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Abstract

This annual report covers the period September 1995 through August 1996.

1 Personnel

During the period covered by this report, the regular academic staff of the Department of Astronomy included Richard N. Boyd, Darren L. DePoy, Jay A. Frogel, Andrew P. Gould, Eric Herbst, Gerald H. Newsom, Patrick S. Osmer (chairman), Bradley M. Peterson, Marc Pinsonneault, Richard W. Pogge, Anil K. Pradhan, Barbara S. Ryden, Robert J. Scherrer, Kristen Sellgren, Gary Steigman, Donald M. Terndrup, Terrence P. Walker, David H. Weinberg, and Robert F. Wing. Michelle Kaufman held an appointment as Research Scientist. Michael R. Savage was manager of the Astronomy Department computer resources. Thomas Burns was Director of the Perkins Observatory. Emeritus members of the Astronomy Department are Eugene R. Capriotti, George W. Collins II, Stanley J. Czyzak, Phillip C. Keenan, Geoffrey Keller, William M. Protheroe, and Arne Slettebak. We are sorry to report the death of Emeritus Professor Walter E. Mitchell, Jr., on July 29, 1996, at the age of 70.

The staff of the Imaging Sciences Laboratory (ISL; formerly known as the Astronomical Instrumentation Facility) included Bruce Atwood (director), S. Ralph Belville, David F. Brewer, Paul L. Byard, Kevin R. Duemmel, Jerry A. Mason, Thomas P. O'Brien, David Steinbrecher, Robert Stonebreaker, and Edward J. Teiga.

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

Postdoctoral researchers in astronomy during this period included Rupert Croft, Julia Kennefick, Sultana Nahar, Alice Quillen, João Santos, Kevin Uchida, Ignaz Wanders, and Honglin Zhang.

Graduate students in the OSU astronomy department included Babar Ali, Manuel A. Bautista, Andreas Berlind, Dixie Burns, Alberto Conti, Mark E. Everett, Scott Gaudi, Cheongho Han, Anita Krishnamurthi, Leslie E. Kuchinski, Tina Mailloux, Paul Martini, Vijay Krishna Narayanan, J. Michael Owen, Jianfang Peng, Piotr Popowski, Solange V. Ramírez, Ani R. Thakar, and Glenn P. Tiede. The Ph.D. degree was awarded to Ali.

2 Instrumentation

The Imaging Fabry-Perot Spectrometer (IFPS) was completed in November 1995 with the installation of its final UV-to-IR optics, a UV medium-resolution ($R = 4500$) etalon, and a new blue-sensitive CCD detector. The systems electronics was upgraded at the same time to make use of the new OSU CCD controller system, and to use the first generation of our new instrument control computer system based on the ICIMACS software. The ICIMACS computers and 'Prospero' data-taking program were installed at the 1.8m Perkins telescope on Anderson Mesa in November 1995. The new CCD detector was removed in February 1996 to investigate an apparent antireflection coating contamination problem; testing revealed previously undetected stress cracks in the detector substrate that caused electrical failure of the device. A new CCD is being thinned and packaged, and will be installed late in 1996.

During the past year, the MDM-Ohio State Active Infrared Camera (MOSAIC) was largely completed. This is a joint project between Ohio State and the Michigan-Dartmouth-MIT (MDM) Observatory to build an infrared camera/spectrometer for the MDM 2.4m and 1.3m telescopes. The instrument was completed mechanically and there were several observing runs on the telescopes with a 256×256 HgCdTe array. During the year, MDM, Ohio State, and NOAO came to an agreement to provide a large format InSb array for MOSAIC, which significantly enhances its scientific capabilities. In exchange, OSU will make the instrument available to the entire US astronomical community at Kitt Peak National Observatory. The first engineering run with a 512×1024 InSb array was in September 1996. Atwood, Byard, DePoy, Mason, O'Brien, and Pogge have all been actively involved in this project.

