The Ohio State University

Astronomy Department

Columbus, Ohio 43210

Abstract

This annual report covers the period 2002 September through 2003 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, Smita Mathur, Jordi Miralda-Escudé, 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, and David Weinberg. In addition, Christopher Kochanek has been appointed Ohio Eminent Scholar in the Department of Astronomy, starting October 1, 2003. Boyd was on leave, serving in the Physics Division of the National Science Foundation in Washington, D.C. as Program Director for Nuclear Physics and for Particle and Nuclear Astrophysics. Frogel was on leave at NASA Headquarters in Washington, D.C.

Michele Kaufman and Sultana Nahar held appointments as Research Scientist, and David Ennis and Eric Monier were Lecturers. Emeritus members of the Astronomy Department are Eugene Capriotti, George Collins II, Stanley Czyzak, Geoffrey Keller, William Protheroe, and Robert Wing.

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

In Tucson, AZ, Mark Wagner held the position of Research Scientist, while Ray Bertram was Research Associate. Wagner and Bertram are assigned to work full-time on the Large Binocular Telescope (LBT) project. Wagner is Instrumentation Scientist for the LBT, coordinating the instrumentation efforts of the LBT partners and developing instrument support on the mountain.

Postdoctoral researchers in Astronomy during part or all of this period were David Graff, Dirk Grupe, Eric Monier, and Marianne Vestergaard (Columbus Fellow).

Graduate students in the Astronomy Department during the academic year included Deokkun An, Nikolay Andronov, Misty Bentz, Christopher Burke, Julio Chanamé, Guo-Xin Chen, Franck Delahaye, Dale Fields, Stephan Frank, Angela Hanson, Susan Kassin, Juna Kollmeier, Jennifer Marshall, Christopher Morgan, Grant Newsham, Christopher Onken, Josh Pepper, James Pizagno, Adam Steed, Jeremy Tinker, Rik Williams, and Zheng Zheng. Justin Oelgoetz is an OSU Chemical Physics graduate student working on his Ph.D. thesis with Pradhan.

The Masters Degree was awarded to Fields, Marshall, and Onken.

Osmer represents OSU on the Board of Directors of the Large Binocular Telescope Corporation. He is a member of the Publications Board of the American Astronomical Society and also serves on the Board of Directors of Research Corporation.

Peterson completed a term as a member of the NASA Structure and Evolution of the Universe Subcommittee. He continues to serve as a member of the Astronomy and Astrophysics Advisory Committee (AAAC), which was established by Congress to facilitate greater cooperation between the National Science Foundation and NASA. Peterson is OSU's institutional representative to the AURA Board and this year he was elected to the Space Telescope Institute Council (STIC).

Sellgren began service on the SOFIA Science Council, and served on the Scientific Organizing Committees for Galactic Center 2002 (Kona, HI, November 2002) and Astrophysics of Dust (Estes Park, CO, May 2003). She is also a member of the search committee for the Deputy Director for the U.S. National Gemini Science Council.

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 the Large Binocular Telescope (LBT), which is under construction at the Mt. Graham International Observatory in Arizona, and will have one-sixth of its observing time. Other partners in the LBT 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 22.8-m baseline for inteferometric observations. During the last year, the polishing of the first primary mirror was completed at the Steward Observatory Mirror Laboratory, and the mirror is being integrated into its cell. Figuring work on the back side of the second primary has begun. The telescope enclosure is complete, and work is well along on assembling the telescope structure. Fabrication of the first adaptive secondary is being done in both Arizona and Italy. The prime focus camera is being completed in Italy. First light with the prime focus camera and the first primary is planned for the summer of 2004.

OSU is providing the aluminizing system as part of its in-kind contribution to the LBT. During the year the dummy mirror cell and vacuum bell jar were unpacked and set up in rented hangar space at Rickenbacker airport near Columbus. The mechanical pumps were reinstalled and the O-ring assembly was cleaned. Tests show that the pumps and vacuum seal are performing well. The cryogenic panels for producing high vacuum were fabricated and installed, and first tests show that the overall system achieves the required vacuum level. The design of the boron nitride crucibles was completed and a prototype unit was built and tested; then the remaining crucible assemblies were fabricated. The design of the electrical power distribution system was completed and its fabrication and installation are nearing completion. A first test of the system with four crucibles has been carried out. The remaining crucibles are to be installed and tested during autumn, 2003.

The instrumentation group continued to work on the Multi-Object Double Spectrograph (MODS) for the LBT. Key milestones met in the past year were procuring the first large optics and ordering the large structural framework for the instrument. There was also substantial work on the various mechanisms, control software, and a system to compensate for any flexure and other image motions for the instrument.

The instrumentation group also worked on general maintenance and repair of existing instruments at MDM Observatory and CTIO. In particular, ANDICAM (a camera capable of simultaneous imaging at optical and near-infrared wavelengths) was moved to the CTIO (ex-2MASS) 1.3-m telescope and returned to nightly operations as part of the SMARTS consortium. Work also continued on upgrading the detector array in the MDM facility near-infrared camera and spectrograph (TIFKAM).

DePoy, Gould, and Pepper are building the 2-in (5-cm) Kilo-square-degree Extremely Little Telescope (KELT), which will carry out a 2π steradian search for planetary transits to $V = 10$.

Marshall has been developing the Image Motion Compensation System (IMCS) for MODS, and has produced results within specifications for flexure compensation in the lab prototype of the IMCS.

Marshall and Kollmeier, with DePoy, have been continuing work on two filter wheels that will be going to the MDM and YALO observatories. The first of these is scheduled for commissioning at MDM in December 2003.

3 EXOPLANETS

DePoy, Gould, Pogge, and Yoo are working in the μFUN collaboration to search for extra-solar planets by intensive follow-up observations of ongoing microlensing events. μFUN has substantial observing time on the SMARTS 1.3-m, the Wise 1-m, and the Hawaii 0.6-m telescopes.

Marshall has worked with Burke, DePoy, and Gaudi on STEPSS: the Survey for Transiting Extrasolar Planets in Stellar Systems. Marshall has obtained spectroscopic data on several open clusters, from which they obtain metallicity estimates. These estimates are used to select ideal clusters for planet searches, as well as adding more accurate metallicity measurements to the literature.

Gould, Pepper, and DePoy have considered the sensitivity of transit searches to habitable-zone planets. Photon-limited transit surveys in the V band are in principle about 20 times more sensitive to planets of fixed size in the habitable zone around M stars than G stars. In the I band the ratio is about 400. The advantages of a closer habitable zone and smaller stars (together with the numerical superiority of M stars) more than compensate for the reduced signal because of the lower luminosity of the later-type stars. That is, M stars can yield reliable transit detections at much fainter apparent magnitudes than G stars. However, to achieve this greater sensitivity, the later-type stars must be monitored to these correspondingly fainter magnitudes, which can engender several practical problems. They show that with modest modifications, the *Kepler* mission could extend its effective sensitivity from its current $M_V = 6$ to 9. This would not capture the whole M dwarf peak but would roughly triple its sensitivity to Earth-like planets in the habitable zone. To take advantage of the huge bump in the sensitivity function at $M_V = 12$ would require major changes in *Kepler*. However, the reduced photometric-precision requirements at $M_V = 12$ makes a search for these transits possible from the ground. Photometric stability requirements are much less severe for M stars than G stars. To detect Earth-mass planets in the habitable zone around G stars, the variability on transit timescales must be less than 2×10^{-5}, but for middle M stars the limit is 1.2×10^{-3}.

Pepper, Gould, and Depoy have proposed an all-sky survey to find planetary transits. Transits of bright stars offer a unique opportunity to study detailed properties of extrasolar planets that cannot be determined through radial-velocity observations. They propose a new technique to find such systems using all-sky small-aperture transit surveys. They derive a general formula for the number of stars that can be probed for such systems as a function of the characteristics of the star, the planet, and the survey. They use this formula to derive the optimal telescope design for finding transits of bright stars: a $1''$ to $2''$ (2.5-cm to 5-cm) "telescope" with a 4k $\times$ 4k camera.

