimated a reduction in the published value of Y_P of order 0.003, which is roughly twice as large as the quoted statistical error in the Y_P determination.

Walker, Pinsonneault, Narayanan, and Steigman used observations of Pop I stars to normalize the rotational mixing of lithium from stellar surfaces, permitting limits (both lower and upper) to be set on lithium mixing in the Pop II stars used to infer the primordial lithium abundance. This work continues, employing a new, independent data set which is being compared to their predictions.

It has long been known that the light elements Li, Be and B can be synthesized in collisions between cosmic ray nuclei and interstellar gas nuclei. For near-solar metallicities, collisions between cosmic ray protons and α–particles and interstellar CNO nuclei dominate. If, naively, the complementary reactions are ignored, a quadratic relation between the LiBeB abundances and Fe/H is "predicted", in contrast to the observed, nearly linear relation. In work in progress, J. Kneller (OSU physics student), Steigman, and Walker have shown that cosmic ray CNO nuclei hitting interstellar hydrogen and helium can dominate LiBeB production below solar metallicities, leading to a more nearly linear abundance relation in agreement — quantitatively as well as qualitatively — with the observed data.

In a broad class of non-standard cosmological models, the universal scale factor increases as a power of the time, independent of the matter density or its equation of state. M. Kaplinghat (OSU physics student), I. Tkachev (CERN), Walker, and Steigman showed that such models fail the Big Bang Nucleosynthesis (BBN) test. Basically, universes described by power-law models take so long to cool down to BBN temperatures that all neutrons have decayed and no significant nuclear reactions can occur. This work has been extended to situations where the expansion of the Universe may be so slow that the weak interaction — weak as it is — can remain in equilibrium to much lower temperatures than is possible in standard BBN. In particular, although in the linear expansion model it is possible to synthesize the requisite amount of ^{4}He, virtually no D, ^{3}He, or ^{7}Li can be produced, and the helium synthesis is at the expense of a baryon density that violates independent observational bounds.

Given the "crisis" in BBN, Steigman, N. Hata (IAS) and J. Felten (NASA GSFC) set aside the BBN path to the baryon density and explored non-BBN observational constraints on the key cosmological parameters, such as the age, expansion rate, and overall density of the Universe. In this manner they were able to "predict" the baryon density and, consequently, the expected primordial yields of the light element abundances. Their results favor "low" primordial deuterium abundances.

Extending this non-BBN approach to constraining the cosmological parameters, Steigman and Tkachev used observations of MACHOs along with the dynamics of the Local Group of galaxies to infer the "universal" baryon fraction. Their results favor a high baryon density, consistent with estimates of the baryon density from observations of the Lyα forest.

Steigman, Walker and OSU physics student A. Zentner are using current estimates of global cosmological parameters, unaffected by bias and independent of specific models of structure formation, to bound several other key cosmological parameters. Combining constraints on the universal density of baryons from BBN with estimates of the universal baryon fraction from studies of X-ray clusters leads to bounds on the total "matter" density Ω_{M}, which, when combined with results from the SN Ia magnitude-redshift relation, also constrain the cosmological constant (or, equivalently, Ω_Λ). Armed with these constraints on Ω_{M} and Ω_Λ, they proceed to bound the 3-space curvature, $\Omega_k \equiv 1 - (\Omega_{\mathrm{M}} + \Omega_\Lambda)$, the present value of the deceleration parameter, $q_0 = \Omega_{\mathrm{M}}/2 - \Omega_\Lambda$, and other cosmological parameters.

9.4 Particle Astrophysics

It is rapidly becoming apparent that measurements of the cosmic microwave background may produce a gold mine of new particle physics constraints. In collaboration with S. Dodelson (Fermilab), M. Turner (U. Chicago), and R. Lopez (U. Chicago), Scherrer examined distortions in the pattern of cosmic microwave anisotropies that might result from the presence of a massive, unstable neutrino. Their results indicated that even the very crude current set of cosmic microwave background measurements rules out a wide range of masses and lifetimes: $\tau = 10^{13} - 10^{17}$ sec, $m_\nu > 10$ eV is excluded.

Scherrer's student Kaplinghat discovered that one of the approximations used in this paper, namely, treating the decay products as part of the cosmic neutrino background, leads to an over-estimate of the effect on the cosmic microwave background. In collaboration with Lopez and Dodelson, Scherrer and Kaplinghat have reexamined the CMB constraint on decaying neutrinos and improved considerably on the accuracy of this calculation.

Kaplinghat, Scherrer, and Turner, also used the cosmic microwave background to constrain the time-variation of the fine-structure constant. Their limits on $\Delta\alpha/\alpha$ are of the order of 10^{-3} and provide the best upper bound that can be placed at redshifts on the order of 1000. This work is of particular current interest because of recent claims of a detection of a change in α at high redshift.