In November 1995, MOSAIC was taken to the Starfire Optical Range 1.5m Laser Guide-Star Adaptive Optics Telescope at Kirtland AFB near Albuquerque. This project was part of an NSF program to give U.S. astronomers hands-on experience with recently declassified military adaptive optics technology. Despite unstable weather and a government shutdown during the run, the system attained diffraction limited performance at J, H, and K using both bright 'natural' guide stars and the laser Rayleigh beacon artificial guide star.

3 Stars and Stellar Evolution

Krishnamurthi, Pinsonneault, S. Barnes (Yale), and S. Sofia (Yale) have done a theoretical study of how the surface rotation of stars is affected by initial conditions, angular momentum loss, and angular momentum transport. Young slow rotators, it was found, are the best test of angular momentum transport; the behavior of the rapid rotators requires a mass-dependent angular momentum loss law. A range of accretion disk lifetimes can generate the observed range of rotation rates in young stars. Models with solid-body rotation require very long disk lifetimes, in conflict with pre-main-sequence observations, while models with differential rotation can have short disk lifetimes, in agreement with the data. In a parallel project, Pinsonneault, Krishnamurthi, Terndrup, Sellgren, and J. Stauffer (CfA) have obtained a large body of data on rotation periods and velocities in the Pleiades and Hyades. Pinsonneault, Barnes, and Sofia have investigated the sensitivity of the angular momentum evolution of low mass stars to the initial rotation rate. The found that the qualitative behavior of the different models was similar, but that both a higher saturation threshold (for fast spinners) and a shorter disk locking timescale (for slow spinners) are needed for a range of initial rotation rates.

R. Blum (JILA), Sellgren, and DePoy have analyzed new and existing K-band spectra for 19 Galactic center late-type stars, along with representative spectra of disk and bulge M giants and supergiants. Absorption strengths for strong atomic and molecular features have been measured. The Galactic center stars generally exhibit stronger absorption features centered near Na I (2.206 μm) and Ca I (2.264 μm) than representative disk M stars at the same CO absorption strength. Based on the absolute K-band magnitudes and CO and H_2O absorption strengths for the Galactic center stars and known M supergiants and asymptotic giant branch stars, we conclude that only IRS 7 must be a supergiant. Three other bright stars in the Galactic center are likely supergiants as well. The remaining bright, cool stars in the sample are consistent with being intermediate mass/age AGB stars. Estimates of initial masses and ages for the Galactic center stars suggest multiple epochs of star formation have occurred in the Galactic center over the last 7–100 Myr.

Frogel, DePoy, and Ramírez have been using medium resolution near-infrared spectra, primarily obtained with the Blanco 4m telescope at CTIO, to study chemical abundances in heavily obscured stellar populations, such as the central bulge of the Galaxy and its globular clusters. They measure strong lines of Na I and Ca I and the first overtone band head of CO in 2.1 to 2.3 μm spectra of cool giants in these populations. To calibrate the abundance scale, they obtained spectra of 43 K0 to M6 local giants and are beginning to assemble and analyze data on well-studied globular clusters. From the strength of the CO absorption alone they can estimate the $T_{\rm eff}$ of a giant star with an uncertainty of less than 200 K. They also find that the ratio of the equivalent width of the CO band to the sum of the equivalent widths of the Na I and Ca I lines is a powerful luminosity discriminant between giants and dwarfs. This ratio is nearly independent of temperature between 4800 and 3200 K and also appears to be independent of metallicity. The sum of the equivalent widths of Na I and Ca I, once its temperature and luminosity dependences are removed, correlates well with optically determined values for [Fe/H] at least over a range from solar to 1/20 solar. Thus, in spite of the fact that both Na and Ca may have undergone selective enhancement via helium-burning processes, the data obtained so far indicate that these enhancements go in lockstep with overall Fe variations.