4 MICROLENSING

Gould is currently focusing his work on applications of microlensing and Galactic structure. Microlensing work includes 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. Gould is PI on a *SIM* Microlensing Key Project whose primary aim is to measure the mass function of both dark and luminous objects in the Galactic Bulge. Galactic structure work is primarily focused on completing a Revised NLTT Catalog with better astrometry and new optical/infrared photometry, and using the reduced proper motions from this catalog to isolate various stellar populations for further study.

Terndrup has contributed to several ongoing studies of galactic microlensing and of gamma-ray burst afterglows, using data obtained at MDM.

5 STARS

Fields, Gould, J. An (Cambridge), the PLANET Collaboration, J.-F. Glicenstein (DAPNIA-SPP) of the EROS collaboration, and P. Hauschildt (Hamburg), compared the limb darkening, measured for the K3 III source star for the microlensing event EROS BLG–2000–5, with predictions from atmospheric models. These are the first limb-darkening data to be taken of this type of giant (giants approximately 10 times its physical size have been resolved by near-infrared interferometry). In addition, the quality of their data makes this limb-darkening measurement the second best ever (next to the sun).

Marshall, together with DePoy, Gould, Pinsonneault, and Terndrup, is undertaking a survey of metal-poor subdwarfs. They are obtaining photometry and moderate resolution spectroscopy for a sample of 1000 stars in the solar neighborhood. ¿From these data they plan to obtain accurate colors and metallicity estimates for these halo stars. Once an astrometric mission (such as *FAME* or *SIM*) obtains parallaxes of these stars, they will be able to calibrate theoretical Galactic globular cluster CMDs to obtain much more accurate distance estimates to globular clusters in the Galaxy than currently exist. These data will also allow them to study stellar populations in the Galaxy and Galactic abundance patterns.

Marshall is working with DePoy and Gould on compiling a similar database of photometric and spectroscopic data on a sample of 50 extreme subdwarfs. This unique population of halo stars defines the metal-poor lower main sequence. From the colors they obtain for these objects, they will better define the red end of the main sequence. Spectroscopic observations will yield metallicity estimates as well as 3-D space velocities for these objects. This work will triple the currently known number of such stars.

Newsham and Pinsonneault are investigating the role of hydrodynamic and magnetohydrodynamic mechanisms for angular momentum transport (and the associated chemical mixing) in low-mass stars. The observations to be reconciled with theory include helioseismological data on the solar internal rotation rate, the solar abundances of light elements such as ^{7}Li and ^{9}Be, the observed spin-down of open cluster stars of known ages, and their surface elemental abundances. The impact of pre-main sequence accretion disks upon the subsequent rotational evolution of stars is also under investigation and conversely what the observed angular momentum distributions of open cluster stars have to tell us about the processes of star formation and star-disk interactions.

Delahaye and Pinsonneault are expanding the treatment of microscopic diffusion processes (radiative acceleration, detailed gravitational settling) in the stellar evolution code. In particular, they are comparing results derived from OPAL data with recent Opacity Project work on radiative acceleration rates. The resolution of the monochromatic opacities is proving to have a significant impact on the radiative acceleration rates. The main focus of this work will be the effect of radiative levitation on horizontal branch stars and the interaction between mixing and diffusion processes.

Chanamé, Pinsonneault, and Terndrup are investigating giant branch models with rotational mixing. Models compatible with the survival of angular momentum in horizontal branch stars are found to have mixing on the RGB consistent with the data. They are exploring the inhibiting effects of μ gradients on mixing and angular momentum transport, as well as self-consistent models including both mixing and angular momentum transport.

Pinsonneault, with J. Bahcall (IAS), is working on a revision of the solar neutrino fluxes and helioseismic properties of the standard solar model. Recent proposed reductions in the solar CNO abundances may be creating a conflict between the predicted and observed depth of the solar surface convection zone.

Andronov and Pinsonneault have continued to investigate the evolution of interacting binaries. They have found that evolved secondary stars in CVs are required to understand the observed mass–period relationship in CVs. In addition, they found that tidally-induced mixing may occur on a short enough timescale to induce changes in the mass–radius relationship for evolved secondary stars in CVs; this may explain the CV period gap.

Andronov and Pinsonneault are currently studying the impact of spots covering a large fraction of the stellar surface on the structure and evolution of low mass stars. Potential features that could be impacted would be the radii of short-period eclipsing binaries, pre-main sequence light element depletion, and the mass–radius relationship for interacting binary stars.

Zheng and Gould, with S. Salim (UCLA), C. Flynn (Tuorla Obs., Finland), and J. Bahcall (IAS), derived the $I-$band luminosity function of Galactic disk dwarfs using *HST* star counts.

6 STAR CLUSTERS

Burke, Pinsonneault, and A. Sills (McMaster U.) have completed their thorough investigation of the input physics uncertainties for determining the ages of open clusters using the lithium depletion boundary (LDB) technique. Ages for 20–200 Myr open clusters using the traditional main-sequence fitting technique are uncertain by a factor of nearly 2. The main uncertainty in main-sequence fitting arises from the amount of convective core overshoot in the theoretical models. Stellar models that include convective core overshoot have a longer main-sequence lifetime and result in older open cluster ages. The LDB age technique is an independent method to determine the ages of open clusters and can be used to determine how much, if any, convective core overshoot is required for main-sequence fitting ages. Ages for open clusters determined with the LDB age technique are consistent with including modest amounts of convective core overshoot in the theoretical models. However, the significance of the age difference has not previously been quantified. This study shows that based on theoretical errors alone, absolute open cluster ages with the LDB age technique are possible to 3 – 8% precision. The observational uncertainties of locating the LDB and bolometric corrections (10% and 7%, respectively) are currently larger than the theoretical errors. Ages of open clusters obtained without convective core overshoot are ruled out with high confidence.

Andronov and Pinsonneault have examined blue stragglers from binary mergers. The observed blue straggler population in old open clusters can be explained with the angular momentum loss rate inferred from young open cluster stars if the mass function of secondary stars in close binaries relative to primary stars is flat. Another production mechanism related to rotational mixing is likely necessary to explain blue stragglers in young open clusters.

Pinsonneault, with L. Hobbs (U. Chicago), Schuler, and King (Clemson U.), is involved in a spectroscopic study of oxygen abundances in dwarf stars of the Pleiades and M34. Large differences between oxygen abundances derived from the O I triplet and from the forbidden [O I] line were found. If the forbidden line is treated as a more reliable indicator, the Pleiades has a moderately high [O/Fe] ratio of +0.14.

Terndrup and Pinsonneault are continuing their studies of the angular momentum evolution of stars in young and intermediate age open clusters. K. Stassun (Vanderbilt U.) and Terndrup organized a conference reviewing angular momentum evolution at the Albuquerque AAS meeting.

Terndrup and Pinsonneault, with J. Stauffer (IPAC/ Caltech), R. Hanson (UCO/Lick), and An, have begun a new study designed to obtain precise distances, reddening estimates, and photometric metallicities for several nearby open clusters. One new aspect of this work is that the distances and age estimates from the lower main sequence may be affected by the presence of rapid rotators that have blue colors that leave them markedly below the main sequence, as shown previously by Stauffer.

Wing and OSU undergraduate student K. Walker, in collaboration with D. J. MacConnell (CSC/STScI) and E. Costa (U. de Chile), have compared a set of 36 red supergiants in the Small Magellanic Cloud to similar stars in NGC 2100 of the LMC and the Double Cluster h & χ Per of the Galaxy. The stars were observed on a six–color system of narrow-band photometry that measures bands of TiO and CN together with near-infrared continuum points. Two new SMC variables were found, both of which reach types later than M2.0 at minimum light; these are the latest spectral types found to date for SMC supergiants. The relation between CN strength and the near-infrared absolute magnitude $M(104)$ differs significantly between the SMC, the LMC, and the Galaxy, indicating the extent to which the CN strength depends upon the metallicity. This result makes it possible to express the CN–luminosity calibration as a function of metallicity, thereby enhancing the usefulness of red supergiants as distance indicators for nearby galaxies of known metallicity.

