

The Ohio State University
Astronomy Department
Columbus, Ohio 43210

This annual report covers the period 1999 September through 2000 August.

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, Terrance Walker, David Weinberg, and Robert Wing. Jordi Miralda-Escudé joined the faculty as an Assistant Professor in 2000 January. Sellgren was on sabbatical for the academic year and spent one month as the Cox Visiting Professor at the University of Texas at Austin. Michele Kaufman and Smita Mathur held appointments as Research Scientists, and David Ennis and Eric Monier were lecturers. Sultana Nahar was a senior research associate. Emeritus members of the Astronomy Department are Eugene Capriotti, George Collins II, Stanley Czyzak, Geoffrey Keller, and William Protheroe.

We report with sadness the death of emeritus professor Philip Keenan, who had been associated with the Department of Astronomy since 1946.

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, Arizona, Mark Wagner held the position of Research Scientist, while Ray Bertram was Research Associate. Starting in 2000 July, both Wagner and Bertram were assigned full-time to work on the Large Binocular Telescope (LBT) project. Wagner was appointed as Instrumentation Scientist for LBT and will help plan and coordinate the instrumentation efforts of the partners and will develop and supervise the instrument support on the mountain.

Postdoctoral researchers in Astronomy during most or all of this period included James Bullock, Stefan Collier, Paul Eskridge, Eric Monier, and Alison Sills. In addition, Andrey Kravtsov holds a Hubble Fellowship within our department, and Marianne Vestergaard is the current holder of the Astronomy Department's Columbus Fellowship. Postdoctoral researchers and staff in the Physics Department doing astrophysical research included Yuri Aikawa, Xuelei Chen, David Graff, Alexander Murphy, and Deborah Ruffle.

Graduate students in the Astronomy Department

during the academic year included Khairul Alam, Jin An, Nikolay Andronov, Andreas Berlind, Christopher Burke, Guo-Xin Chen, Alberto Conti, Franck Delahaye, Scott Gaudi, Susan Kassin, Paul Martini, James Pizagno, Solange Ramírez, Patrizia Romano, Samir Salim, Kenneth Sills, Adam Steed, Andrew Stephens, Ewan Todd, Yongquan Yuan, and Zheng Zheng. Patrick McDonald is a visiting graduate student from the University of Pennsylvania, completing his Ph.D. thesis with Miralda-Escudé. Justin Oelgoetz is an OSU Chemical Physics graduate student working on his Ph.D. thesis with Pradhan. Students arriving in 2000 summer were Julio Chanamé, Dale Fields, Jennifer Marshall, Christopher Onken, and Jeremy Tinker. Students completing their Ph.D. were Gaudi (now at the IAS at Princeton, as a recipient of the Hubble Fellowship), Martini (now at OCIW in Pasadena, holding a Carnegie Fellowship), and Ramírez (now at Caltech as a postdoctoral fellow). Yuan received an M.S. degree.

2 TELESCOPES AND INSTRUMENTATION

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 is also a partner in and will have one sixth of the observing time on the LBT, which is under construction at the Mt. 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 telescope on a single mount and will have a 23-m baseline for interferometric observations. During the year the second primary mirror for the telescope was cast successfully in Tucson by the Steward Observatory Mirror Laboratory. Assembly and testing of the telescope structure has begun in the Ansaldo Energia plant in Milan. The structural work for the telescope building and enclosure on Mt. Graham is complete, with the major effort now concentrating on finishing the exterior paneling and trim and the interior of the building. First light for the first mirror is scheduled for 2003, and the second mirror should be installed within the following two years.

OSU is providing the optical spectrograph and the aluminizing system for the telescope as part of its contribution to the project. During the year the department received a major grant from the NSF that will enable the construction of a two-channel, multi-object spectrograph to be mounted at the Gregorian focus.

The past year was very active for the instrumen-

tation group at Ohio State. The group completed two instrumentation projects: an upgrade and refurbishment of a CCD spectrograph and an optical-infrared camera. The focus also shifted towards working on the optical spectrograph and the aluminizing system for the LBT. These new projects are expected to occupy most of the group's effort for the next several years. The group also continued to provide support for the OSU-built instruments and detector systems in use around the world; these include systems on five continents.

A venerable Boller & Chivens spectrograph, the CCDS, was refurbished for use at the MDM Observatory. The CCDS had received occasional upgrades throughout its long use on the Perkins 1.8-m telescope, but needed some modification for use at MDM. The optics were reconfigured to better match the 2.4-m and 1.3-m telescopes; the optics were also recoated and realigned. Computer-controlled motors were added to all the mechanisms in the CCDS (slit, gratings tilt, collimator focus, filter slide, and calibration unit) which made the CCDS easier to use and improved its reliability. The CCDS has excellent response from 320 to 900 nm and is a powerful complement to other MDM instruments. The renovated CCDS was commissioned at MDM in the fall of 1999 and began regularly scheduled use in 2000 January. The web site <http://vela.as.arizona.edu/~rmw/ccds/> provides more information about the CCDS.

A camera capable of simultaneous optical and near-infrared (near-IR) imaging was completed and deployed to the South African Astronomical Observatory (SAAO) 1-m telescope. The instrument, named DANDICAM (for the Dutch-funded A Novel Double Imaging Camera), is the second such instrument built at OSU; a similar instrument (ANDICAM) is permanently mounted on the Yale 1-m telescope (YALO) at Cerro Tololo Inter-American Observatory (CTIO). Both these cameras are engaged in a wide variety of astronomical observations; OSU's primary science use is to monitor gravitational microlensing events as part of the PLANET network (the OSU involvement in PLANET is described in §3 below).

Work has begun on two major projects for the LBT: the aluminizing system for the primary mirrors and a high-throughput, optical spectrograph. In particular, for the aluminizing system the instrumentation group will build and test the complete system for evaporating aluminum onto the 8.4-m primary mirrors. The Multi-Object Double Spectrograph (MODS) will have two channels to maximize throughput over the 300 – 1000 nm wavelength range and multi-slit capability for high multiplex advantage. The optical design of the instrument is complete and optics vendor selection is underway. The mechanical design of the instrument structure and mechanisms is in progress. We anticipate that these two projects will occupy the majority of our instrumentation efforts for the next ~4 years.

Savage and Pogge spent a week in 2000 July at MDM updating the observatory computing system. This involved porting all observatory software to Solaris from

the aging SunOS system, and setting up the observing and data-analysis workstations at each telescope. The manuals and on-line documentation were also updated and extended.

Pogge set up a web-based system for queue-scheduled operation of the YALO 1-m telescope at CTIO. Observers awarded time on the YALO telescope use a series of interactive forms to create observing “template files” that configure the ANDICAM and set the exposure times for their observations, and then submit sets of templates along with observing instructions for execution. Other tools provide observing log archiving and project status tracking, and observing program management (e.g., modifying observing templates or building new programs). Automatic archiving of observing logs, observer reports, and trouble reports was also implemented, along with an observing log search engine. The system has been in operation for nearly a year with surprisingly few problems.

A set of six 2-inch diameter narrow-band filters, representing the first 6 filters of Wing's eight-color system (712 – 1056 nm), has been ordered for use with CCD cameras at the MDM Observatory. They will be used initially for two-dimensional classification of faint M supergiants in the northern Milky Way.

A pair of narrow-band (~1%) filters at 2.122 μm and at an adjacent continuum wavelength, for imaging the 1–0 S(1) line of H₂, have also been purchased for the TIFKAM IR imager/spectrograph at MDM.

3 EXTRA-SOLAR PLANETS

An, DePoy, Gaudi, Gould, and Pogge worked in the PLANET collaboration to search for extra-solar planets by intensive follow-up observations of ongoing microlensing events. PLANET has substantial observing time on four telescopes, the YALO 1-m, the SAAO 1-m, the Canopus 1-m in Hobart, Tasmania, and the Perth 0.6-m in Western Australia.

Gaudi continued to work on topics related to the detection of extrasolar planets. For his Ph.D. thesis work, together with the PLANET collaboration, he analyzed the PLANET data set for the microlensing event OGLE 1998-BUL-14, searching for the short duration deviations from the smooth, symmetric, single-lens light curve that are the signatures of planetary companions to the primary lens. No such anomalies were present, enabling PLANET to exclude companions to the primary lens of mass > 10 Jupiter masses for separations in the range 1 – 7 AU. In a similar manner, he also analyzed five years of PLANET photometric data of microlensing events toward the Galactic bulge. Again, no anomalies were present, implying that less than 1/3 of the $\sim 0.3 M_{\odot}$ stars that typically comprise the lens population have Jupiter-mass companions in the range of semi-major axes $1.5 \text{ AU} < a < 4 \text{ AU}$.

Together with Graff, Gaudi proposed a method to directly detect planetary companions to stars in the Galactic bulge, using caustic-crossing microlensing events. Finally, Gaudi demonstrated that by monitoring the

Galactic bulge for 10 nights on a 10-m telescope, one could detect two to 15 planets with radius equal to that of Jupiter via the transit technique.

Together with the PLANET collaboration, Gaudi also analyzed the unusual light curve of microlensing event MACHO 97-BLG-41. This analysis demonstrated that the light curve is well explained by a rotating binary lens with total mass of $\sim 0.3 M_{\odot}$ and period ~ 1.5 yr, obviating the need for the previously suggested planetary companion to the binary lens.

Herbst's work on protoplanetary disks, done in collaboration with Aikawa, is continuing.

4 STARS

Sellgren devoted much of her sabbatical to working on a SIRTf Legacy Science proposal, with C. Woodward (U. Minn.) as principal investigator. The Legacy proposal is a study of mass-loss and dust formation for all types of mass-losing stars.

Herbst, along with T. Millar (UMIST) and R. Betens (Singapore), has modeled the chemistry of the outer envelope of IRC +10216 and predicted that large molecules, including negative ions, should be very abundant in that source.

Newsom is compiling the revisions that Keenan made in his spectral classifications before his death last April. The goal is to see if clump giant stars can be reliably identified spectroscopically for use as distance indicators. Newsom and Keenan also presented a poster paper on Hipparcos luminosities for giants with non-solar abundances, in Joint Discussion 13 on "Hipparcos and the Luminosity Calibration of the Nearer Stars," at the 24th IAU General Assembly.