Another major new area of research for Scherrer is the evolution of cosmological scalar fields in relation to the cosmological constant. It was recently suggested by Zlatev, Wang, and Steinhardt that a particular set of scalar field potentials could lead to a change in the behavior of the scalar field at the transition from a radiation-dominated to a matter-dominated universe. Such behavior might explain the apparent coincidence in the approximate equality between the density of matter and the density of a negative-pressure component (or cosmological constant) suggested by recent high-redshift supernova observations. In collaboration with A. Liddle (Imperial College), Scherrer investigated the general behavior of such "tracker" potentials, with the aim of determining the sorts of potentials that can give rise to such behavior. They were able to provide a complete classification of all such tracker fields. Liddle and Scherrer are currently working to extend these results to the case of non-minimally-coupled fields.

Scherrer completed work with A. Vilenkin (Tufts) on a project concerning lattice effects in simulations of the formation of topological defects (monopoles, cosmic strings, and domain walls). They showed that simulating such objects on a cubic lattice leads to errors in the estimate of the total defect density, and they provided some methods for correcting this problem. Their work led to a "lattice-free" simulation of cosmic string initial conditions. Since almost all previous simulations of topological defects have used a cubic lattice, their results are widely applicable.

10 Atomic Astrophysics

The research interests of the group led by Pradhan, which includes Nahar and graduate students Chen, Delahaye, and J. Oelgoetz (OSU Chemistry), encompass many atomic radiative and collisional processes and their applications to a wide range of astrophysical problems. They are involved in a variety of problems with collaborators H. Zhang (LANL), M. Bautista (NASA GSFC), A. Sigut (U. Western Ontario), C. Zeippen (Obs. de Paris), C. Mendoza (IVIC, Venezuela), N. Haque (Moorhouse College), and F. Keenan (Queens U. of Belfast).

The group is involved in accurate calculations using *ab initio* quantum mechanical methods of collision strengths, photoionization cross sections, transition probabilities, and electron-ion recombination rates. The results are incorporated into a number of astrophysical applications, such as spectral analysis of ground and space based observations. The large-scale quantum mechanical calculations are being carried out on the Cray T94 and the massively parallel Cray T3E at the Ohio Supercomputer Center in Columbus.

10.1 The Iron Project

The OSU group is also the U.S. part of the international Iron Project (IP) team, with members from the U.K., France, Germany, Canada, and Venezuela. The primary aim of the Iron Project is to compute accurate atomic parameters for collisional excitations, photoionization, and fine structure bound-bound transitions mainly for iron and iron-peak elements for analysis of the astrophysical emission spectra which reveal the existence of iron-peak heavy elements such as iron, cobalt, and nickel as end products of stellar nucleosynthesis. The work complements, and provides improved results especially for heavy ions, the work under the Opacity Project

(OP) of calculating accurate atomic radiative data and applying these for calculations of stellar opacities. With the new developments in the relativistic close coupling approximation using the Breit-Pauli R–matrix (BPRM) method under the IP, it is now feasible to carry out large-scale, highly accurate relativistic Breit-Pauli calculations for both atomic radiative and collisional processes.

Under the IP, work has been completed recently for the collision strengths and rates for the large and complex ion Fe VI. The electron impact excitation collision cross sections include fine structure with allowance for strong coupling and relativistic effects.

10.2 H II regions and Gaseous Nebulae

Zhang and Pradhan have completed a comprehensive and up-to-date review of electron collision processes, excitation and recombination with positive atomic ions, in H II regions. It includes extensive tabular material, evaluated and compiled by Pradhan and Zhang, on the excitation rate coefficients and transition probabilities required to calculate density and temperature sensitive line ratios for nearly all atomic species observed in gaseous nebulae.

With a view to the development of spectral diagnostics in the ultraviolet and the interpretation of data from SOHO, FUSE, and other observatories, Chen and Pradhan are computing accurate excitation rate coefficients for iron ions. In the past year the work has included [Fe VI] lines observed in planetary nebulae, novae, and hot stars. Certain new developments were reported that should enable more accurate theoretical treatment of the underlying atomic physics.

10.3 Photoionization

The radiative process of photoionization has been studied by Nahar for all ionization stages of oxygen. The study is more extensive than that carried out under the Opacity Project. The purpose was to obtain more accurate details of the process, both for partial ionization into the ground state and for total ionization into various thresholds of the target or core ion. The new calculations have shown more resonance features and enhanced background cross sections compared to the earlier ones. The partial cross sections provide state-specific recombination rate coefficients. The total cross sections are needed, for example, in calculations of ionization fractions and ionization structure in an astrophysical plasma source.