Wing and Walker have observed a number of well-studied open clusters and Landolt standard fields with a set of narrow-band filters in order to establish standard stars for CCD observations on their six–color, near-infrared photometric system. Work is underway to derive the transformations between this system and the similar eight–color system previously used for photoelectric work.

7 STELLAR POPULATIONS

With R. Peterson (Astrophysical Advances), E. Sadler (U. of Sydney) and A. Walker (NOAO/CTIO), Terndrup, An, and Hansen continue work on their survey for extreme horizontal branch (EHB) stars in the Bulge. They show that the Bulge contains the same sorts of faint ($M_V \geq 4.5$) blue objects on color-magnitude diagrams that are confirmed EHB stars in many galactic globular clusters. Terndrup and Peterson are now writing up the results of their imaging and spectroscopic survey.

Terndrup is also finishing a study on carbon isotopic abundances in the Bulge, a continuation of an earlier study by Smith, Terndrup, and Suntzeff on ω Centauri. They find that luminous, metal-poor Bulge stars show signs of deep mixing, as indicated by an abundance ratio $^{12}C/^{13}C \approx 4$, but that mixing is greatly reduced in metal-rich Bulge giants.

8 INTERSTELLAR MEDIUM

Herbst has calculated intensity factors to allow recent observations of rotational spectral lines of deuterated methanols in the protostellar source IRAS 16293 –2422 to be converted into column densities. The ratio of deuterated methanols to normal methanol is quite high, and indicates an active grain surface chemistry.

Herbst's program of research into the modeling of the gas-phase and grain–surface chemistry of interstellar clouds continues, with an emphasis on star formation regions. With postdoctoral associate H. Roberts (OSU Physics), Herbst has shown that standard models of deuterium fractionation underestimate the effect at high densities, such as pertain at the center of pre-stellar cores. Here, the depletion of heavy molecules such as CO onto grains leads to a much stronger fractionation, which is confirmed by observations of the ion H_2D^+ in the pre-stellar core L1544.

With T. Millar (UMIST) and other members of the UMIST group, Herbst has explored the chemistry of protoplanetary nebulae in general and the source CRL 618 in particular.

With Y. Aikawa (Kobe, Japan), Herbst has studied molecular evolution in a collapsing pre-stellar core using both gas-phase and grain–surface chemistry.

Herbst and I. Smith (Birmingham, UK) are in the final stages of developing a new chemical network for low-temperature interstellar clouds.

With a group headed by O. Biham (Hebrew U., Jerusalem), Herbst has studied the formation of H_2 and its isotopomers HD and D_2 on the surfaces of small grains using a mathematical technique known as the direct master equation. The results show that HD and D_2 have enhanced rates of production compared with H_2 at certain temperatures. After learning to use the master equation technique for small systems, Herbst and OSU Physics graduate student T. Stantcheva are currently incorporating this technique for surface chemistry into large-scale gas–grain chemical models of interstellar clouds. The results are expected to be more accurate than those of previous models, in which approximate techniques for the rates of surface reactions were used.

With E. Falco (SAO), E. Mediavilla (IAC) and J. Muñoz (Valencia), Kochanek has been measuring the extinction curves of the dust in distant lens galaxies using a combination of *HST* imaging and spectroscopy designed to reach the region around the redshifted 2175 Å bump. So far they have one system with a relatively normal Galactic extinction curve including the 2175 Å feature, one system which must lack the feature and have an extinction curve similar to the SMC, and one system where the image is behind a molecular cloud and has a peculiar high R_V extinction curve like those observed for dust in Galactic molecular clouds. More data are being obtained in the current *HST* Cycle.

Pizagno, Sellgren, K. I. Uchida (Cornell) and M. W. Werner (JPL) are comparing the fraction of total dust emission emitted in the IRAS 12 μm band to predictions from models of various polycyclic hydrocarbon (PAH) molecules, and to theoretical models for a size distribution of PAHs. They find that no single analog material can recreate the ratio of 12 μm to total infrared emission from dust, but that a model including a range of PAH molecule sizes provides a better fit.

Honors undergraduate student M. Pitts (now U. Hawai'i), working with Sellgren, completed his Senior Honors thesis on the molecular hydrogen lines in the reflection nebula NGC 7023. They derived the rotational temperature of H_2 in the photodissociation region in NGC 7023, using spectra of pure H_2 rotational lines obtained with the Short Wavelength Spectrograph on the Infrared Space Observatory. Previous observations of other photodissociation regions show that the rotational temperatures are too high to be explained by current models.

Sellgren and J. An (U. Cambridge) have completed a paper on the difference in spatial morphology of the 3.3 μm aromatic emission feature and the 2.18 μm narrowband continnum filter in the visual reflection nebula NGC 7023. Surprisingly, they find the 3.3 μm emission feature is strongest in narrow filaments, previously detected in fluorescent H_2, but that the 2.18 μm continuum is strongest in a broad region halfway between the illuminating star of NGC 7023 and the filaments observed in the 3.3 μm aromatic feature. Furthermore, the ratio of 2.18 μm flux to 3.3 μm flux decreases with projected distance r from the star as r^{-2}. This suggests that the carriers of the 3.3 μm aromatic emission feature and the 2.18 μm continuum are not identical, as previously assumed. Instead they are separate ISM components, but their flux ratio is regulated by the strength of the stellar illumination.

Yoo, Sellgren, and R. Blum (CTIO) are pursuing follow-up images of other reflection nebulae with a range of physical conditions ($T_{\rm eff}$, G_0, and n). Successful observing runs at the IRTF in December 2002/January 2003 and July 2003 produced high-quality data for the follow-up analysis.

9 GALACTIC CENTER

R. Blum (CTIO), S. V. Ramírez (SIRTF Science Center), Sellgren, and K. Olsen (CTIO) have completed a project on the star formation history of the innermost regions of the Galaxy. They have obtained low-resolution $H-$band and $K-$band spectra for roughly 60 stars to derive $T_{\rm eff}$ and $M_{\rm bol}$ for the Galactic Center stars. They place the Galactic Center stars on the H–R diagram, compare their positions to theoretical isochrones with ages between 10 Myr and 12 Gyr, and derive a star formation history for the central 5 pc of the Galaxy. Most stars in the Galactic Center formed more than 5 Gyr ago, but star formation has continued through the lifetime of the Milky Way, with star formation rates that vary from epoch to epoch.

Ramírez, Sellgren, Blum, and Terndrup continue their work on elemental abundances in cool, luminous stars near the Galactic Center. They found in a previous paper that M supergiants and AGB stars in the GC have a distribution of [Fe/H] indistinguishable from that of similar cool, luminous stars in the solar neighborhood. The range of ages for the Galactic Center supergiants and AGB stars, from $\sim$ 10 Myr to $\sim$ 1 Gyr, suggests that some mechanism, or interplay between several mechanisms, in the Galactic Center is holding the iron abundance at a fixed value over a Gyr of star formation. They are currently acquiring data to detemine the ratio of $\alpha-$element abundances to iron abundances, as a clue to the type of stars (high-mass or low-mass) that dominate chemical enrichment in the Galactic Center.

Ramírez, Sellgren, Blum, and Terndrup are following up on Sellgren's earlier work with J. Carr (NRL) and S. Balachandran (U. Maryland), which found that the abundances of C, N, and O in one Galactic Center M supergiant implied extreme stellar mixing, beyond the predictions of the most recent high-mass stellar models including stellar rotation. They are currently analyzing CNO abundances in several additional Galactic Center stars, and proposing to obtain more observations, to see if the extremely strong mixing in one Galactic Center M supergiant is unique to that star. A second Galactic

M supergiant shows normal mixing. It is intriguing that the star with extra mixing is only 0.2 pc from the 4 $\times\ 10^6\ M_\odot$ black hole at the Galactic Center, while the star with normal mixing is 30 pc from the central black hole, but more results are needed to distinguish between possible explanations of unusual CNO abundances in one Galactic Center star.