In collaboration with S. Sofia (Yale), Pinsonneault combined new data on the measured solar oblateness with an exploration of the solar rotation as a function of depth and its sensitivity to theoretical uncertainties. They found that hydrodynamic mechanisms had an oblateness only marginally consistent with the data, and that the models preserve too much internal angular momentum. Including a long timescale and constant angular momentum transport process can bring the models into agreement with the data, even for a timescale greater than 1 Gyr. This result indicates that a flat solar rotation curve does not require a very short timescale for internal transport, as has been commonly assumed.

Pinsonneault, J. Bahcall (IAS), Basu (Aarhus), and Christensen-Dalsgaard (Aarhus) examined the implications of helioseismology for the solar neutrino problem. The sound speed as a function of depth inferred from seismology agrees with standard models to within 0.2% for radii in the range $0.05 \rightarrow 0.95\,R_\odot$. This drastically restricts the interesting classes of nonstandard models – in particular, the recently proposed models with extensive mixing. The inclusion of an improved equation of state (from OPAL) also improves the agreement with helioseismology, but has little impact on neutrinos.

Wing served as SOC Chair for IAU Symposium 177 on *The Carbon Star Phenomenon*, which was held in Antalya, Turkey, in May 1996. The symposium was attended by 150 scientists including Wing and Frogel. Wing is now editing the Proceedings.

In collaboration with R. Garrison (U. Toronto) and T. Koktay (Istanbul U.), Wing has estimated the temperatures of 16 peculiar G-type stars with abnormal CH and CN strengths. The temperatures are based on narrow-band photometry at good near-IR continuum points, and are being used by Koktay in her spectroscopic abundance analysis, which may shed light on the origin of these mysterious objects.

Pinsonneault, in collaboration with F. Primas (Trieste), D. Duncan (U. Chicago), J. Thorburn (U. Chicago), and C. Deliyannis (Yale), obtained new measurements of beryllium in α Cen A and B. They found a beryllium abundance in A consistent with the solar photospheric value, and a significantly lower abundance in B. The low beryllium abundance in α Cen B is evidence for deeper mixing in low mass stars than can be inferred from data indicating lithium depletion.

Narayanan and Pinsonneault are investigating the mixing produced by models of open cluster stars and halo stars. They use open cluster rotation rates to set the range of initial conditions, and look at the resulting lithium depletion pattern. Because lithium depletion depends on the initial rotation rate, this provides a possible diagnostic of the star formation process in old systems. The new models can be used to constrain the possible range of primordial lithium abundances, with interesting consequences for cosmology.

Wing and U. Jørgensen (Niels Bohr Inst.) have used a new grid of model atmospheres which includes a detailed treatment of H_2O opacity to explore the *JHK* two-color diagram. The observed separation of M dwarfs from M giants is due partly to H_2O absorption (which affects dwarfs as early as M0, but giants not until M6), but a major portion of the separation is reproduced by the models even when H_2O (and other molecules) is omitted from the synthetic spectra. The separation in the continuum colors is caused by the differing effects of H^- opacity in giants and dwarfs due to their different temperature structures. Wing and Jørgensen also studied the *JHK* colors of carbon-rich giants and dwarfs, to see if dC stars can be identified by their near-IR colors, as has been suggested from empirical evidence. They found that at a given effective temperature, dwarf and giant carbon stars have very different *J–H* and *H–K* colors, but that the shift is nearly parallel to the sequence of giants of different temperature. Thus it will be difficult to isolate dC stars by their *J–H* and *H–K* colors unless some other indicator of $T_{\rm eff}$ is available. The computed near-IR spectra of carbon dwarfs differ from those of normal carbon giants in having much weaker spectral features, except those of polyatomic molecules such as C_2H_2 and C_3, and a much smaller hump due to the H^- opacity minimum.