In collaboration with J. Stauffer (IPAC/Caltech), Terndrup, Pinsonneault, and A. Sills have been obtaining new data on stellar rotation rates ($v \sin i$) in young and intermediate-age stellar clusters and rotation periods (from starspots) in low-mass stars and brown dwarfs. Their followup to their 1999 paper on the Pleiades focuses on NGC 2516, a cluster of about the same age (120 Myr), but more metal deficient by about 0.3 dex. Data analysis for this project is almost complete. They have also obtained an extensive sample of rotation rates in the intermediate-age clusters NGC 752 and NGC 2420, two prototype clusters for the calibration of convective overshoot in stellar evolutionary models. They obtained data at CTIO in June for NGC 5822 (in collaboration with S. Hawley, U. Washington). These data will provide an important first look at the effects of metallicity on angular-momentum evolution, and will yield important calibrating data for the production of giant-branch models that properly treat rotationally induced mixing and dredge-up.

In order to constrain the angular momentum evolution of giant stars, Pinsonneault and A. Sills have investigated the properties of their descendants, the horizontal-branch (HB) stars, and have published results for globular cluster HB stars. The rotation of HB stars provides important information on angular-momentum evolution

in evolved stars, and therefore on rotational mixing on the giant branch. Prompted by new observations of rotation rates of HB stars, they have calculated simple models for the angular-momentum evolution of a globular cluster star from the base of the giant branch to the star's appearance on the HB. The models included mass loss and explored the consequent loss of angular momentum for each of four assumptions about the internal angular-momentum profile. Mass loss was found to have important implications for angular-momentum evolution. These models were compared to observations of HB rotation rates in M13. It was found that rapid rotation on the HB could be reconciled with slow solid-body main-sequence rotation if giant branch stars have differential rotation in their convective envelopes and a rapidly rotating core, which is then followed by a redistribution of angular momentum on the HB. They discussed the physical reasons why these very different properties, relative to the solar case, may indeed exist in giants. Rapid rotation in the core of the main-sequence precursors of a rapidly rotating HB star, or an angular momentum source on the giant branch, is required for all cases if the rotational velocity of turnoff stars is less than 4 km s^{-1} . They suggested that the observed range in rotation rates on the HB is caused by internal angular momentum redistribution that occurs on a timescale comparable to the evolution of the stars on the HB. They postulate that the apparent lack of rapid HB rotators hotter than 12,000 K in M13 could be a consequence of gravitational settling, which inhibits internal angular-momentum transport.

As the first step in their attempt to create a physically motivated model of the chemical anomalies on the giant branch, Pinsonneault and A. Sills are currently investigating the "maximal mixing" case. They have made a number of assumptions about the angular momentum distribution and transport in giant-branch stars and about the efficiency of mixing, and these assumptions were adjusted to produce the maximum amount of mixing on the giant branch. Such assumptions are prompted by theoretical predictions of mixing efficiencies and by the constraints placed by rotation of HB stars. The early results are most encouraging. The models with no rotation, and those with rotational parameters appropriate for the Sun, show little or no mixing beyond that expected from standard first dredge-up. The maximal-mixing models show evidence of additional deep mixing in the CNO abundances. This additional mixing becomes apparent at about the position of the giant branch bump. Both the position of this change in behavior and the trend that each element follows agree in remarkable detail with observations of elemental abundances in globular clusters.

Mass loss is an important, and often neglected, component of evolution up the giant branch. A. Sills has added machinery into the code that allows them to include the effects of mass loss and the accompanying angular-momentum loss on giant-branch evolution. Of particular interest to this project is the effect of mass loss on elemental mixing on the giant branch. Their early

results suggest that mass loss, combined with rotation, is the only way to produce giants with a $^{12}\text{C}/^{13}\text{C}$ ratio of the equilibrium value of 4, in agreement with the observations. They have also developed coding which will allow them to treat the strong mixing characteristic of their giant-branch models; in prior work rotational mixing was treated as a minor perturbation on the structure, which is no longer true for the strong mixing that they now are able to produce in giants.

At IAU Symposium 198, Pinsonneault reported on ongoing work comparing theoretical calculations of rotational mixing with observations of the light element lithium in metal-poor stars. He and his collaborators find that the most recent data sets indicate modest, but non-zero, stellar lithium depletion in halo stars. Recent work in progress has established that there is marginal evidence for an increase of lithium with increased metal abundance in halo stars, although the slope varies by a factor of three depending on the choice of the sample and the source of the metal abundance. When the variables are treated in a physical manner (e.g., linear Li vs. linear metallicity), however, the dispersion in the sample is greater than the observational errors, indicating that there is an intrinsic range in abundance that can be traced to mild rotational mixing. They also find that there are unexplained differences between the inferred observational properties of the same stars as reported by different investigators, indicating the need for further observational work in this area. New and extensive sets of observations are presently being conducted at the Very Large Telescope (VLT) and elsewhere, so this information is expected soon.

Wing has collaborated with M. Houdashelt and R. Bell (U. Maryland) and A. Sweigart (NASA/GSFC) in a study of the spectra and colors of M-type giants. Synthetic spectra were computed from plane-parallel models ranging from 4000 to 3400 K in T_{eff} and from -0.5 to $+1.5$ in $\log g$ and were compared to a library of observed spectra. The spectral types of the models were determined from synthetic narrow-band colors on Wing's eight-color system, and relations between broad-band colors and spectral type were computed. Among the by-products of the study are a set of "astrophysical" oscillator strengths (f_{00} -values) for the several band systems of TiO and a reappraisal of the effective temperature scale for M giants.

Wing has undertaken a study of the variability of M-type supergiants in collaboration with D. Alves, J. MacConnell, and H. Bond (STScI), D. Zurek (American Museum of Natural History), and D. Hoard (CTIO). Eighty target stars were selected from the MacConnell-Wing-Costa survey for red supergiants in the southern Galactic plane and were observed photometrically in V and I an average of 9 times each during the first semester of 2000 (February through July) using the CTIO 0.9-m telescope in queue-scheduled mode. Further monitoring is planned for stars showing significant variability in order to determine periodicities. Since distances can be estimated from a recently-established period-luminosity

relation for M supergiant variables, the target list for this study consists mostly of relatively faint supergiants with typical distances of 4 – 6 kpc, according to their near-IR magnitudes and CN-based luminosities.

Pinsonneault, with Burke and A. Sills, investigated the sensitivity of the lithium age dating technique for young open clusters to errors in the theoretical model input physics. An uncertainty of order 10% was found for plausible changes in the standard model input physics; in addition, rotation was found to have a larger effect, implying that the rotation rate of stars must be taken into account when determining ages using this method.

Andronov, Pinsonneault, and A. Sills investigated the application of the angular momentum loss law, as derived in open clusters, to the evolution of cataclysmic variables (CVs). The empirical open cluster angular momentum loss law was found to be in strong contradiction with the disrupted magnetic breaking model used to explain the period gap in the distribution of CVs; in addition a method for inferring the time averaged mass loss rate from the mass-radius relationship and the angular momentum loss prescription was developed.

C. Watson (OSU Physics graduate student) and Pinsonneault investigated the sensitivity of solar model properties to changes in the $\text{He}^3 + \text{p}$ reaction cross section; even large changes in this reaction rate, of possible interest for solar neutrino studies, were found to have only a small impact on helioseismic properties.

Pinsonneault, with J. Bahcall (IAS) and S. Basu (Yale), investigated the solar neutrino fluxes and helioseismic properties of a large set of solar models. In addition to an exploration of the time dependence of global solar model properties, they found that different solar mixtures could produce significant signals in the solar sound speed and inferred surface solar helium abundance. The overall helioseismic properties were found to be within the range expected from known errors in the input physics and solar composition; the neutrino fluxes are in strong disagreement with the experimental data, supporting the idea of neutrino oscillations.

Wagner, E. Ryan (U. Arizona), and S. Starrfield (ASU) obtained deep optical images at the location of the point-like X-ray source at the center of the ~ 300 yr old Cassiopeia A supernova (SN) remnant discovered in the Chandra first light observation. The R -band images were obtained with the Steward Observatory 2.3-m telescope and direct CCD on four nights in 1999 September and set a new brightness limit of $R \gtrsim 26.3$ mag (1σ) on the presence of any optical object associated with the X-ray source. The new limit implies $M_R \gtrsim 10.3$ mag and $L_X(0.2 - 10 \text{ keV})/L_{\text{opt}} \gtrsim 800$. Accretion models are the most constrained by the optical results. Binary accretion models and scenarios involving very low accretion rates from a disk onto a neutron star or a black hole similar to models for quiescent transient low-mass X-ray binaries are effectively ruled out. fallback accretion models may be ruled out in some circumstances, but the emitted optical and IR flux is sensitive to the location of the transition radius, the geometry of the disk,

and its inclination to the line-of-sight.

Wagner in collaboration with F. Vrba and A. Henden (USNO), A. Filippenko and W. Li (UC Berkeley), G. Schmidt and P. Smith (U. Arizona), and Starrfield obtained photometric and spectroscopic observations of an unusual, extremely luminous, variable star located in the galaxy NGC 3432. Its photometric behavior, spectrum, and luminosity suggest that the object is a very massive, luminous blue variable star analogous to η Carinae and SN 1997bs in NGC 3627 and that the variations are due to repeated mass-ejection events. The new object was discovered with the 0.8-m Katzman Automatic Imaging Telescope (KAIT) on 2000 May 3.2 at an unfiltered magnitude of about 17.4. Pre-discovery images obtained by KAIT between 2000 April 10 and 24 and by the Second Palomar Sky Survey in 1998 May show the object with $R = 19.2 - 19.5$ mag, but it is absent on a KAIT image obtained on 2000 April 29 (> 19.2 mag). Optical spectra obtained at the Steward Observatory 2.3-m Bok telescope on 2000 May 6.2 ($R \simeq 20.5$) show a smooth continuum and strong Balmer emission lines at wavelengths consistent with the cataloged redshift of NGC 3432 ($z = 0.002$). Photometric monitoring in the R -band with the USNO 1-m telescope, KAIT, and others reveals a complex light curve in which the object brightened from $R \simeq 19.3$ to 17.4 over ~ 2 days and then abruptly faded to $R \simeq 20.8$ over the following 8 days. The variable then brightened to $R = 18.6$ within 4 days of having reached minimum brightness, after which it faded to $R \simeq 19$ and varied by ~ 0.8 mag on a timescale of 5 – 10 days until their final measurement on 2000 July 4. Subsequent optical spectra obtained in 2000 May and June at the MDM Observatory 2.4-m Hiltner and Lick Observatory 3-m Shane telescopes continued to show strong Balmer emission lines with a mean full-width at half-maximum (FWHM) $\simeq 1550$ km/s and a distinct red asymmetry. The maximum apparent magnitude implies an absolute magnitude of at least -12 at the distance of NGC 3432.