10 NORMAL GALAXIES

A. Stephens (U. Católica, Chile) and Frogel completed their analysis of NICMOS/HST data for M31. In this final part of their study they determined the stellar populations present in M31 using nine sets of adjacent HST–NICMOS Camera 1 and 2 fields with distances ranging from $2'$ to $20'$ from the center of the galaxy. These infrared observations provide some of the highest spatial resolution measurements to date of the central regions of M31. Their data place tight constraints on the maximum luminosities of stars in the bulge of M31. The tip of the red giant branch (RGB) is clearly visible at $M_{\rm bol} \sim -3.8$, and the tip of the asymptotic giant branch (AGB) extends to $M_{\rm bol} \sim -5.0$. This AGB peak luminosity is significantly fainter than claimed; through direct comparisons and simulations they show that previous measurements were affected by image blending. They do find field-to-field variations in the luminosity functions, but simulations show that these differences can be produced by blending in the higher surface brightness fields. They conclude that the RGB of the bulge of M31 is not measurably different from that of the Milky Way's bulge. They also found an unusually high number of bright bluish stars (7.3 per square arcmin) which appear to be Galactic foreground stars.

Kaufman, C. Struck (Iowa State), E. Brinks (U. Guanajuato), B. G. Elmegreen (IBM), D. M. Elmegreen (Vassar), K. Sheth (Caltech), and M. Thomasson (Onsala) continued their study of the grazing encounter between the ocular galaxy IC 2163 and the spiral galaxy NGC 2207. Previous data are supplemented by ^{12}CO observations at SEST and OVRO and a radio continuum image with 250 pc resolution. The star formation rates per unit mass of gas are normal in both galaxies, and neither galaxy contains an AGN, but the ratio of FIR/radio continuum is abnormally low. Enhanced radio continuum emission, indicative of large-scale shock fronts, occurs along the rim of the eye-shaped oval of IC 2163 and in the outer part of the companion side of NGC 2207, particularly along a backlit spiral arm. New two-disk models of the encounter suggest moderate mass transfer from IC 2163 to NGC 2207 and that tidal torques on NGC 2207 may have led to bulk compression of gas and magnetic fields on the companion side of NGC 2207.

In another study of close, non-merging encounters, Kaufman and the same group have obtained broad–band optical, Hα, radio continuum, and H I observations of the spiral galaxy NGC 3145 and its two companions. Optically, NGC 3145 appears to have a swallowtail structure, a caustic that can be generated by a somewhat off-center perpendicular collision with a small companion.

Kassin, Pogge, and R. de Jong (STScI) used surface photometry of nearly 50 galaxies from the Ohio State University Bright Spiral Galaxy Survey (OSUBSGS), that span the Hubble sequence and have highqualtiy rotation curves in the literature, to map radial distributions of dark and luminous matter.

Kassin, Frogel, Pogge, G. Tiede (U. Florida), and Sellgren completed their pixel-by-pixel analysis of optical and near-infrared images of NGC 4038/4039 (the Antennae). Their analysis of images from the OSUBSGS used multicolor techniques developed for analyzing the colors of stars. They derived maps of the distributions of stellar populations and dust extinction for the two galaxies. Their analysis of the pixel-by-pixel stellar population maps reveals two distinct episodes of star formation: one currently in progress and a second that occurred about 600 Myr ago. A roughly 15-Gyr-old population is also found which traces the old disks of the galaxies and the bulge of NGC 4038. The ages derived are consistent with those found from previous *HST* observations of individual star clusters. In addition, they found five luminous super-star-clusters in the $K-$band images of the galaxies that do not appear on the B or V images. These clusters are located in the overlap region between the two galaxies, and are hidden by dust with visual extinctions of $A_V > 3$ mag. The techniques they have developed should be generally applicable to the study of stellar populations in galaxies for which detailed star-cluster-scale resolution with *HST* is not possible.

Kochanek is PI of a large *HST* program to obtain images of 45 multiply-imaged gravitational lenses. The largest segment of the collaboration, known as CASTLES, consists of Kochanek, E. E. Falco (SAO), C. D. Impey (Steward), C. R. Keeton (Chicago), B. McLeod (SAO), J. Muñoz (Valencia), C. Peng (Steward), H.-W. Rix (MPIA), D. Rusin (U. Penn) and J. Winn (Harvard). Recent applications of these data and their earlier *HST* imaging surveys have been to use the fundamental plane of gravitational lenses to determine the rate at which the stellar populations of early-type galaxies evolve between now and redshift unity and to estimate the mean mass distribution of early-type galaxies. The measured evolution rate is consistent with a typical star formation redshift of $z_f \simeq 2-3$, very similar to what is measured for galaxies in rich clusters. The mass profile of the galaxies must be very close to isothermal, indicating that early-type galaxies have the same conspiracy between their luminous and dark components to jointly produce a flat rotation curve as is observed in spiral galaxies.

With the CASTLES collaboration, Kochanek has obtained deep infrared images of time-delay gravitational lenses using *HST* to measure the properties of the lensed images of the quasar host galaxies in detail. These can be used to constrain the gravitational field of the lens galaxy in order to understand the estimates of the Hubble constant from the time delays. As part of this program they also obtained *Chandra X-ray Observatory*

(CXO) images of the time-delay lenses, for which X-ray images were lacking, in order to search for nearby groups or clusters that need to be included in the models.

Kochanek, in collaboration with E. Falco (CfA), M. Hartman (CfA), V. Hradecky (CfA), J. Huchra (CfA), L. Macri (NOAO), and M. Pahre (CfA), has been studying the properites of local infrared-selected galaxies from the 2MASS survey. They have redshifts for all 2MASS galaxies with K $\leq$ 11.25 mag and a galactic latitude $|b| > 5°$. These will be used to produce revised J, H and K infrared galaxy luminosity functions and densities. They have obtained deeper optical and infrared images of a random sample of roughly 450 2MASS galaxies to measure their photometric profiles and to accurately calibrate the conversion of 2MASS luminosities into total luminosities and estimates of the infrared luminosity density. They have also obtained long-slit spectra of these galaxies to measure rotation curves and velocity dispersions in order to make an accurate estimate of the local velocity function of galaxies. M. White (Berkeley) and Kochanek are using the 2MASS galaxies to produce local X-ray cluster catalogs using a modern matched filter method. The catalogs are cross-correlated with X-ray luminosity and temperature measurements and are used to explore the halo occupancy distribution.

Kollmeier and Miralda-Escudé have been working on a project aimed at understanding black hole growth in the centers of galaxies, and the connection between this growth and the dynamics of the stars in the bulge component of these galaxies.

Pizagno, Weinberg, Pogge, F. Prada (Calar Alto), and H.-W. Rix (MPIA) are studying the Tully-Fisher relation for a sample of galaxies selected from the Sloan Digital Sky Survey (SDSS). The galaxies were selected from the SDSS database to cover a wide range in luminosity, but have no restrictions on the morphology or degree of interaction of the galaxy. To obtain dynamical information, long-slit Hα spectra have been taken at Calar Alto (Prada) and MDM observatories (Pizagno, Pogge, and Weinberg). It is found that the intrinsic scatter is slightly larger for this sample than previous pruned Tully-Fisher samples. A correlation between color and Tully-Fisher residual is found that resembles the findings of previous studies. A more detailed study of correlations among residuals, and making mass models from the SDSS images at g, r, and i, are planned for the future.

The global ellipticity of disk galaxies is of interest because the shape of the luminous disk is linked to the poorly determined non-axisymmetry of dark halos. Ryden, using photometric information from the Sloan Digital Sky Survey, determined that the projected shapes of disk galaxies are consistent with a log–normal distribution of intrinsic ellipticities, with $\ln \varepsilon \approx -1.8 \pm 0.9$ in the i band. This much ellipticity in the underlying potential would produce a full magnitude of scatter in the Tully-Fisher relation, more than is observed. Thus, the distribution of starlight is not a good tracer of the underlying potential shape.