The Magellanic Clouds have been the key to the development of a coherent picture for the formation and evolution of AGB carbon stars. E. Costa (Universidad de Chile) and Frogel obtained *RI* photometry for an unbiased sample of ~900 C stars in 52 fields of the Large Magellanic Cloud (LMC), and *JHK* photometry for ~200 of them. For the stars with *RIJHK* data, they derive an equation that gives $m_{\rm bol}$ (±0.34 mag) from the R_0 and I_0 data alone. This results in a definitive luminosity function for all 900 stars. Only two C stars brighter than $m_{\rm bol} = 12.5$ are found, and there are fewer than 10 fainter than $m_{\rm bol} = 15.5$. A comparison of the data with the models of Lattanzio shows that $\sim 1{\rm M}_\odot$ is the minimum mass needed to produce a somewhat metal poor C star. The observed lower limit to the C star luminosities corresponds to the luminosity at which a 1 $M_\odot$ Pop II star is predicted to have its first major thermal pulse. The metallicity range of the field C stars appears to extend to a higher value than that of the populous star clusters in the Clouds. Each field observed can be characterized by a transition luminosity $m_{\rm bol}(t)$ that marks the transition between an M and a C star as stars evolve up the AGB. Frogel and Costa find that these values of $m_{\rm bol}$ get brighter with increasing distance from the LMC's bar. This result would be expected if the upper limit to C star ages decreased as one approached the periphery of the LMC, by an amount corresponding to an increase of $\sim 30\%$ in the minimum main sequence turnoff mass. The oldest C stars are probably associated with the LMC's major epoch of star formation, a few Gyr ago.

With collaborators from the Center of EUV Astrophysics, at the University of California, Berkeley, Pradhan has been studying white dwarfs observed with the Extreme Ultraviolet Explorer satellite. The main areas of investigation are the abundances and the atmospheres in hot young dwarfs as they form and evolve along the stellar sequence. Of particular interest is radiative levitation of heavy elements (such as iron and nickel) due to intense radiation pressure, and gravitational stratification due to intense gravitational fields.

4 Interstellar Medium

Bautista and Pradhan continue the study of high-density partially ionized zones in gaseous nebulae. For this, extensive analyses of the emission spectra of [Fe II], [Ni II], and [O I] were carried out for a large sample of H II regions, circumstellar nebulae, Seyfert galaxies, supernova remnants, and Herbig-Haro objects. It is found in all cases that the electron densities derived are higher, by 1–3 orders of magnitude, than those obtained from ions present primarily in fully ionized regions.

Bautista and Pradhan are also studying the ionization structure and emission spectra of iron in low excitation nebulae. This work includes: (1) use of the new atomic data – photoionization cross sections, total electron-ion recombination rates, collision strengths, and transition probabilities for Fe I–Fe VI, (2) detailed study of excitation mechanisms of Fe ions, and (3) study of the physical structure of nebulae including density variations, temperature variations, and kinematic effects.

The most complete archival record of Hubble's 'variable' nebula (NGC 2261) was obtained by C. O. Lampland between 1916 and 1951 using Lowell Observatory's 42″ reflector on nearly 1000 photographic plates. Using a CCD camera on loan from Lowell with a renovated OSU precision plateholder, Bertram has completed digitizing the best of these plates (now showing serious signs of deterioration). A sequential animation created from the processed CCD frames will be assembled, then expanded with the contributions of other data sets. The goal of this work is to create an improved dynamic model of the R Mon/NGC 2261 system.

Sellgren, Martini, and J. Hora (U. Hawaii) have obtained infrared spectra of two filaments in the reflection nebula NGC 7023. Both filaments, which probably trace the photodissociation region, show H_2 emission coincident with emission from the 3.3 μm aromatic emission feature, extended red emission at 0.67 μm, and HCO^+ emission. The strengths of H_2 emission lines in the *H* and *K* bands show that a mixture of fluorescent excitation and collisional excitation is required to explain the observations. The central star of NGC 7023, a pre-main sequence B star, can provide the needed UV photons for fluorescence and also could drive a bipolar outflow which collisionally excites the photodissociation region.