5 INTERSTELLAR MEDIUM

Sellgren has begun a collaboration with H. Dinerstein and J. Lacy (U. Texas) to search for rotational lines of H_2 in planetary nebulae, which should have large neutral or molecular envelopes from earlier phases of mass loss.

Sellgren planned for SIRTf guaranteed time observations of reflection nebulae, in collaboration with M. Werner (JPL) and K. Uchida (Cornell), and of planetary nebulae, in collaboration with Y. Pendleton and D. Cruikshank (NASA Ames). These two projects are both explorations of polycyclic aromatic hydrocarbons (PAHs), thought to be responsible for the IR emission features (IEFs) at 3.3, 6.2, 7.7, 8.6, 11.3, and 12.7 μm .

Pizagno, Sellgren, and Uchida are currently convolving laboratory absorption spectra at ultraviolet (UV) and visible wavelengths with the energy distributions of the stars illuminating different reflection nebulae, to make quantitative tests of laboratory analogs for the ma-

terials 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 2 – 45 μm spectra of the bright reflection nebulae NGC 7023 and NGC 2023, in collaboration with C. Moutou (ESO), A. Léger and L. Verstraete (Institut d'Astrophysique Spatiale). They have completed a paper on the IEF profiles observed at high spectral resolution, comparing observations of NGC 2023, M17, and the Orion Bar to current models of PAH emission. They are also working on measurements of pure rotational transitions of H_2 in NGC 7023 and NGC 2023. These lines are good measures of the gas temperature in the photodissociation region.

Sellgren and An are intercomparing the spatial distribution of H_2 emission, the 2 μm continuum, and the 3.3 μm IEF in NGC 7023. 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 it is predominantly associated with neutral rather than molecular gas. The 3.3 μm IEF is associated 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.

T. Brooke (JPL) and Sellgren continue their IR spectroscopy of protostars, to search for molecules which may be related to molecules contained in comets. They plan this year to search for ethane (C_2H_6), which has been detected in comets.

Herbst, in collaboration with F. De Lucia (OSU Physics) and G. Winnewisser (U. of Cologne), has long directed a program in laboratory spectroscopy of molecules of interstellar interest. In the last year, the millimeter-wave spectra of the molecules NO and CF have been investigated in Cologne and the spectrum of glycolaldehyde ($HOCH_2CHO$) has been measured at Ohio State in collaboration with a group from Norway. Glycolaldehyde, an isomer of methyl formate and acetic acid, and in some sense the simplest sugar, has recently been detected in emission towards the Galactic Center (GC) source Sgr B2. Laboratory spectra have been taken at frequencies up to and surpassing 1 THz. Millimeter-wave spectra have also been utilized to determine cross sections for rotationally inelastic collisions at low temperatures between several species (CO , H_2CO , and HCO^+) and H_2 ; such cross sections are needed to convert interstellar emission spectra into column densities under non-LTE conditions. Interestingly, the experimental results for HCO^+ are not in excellent agreement with a previous theory.

Herbst's program of research into the gas-phase and grain surface chemistry of interstellar and circumstellar clouds is continuing. Current generation chemical models include over 4000 gas-phase reactions and several hundred grain surface reactions. With Ruffle, Herbst has studied the chemistry occurring along the line of sight to

Elias 16, with a particular emphasis on reproducing the abundances of the condensed-phase species detected in large ice mantles surrounding interstellar grains. With B. Turner (NRAO) and R. Terzieva (OSU Chemical Physics graduate student), he has continued to study the chemistry of high latitude translucent clouds in our Galaxy.

Herbst and Aikawa are studying starless cores and using chemical models to deduce the details of collapse for the source L1544.

Herbst and Terzieva have studied the sticking of electrons to carbon chain molecules under low density interstellar conditions and concluded that the process is efficient. Terzieva and Herbst have also studied nitrogen isotopic fractionation in interstellar clouds and found that it is rather small, unlike the case of deuterium or even carbon-13. Along with T. Stancheva (OSU Physics graduate student) and P. Caselli (Arcetri), Herbst continues to study the details of diffusive grain chemistry in the so-called accretion limit, where few reactive species exist simultaneously on an individual interstellar grain.

6 MILKY WAY STRUCTURE

Gould is currently focusing his work on applications of 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 R_0 using kinematics and measuring the absolute magnitude of RR Lyrae stars using the FAME satellite which is scheduled as a 2004 NASA MIDEX launch and for which Gould serves on the Science Team.

Zheng, Gould, and Salim are working with collaborators C. Flynn (Tuorla Obs., Finland) and J. Bahcall to measure the local M dwarf mass and luminosity functions using HST star counts.

Bullock, Kravtsov, and Weinberg developed an explicit model for the formation of the Milky Way stellar halo from accreted tidally disrupted dwarf galaxies, focusing on predictions testable with the Sloan Digital Sky Survey (SDSS) and other wide-field surveys. The disrupted satellites in this model yield a stellar profile consistent with that observed for the Milky Way stellar halo, and the model predicts the presence of many large-scale, coherent substructures in the outer stellar halo. The detection or non-detection and characterization of such substructures could eventually test models of galaxy formation and proposed solutions to the dwarf satellite problem.

Salim and Gould are investigating methods for the analysis of parallax and proper motion data expected from the FAME astrometry satellite, in order to map the Galactic gravitational potential several kpc around the Sun. They are also investigating the benefits of acquiring radial velocity data of FAME stars.

Graff and Salim, in collaboration with Flynn, J. Sommer-Larsen (TAC, Copenhagen) and B. Fuchs (ARI, Heidelberg), reviewed claims of the detection of halo white dwarfs (WDs) in the Hubble Deep Field (HDF). They looked for members of this population in local proper motion surveys, and did not find enough of them to substantiate claims that purported WDs in the HDF make up a significant fraction of the dark halo.

At a workshop on Stellar Clusters and Associations, Pinsonneault reported on ongoing work by him and his collaborators on the open cluster distance scale, extending earlier work that revealed significant systematic errors in the Hipparcos distances to certain open clusters. They examined a larger set of open clusters and confirmed the power of multicolor main-sequence fitting techniques for the inference of cluster metal abundances and distances; they also reported on a new method for accurate determination of open cluster ages using the boundary between the main sequence and pre-main sequence in solar analogues.

7 GALACTIC CENTER

Ramírez has completed her Ph.D. thesis work on iron abundances of cool, luminous stars in the central 60 pc of the Galaxy. In collaboration with her advisor Sellgren, J. Carr (NRL), S. Balachandran (U. Maryland), R. Blum (CTIO), and Terndrup, Ramírez performed a detailed abundance analysis of high resolution ($\lambda/\Delta\lambda = 40,000$) K -band spectra, obtained with CSHELL at the NASA Infrared Telescope Facility. They find that the mean $[\text{Fe}/\text{H}]$ of the GC stars is near solar, $[\text{Fe}/\text{H}] = +0.12 \pm 0.22$. They observed and applied the same analysis techniques to eleven cool, luminous stars in the solar neighborhood with similar temperatures and luminosities as the GC stars and with known abundances from optical spectra. This *differential* analysis shows that the mean $[\text{Fe}/\text{H}]$ of the solar neighborhood comparison stars, $[\text{Fe}/\text{H}] = +0.03 \pm 0.16$, is similar to that of the GC stars. The width of the GC $[\text{Fe}/\text{H}]$ distribution is found to be narrower than the width of the $[\text{Fe}/\text{H}]$ distribution of Baade's Window (BW) in the bulge but consistent with the width of the $[\text{Fe}/\text{H}]$ distribution of giant and supergiant stars in the solar neighborhood. Ramírez, Sellgren, and Blum plan next to measure stellar abundances of α -elements (Mg, Si, Ti) to address the issue of selective enrichment in the GC.

Ramírez, Blum, and Sellgren are using low-resolution $1.4 - 2.3 \mu\text{m}$ spectra of ~ 50 GC stars to measure the strengths of CO and H_2O bands in these stars. These two spectral features combined can provide a measure of the effective temperatures for the GC stars. This, combined with the stellar luminosity, allows them to derive the mass and age of each GC star by comparison to published stellar evolutionary tracks. Initial results suggest that the most IR-luminous stars in the GC 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 or episodic.

Gould and Miralda-Escudé have made a prediction that a cluster of $\sim 20,000$ stellar black holes are in orbit around Sgr A*, within a distance of ~ 0.7 pc, resulting from dynamical friction. Work related to this cluster of black holes is continuing. Chanamé is working on calculating the rates of microlensing events on background bulge stars lensed by Sgr A*, which should undergo secondary, planet-like microlensing events due to the black holes in the cluster or any stars that are present in the same region. Other work is also being planned to compute the evolution in the spatial and velocity distribution of stars of different mass around Sgr A*, in response to the migration of the black holes to the central parts, in order to make predictions for the red giant and main-sequence stellar populations that are observable.

8 GALACTIC BULGE

In their first paper reporting on an extensive survey to find and characterize hot HB stars in the Galactic bulge, R. Peterson (Lick Obs.), Terndrup, E. Sadler (U. Sydney), and A. Walker (NOAO) describe their survey technique and discuss early results. Candidates selected with wide-field *UBV* photometry in a field 7.5° from the GC were observed in the blue at 2.4 \AA resolution with the Anglo-Australian Telescope (AAT) 2dF spectrograph. Radial velocities were measured for all stars. For stars with strong Balmer lines, their profiles were matched to theoretical spectrum calculations to determine stellar temperature, T_{eff} , and gravity, $\log g$; matches to metal lines yielded abundances. The *UBV* photometry then gave the reddening and distance to each hot star. The reddening was found to be highly variable, with $E(B-V)$ ranging from 0.0 to 0.55 around a mean of 0.28. Forty-seven HB candidates were identified with $T_{\text{eff}} \geq 7250$ K, of which seven have the gravities of young stars, three are ambiguous, and 37 are HB stars. They span a wide metallicity range, from solar to $1/300$ solar. The warmer HB stars are more metal-poor and loosely concentrated towards the GC, while the cooler ones are of somewhat higher metallicity and closer to the center. They detected two cool solar-metallicity HB stars in the bulge of our own Galaxy, the first such stars known.

Frogel, Ramírez, and Stephens have completed the analysis of *K*-band ($2.2 \mu\text{m}$) spectra of more than 100 M giants along the minor axis of the Galactic bulge extending from 0.5° to 8° from the center. 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 (see §9) are used for calibration purposes. They find no evidence for a metallicity gradient along the minor or major axes of the inner bulge ($R < 560$ pc). This lack of a metallicity gradient in the inner bulge is not predicted by some recent theoretical modes for bulge formation via dissipative collapse. A metallicity gradient along the minor

axis found previously by Frogel, G. Tiede (OSU, now KPNO), and L. Kuchinski (OSU, now IPAC) only arises when fields located at larger Galactic radius are included in the analysis. These more distant fields are located outside of the IR bulge as defined by the COBE/DIRBE observations. For the inner Galactic bulge they find a mean value for $[\text{Fe}/\text{H}]$ of -0.21 with a dispersion of ± 0.30 , close to previously published values BW. Unlike the absence of a gradient, these values are close to theoretical predictions for a bulge formed via dissipative collapse.