The results obtained from the R–matrix close coupling calculations are being verified from sophisticated experiments at a few places, including the merged photon-ion experiment at Aarhus University in Denmark and the Advanced Light Source at Berkeley. Recent measurements of photoionization cross sections of the $2s^2 2p(^2P^o)$ ground state of C II show very good agreement with R–matrix calculations.

Zhang and Pradhan have calculated the photoionization cross sections and recombination rate coefficients for the L–shell ground state levels of Fe XIX including relativistic effects. Haque and Pradhan have also done calculations for Fe XV, showing the importance of L–shell resonances in enhancing the total photoionization cross sections.

10.4 Electron-ion recombination

A new unified method for total electron-ion recombination rates, which accounts for both the radiative and dielectronic recombinations in a self-consistent manner, was developed by Nahar and Pradhan. Nahar has calculated total recombination rate coefficients for all oxygen ions, O I – O VIII. Calculations of ionization fractions in plasma equilibrium need recombination rates at all ionization stages. The new rates show significant differences with the earlier calculations in ionization fractions at various temperatures in plasmas in coronal equilibrium.

Much effort was also devoted to calculating the total and state-specific recombination rate coefficients of heavy and complex iron ions in an *ab initio* manner for the first time. Work on two iron ions, Fe IV and Fe V, was completed. An astrophysical application of the new rates for the ionization structure of iron in planetary nebulae shows that the relative ionization fractions of Fe V and Fe VI change by nearly a factor of two compared to those using earlier data under typical conditions.

Nahar has recently calculated the recombination rates for Si-like ions Si I, S III, Ar V, Ca VII, and Fe XIII using the unified treatment. The general features of the total recombination rates are the following: starting with a high recombination rate at very low temperatures, recombination decreases until it reaches a minimum, and then rises again due to the dominance of dielectronic recombination at high temperatures. One exception to this general pattern is that some ions, e.g. Ar V, Ca VII and Fe XIII, exhibit a low temperature rise in the form of a "bump" due to near-threshold autoionizing resonances in the photoionization cross sections. These features confirm those found earlier by Nahar and Pradhan for other ions obtained using the unified method.

Zhang and Pradhan, in their work for Fe XXI photoionization and recombination, calculated the level–specific rates for the ground levels of Fe XXI. They included the effect of radiation damping as it has significant effect on the recombination/photoionization process of highly charged ions.

10.5 Radiative Transition Probabilities

Large numbers of accurate transition probabilities are needed for applications such as calculations of stellar opacities and non-local thermodynamic equilibrium (NLTE) spectral models. Under the Opacity Project a large number of transition probabilities were obtained for astrophysically abundant atoms and ions. However, those values were obtained in LS coupling, although for a number of cases fine structure was introduced for dipole allowed transitions through algebraic transformation of the LS line strengths (calculated without relativistic effects). It is now feasible to include the relativistic effects through BPRM calculations which provide both the dipole allowed and intercombination transition probabilities. Extensive work is in progress on transition probabilities for heavy elements.

For example, the BPRM method has been applied to calculate about 1.5 million oscillator strengths of Fe V involving 3,865 bound fine structure levels. The computations are extensive, and CPU time and disk-space requirements increase considerably due to fine structure splitting of states. One major task in BPRM calculations has been the identification of the large number of bound levels. The BPRM Hamiltonian calculates the bound levels identified by minimum information such as the values of J_π only. Complete designation of configurations and terms are needed for various diagnostic and spectroscopic analysis. Nahar and Pradhan have developed an identification procedure for the fine structure levels by applying theories of quantum defects and collisional channels. The procedure has been implemented successfully for a few ions.

In addition to the allowed transitions (dipole allowed and intercombination), oscillator strengths for a large number of forbidden transitions for Fe V are also being computed through extensive atomic structure calculations.

10.6 X-ray spectroscopy of astrophysical objects

The new space observatories — Chandra Space Observatory, the X-ray Multi-Mirror Mission, and Astro-E — are expected to provide a large amount of observational data for a variety of X-ray sources such as supernovae, AGNs, and novae. A comprehensive program devoted to X-ray astronomy, particularly the analysis of space observations of AGNs, is under way at OSU. One main emphasis is on the He- and Li-like ions. The fundamental parameters essential to the modeling of X-ray sources — photoionization, recombination, and excitation cross sections and transition probabilities — are being computed with unprecedented accuracy. For example, Nahar and Pradhan have recently computed the most extensive and accurate set of transition probabilities for He-like Fe XXV and Li-like Fe XXIV, required for the interpretation of the Helium-like K-α complexes expected to be seen in the observed X-ray spectra of AGNs and SNRs. Chen and Pradhan have nearly completed what is probably the largest scattering calculation for an atomic system, for Fe XVII, which is a copious producer of X-ray emission (including X-ray lasers observed in the laboratory). Efforts are being made for relativistic calculations of fine structure level-specific recombination rate coefficients of these highly charged ions.