Ryden is undertaking a comparison of the global ellipticity of late-type to early-type spirals, using near infrared imaging. Preliminary results indicate that late-type spirals (Sc to Sm) have apparent shapes which are consistent with a population of thin, axisymmetric disks. Early-type spirals (Sa to Sbc) are markedly nonaxisymmetric in addition to being thicker. The different degrees of axisymmetry indicate different formation and evolution histories for early-type and late-type spirals.

11 AGNs

Fields collaborated with Pogge, P. Martini (Carnegie Obs.) and J. Shields (Ohio U.) to use narrow-slit STIS observations of the nuclei of Seyfert 2 galaxies to get a view of the nucleus with a minimum of contaminating starlight.

Fields, with Mathur and Pogge, is investigating the narrow-line Seyfert 1 galaxy Mrk 1044 with UV observations from *HST*. High-resolution spectra around Lyα, C IV and N will give the metallicity of the warm absorber material intrinsic to Mrk 1044, as well as of interstellar material resident in our own Galaxy. This analysis will be heavily strengthened by the inclusion of two other datasets, near-simultaneous observations by *FUSE* and *Chandra*.

Grupe, Mathur and M. Elvis (CfA) have analyzed the *XMM–Newton* data of two Broad Absorption Line Quasars (BAL QSOs), Q1246−057 and SBS 1542+541. They found that the intrinsic X-ray luminosity is similar to non-BAL QSOs suggesting that the often observed X-ray weakness in BAL QSOs is due to absorption rather than being intrinsically X-ray weak.

Grupe and Mathur, in collaboration with B. Wilkes and M. Elvis (both CfA), studied the *XMM-Newton* data of two high redshift quasars: RX J1028−0844 and BR 0351−1034. The data for the radio-loud quasar RX J1028−0844 showed that the high intrinsic absorption of neutral elements is lower by at least a factor of 10 than previously claimed from ASCA observation. Most likely this is due to calibration uncertainties in the ASCA data below 1 keV and the superior sensitivity of the EPIC PN detector down to energies < 0.2 keV. The radio-quiet quasar BR 0351−1034 became fainter by a factor of 6 between the *XMM* observation and a pointed *ROSAT* PSPC observation ten years earlier. A change in the spectral shape of the X-ray spectrum suggests that part of this variability is due to a variable cold absorber in the source.

Grupe, B. J. Wills (UT Austin), K. M. Leighly (U. Oklahoma, Norman), and H. Meusinger (Thueringer Landessternwarte Tautenburg, Germany) have studied the optical properties of a complete sample of bright, soft-X-ray-selected AGN. About half of these sources are Narrow-Line Seyfert 1 galaxies (NLS1s) which show the strongest Fe II emission, steepest X-ray spectra and strongest soft X-ray variability. They found that there are no differences in the luminosity, redshift, and Hβ equivalent width distributions between NLS1s and Broad Line Seyfert 1s. Grupe was able to show, in a Principal Component Analysis of the soft-X-ray-selected sample, that the most important parameter that governs the properties of the AGN is the Eddington accretion rate.

Kochanek and collaborators have developed a radically new method of analyzing quasar microlensing light curves. They have applied it to the lens Q2237+0305 to estimate the mean stellar mass, the size of the quasar accretion disk, and the mass of its black hole. They find, for example, that the black hole mass is $10^9\ M_\odot$ (factor of two uncertainty) and that the lens galaxy is composed mostly of stars (as expected for a lens where the images are seen through the bulge of a large, nearby spiral galaxy). With Gould, Depoy, E. Falco (SAO), E. Mediavilla (IAC), N. Morgan (Yale), Pogge, P. Schechter (MIT), E. Turner (Princeton), and J. Winn (SAO) he has assembled a consortium to industriously monitor gravitational lenses in order to mass-produce both time delays and microlensing light curves. The primary objective is to determine the surface density and stellar mass fraction of the lens galaxies in the transition region near 1–3 effective radii where the galaxy changes from being dominated by the stars to being dominated by dark matter. Secondary objectives are to survey the size and structure of the source quasar accretion disks, to estimate their black hole masses, and to determine the mean stellar masses in the lens galaxies.

Kollmeier and Weinberg have been working on a project aimed at determining the connection between optical and X-ray obscuration in AGN. They are developing a theoretical framework for predicting how the AGN luminosity function should look as a function of wavelength and selection criteria. This gets to the heart of the X-ray/optical obscuration connection in AGN.

Mathur has been using X-ray and UV spectroscopy to probe the regions near the central black hole in active galactic nuclei using *Chandra*, *XMM–Newton*, *HST*, and *FUSE*. Her interests include broad absorption line quasars, narrow line Seyfert 1 galaxies, high redshift quasars, and AGN evolution. Recently she has been working on understanding the low redshift warm–hot intergalactic medium using high resolution spectroscopy with *Chandra* and *FUSE*.

Miralda-Escudé and OSU Physics graduate student M. Schirber found three pairs of quasars in the Sloan survey within an angular separation of 4 arc minutes, at different redshifts, to measure the effect of the lower redshift quasar on the Lyα forest in the spectrum of the higher redshift quasar. They calculated that the intensity of ionizing radiation from the foreground quasar should be many times larger than the cosmic ionizing background. Although they were expecting to see reduced Lyα absorption because of the higher ionizing intensity, the spectra show, if anything, an increase in absorption. They investigated three possible explanations: high gas density near a quasar, quasar variability over timescales of order millions of years, or anisotropy of the ionizing emission. They discussed problems with each of these explanations.

Monier, in collaboration with D. Turnshek, S. Rao, D. Nestor, (U. Pittsburgh), W. Lane (NRL), and J. Bergeron (Institut d'Astrophysique), studied four absorption systems with $z < 1$ from their sample of damped Lyα (DLA) systems at low redshifts. They used optical and near-infrared imaging from MDM, WIYN, and IRTF to derive photometric redshifts for galaxies in the fields surrounding background QSOs. The identified DLA galaxies span a mixture of morphological types from patchy, irregular, and low surface brightness to spiral galaxies. The luminosities range from 0.02 L^*_K to 1.2 L^*_K. The total sample now contains 14 DLA galaxies in the redshift range $0.05 \leq z \leq 1$, with low-luminosity dwarf galaxies at small impact parameters being most common. Four of the five highest column density systems, which dominate in the determination of the cosmological neutral gas mass density, arise in low surface brightness dwarf galaxies.

Bentz and Osmer carried out a search of the Sloan Early Data Release (EDR) for nitrogren–rich quasars to see if more objects like Q0353−383 could be found. Q0353−383 shows evidence for CNO processing and a metallicity greater than solar, but it is the only object of its kind that is known. It may represent a late stage in the evolution of the central region of its host galaxy, and it is important to find more such objects. Sixteen candidates were found in the EDR, four of which had prominent emission lines of N III] and N IV], but none had emission as strong as in Q0353−383. Subsequently, in a collaboration with P. Hall (Princeton), they searched the Sloan Data Release 1 (DR1) and found 20 objects with strong nitrogen emission, four of which have strengths comparable to Q0353−383. The search also uncovered a number of quasars with unusual emission-line or absorption-line properties.

One such object is a bright Lyman break galaxy (LBG) candidate at $z = 2.55$. This led Bentz, Osmer, and Weinberg to search the DR1 for similar objects, and five more were found. The candidates have r magnitudes of 19.8 to 20.5 and redshifts of 2.5 to 2.8. If they are starburst galaxies and are not gravitationally lensed, they are the most luminous LBGs known. However, their spectra are unusual and do not match in detail known LBGs, AGNs, or submm–selected starburst galaxies. It is possible they are hybrid starburst/AGNs.

Onken, Peterson, Pogge, and Vestergaard, with L. Ferrarese and D. Merritt (Rutgers) and A. Wandel (Hebrew U.) are investigating the relationship between host-galaxy bulge velocity dispersion and the central black hole mass inferred from reverberation mapping measurements. They find that active galaxies show the same strong correlation between these properties that is found in quiescent galaxies, and that the black hole mass measurements based on reverberation results are accurate to a factor of ~ 3. In collaboration with M. Malkan (UCLA) and H. Netzer, D. Maoz, and S. Kaspi (Tel-Aviv U.), they are also working towards improving both the accuracy and precision of reverberation-based mass measurements. Once this is complete, improved luminosities, both absolute and relative to the Eddington luminosity, and scaling relationships between the broad-line region size and luminosity will be defined more precisely.