9 GLOBULAR CLUSTERS

Frogel and Stephens have completed their analysis of *K*-band spectra of globular cluster giants. Based on observations of more than 100 stars in 15 globular clusters they set up a metallicity calibration accurate to ± 0.1 dex over a range in $[\text{Fe}/\text{H}]$ from -1.7 to -0.1 . They find that observations of only about half a dozen stars per cluster are needed to achieve very good agreement with the best determined optical $[\text{Fe}/\text{H}]$ spectroscopic values. They do not see evidence for α -process enhancement of abundances having an effect on their values. Their 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. They have already determined that optical abundances of two clusters are in error by as much as a factor of 10. They are now extending their technique to the integrated light of Galactic globular clusters. This will allow application to extragalactic clusters via observations with NGST.

10 NORMAL GALAXIES

Martini, Pogge, J. Mulchaey (OCIW), and M. Regan (STScI) began an HST snapshot survey of the circumnuclear regions of normal galaxies. The goal of this program is to acquire *V*-band images with the WFPC2 camera to compare the morphology in the central kiloparsec of these galaxies relative to their prior work on Active Galactic Nuclei (AGNs). In particular, this work will determine if normal galaxies have the same ubiquitous nuclear spiral structure as the AGN sample.

Eskridge is working with Frogel on the OSU Spiral Galaxy Survey. The first results on the full survey database show that 56% of the sample is strongly barred in the *H*-band, compared with 30% in the *B*-band. Roughly 3/4 of the sample have detectable bars. Eskridge and Frogel are currently working on a general spiral galaxy morphological classification in the near-IR. 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. This collaboration has already resulted in the discovery of spiral arm modulation in near-IR images of a pair of spirals, one with optically flocculent structure. The OSU survey is also engaged in collaborations with M. Thornley (NRAO) to combine the survey data with the BIMA SONG CO survey, with D. Elmegreen (Vassar) to in-

investigate the arm-interarm contrast in normal and anemic spirals, and with R. Windhorst and C. Chiarenza (ASU) to extend the survey wavelength coverage to the U -band.

The OSU survey is an important zero-redshift calibrator for studies of galaxies at high redshift. This has led to ongoing collaborations with S. Odewahn (ASU) to use the Survey data as a training sample for neural network galaxy classification algorithms, and with R. Abraham (U. Toronto) to compare color maps from local galaxies with those in the HDF as a probe of their star-formation histories.

Frogel and Stephens have obtained JHK images with NICMOS/NIC2 of four fields in the central bulge of M31 and one in its disk. From these data they have determined the bolometric luminosity function and colors for stars on the upper giant branch of M31's bulge and distinguished between long period variables (LPVs) and other giants. They can then derive estimates for the age and metallicity of these stars as a function of distance from the center of M31. These observations should definitively answer the question of whether or not there is a significant component of intermediate age stars in M31's bulge. This is especially relevant to the study of other bulges and spheroids since M31's integrated light is often used as a template for population synthesis studies and the interpretation of the integrated light from other galaxies. Indeed, the bulge of M31 harbors the nearest stellar population that is similar to that found in giant elliptical galaxies. Stars in the Milky Way's bulge are also often used as templates in stellar synthesis studies, yet its average metallicity is appreciably lower than that of M31's bulge and of giant ellipticals. Thus, a delineation of the differences in the luminous M giant population of the bulges of M31 and the Galaxy will also be of considerable interest for stellar synthesis work and for understanding the evolution of spiral bulges in general.

Frogel and Stephens use three different techniques to analyze the effects of crowding on their data, including the insertion of artificial stars (traditional completeness tests) and the creation of completely artificial clusters. These computer simulations have proven invaluable in interpreting the data. They are used to derive threshold- and critical-blending radii for each cluster, which determine the proximity to each cluster where reliable photometry can be achieved. These simulations allow Frogel and Stephens to quantify and correct for the effects of blending on the slope and width of the red giant branch at different surface brightness levels. They then use these results to estimate the limits blending will place on future space-based observations.

Frogel and Stephens have obtained HST-NICMOS observations of five of M31's most metal rich globular clusters: G1, G170, G174, G177 & G280. For the two clusters farthest from the nucleus they statistically subtract the field population and estimate metallicities of -1.2 for G1 and -0.2 for G280 based on the slopes of their giant branches. They have identified at least one LPV based on color and variability. The location of G1's

giant branch in the K vs. $V-K$ color-magnitude diagram (CMD) is very similar to that of 47 Tucanae, indicating a higher metallicity than their purely IR CMD: $[\text{Fe}/\text{H}] \approx -0.8$. For the three central clusters, which are too compact for accurate cluster star measurements, they present integrated cluster magnitudes and field CMDs. For the field surrounding G280, they estimate the metallicity to be -1.3 from the slope of the giant branch, with a spread of $\sigma_{[\text{Fe}/\text{H}]} \approx 0.5$ from the width of the giant branch. Based on the numbers and luminosities of the brightest giants, they conclude that only a small fraction of the stars in this field could be as young as 2 Gyr, while the majority have ages closer to 10 Gyr.

11 INTERACTING GALAXIES

To see the effects of grazing encounters on the structures and internal kinematics of spiral galaxies, Kaufman, E. Brinks (U. Guanajuato), B. Elmegreen (IBM), D. Elmegreen (Vassar), M. Klarić (Columbia, SC), C. Struck (Iowa St.), and M. Thomasson (Onsala) continued their detailed studies of several interacting galaxy pairs. From HST WFPC2 observations in $UVBI$, they found that star-forming regions in the interacting galaxies IC 2163/NGC 2207 have the same fractal dimension and thus the same geometric structure as the interstellar gas in the Milky Way. They used the HST images to determine the extinction in the part of NGC 2207 seen in projection against IC 2163 via the method of White and Keel. A 1997 paper by Berlind and OSU collaborators had previously done this with ground-based images. The HST observations reveal a lot of small-scale dust structure, with some dust clouds as small as the resolution limit of $0.1'' = 17$ pc.

The previous study by Kaufman and her collaborators of the interacting galaxies NGC 5394/95 presented the following puzzle about star formation: despite the presence of H I gas, two of the very bright, inner-disk arms of NGC 5394 show no evidence of ongoing star formation. In collaboration with K. Sheth (U. Maryland), they have since made $^{12}\text{CO } J = 1 \rightarrow 0$ observations with BIMA so that they can determine the value of the instability parameter Q_{gas} at the inner-disk arms.

Tinker and Ryden are beginning a numerical study of merging galaxies. When two galaxies merge, the morphology and dynamics of the merger remnant depend on whether a central supermassive black hole existed in one or both of the merging galaxies. In particular, a black hole binary may be able to carve out a central core in the merger remnant. However, the density profile of the merger remnant also depends on whether the merging galaxies contained significant amounts of gas. A goal of Tinker and Ryden is to judge the relative importance of dissipative gas and of supermassive black holes in dictating the final morphology and kinematics of the merger remnant.

Frogel, Kassin, Eskridge, Pogge, & Sellgren have begun an analysis of the Antennae Galaxy. They are using their multi-color optical/IR images to identify reddened star clusters and trace the history of star forma-

tion across the face of the galaxies. Their technique is based on a pixel by pixel analysis of the colors as is being used by Abraham.

12 ACTIVE GALACTIC NUCLEI

Although the spectra of observed quasars do not generally show self-absorption by hydrogen in the vicinity of the quasar, low-luminosity quasars at high redshift have not been well observed and might have significant self-absorption. This would be important for estimating the total contribution from quasars to the intensity of the ionizing background at high redshift. Graduate student K. Alam is involved in work with Miralda-Escudé on a model to predict the amount of self-absorption as a function of quasar luminosity, based on a simple assumption about the gas distribution in galactic halos that are presumed to host quasars.

Mathur uses X-ray and UV spectroscopy to probe the regions near the central black hole in AGNs. Her interest includes broad absorption line quasars, narrow line Seyfert 1 galaxies (NLS1s) and high redshift quasars. She will use XMM and Chandra observations to study the intergalactic medium (IGM) at high and low redshifts.

Martini and Pogge are studying the complete CfA Seyfert sample using visible-wavelength archival HST imaging. This work extends the results of their previous NICMOS imaging survey to include both Seyfert 1s and 2s for a nearly complete, host-galaxy selected sample of nearby Seyfert galaxies. They are using a novel image processing technique to enhance dust features in the V-band images, providing maps of circumnuclear dust and star formation regions. A virtue of the technique is that they can create dust maps for galaxies without NICMOS imaging (most of the Seyfert 1s). They find that the spiral circumnuclear dust features seen in Seyfert 2s with NICMOS are common in both types, and thus apparently a generic feature of Seyferts. A paper describing their results being prepared for submission.

Pogge and J. Shields (Ohio U.) have begun a program to search for the [Ca II] λ 7291 emission line in NLS1 galaxies. Simple photoionization models that assume solar abundances for the narrow-line region (NLR) in Seyferts predict that the [Ca II] lines should be important nebular coolants, with strengths rivaling those of other, more familiar optical forbidden lines (e.g., [S II] or [O I]). However, [Ca II] lines are almost never seen, which may be understood if the NLR has a depletion pattern onto grains resembling our local interstellar medium, in which case only 10^{-3} of the total calcium remains in the gas phase. The *only* AGNs that show [Ca II] emission are three NLS1s. These objects are also noted for strong, but narrow, [Fe II] emission. If Fe is being released from grains by shocks or grain evaporation, it should release Ca as well. The first observations have been completed, and are being analyzed at this time. The goal is to make a systematic study of NLS1s in this overlooked region of the spectrum to see if [Ca II] is generic to the NLS1 class.

Peterson is continuing to carry out multiwavelength monitoring programs on AGNs. He is currently leading a multiwavelength program to study optical, UV, and X-ray variations in the NLS1 galaxy Akn 564; Bertram, Collier, Martini, Mathur, Romano, Vestergaard, Wagner, and Zheng are also participating in this program, which involves optical photometry and spectroscopy from MDM and other observatories, UV spectroscopy with HST, and X-ray observations with ASCA, RXTE, Chandra, and XMM. Collier has principal responsibility for the HST part of the program. Romano is involved in the analysis of the ASCA data, in collaboration with J. Turner (NASA/GSFC) and Mathur. Most of the multiwavelength observations were obtained during two periods, 1999 October – November, and 2000 May – July. The data are still being analyzed, but it is already clear that while NLS1s undergo dramatic X-ray variations, their UV/optical continua are *much less* variable than in normal Seyfert 1 galaxies.