In addition to the theoretical atomic astrophysics work, collaborators T. Kallman (NASA GSFC) and Bautista are carrying out X-ray spectral modeling work at the High Energy Astrophysics Research Center at NASA GSFC, using a new version of their photoionization modeling code XSTAR.

Bautista, Romano, and Pradhan have done elaborate numerical fits to the photoionization cross sections in the Opacity Project database, TOPbase, for nearly all astrophysically abundant elements in various ionization stages. The new fits are suitable for direct input into photoionization modeling codes, and they implement an accurate averaging procedure over the extensive resonance structures in the cross sections. This reduces the tabulation requirements for these cross sections by orders of magnitude, from hundreds or thousands of points for the photoionization cross section of each level to about 20–30 points. The new fits also incorporate the inner K– and L–shell ionization edges of importance in X-ray modeling work.

11 Nuclear Astrophysics, Neutrinos, and Supernovae

Boyd's group continued its efforts to develop OMNIS, the Observatory for Multiflavor NeutrInos from Supernovae. OMNIS will consist of 4 kT of lead and 10 kT of iron, and will observe neutrinos by using their interactions with the lead and iron to produce neutrons, then detecting the neutrons in scintillators embedded in the lead and iron. The actual detector modules will consist of slabs of the iron or lead alternated with planes of the detectors. Monte Carlo simulations have shown that they can expect to observe about 2000 events from a supernova at the center of the Galaxy. The observatory is to be sited in the Center for Applied Repository and Underground Science, in southeastern New Mexico. OMNIS participants include collaborators from UCLA, UCSD, UCI, the Universities of Wisconsin and Texas, and the Lawrence Livermore and Oak Ridge National Laboratories, as well as OSU Physics graduate students J. Zach and D. Marriott and Research Associate A. Murphy.

OMNIS data on a supernova event will yield several types of information, not just from the electron antineutrinos that would produce most of the events at SuperKamiokande and Sudbury Neutrino Observatory, but from μ– and τ–neutrinos as well. Thus, very basic information will be obtained about the production of the neutrinos from the supernova and about the interactions of the neutrinos with the medium through which they must pass in exiting the supernova. It may also be possible to measure masses of neutrinos from their time of flight differences to a few eV/c^2, a level of precision not possible with any other technique. Neutrino oscillations of the type μ– or τ–neutrino to electron neutrino should provide a clear signature from two-neutron events from the lead module. Finally, the fast timing of OMNIS, better than 1 ms, should make it possible to observe and diagnose the collapse to a black hole, should that occur.

An experiment was conducted at the University of Notre Dame tandem accelerator laboratory as part of the Ph.D. thesis of F. Chloupek (OSU physics), advised by Boyd. This experiment was designed to test the nuclear reaction theory that is generally used to describe the stellar reactions between nuclei in the variety of nucleosynthesis sites that produce heavy nuclides. Reactions studied included proton radiative capture on ^{96}Zr, ^{112}Sn, and ^{119}Sn. The method used was off-line detection of γ–rays produced when the nuclei created by the reactions of interest by proton irradiations decayed. The range of incident proton energies was chosen to span those relevant to hot stellar conditions, where the reactions studied would be of interest. Although some differences were observed between the theoretical description of the reactions and the data, the theoretical descriptions were generally within a factor of two or three of the data, probably a sufficient level of accuracy for most of the situations in which the theoretical description is used. OSU Research Associates Murphy and G. Raimann and physics graduate students A. Cole, T. Guray, and J. Zach were involved in the experiment, in addition to several collaborators from Notre Dame.

Boyd has also been involved in an ongoing study conducted with the TISOL radioactive beam facility at TRIUMF (Canada) to study the ^{12}C(α,γ)^{16}O reaction. This reaction, the cross section for which is known only to about a factor of 3 in the energy regime of importance to nuclear astrophysics, has been called the most important one in nuclear astrophysics. Its low energy cross section is dominated by two sub-threshold resonances, the effects of which are virtually impossible to measure by simply bombarding ^{12}C with α particles. The method currently under study for providing indirect information on the low energy cross section for this reaction involves producing and stopping a ^{17}Ne beam, then letting it undergo β–delayed proton emission to states of ^{16}O that can subsequently decay by α emission to ^{12}C. At present a feasibility study is still being conducted to see if it is possible to obtain the information needed from the data one might obtain. Collaborators are from TRIUMF, Simon Fraser University, the University of Toronto, the University of Alberta, Belgium, and Scotland.

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