Bentz, Peterson, Pogge, and Vestergaard are working on a *Hubble Space Telescope* project to image all the reverberation–mapped AGNs for the purpose of determining the host–galaxy contribution to their optical fluxes.

Peterson is leading two approved *HST* target-of-opportunity (TOO) programs. The first of these is intended to measure nuclear stellar kinematics in order to use stellar dynamical methods to measure the black hole mass in two AGNs for which the black hole radius of influence is resolved with *HST*. The TOO will be initiated when one of the sources goes into a low–flux state, thus reducing the problem of nuclear glare. The second TOO program is to obtain an ultraviolet spectrum of NGC 4051 to complement optical data that suggest that, in faint states, the inner part of the accretion disk goes into a radiatively inefficient accretion mode. Collaborators are monitoring these candidate targets in X-rays with *RXTE* (I. McHardy, U. Southampton) and in the optical (S. Sergeev, Crimean Astrophysical Obs.).

Peterson continues to work with K. Horne (U. of St. Andrews) on reverberation–mapping simulations for the purpose of defining observational requirements for future efforts, one of which will be a proposal for a multi-wavelength Medium Explorer, *Kronos*, which is designed specifically for astrotomography.

Pogge and Fields, along with P. Martini (Carnegie Obs./CfA) and J. Shields (Ohio U.), are completing a 33–orbit *Hubble Space Telescope* study of the nuclear ($r < 30$ pc) spectra of a sample of 20 Seyfert 2 galaxies using the STIS spectrometer. They have detected weak, broad Hα emission lines characteristic of Type 1 Seyfert nuclei in a number of these galaxies, and often see faint high-excitation narrow lines that are only visible because *Hubble* allows them to get past the contaminating starlight into the nucleus proper. These objects are effectively "declassified" as Seyfert 2s. A few of these Seyfert 2s, however, are clearly unreddened and do *not* show broad emission lines, and therefore are plausible candidates for "true" Seyfert 2s: objects without broad lines not because they are blocked by the so-called "obscuring torus," but because they are truly absent. They have been granted 40 ksec with the *Chandra X-ray Observatory* to investigate their X-ray properties.

Pradhan's group is theoretically studying the time dependence of Kα lines of helium–like iron as function of temperature, density, and non-thermal photoexcitation, that may be applicable to accretion disk flares and temporal temperature variability of AGN.

X-ray O VI lines formed by resonance absorption, as predicted by Pradhan, have been observed in AGN outflows. It is inferred that the column densities from O VI UV absorption alone are 'often severely underestimated.' This concept can also be applied to resonance complexes in several ionization states of an element for abundance/column-density determinations. Pradhan, Chen, Delahaye, Nahar, and Oelgoetz have recently calculated Kα resonance strengths in O I – O VI.

T.A.A. Sigut (U. Western Ontario) and Pradhan have computed theoretical templates of $\sim$ 23,000 Fe II spectral lines from IR to UV for conditions in the broad line regions of AGN, incorporating exact radiative transfer and using the Iron Project data computed by Nahar. Among the important physical processes included is Lyα fluorescent excitation. The theoretical line fluxes are available from the authors and have been used for spectral analysis of AGN by a number of researchers.

Steed and collaborators present a flexible framework for constructing physical models of quasar evolution that can incorporate a wide variety of observational constraints, such as multi-wavelength luminosity functions, estimated masses and accretion rates of active black holes, space densities of quasar host galaxies, clustering measurements, and the mass function of black holes in the local universe. The central actor in this formulation is the accretion rate distribution $p(\dot{M}|M,z)$, the probability that a black hole of mass M at redshift z accretes at a rate $\dot{M}$ in Eddington units. Given a model of accretion physics that specifies the radiative efficiency and spectral energy distribution as a function of $\dot{M}$, the quasar luminosity function (QLF) is determined by a convolution of $p(\dot{M}|M,z)$ with the black hole mass function $n(M,z)$. In the absence of mergers, $p(\dot{M}|M,z)$ also determines the full evolution of $n(M,z)$, given a "boundary value" of $n(M)$ at some redshift. If $p(\dot{M}|z)$ is independent of mass, then the asymptotic slopes of the QLF match the asymptotic slopes of $n(M)$, and $n(M)$ evolves in a self-similar fashion, retaining its shape while shifting to higher masses. Matching the observed decline of the QLF "break" luminosity at $z < 2$ requires either a shift in $p(\dot{M}|z)$ that increases the relative probability of low accretion rates or an evolving mass dependence of $p(\dot{M}|M,z)$ that preferentially shuts off accretion onto high mass black holes at low z. These two scenarios make different predictions for the masses and accretion rates of active black holes. If the first mechanism dominates, then the QLF changes character between $z = 2$ and $z = 0$, shifting from a sequence of black hole mass towards a sequence of $L/L_{\rm edd}$. Steed and collaborators use their framework to compare the predictions of five models that illustrate different assumptions about the quasar population: two dominated by unobscured thin-disk accretion with short and long quasar lifetimes, respectively, one with a 4:1 ratio of obscured to unobscured systems, one with substantial black hole merger activity at low redshift, and one with substantial low redshift growth in radiatively inefficient flows. They discuss the observational advances that would be most valuable for distinguishing such models and for pinning down the physics that drives black hole and quasar evolution.

Vestergaard is continuing to study the distribution of black-hole masses in the centers of high redshift ($z > 1.5$) quasars. The first results show that even at the highest redshifts ($4 < z < 6$) the currently known quasars have very massive ($10^8 - 10^{10} M_\odot$) black holes, comparable to quasars at lower redshift. This indicates that black holes must form early or fast.

Vestergaard and Osmer are continuing their investigation of the mass distribution of active black holes in nearby and distant quasars and how these distributions compare to inactive black holes in centers of local galaxies. The ultimate goal is to place constraints on the evolution of quasars and the growth of black holes. The latter is done in collaboration with Steed and Weinberg.

Vestergaard and Peterson are studying the variability properties of the optical and UV iron emission in a sample of nearby active galaxies using monitoring data from the International AGN Watch efforts. The goals are to perform a systematic study of the iron emission to identify the properties of active galaxies favorable for strong iron emission and to constrain the vast parameter space which current theoretical models must cover, complicating the theoretical approach in explaining this important line emission.

With M. Dietrich (GSU) and collaborators from Heidelberg, Vestergaard is involved in a continuing study of the metal abundances of high-redshift ($z > 3.4$) quasars. The goal is to attempt to constrain the epoch of the early star formation in the universe by combining the relative Fe II to Mg II strength measured in high-redshift quasars with chemical evolutionary models. The studies so far show that high metal abundances are present in the center of even the highest redshift ($z \approx 6$) quasars and that the first epoch of star formation must occur in the redshift range $6 \lesssim z \lesssim 9$, consistent with the epoch of reionization.

Williams, Pogge, and Mathur have found a large, new sample of narrow-line Seyfert 1 galaxies in the Sloan Digital Sky Survey Early Data Release. They have begun follow-up observations with the *Chandra X-ray Observatory* in order to better determine the X-ray properties of NLS1s. They are now in the process of analyzing these X-ray data.

Mathur and Williams found the second highest redshift ($z = 1.47$) X-ray cluster around a pair of broad absorption line quasars, through archival *Chandra* data. Recently, they began working on a *FUSE* observing program to search for hot, nearby intergalactic gas through high-velocity UV absorption lines seen toward bright quasars.

12 COSMOLOGY AND STRUCTURE FORMATION

With N. Dalal (IAS), Kochanek has been exploring the problem of CDM substructure using gravitational lenses. Gravitational lenses show flux ratio anomalies that can be explained by substructure, either satellites or stars, in the lens galaxy. Using radio lenses, which are insensitive to the effects of stars, they argued that the flux ratio anomalies imply a mass fraction in satellites consistent with the expectations for CDM. They also showed that the anomalies distinguish between images which are minima and saddle points of the time-delay surface, a property which is a unique prediction of models with modest surface densities of substructure.