Peterson, A. Wandel (UCLA and Hebrew U.), and M. Malkan (UCLA) are continuing their investigation of the mass vs. 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. Three AGNs clearly show a virial-type relationship (i.e., line width inversely proportional to the square root of the reverberation lag) for multiple emission lines. Peterson and his collaborators are also continuing their investigation of the relationship between black-hole masses and their environments in both active and normal galaxies.

Collier, Peterson, and K. Horne (St. Andrews U.) continue with numerical simulations to quantify the observational requirements for future AGN echo-mapping experiments. The simulations are to aid in the design of a multiwavelength observatory, led by Peterson, to be proposed for flight under the NASA Explorer program. These experiments will map the geometry and kinematics of the broad emission regions on size scales of submilliparsecs, determine the origin of the continuum source, and provide accurate black-hole masses.

Peterson is also continuing to coordinate ground-based monitoring programs undertaken by the International AGN Watch consortium. The AGN Watch has now completed 11 years of optical spectroscopic monitoring of NGC 5548, and the most recent three years of data will be prepared for publication in the near future. Analysis of new and archival data is continuing in collaboration with Collier and Romano and with V. I. Pronik and S. G. Sergeev (Crimean Obs.).

Collier has been making use of archival multiwavelength monitoring data for a number of purposes, including estimating luminosity distances to quasars, constraining the underlying physical mechanism(s) responsible for the UV/optical variations, and measuring characteristic variability time scales. This work will constrain

the fundamental nature of the AGN energy source.

Vestergaard and B. J. Wilkes (CfA) generated an empirical template of UV iron emission in active galaxies using HST archival FOS spectra of the NLS1 galaxy, IZw1. Iron emission is often a severe contaminant in optical-UV spectra of AGNs. The characteristically large, intrinsic line broadening (up to $\sim 10,000 \text{ km s}^{-1}$) in AGNs cause the thousands of iron lines to blend with themselves and with other (non-iron) line features. This strongly blended line emission, which at some wavelengths forms an artificial continuum enhancement, complicates and limits the accuracy of measurements of both strong and weak emission lines, as well as of the underlying continuum emission. If the iron emission is not somehow accounted for, it affects studies of line and continuum interrelations, the ionization structure, and the chemical abundances in AGNs. The theoretical modeling of the iron emission is non-trivial. However, whereas significant progress has been made in recent years, current models cannot yet adequately account for the full iron spectrum as it is observed in AGNs. Until such models become available, empirical templates are important tools for generating approximate empirical models of the observed iron emission. The template can be used to fit and eliminate the iron emission in AGN spectra permitting a more accurate study of the non-iron line and continuum emission. Furthermore, the fitted iron emission spectra may help in attempts to understand the complicated iron emission processes. The IZw1 spectrum has a rather narrow intrinsic line width ($\sim 900 \text{ km s}^{-1}$) which makes it particularly suitable as an empirical template as it can be applied to most AGNs (which have broader intrinsic widths). Applications of the Fe II and Fe III templates from IZw1 to large samples of AGN spectra are underway in separate studies.

Vestergaard is fitting the iron emission in a sample of high-quality rest frame UV spectra of intermediate redshift quasars with the aim of studying both the iron emission and the line spectral properties, and how they vary with radio properties, with P. Barthel (Groningen), and with optical properties.

K. Forster, P. Green, T. Aldcroft (CfA), Vestergaard, C. Foltz (MMTO), and P. Hewitt (IoA) fit the templates in a mostly automated way to ~ 1000 optical-UV spectra of the Large Bright Quasar Survey to allow a more detailed study of the quasar emission line and continuum properties using survival analysis techniques.

Vestergaard and L. Ho (OCIW) are carrying out a spectroscopic program to determine how the properties of intrinsic C IV $\lambda 1549$ absorbers vary with quasar properties in a large sample of intermediate-redshift quasars.

J. Kuraszkiewicz (CfA), Wilkes, W. Brandt (Penn State) and Vestergaard have examined new optical spectroscopic data of selected radio-quiet sources in the Bright Quasar Survey to address the issue of whether the strongest AGN property differences ('eigenvector 1') are driven by the source inclination, as has been long debated. The analysis included a careful fitting and subtraction of the contaminating optical Fe II emission.

They find that source inclination is not driving the eigenvector. The discrepancies with prior studies of radio-loud AGN may be due to iron emission contamination.

Osmer, Monier, and Conti continued their work on two multi-color searches for quasars intended to investigate the evolution of quasars and to determine the quasar luminosity function at high redshifts. These optical surveys, the BTC40 and BFQS surveys, are designed to detect the presence of Ly α emission and continuum flux in one filter and the fainter, depressed continuum to the blue of Ly α 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 being led by J. Kennefick (OSU, now at Oxford) and also 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 BVI bands and reaches to $m_{\text{lim}} \approx 25$ at its deepest limit. The imaging data have been reduced and catalogs were generated using the SKICAT catalog management software. Follow-up spectroscopy at the AAT and the CTIO 4-m during the past year has resulted in the discovery of two quasars at redshifts 4.7 and 4.8.

The BFQS is a collaboration of the same group and is being led by Hall. It also uses BTC camera data and reaches to $m_{\text{lim}} = 26.7$ over 7 deg^2 . It uses the BRI bands and is aimed at quasars with $3.3 < z < 5$ down to L^* luminosities. The data are currently being reduced and candidates selected.

Monier and Conti used ground-based BTC Z -band imaging of the HDF-South (HDFS) along with with the HST data to perform a color-color search for quasars in the redshift range $1.0 < z < 5.5$. Several candidates were found at lower redshifts.

Martini and Weinberg completed their study of the relation between the clustering and characteristic lifetime of high-redshift quasars. If the luminosity of a quasar is an increasing function of its host halo mass, then a shorter lifetime implies more massive hosts, which exhibit stronger (more highly biased) clustering. Clustering can therefore serve as a diagnostic for the quasar lifetime, and measurements of the quasar clustering by the 2dF and SDSS surveys in the next few years could determine the quasar lifetime to within a factor of three.

13 GAMMA-RAY BURSTERS

With M. Andersen (Oulo U.), J. Hjorth (Niels Bohr Institute) and others, Vestergaard optically identified the Gamma-Ray Burster GRB 000131 and its optical afterglow using the VLT, NTT and the Danish 1.54-m

telescopes 84 hours after the burst following the BATSE detection and an Inter Planetary Network localization. This afterglow is the first to be detected with an 8-m class telescope. The sharp Ly α absorption edge places the GRB at $Z = 4.5 \pm 0.015$. The rapid power-law decay of the afterglow, $\alpha = 2.25$, suggests that it originated in a collimated outflow, such as a jet. The data indicate a jet opening angle of 7° or more and a lower limit to the released energy of $\sim 5 \times 10^{51}$ erg.

14 COSMOLOGY

14.1 Galaxy Formation, Evolution, and Clustering

Martini, DePoy, and Osmer completed their near-IR imaging of a subset of the Deep Multicolor Survey. The near-IR and visible wavelength data for this survey include a total of nine filters. The number–magnitude relations for the three near-IR filters agree well with simple passive evolution galaxy models with the addition of at most a small amount of merging. There are nine resolved objects in this survey that are classified as Extremely Red Objects (EROs), defined here as galaxies with $R-K > 5.3$, $K < 18$ mag. Photometric redshifts for these galaxies predict that all lie at redshifts $0.8 < z < 1.3$. The surface density of these galaxies is higher than the prediction of hierarchical galaxy formation models for a flat, matter-dominated universe, although the measured surface density is in better agreement with a Λ -dominated, flat universe.

With D. Forbes (Swinburne U.) and A. Terlevich (U. Birmingham), Ryden is investigating the relation between the apparent axis ratio of elliptical galaxies and the age of their stellar population. They find that at radii much smaller than the effective radius, ellipticals with an old stellar population (age > 7.5 Gyr) are rounder than ellipticals with a younger population. In addition, ellipticals with a core surface brightness profile are rounder at small radii than ellipticals with a power-law profile. The correlation among age, shape, and profile type may help to discriminate among mechanisms for elliptical galaxy formation.

In collaboration with G. Yepes (U. Madrid), Kravtsov has estimated the possible input of SN energy into intracluster gas. Heating by SNe was proposed as an explanation for deviations from self-similarity in properties of galaxy clusters. In this study the authors have estimated the possible energy from SNe using the observed amount of metals in the intracluster gas and gas dynamic simulations of galaxy formation. The main conclusion of the study was that for typical galactic star-formation histories, SNe are unlikely to be the only source of energy for intracluster heating.

Kravtsov has studied numerical effects in dissipationless N -body simulations and performed cosmological N -body code comparisons in collaboration with A. Knebe (Oxford), S. Gottlöber (AIP, Potsdam), and A. Klypin (NMSU).

Kravtsov, Gottlöber, and Klypin have finished a

study of the evolution of dark matter halo merger rate in cold dark matter (CDM) structure formation models as a function of halo environment. The theoretical predictions on this subject are important for interpreting the observed evolution of the galaxy merger rate and the frequencies of close galaxy pairs at different redshifts. The new feature of the study, made possible thanks to the very high mass and force resolution of the simulations, is an analysis of the merger rate in different environments including galaxy clusters and groups.

In collaboration with Klypin, Bullock, and J. Primack (UCSC), Kravtsov performed a study of the density profiles of dark matter halos. This study is based on the new high-resolution simulations using multiple mass resolutions.

During the past year, Kravtsov has also dedicated a substantial effort to developing and testing the new adaptive mesh refinement code for cosmological gas-dynamics simulations. The code is designed to handle an extremely high dynamic range that is beyond the capabilities of a Eulerian uniform grid or even the SPH algorithms. This effort is starting to pay off as recent tests show that the code performs very well compared to other cosmological gas-dynamics codes. During the next year, the code will be actively used to perform high-resolution simulations of formation of galaxies and galaxy clusters.

Bullock, in collaboration with T. Kolatt, Y. Sigad, A. Dekel (Hebrew U.), Primack, Kravtsov, and Klypin, studied the density structure in dark matter halos in a high-resolution N -body simulations. They found that halos of a fixed mass show significant scatter in their density concentrations, which may have implications for understanding the Tully-Fisher relation of galaxies, as well as the origin of galaxy types. In addition, they showed that halos are typically much less concentrated at high redshift, and presented an analytic model that explains this behavior. These results provide clues to the process of galaxy assembly and the nature of star formation in the early universe.

Bullock investigated the angular momentum structure of dark matter halos using high resolution N -body simulations in collaboration with Dekel, Kolatt, C. Porciani (Hebrew U.), Kravtsov, Klypin, and Primack. They discovered that the angular momentum distributions in a statistical sample of dark matter halos spanning three decades in mass obey the same “universal” form, and used analytic models to help explain this result. They also worked out the first-order implications of this profile for galaxy formation, addressing the fundamental problem of the origin of exponential disk galaxies and galaxy bulges. As part of this investigation, they presented statistics for the alignment and spatial distribution of angular momentum within halos.

In collaboration with R. Wechsler (UCSC), Primack, Klypin, and Kravtsov, Bullock is working on a series of projects based on the construction of “structural merger trees” of dark matter halos using high-resolution N -body simulations. The merger trees record the history of mass accretion and merger events for every iden-

tified halo in the simulation, as well as their density profiles and angular momentum structure. A major goal of this research is to understand how a halo’s merger history affects its final density profile and angular profile, and, in turn, to understand how the merger history of a galaxy will affect its structural and morphological properties.

In collaboration with R. Somerville (IoA) and Primack, Bullock continues research aimed at predicting the diffuse extragalactic background light (EBL) using semi-analytic models of galaxy formation. This work compares theoretical calculations with the observed EBL spanning the UV to the sub-mm. The main goal of this research is to use the EBL to test aspects of galaxy formation, including the nature of the initial mass function of stars, high-redshift star formation, and dust modeling.

Bullock, in a continued collaboration with Somerville and Primack, is exploring how TeV γ -ray telescopes can be used as to test galaxy formation models. The attenuation of γ -rays from distant sources via the process of pair production off lower-energy background photons provides an indirect probe of the EBL. This research uses semi-analytic models of galaxy formation in order to predict how the expected attenuation of γ -rays should change depending on the type of galaxy formation model assumed. In addition, the predicted EBL provided by this work can be used to estimate the redshifts of the most distant objects observable by new γ -ray telescopes soon to be in operation.

Bullock, in collaboration with Dekel, Kolatt, Primack, and Somerville proposed a method for constraining the evolution of the Tully-Fisher relation using galaxy counts as a function of redshift convolved with the expected evolution of the velocity function of dark halos. Preliminary indications from the HDF indicate that the Tully-Fisher relation dims dramatically at high redshifts, by roughly two magnitudes by $z = 1.5$. Such a drastic dimming is puzzling within the context of most models of galaxy formation.

In collaboration with M. Schirber, S. Koushiappas (OSU Physics graduate students), and Walker, Bullock explored the AGN contribution to the EBL from the soft X-ray to the near-IR. They find that between UV and IR wavelengths, the AGN contribution is small compared to that of galaxies, but begins to dominate around 100 eV. They calculate the optical depth of GeV photons to the AGN-produced background and explore how direct measurements of the soft X-ray background may provide constraints on models of AGN formation. Measurements of the UV to sub-mm background light provide direct probes of galaxy formation models, with little contamination due to AGN light.

In collaboration with Kolatt, Sigad, Dekel, Klypin, Primack, and Kravtsov, Bullock used high resolution N -body simulations to calculate the interaction rates for dark matter halos and subhalos. The N -body results were used to test analytic models for the interaction rates and to test simple estimates for the dynamical friction timescales of subhalos.

Continuing a collaboration with Kolatt, Sigad, and Dekel, Klypin, Primack, and Kravtsov, Bullock studied the mass exchange rates between various dark matter components in high resolution cosmological N -body simulations. In contrast to what is usually assumed in analytic treatments of dark matter halo build-up, they find that dark halos lose a non-negligible component of their mass to the background material as a result of gravitational interactions. A possible implication is that gravitational energy provides an additional mechanism for enriching the IGM with metals. By using a simplified model, they show that the predictions of such a gravitational mixing scenario reproduce observed trends in the relative metallicities of the IGM, galaxies, and clusters both locally and at high redshift.

In collaboration with Sigad, Kolatt, Dekel, Klypin, Primack, and Kravtsov, Bullock studied the mass and velocity functions of halos and subhalos using high-resolution N -body simulations and compared them with analytic models. They found that the slope of the velocity function of isolated halos is significantly steeper than that of clustered halos, providing a testable prediction for hierarchical models of galaxy formation.

Bullock, working with Weinberg, N. Katz (U. Mass.), and L. Hernquist (Harvard), is studying high-redshift galaxies using cosmological hydrodynamic simulations. This research aims at constraining models of galaxy formation using a wide variety of available data, with comparisons to the Lyman-break galaxy data of Steidel and collaborators, as well as the IR background, SCUBA counts, and SIRTf counts, among others.

As part of his thesis, Conti worked with Ryden and Weinberg to develop a simple and flexible framework for interpreting a Principal Component Analysis (PCA) of the observable properties of disk galaxies as predicted by semi-analytic models of galaxy formation. The approach takes as its starting point the disk scaling relations developed by Mo et al. in 1997. However, while Mo et al. focused on the predictions of specific cosmological models, Conti instead considered a broad range of input assumptions and examined the relation between the observable properties of disk galaxies (luminosities, scale lengths, colors, 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).

This framework was applied to mock samples of disk galaxies in a Λ -CDM cosmology under diverse initial conditions. Each sample was characterized by a small set of control parameters to defined the maximum allowed variability and by a large set of observables for which the principal components were computed. Conti recovered a strong first principal component associated with the spectrophotometric properties of galaxies (such as colors, birth parameter and 4000 Å break) that arise almost exclusively from the distribution of input spin parameters in the theoretical description of galaxies. A sec-

ond principal component is associated with the energetic output of the system and was determined by a weighted average of the system’s mass and formation redshift. Finally, a third component, associated with the slope of the system’s rotation curve, arises from the interplay of disk baryonic fraction, halo concentration and specific angular momentum. An ideal sample for Conti’s theoretical framework will be the SDSS. The goal is to show that this framework can provide an interpretation of the results of PCA on SDSS data and hence useful insights into the process of galaxy formation.

Berlind and Weinberg are studying galaxy clustering in the framework of halo occupation distribution (HOD) models, where the relation between the galaxy and mass distributions is parametrized by prescriptions of how galaxies occupy dark matter halos. The ultimate goals of this work are to develop a method for determining the HOD empirically and to apply this method to the SDSS galaxy redshift survey.

14.2 Lyman Alpha Forest and Large-Scale Structure

Miralda-Escudé has been engaged for some time in research on the reionization of the IGM. At present he is focusing his efforts on constructing a model for the expansion of ionized regions, including the effect of clumping in the gas distribution in a statistical way, based on the reionization model developed previously with M. Haehnelt (Max-Planck Institut, Garching) and M. Rees (IoA). The objective is to make predictions for the time evolution of the filling factor of the ionized regions, and their imprint in the observable Ly α spectra, for both the hydrogen and He II reionizations, using analytical approximations of much greater simplicity than a full radiative transfer 3D simulation.

McDonald has been working on his Ph.D. thesis with Miralda-Escudé, measuring the power spectrum and flux distribution from a set of eight high-resolution quasar spectra. McDonald also developed a new method to measure absorption line widths and to estimate the gas temperature from their distribution. In other work, the evolution of the intensity of the ionizing background over the range $2.5 < z < 5.2$ has been determined from observations of the mean flux decrement of the Ly α forest, using the predictions of theories of the Ly α forest based on gravitational structure formation, showing that the intensity declines with redshift by a factor of 3 over this redshift range. More recently McDonald is also engaged in other work to predict the Ly α forest redshift space power spectrum that can be observed in double or multiple lines of sight.

X. Chen is working in collaboration with Miralda-Escudé on a Monte-Carlo simulation of the scattering of Ly α photons produced by the first generation of stars in the neutral IGM, before reionization. These Ly α photons have the effect of coupling the spin temperature to the gas kinetic temperature, causing absorption or emission in the 21 cm line against the cosmic microwave background (CMB). Whether absorption or emission is

seen depends on the temperature, which is affected by the scattering of Ly α photons. The objectives of this work are to accurately calculate the thermal evolution, which will determine how long the 21 cm line can be seen in absorption before the atoms are heated up by the scattering process.

Ryden and J. Schmidt (OSU physics) have devised a new void-finding algorithm which permits the user to vary the density threshold at which voids are defined, but which does not impose a predefined shape on the voids. They have applied their algorithm to three-dimensional numerical simulations of galaxy surveys. They find that if a galaxy survey has a sufficiently high sampling density, redshift distortions along the line of sight can be detected and accurately measured. In simulations with a CDM power spectrum, large voids are stretched along the line of sight in redshift space.

Monier continued work with D. Turnshek, S. Rao, and D. Nestor (U. Pittsburgh), F. Briggs and W. Lane (Kapteyn) to investigate the properties of galaxies responsible for damped Ly α 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 includes the lowest-redshift ($z \approx 0.09$) damped Ly α 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.

McDonald and Miralda-Escudé, in collaboration with M. Rauch (OCIW), W. Sargent and T. Barlow (Caltech), and R. Cen and J. Ostriker (Princeton), have analyzed observed quasar spectra to determine the flux distribution and spatial correlation of the Ly α forest absorption. The same statistics were extracted from a cosmological numerical simulation and compared to the observations to test the current Ly α forest model, and to estimate the amplitude of the primordial density fluctuations on $\sim 1 h^{-1}$ Mpc scales.

McDonald, Miralda-Escudé, Rauch, Sargent, Barlow, and Cen compared the observed and simulated distributions of line widths in the Ly α forest to determine the relation between gas temperature and density in the IGM.

McDonald and Miralda-Escudé simulated the Ly α absorption in the quasar with the highest presently known redshift ($z = 5.8$), and other high- z quasars, and used these and the previous results to estimate the evolution of the intensity of the intergalactic ionizing background from $z \simeq 2.4$ to $z \simeq 5.2$.

Berlind, Weinberg, and V. Narayanan (OSU, now Princeton), used a combination of cosmological N -body simulations and analytic arguments to show that a regression of unsmoothed peculiar velocity measurements against peculiar velocities predicted from a smoothed galaxy density field leads to a biased estimate of the cosmological density parameter Ω_m , even when galaxies

trace the underlying mass distribution and galaxy positions and velocities are known perfectly. The effect on current estimates of Ω_m is probably small relative to other uncertainties, but taking full advantage of the statistical precision of future peculiar velocity data sets will require either equal smoothing of the predicted and measured velocity fields or careful accounting for these biases.