Kochanek, A. Dey (NOAO), W. Forman (CfA), B. Januzzi (NOAO), C. Jones (CfA), A. Kenter (CfA), and B. McNamara (Ohio U.) have obtained a 5 ksec *Chandra X-ray Observatory* (CXO) image of the northern NOAO Deep Wide Field Survey (NDWFS) field, identifying 3200 X-ray point sources and 42 extended sources. In 2004 they will obtain redshifts of most of these sources as well as a large sample of galaxies in the field. The data will be used to study the nature of the X-ray sources, to measure the correlation function of AGNs near $z \sim 1$ and to measure the accretion and star formation history of the universe. With Einsenhardt (JPL) and Fazio (CfA), they will also measure the redshifts of *SIRTF*/IRAC sources in the NDWFS field.

Over the past year Kollmeier has been continuing her work on Lyman Break Galaxies and the Lyα forest with Miralda-Escudé using new hydrodynamic simulations that include feedback. The purpose of this project is to compare the results of simulations with winds to those of the SPH simulations without winds.

Miralda-Escudé and X. Chen (UC Santa Barbara) have computed the heating rate of the atomic intergalactic medium by Lyα photons from the first stars. These Lyα photons are important for coupling the spin and kinetic temperature of H I, which results in changing the spin temperature from the Cosmic Microwave Background temperature and allowing H I to be observed at the 21-cm line. They show that the heating of the kinetic temperature that results from these Lyα photons is much less than previously expected, allowing in principle for a substantial epoch at which the spin temperature is much less than the CMB temperature and H I can be observed in absorption against the CMB, although they compute also that X-rays from the first stars can heat the medium after a certain time. There are plans for future searches for the redshifted 21-cm signal with SKA and LOFAR.

Miralda-Escudé wrote a review article for *Science* summarizing current ideas on the formation of the first stars and the reionization epoch. Miralda-Escudé and Onken have presented a model for reionization from the first stars. They showed the difficulty in accounting for the reported Thompson optical depth by *WMAP*, because of the large rate of emission of ionizing photons required from the first halos able to form stars at high redshift, compared to similar halos present at lower redshifts at which the rate of emission can be measured.

Miralda-Escudé and Yoo are developing a model, based on halo merger trees and a semi-analytic calculation of the dynamical evolution of satellites within halos, with the purpose of investigating if the first star clusters formed in low-mass dark matter halos before the epoch of reionization could account for a small fraction of the globular cluster population at present. These globular clusters would be distinguished by their content of dark matter. Miralda-Escudé and Morgan are using a similar model to follow the mergers of black holes that existed at $z \sim 1 - 6$ to account for observed quasars. By these mergers, the early black holes in quasars should evolve to the black holes observed today. The aim is to predict the largest black hole masses one should observe at present, and see if they agree with the observations of black holes in massive ellipticals.

Miralda-Escudé and Kollmeier have developed a model to explain the quasar phenomenon based on supplying matter to an accretion disk around a black hole with stars that are perturbed into radial orbits which lead them to collide with the disk. The stars are gradually slowed down until they merge with the disk. The model leads to a prediction of a relation between the black hole mass and the velocity dispersion of the stellar system around it that may be able to explain the observed correlation of these two quantities.

Weinberg and Zheng, in collaboration with I. Zehavi (Fermilab) and other members of the Sloan Digital Sky Survey (SDSS) collaboration, showed that the real space correlation function of galaxies selected from the SDSS exhibits significant departures from a power-law on scales of a few Mpc, and that these departures can be naturally interpreted in halo occupation models of galaxy bias, where they represent the transition from galaxy pairs in the same halo to galaxy pairs in separate halos. They are now investigating the halo occupation distribution (HOD) as a function of galaxy luminosity and color and comparing the HOD inferred from modeling the correlation function to that derived from the group multiplicity function. Tinker, Zheng, and Weinberg are investigating redshift–space distortions of structure in the HOD formalism, with the goal of developing an accurate model that can be applied to the SDSS data to obtain constraints on cosmological parameters.

Weinberg has contributed to a number of other papers involving SDSS data, most notably an improved estimate of the galaxy luminosity function and its evolution, a measurement of the real space galaxy power spectrum, and the SDSS First Data Release.

Weinberg continues work with N. Katz (U. Mass.) and R. Davé (Arizona) on hydrodynamic simulations of galaxy formation and the intergalactic medium. The most exciting recent results (with D. Keres of U. Mass.) concern the process by which gas gets into galaxies; much gas accretion in the simulations occurs in a cold, filamentary mode that is quite different from that envisioned in conventional analytic models of galaxy formation. With S. Colombi (IAP), they are investigating the degree of correspondence between galaxies formed in hydrodynamic simulations and dark matter substructure formed in purely gravitational simulations with the same initial conditions.

Zheng has applied Halo Occupation Distribution (HOD) models to interpret the strong clustering of a population of $z \sim 3$ red galaxies discovered in the HDF–South. ¿From a power-law fit to the observed angular correlation function, it has been claimed that these galaxies have a large correlation length that is hard to reconcile with the ΛCDM structure formation model. However, Zheng's HOD modeling shows that the observed signals are mostly from galaxy pairs within the same dark matter halos and that a power-law extrapolation in the galaxy correlation function to large scales is not appropriate. Zheng has shown that the clustering of these red galaxies can be well explained within the ΛCDM model.

Weinberg and Zheng are taking part in the HOD modeling of the luminosity and color dependence of galaxy clustering in the Sloan Digital Sky Survey (SDSS).

13 BIG BANG NUCLEOSYNTHESIS

Scherrer investigated Big Bang Nucleosynthesis (BBN) under a variety of conditions. These included Gaussian inhomogeneous neutrino degeneracy, with S. Stirling (U. Texas); brane cosmologies, with J. D. Bratt (Geneva Coll.), A. C. Gault (U. Toledo), and Walker; and the time variation of the Higgs vacuum expectation value, with Yoo.

Steigman, with V. Barger (Wisconsin), J. P. Kneller (NC State), H.-S. Lee (Wisconsin), and D. Marfatia (Boston U.), has placed constraints on the number of relativistic degrees of freedom ("equivalent neutrinos") and on the baryon asymmetry at the epoch of BBN (≈ 20 minutes after the "bang") and at recombination (≈ 400 kyr later), using CBR data from *WMAP*, complemented by the *Hubble Space Telescope* Key Project measurement of the Hubble constant, along with the latest compilation of primordial deuterium and helium abundances. The excellent agreement found for the derived values of these key cosmological and particle physics parameters at such widely separated epochs provides strong support for the standard models of particle physics and of cosmology. From the combination of CBR and BBN data they are able to significantly constrain the allowed ranges for the effective number of neutrinos and for the baryon asymmetry.

Barger, Kneller, P. Langacker (U. Penn), Marfatia, and Steigman quantified the extent to which extra relativistic energy density (e.g. extra, equivalent neutrinos) can be concealed by a neutrino asymmetry (unequal numbers of neutrinos and antineutrinos). This project has implications for models of lepto- and baryogenesis. The new CBR data from *WMAP* complements that from BBN, enabling them to simultaneously constrain the lepton asymmetry, the baryon asymmetry, and any extra energy from physics beyond the standard model (e.g. higher-dimensional models). One of the interesting consequences of this study is that the result from the LSND neutrino experiment is shown to not be excluded on the basis of BBN, in contrast to many previous claims that it was. This lends support to the value of pursuing the Mini-Boone experiment currently running at Fermilab.

In the past few years many "beyond the standard model" models have been proposed to explain the "dark energy" which dominates the energy density of the present Universe. Steigman and Kneller investigated the constraints on dark energy models coming from the cosmic microwave background (CMB) and from BBN. While they limited the ranges of the new, free parameters in the so-called minimally coupled models, they found that the non-minimally coupled models are seriously challenged by the BBN and CMB constraints.

14 ATOMIC ASTROPHYSICS

The atomic astrophysics group consists of Pradhan, Nahar, Chen, Delahaye, and Oelgoetz. The group studies atomic radiative and collisional processes and applications to astrophysical spectroscopy and modeling. The atomic calculations are mainly in *ab initio* quantum mechanical close–coupling approximation using the R–matrix method. These involve large-scale computations which are carried out at the Ohio Supercomputer Center in Columbus, Ohio, on a variety of computational platforms such as the Cray–SV1 and massively parallel clusters. Results of interest are collision strengths, photoionization cross sections, transition probabilities, and electron–ion recombination rates. These results are incorporated into astrophysical models for spectral analysis of ground-based and space-based observations, for example in predicting Fe II emission line strengths in AGN. Collaborators include H. Zhang (Los Alamos), W. Eissner (Stuttgart, Germany), C. Zeippen (Obs. de Paris), A. Sigut (U. of Western Ontario), R. Phaneuf (U. Nevada), and F. Wuilleumier (Univ. Paris-Sud).

Nahar was the scientific organizer for an international symposium, "Advances in Atomic Physics and Applications to Astrophysics" held on December 13, 2003, at University College, London, U.K., honoring the birthdays of M. J. Seaton and W. Eissner for their lifetime contributions to atomic physics and astrophysics. The organized sessions were on (i) Atomic structure & collision theory, (ii) Atomic theory, (iii) Astrophysics, and (iv) Photon absorption/emission. Pradhan gave an invited talk on "Atomic processes in X-ray astronomy."

14.1 The Iron Project

The atomic astrophysics group at OSU is part of the international Iron Project (IP) team, with members from the UK, Germany, France, Canada and Venezuela. The aim of the IP is to investigate and calculate atomic parameters for collisional and radiative processes for astrophysically important elements, particularly the iron group. The IP team produces results on collisional excitation, photoionization, and fine structure bound–bound transitions for analysis of astrophysical spectra of iron–peak elements such as iron, cobalt, and nickel which are the end products of stellar nucleosynthesis. The work under the IP complements and improves upon the work of the earlier Opacity Project (OP) which resulted in the calculation of a huge quantity of radiative data for stellar opacities.

In contrast to the OP, the IP implements relativistic effects in Breit–Pauli approximations with an R–matrix approach. This enables highly accurate and large-scale calculations for both atomic radiative and collisional processes. Recent results include the completion of five years of work on electron impact excitation collision strengths for one of the most difficult, but astrophysically important, ions, Fe XVII, whose spectral features are prominent in X-ray sources.

14.2 Photoionization

Photoionization cross-sections of highly charged but complex ions such as Ar XIII, Ca XVII, Fe XXI, and Fe XVII are being studied in detail to investigate presence of near-threshold resonances as well as large enhancement at high energies due to $n = 2 - 3$ core transitions. Fe XXI is of special interest due to recent measurements of cross-sections at low energies.

Nahar is continuing her collaboration with the experimental group of R. Phaneuf at Reno/Berkeley measuring precise photoionization cross sections of multply–charged iron ions for low–lying states. She has carried out a 16–term close–coupling calculation of photoionization cross-sections of Fe IV for the low–lying states of sextet, quartet, and doublet symmetries to compare with the recent measurements at the Advanced Light Source in Berkeley. Work is in progress to convolve the theoretical results with the experimental parameters for comparison. Compared to theoretical results for individual states, experiments often measure combined features of several states pertaining to the experimental beam.

Nahar has also completed theoretical work on O II, O III, O IV, and O V using the relativistic Breit–Pauli R–matrix method, to delineate features observed experimentally, at three different experimental set-ups: at the Advanced Light Source, the synchrotron radiation source at U. de Paris–Sud, and at the Photon–Ion merged beam experiment at U. Aarhus. The agreement between theoretical and measured results of various set-ups establishes the accuracy and validity of the theory. This work shows that fine structure introduces features, even for relatively lighter elements such as oxygen, for a number of ionic stages.

14.3 Electron–Ion Recombination

The unified method for the total electron-ion recombination, that accounts for both the radiative and dielectronic recombination in a unified manner, was developed by Nahar and Pradhan, and was extended to include relativistic effects and radiation damping of low-n resonances by Zhang, Nahar, and Pradhan. This method is being used for highly charged and complex ions, Ar XIII, Ca XV, and Fe XXI. The unified method makes it possible to obtain self-consistent sets of photoionization cross-sections and recombination rate coefficients inverse processes in a self-consistent manner for astrophysical photoionization models.

Nahar is working on the total and level–specific recombination rate coefficients for He–like and Li–like ions. Relativistic effects are included for these ions. These are much–needed data in order to analyse the recent observations by *Chandra* and *XMM–Newton*. Cross-sections and rate coefficients for He–like and Li–like O VI and O VII have also been calculated by Nahar and Pradhan.

14.4 Radiative Transition Probabilities and Photoabsorption

The Atomic Astrophysics group has been involved in computing extensive sets of transition probabilities using the relativistic Breit–Pauli R–matrix method. This is the only currently available method to consider large number of transitions in an *ab initio* manner through many energy eigenvalues of the Hamiltonian matrix with consistent accuracy. Nahar obtained radiative transition probabilities of Fe XX for 3.8×10^5 dipole–allowed, intercombination, and forbidden electric quadrupole, octupole, and magnetic quadrupole transitions among about 1800 fine structure levels. These are needed for the analysis of recent observations of most ionization stages of iron from space observations in the UV and X-ray regions. The recently computed data far exceed the available data in literature.

Nahar has found that for transitions in He–like ions, weak Breit two-body interaction terms, neglected in the BPRM approximation, become important contributors for the intercombinaton and forbidden transitions. Chen and Eissner have been involved in coding this complicated interaction in the close–coupling approach for the last two years. They have made considerable progress in coding the radial integrals and angular algebra in the R–matrix package of codes.

14.5 X-Ray Astronomy

A Joint Discussion on *Atomic Data for X–Ray Astronomy* was organized by Pradhan (SOC Chair) and held at the General Assembly of IAU in Sydney, Australia during July 2003. JD 17 included talks on (i) X-ray Observations, (ii) Atomic Theory, (iii) Atomic Experiments, (iv) X-ray Modeling, and (v) Databases for X-ray Astronomy. Invited talks were presented by Pradhan on “The IRON project: Applications to X-ray astrophysics” and by Nahar on “New Atomic Radiative Data”.

14.6 Database Activities: Stellar Opacities

The on-line database for stellar opacities at the Ohio Supercomputer Center established by M. J. Seaton (UCL), C. Mendoza (IVIC, Venezuela), Nahar, and Pradhan has been updated. “Customized” opacities can be computed for an arbitrary mixture of elements specified by the user for modeling stellar structure and evolution. Radiative accelerations may also be computed to investigate the effect of radiative “levitation” versus gravitational settling of elements in stars.

15 MOLECULAR ASTROPHYSICS

In the last year, Herbst, F. De Lucia (OSU Physics) and colleagues from the University of Cologne, Germany, studied the laboratory rotational spectra of known and likely interstellar molecules. Much of the work is in the submillimeter-wave region of the spectrum, in preparation for astronomical results from *Herschel*. The molecules studied this year include the methylene radical (CH_2) and the lowest energy conformer of diethyl ether.

16 NUCLEAR ASTROPHYSICS

Boyd’s efforts this past year have been in developing the capabilities of lead perchlorate as a supernova neutrino detector. It was also found that lead perchlorate has an interesting capability in detecting nucleon decay modes that are the most difficult to detect, i.e., that in which a neutron decays to unobservable particles such as three neutrinos. ^{35}Cl was found to be especially interesting in this context, as it produces a definitive signature: γ–rays from decay of excited states of ^{34}Cl followed by a β particle, within a few seconds, from the decay of ^{34}Cl. Furthermore, the dominant background for this decay mode, that produced by neutrinos knocking out neutrons from ^{35}Cl, could be rejected by using the resulting neutron as a veto. A rather modest amount of lead perchlorate should allow improvement of the lifetime limit for this difficult-to-detect decay mode by several orders of magnitude within a few years of operation.

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