Weinberg continued participation in the Sloan Digital Sky Survey, including work on galaxy target selection for the spectroscopic survey and a first estimate of the galaxy luminosity function estimated from survey commissioning data.

14.3 Dark Matter and Cosmological Parameters

Early in 2000, there was a flurry of interest in dark matter models in which the dark matter is self-interacting with a large cross-section, but does not couple to ordinary baryonic matter. Such models can explain certain problems in the theory of galaxy formation. In collaboration with S. Hannestad (NORDITA), Scherrer proposed the possibility of self-interacting warm dark matter, and Scherrer and Hannestad investigated various observational consequences of this idea.

The existence of a non-zero cosmological constant remains perhaps the most mysterious problem in cosmology. An interesting alternative is provided by “quintessence” models, in which the unclustered energy density (which appears to make up 70% of the density of the universe) is not constant, but is due to a scalar field energy density which can vary with time. Such models can be parametrized in terms of the quintessence equation of state. Scherrer has been working with A. Linn and J. Kujat (OSU Physics graduate students) and Weinberg to catalogue possible observational tests which might discriminate between quintessence models with different equations of state.

If dark matter consisted of self-interacting particles, the centers of dark matter halos would become spherical as a result of the relaxation due to particle collisions. This self-interaction has been suggested as a mechanism to introduce cores in the dark matter density profiles of dwarf galaxies. Miralda-Escudé shows how the same self-interaction would make the central parts of halos in clusters of galaxies become too spherical to explain the form of gravitationally lensed images observed in one particular cluster, which require an elliptical shape for its dark matter halo.

Steigman, Walker and A. Zentner (OSU Physics graduate student) 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 constrains the cosmological constant (or, equivalently, Ω_Λ). Armed with these constraints on Ω_M and Ω_Λ they then proceed to bound the 3-space curvature ($\Omega_k \equiv 1 - (\Omega_M + \Omega_\Lambda)$), the present value of the deceleration parameter ($q_0 = \Omega_M/2 - \Omega_\Lambda$), and other cosmological parameters.

Weinberg, in collaboration with Katz and M. Fardal (U. Mass.), Hernquist and R. Croft (Harvard), R. Davé (Princeton), and J. Gardner (U. Washington), used hydrodynamic cosmological simulations to study aspects of galaxy formation, galaxy clustering, and the IGM. Highlights of this work included a comparison between predicted and observed properties of the high-redshift galaxy population, a demonstration that cooling radiation from forming galaxies could produce substantial Ly α emission line luminosities, predictions for the population of damped Ly α absorption systems in various cosmological models, *ab initio* predictions of the bias between galaxy clustering and mass clustering, and a new measurement of the matter power spectrum at redshift $z \sim 2.7$ from Ly α forest data. In related work with Weinberg and several of these collaborators, J. Phillips (OSU Physics graduate student) investigated cosmological implications of an earlier measurement of the matter power spectrum from Ly α forest data, Steed investigated the influence of numerical resolution and physical assumptions on predicted statistical properties of forest absorption, Linn investigated the shapes of Ly α forest lines as a diagnostic test for out-of-equilibrium absorbers, and X. Chen investigated predictions for “X-ray forest” absorption from hot gas in the IGM at low redshift.

14.4 Early Universe and Big-Bang Nucleosynthesis

Scherrer has continued to concentrate much of his effort during 1999 – 2000 on the overlap between particle physics and the CMB. Scherrer finished work with Kujat on an investigation of CMB limits on the time variation of the Higgs vacuum expectation value. In addition to the spatial anisotropy of the CMB, the blackbody spectrum itself can provide useful constraints on particle physics. Along with Walker and McDonald, Scherrer has examined the constraints which can be placed on relic particle properties from the distortion in the CMB spectrum due to the residual annihilations of such particles.

Scherrer also examined, with S. Whitmire (SUNY, Buffalo), the effects of inhomogeneous neutrino degeneracy on Big-Bang Nucleosynthesis (BBN). Scherrer is currently working with S. Stirling (U. Utah) to study some special cases of this model.

The confrontation between the predictions of BBN and the primordial abundances of the light elements inferred from observational data is the main focus of Steigman’s research program. As in the past, he and his collaborators continue to pursue 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 two independent projects aimed at constraining the abundances of ^4He and Li.

S. Viegas and R. Gruenwald (São Paulo) and Steigman continue 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 ^4He . In recently published work they revisit 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 (the “ionization correction factor,” or *icf*, is less than unity). They further explore the effect on the *icf* of more realistic inhomogeneous H II region models, finding that for those 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 estimate 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. This work continues with an exploration of the effect on the H II regions and the *icf* of the “true” helium abundance, and of the age of the star cluster.

In work with Steigman’s collaborators Walker, Pinsonneault, and Narayanan, observations of Pop I stars have been used to normalize the rotational mixing of Li from stellar surfaces, permitting limits (both lower and upper) to be set on Li mixing in the Pop II stars used to infer the primordial Li abundance. This work continues in a comparison between their predictions and a new, independent data set.

Recent CMB results from BOOMERANG and MAXIMA prefer a value of the baryon density which is somewhat higher than that predicted by BBN. One solution to this problem is to postulate new physics for BBN, such as a neutrino chemical potential. This is being explored by Scherrer, Steigman, Walker and J. P. Kneller (OSU Physics graduate student). The need for such new physics, and the discrepancy between BBN and the CMB results, depends on the priors assumed for CMB. Several classes of models are explored to determine the dependence of “new physics” on the assumed priors.

McDonald, Scherrer, and Walker used the observed perfection of the Planck spectrum of the CMB to place a new constraint on residual annihilations of relic particles.

McDonald and Miralda-Escudé, in collaboration with Cen, are developing the theoretical methods needed to analyze large future Ly α forest data sets, and especially to predict the correlation between spectra of quasars separated by small angles in the sky. If properly calibrated, the strength of the correlation between the Ly α forest absorption in nearby lines of sight can be used to measure the geometry of the universe through a version of the Alcock & Pacziński test. This measurement is sensitive to the cosmological constant. The theoretical calibration is being studied using scores of inexpensive Hydro-PM simulations. A huge (768³ cell) fully hydro-

dynamic simulation, and other smaller simulations, will be used to test the accuracy of the Hydro-PM approximation. In collaboration with various observers including Rauch, D. Tytler (UCSD), and G. Williger (NOAO), the methods developed will be applied to observational data with the goal of measuring Ω_Λ to $\pm 15\%$.

15 ATOMIC ASTROPHYSICS

Pradhan, Nahar, G. Chen, Delahaye, and J. Oelgoetz (OSU Chemical Physics graduate student) are carrying out research in various astrophysical and atomic radiative and collisional processes. They also collaborate in a variety of problems with H. Zhang (LANL), M. Bautista (IVIC, Venezuela), C. Zeppen (Obs. Paris), C. Mendoza (IVIC, Venezuela), E. Werner (U. Stuttgart), N. Haque (Moorhouse College), and F. Keenan (Queens U., Belfast).

The group is involved in accurate atomic 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 T90 at the Ohio Supercomputer Center in Columbus.

15.1 The Iron Project

The international Iron Project (IP) studies and calculates 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 reveals the existence of iron peak heavy elements such as iron, cobalt, nickel as end products of stellar nucleosynthesis. The Ohio State group led by Pradhan is the US part of the IP team, with members from the UK, France, Germany, Canada and Venezuela. The work under the IP complements the work under the Opacity Project (OP), and provides improved results especially for heavy ions. The OP aimed in 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, the work on electron impact excitation collision strengths for Fe XVII is nearly complete after two years of effort. It is an important ion astrophysically because of observation of its lines. However, the extensive computations and elaborate testing of the BPRM codes have been demanding on computer resources. The electron impact excitation collision cross sections include fine structure with allowance for strong coupling and relativistic effects. Work is under progress for O VII, another important ion in X-ray plasma diagnostics.

15.2 H II Regions and Gaseous Nebulae

G. Chen and Pradhan have demonstrated fluorescent excitation of spectral lines in planetary nebulae as a function of the temperature and luminosity of the central star and the distance of the emitting region from it. They have applied the method to a detailed analysis of spectral observations of iron [Fe VI] in a high excitation planetary nebula NGC 6741 and determined the electron densities and temperatures. They suggest that fluorescent excitation of forbidden lines is important in the determination of element abundances, particularly iron.

15.3 Photoionization

Photoionization cross section of highly charged ions are now being calculated more accurately as new developments have been made by including the relativistic effects and radiation damping of low-lying resonances in the BPRM method. Nahar, Pradhan, and Zhang have carried out detailed photoionization cross sections for the He- and Li-like ions C IV, C V, Fe XXIV, and Fe XXV. Work on O VI and O VII is in progress. These ions are observed frequently in the X-ray spectra taken by the space observatory Chandra. The K- α lines, due to 1s-2p transitions, of these highly charged ions are distinct in the spectra and provide useful information of various diagnostics of temperature, density, abundances and ionization stages.

Nahar is also calculating the cross sections of C II in the BPRM approximation as for the first time very detailed features of photoionization cross sections of this ion were measured. Previous nonrelativistic *LS* coupling calculations agree quite well with the measured cross sections except several autoionizing resonances due to fine structure which are being revealed in the BPRM calculations.

Zhang and Pradhan are calculating the photoionization cross sections and recombination rate coefficients for Fe XVII in the low energy regions to compare with the measured features of recombination spectra of this important ion. Nahar is carrying out similar computations for C III recombination spectra which have been measured. These efforts aim at benchmarking the theoretical methods for BPRM photoionization cross sections and the unified treatment for electron-ion recombination as described below.

15.4 Electron-Ion Recombination

A unified method for determining total electron-ion recombination rates, which accounts for both radiative and dielectronic recombinations in a self-consistent manner, was developed by Nahar and Pradhan in 1994. The method was subsequently extended to include relativistic effects. Nahar, Pradhan, and Zhang have calculated the level-specific and total recombination rate coefficients, including the relativistic effects, for the highly charged ions C IV, C V, Fe XXIV, and Fe XXV. Work is in progress for O VI and O VII. As mentioned above, the

incentive for the work on these highly charged ions is the application of the data to X-ray spectra taken mainly by Chandra. Zhang and Pradhan are calculating the recombination cross sections for Fe XVII.

Work is nearly complete for state-specific and total recombination rate coefficients for Ni II. Nahar and Bautista have already spent over a year on this ion in resolving various computational problems and in deciphering the complex features more accurately.

15.5 Radiative Transition Probabilities

Radiative transition probabilities are a major part of the radiative-collisional models. Recently Nahar, Delahaye, Pradhan, and Zeippen have obtained all three sets of oscillator strengths for electric dipole allowed, intercombination, and forbidden (electron quadrupole and magnetic dipole) transitions for Fe V. This was the first application of the BPRM method to transition probabilities for a complex ion and has resulted in 1.5 million transitions. The relativistic effects were included in the Breit-Pauli approximation. One major task in the calculations was to carry out spectroscopic identification of the 3,865 fine-structure energy levels. Nahar and Pradhan have developed a spectroscopic identification scheme by quantum defect analysis of the collisional channels.

Nahar has obtained large sets of oscillator strengths for 1274 bound fine-structure levels of Ar III and for 1611 energy levels of Fe XXI. Work is nearly complete or in progress for a number of ions, such as C II, C III, C IV, C V, O VI, and O VII.

15.6 X-ray Spectroscopy of Active Galactic Nuclei

The group led by Pradhan is investigating the four main atomic processes – electron impact excitation, photoionization, electron-ion recombination, and bound-bound transitions – of highly charged ions, as well as developing models for X-ray spectral analysis. The atomic data are to be applied directly to the spectral models.

Pradhan has shown a new way of spectral analysis by calculating the “resonance oscillator strength” \bar{f}_r in terms of the differential oscillator strength df/de of autoionizing resonances in photoionization cross sections. He investigated X-ray photoabsorption in KLL (1s2s2p) resonances of O VI using highly resolved relativistic photoionization cross sections with fine structure and found that \bar{f}_r is comparable to that for UV dipole transitions in O VI (2s - 2p) and the X-ray ($1s^2\ ^1S_0 - 1s2p\ ^1P_1^o$) transition in O VII. He obtains the dominant O VI (KLL) components lying at $\lambda\lambda$ 22.05 and 21.87 Å and predicts that these absorption features should be detectable by Chandra and XMM.

16 NUCLEAR ASTROPHYSICS

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, Kneller, 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.

N. Ozkan (OSU Physics graduate student) and Boyd, along with collaborators from OSU and Notre Dame, have studied the $^{102}\text{Pd}(p,\gamma)$ reaction, which is of interest to the rp- and γ -processes of nucleosynthesis. The inputs for the theoretical description of these processes include (p,γ) , (α,γ) , (γ,p) , and (γ,α) reaction cross sections. Since very few of these have been measured for nuclei heavier than ^{90}Zr , the network calculations used to describe these processes rely on theoretical cross sections, usually provided by the code Non-Smoker. As a test of this code, they have measured cross sections for $^{102}\text{Pd}(p,\gamma)$, $^{112}\text{Sn}(\alpha,\gamma)$, and $^{116}\text{Sn}(p,\gamma)$. The targets were bombarded with beams from the University of Notre Dame tandem van de Graaff accelerator at a succession of energies, after which the activities were measured off-line using hyperpure germanium γ -ray detectors. Analysis of the $^{102}\text{Pd}(p,\gamma)$ data is nearing completion, and that of the other two reactions will be performed in the near future. The preliminary result for $^{102}\text{Pd}(p,\gamma)$ is that the cross section compares reasonably well with the prediction of Non-Smoker.

R. T. Guray (OSU Physics graduate student) and Boyd, along with collaborators from OSU, Notre Dame, and Michigan State, have studied the $^{15}\text{C}(d,p)^{16}\text{C}$ reaction. In the Inhomogeneous Models (IM) of BBN, the reaction networks exhibit several potential branch points, at which β -decay competes with neutron capture. If the former occurs, a subsequent (p,α) reaction will terminate the progression of that nuclide to higher mass. Such a branch point occurs at ^{15}C , and its understanding requires knowing the $^{15}\text{C}(n,\gamma)$ cross section. Since this cannot be measured directly, they have instead measured the $^{15}\text{C}(d,p)$ reaction. $^{15}\text{C}(d,p)$ to ^{16}C bound states would give the direct capture component of the $^{15}\text{C}(n,\gamma)$ reaction, whereas those just above the $^{16}\text{C}(\gamma,n)$ threshold would provide information about potential resonances in the $^{15}\text{C}(n,\gamma)$ reaction.

The experiment was performed at the NSCL at Michigan State University. A beam of ^{15}C radioactive nuclei was directed to a CD_2 foil target. Back-scattered reaction protons were detected in circular strip detectors, in coincidence with the recoiling ^{16}C nuclei, which were detected in the S-800 magnetic spectrometer. The resolution was not adequate to resolve states, but an angular distribution of the sum of the yield to all the states was measured. It was found to be characteristic of an angular momentum transfer of 2 units. This is somewhat unfortunate, as the states populated by an angular momen-

tum transfer of 0 units might produce strong resonances. Since reaction calculations had indicated that the $L=2$ transfers would dominate, resolution of the states would be essential to select the states populated by $L=0$ transfer.

L. Sahin (OSU Physics graduate student) and Boyd, along with collaborators from OSU, Notre Dame and U. Wisconsin at Green Bay, have studied the $^8\text{Li}(d,\alpha)^6\text{He}$ reaction, which is of possible importance to BBN. Very little ^6Li is made therein, so any reaction paths that contribute to its production could be important. In the IM, in particular, the ^8Li abundance is large enough at some stages that the $^8\text{Li}(d,\alpha)^6\text{He} \rightarrow ^6\text{Li}$ process could produce significant amounts of ^6Li . Thus this reaction was studied using the ^8Li radioactive nuclear beam of the University of Notre Dame van de Graaff accelerator laboratory and a CD_2 target. Detector telescopes were used to produce particle identification, and angular distributions were attempted. However, the cross section for this reaction was found to be so small that this reaction could not possibly impact BBN, probably in any region of the possible IM parameter space.

M. Famiano (OSU Physics graduate student) and Boyd examined the effect of excited state β -decays on the abundances in the r-process of nucleosynthesis. Past studies of the r-process suggest that the yields of the nuclides near the mass 195 u abundance peak impose tight constraints on the conditions in which it occurs. This has led to suggestions that undefined phenomena might somehow increase the entropy in the environment by a factor of two, or that a series of neutrino oscillations might reduce the ability of the neutrino flux from the core to convert too many neutrons to protons, or other possibilities.

The possibility that decays from excited states of the nuclei along the r-process path might affect the abundances it produces was studied. To do this, a code was written that modified the “gross theory” of β -decay to include shell effects, so as to extend it to excited states of nuclei. Since, in the high temperature environment in which the r-process occurs, many excited states will be populated, their more rapid β -decay could impact the r-process flow. A simple r-process code was also written to test these assertions. It was found that the excited state β -decays do indeed speed up the r-process flow, and in some test cases result in an enhancement of the mass 195 peak by an order of magnitude. The next step in this study will be to include excited state β -decays in a sophisticated r-process code to study the impact of these more complex decay modes on a real set of r-process abundance predictions.

Murphy, Boyd, M. Howard and J. Zach (OSU Physics graduate students), and the OMNIS collaboration, have continued their efforts to develop an Observatory for Multiflavor Neutrinos from Supernovae. OMNIS is being designed to detect around 2000 neutrinos from a SN at the center of the galaxy. It will consist of 8 kt of lead and 4 kt of iron and will be sited in the Waste Isolation Pilot Plant near Carlsbad, New Mexico. Because

it is being designed to detect μ - and τ -neutrinos, it will complement Super-K and SNO. OMNIS will have the potential to diagnose the core collapse process from observation of the energies of the neutrino distributions, measure neutrino masses and some types of oscillations, and diagnose collapse to a black hole. Note that the μ - and τ -neutrinos, at energies characteristic of SN neutrinos, could be detected only from their neutral current interactions, so several different detection thresholds are necessary to map out the energy distribution of these neutrinos. These different thresholds would be provided by the single- and double-neutron detections in the lead, and by the (single-neutron) events detected in the iron.

Monte-Carlo simulations have shown that the neutron detection efficiency of OMNIS would be around 30%, and that its timing would be much faster than a millisecond (and so would be statistics-limited). Measurements with a test module confirmed the basic conclusions of the Monte-Carlo simulations. The fast timing produces signals capable of measuring neutrino masses (when compared to the $\bar{\nu}_e$ signals from Super-K) at the 30 eV/c² level. If oscillations of the type ν_μ or $\nu_\tau \rightarrow \nu_e$ occurred, the ratio of double-neutron events to single-neutron events in the lead would be enhanced up to a factor of 40 (and observed in OMNIS as up to a factor of 15). In the event of collapse to a black hole, OMNIS, together with Super-K and SNO, could observe the mechanism by which the collapse occurred. The neutrino signatures for collapse resulting from infall exceeding the maximum mass of a neutron star would be expected to be quite different from that resulting from deleptonization of the core in the final 100 ms. The collapse to a black hole might even allow measurement of the neutrinosphere radii from the cutoff-time differences in the luminosities of the different neutrino flavors.

A test setup, OMNISita, is currently being constructed in the WIPP using components from other experiments. It will be used to perform tests necessary for the ultimate design of OMNIS, e.g., background activity levels, neutron detection efficiencies, tests of the Monte-Carlo simulations, issues associated with data handling rates, and, ultimately, measurements of activity levels of the components that are being installed in OMNIS.

J. Beacom (Caltech), Boyd, and A. Mezzacappa (Oak Ridge National Lab) studied the possible neutrino yields in the world's potential SN neutrino observatories with particular attention to the effects that might be realized if collapse went to a black hole. In that case, a zero mass neutrino would terminate within a fraction of a millisecond, whereas neutrinos of nonzero mass would terminate over some fraction of a second, with the length of time depending on the actual neutrino mass. It was found that comparing the neutrino luminosities of Super-K and OMNIS would produce a measurement of the mass of the μ - or τ -neutrinos around 30 eV/c². If the collapse went to a black hole while the neutrino luminosities were still large, Super-K by itself would produce a mass measurement for the $\bar{\nu}_e$ of about 2 eV/c², because it detects both the arrival time and the energy. Comparison of

the signals from Super-K and OMNIS in this case would produce a mass measurement at a level of 6 eV/c².

Famiano, J. Vandegriff (OSU Physics graduate student), Boyd, Osmer, and T. Kajino (U. Tokyo) have studied the possible production of ²H in interactions between jets and clouds as a possible explanation of the "high" ²H primordial abundance observed in some highly red-shifted clouds. This would provide a natural explanation for such high ²H values, since jets and clouds are well known phenomena, and their occasional interactions are inevitable. It was found that, for plausible values of jet intensity and cloud density, size, and (primordial) composition, enhancements of the ²H abundance of at least an order of magnitude above the usually accepted primordial value can be produced.

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