Sellgren, Uchida, and M. Werner (JPL) have used the Infrared Space Observatory (ISO) to obtain images in aromatic hydrocarbon features at 6.2, 7.7, and 11.3 μm of reflection nebulae illuminated by central stars with a range of temperatures. Sellgren and Werner have also used ISO, in collaboration with A. Léger (IAS), to obtain mid-infrared spectra of aromatic hydrocarbon emission features in reflection nebulae. These ISO observations are an extension of a project recently completed by Sellgren, Werner, and L. Allamandola (NASA Ames) in which the same reflection nebulae were searched for near-IR continuum emission at 1.2 – 3.8 μm and aromatic hydrocarbon emission at 3.3 μm. These three projects together will test specific identifications for the aromatic hydrocarbon features, such as polycyclic aromatic hydrocarbon molecules and hydrogenated amorphous carbon grains.

Sellgren, T. Brooke (JPL), R. Smith (U. New South Wales), and T. Geballe (JAC) have recently discovered a new interstellar absorption feature at 3.256 μm in the protostars Mon R2/IRS-3, NGC 7538/IRS-1, and S140/IRS-1. They have obtained spectra of an additional twelve protostars with the goal of characterizing the physical conditions under which this feature arises. The feature may be due to aromatic hydrocarbons at low temperatures. If the feature results from aromatic molecules of roughly the same size as those responsible for aromatic emission features in the interstellar medium, then $\sim$9% of the cosmic abundance of carbon along this line of sight would be in aromatic hydrocarbons.

Everett continues his dissertation research on the near-IR H_2 emission lines from shocks associated with young stellar outflows. Cross-dispersed OSIRIS spectra in the J, H, and K bands were obtained with the Perkins 1.8m telescope for outflow sources such as Herbig-Haro objects HH32A, HH7–11, and HH227, and shocked H_2 emission regions of the OMC-1 molecular outflow. The goal is to utilize the objects as laboratories for studying shock physics in molecular environments and to determine the relationship between the H_2 emission and other components of molecular outflows. The objects and slit positions are chosen to sample a wide range of observed properties and to exploit shocks with known geometries. This approach has proven valuable in constraining models of the objects. Analysis of the spectra towards HH7–11 has shown no significant variations in the line ratios with position, an indication that the H_2 emission arises in the cooling zone behind hydrodynamical J-shocks rather than the MHD shocks or precursors often ascribed to the emission. The HH7–11 H_2 line ratios also show evidence of non-LTE effects attributable to collisional excitation at subcritical densities. This suggests that future shock models may be able to constrain the density of HH7–11. Interpretation of the data for the other objects is underway.

Herbst and R. Bettens (OSU Physics) have started to expand their gas phase chemical models of interstellar clouds to include molecules with up to 64 carbon atoms; previous models have only included molecules through $\sim$10 atoms in size. The new, larger molecules comprise linear and cyclic bare carbon clusters and hydrocarbons. The cyclic species are composed of singly and triply ringed molecules as well as fullerenes. The reactions leading to the syntheses of the complex species are based on laboratory results. The extended model networks are being used to study complex molecule formation in both dense and diffuse clouds; the latter sources are being studied in an attempt to determine possible carriers for the diffuse interstellar bands.

In a collaboration involving scientists at L'Observatoire de Paris-Meudon, Herbst and H.-H. Lee (OSU Physics) have calculated molecular abundances as a function of time in an inhomogeneous cloud divided into 43 slabs of differing density. The radiative transfer of external radiation through the slabs was considered carefully.

In a continuing program to understand reaction rates at low temperature, Herbst, in collaboration with the quantum chemist D. Woon (Molecular Research Institute), has theoretically investigated the rate of the reaction $HOC^+ + H_2 \rightarrow HCO^+ + H_2$ and of the reaction $O + C_3 \rightarrow CO + C_2$. Both reactions were found to be quite slow.

Herbst is continuing a theoretical program to understand nonthermal desorption of interstellar molecules from dust particles. The ubiquitous molecule CO has been chosen for detailed study. Energy is placed in a mode of the CO molecule, and the time dependence of the CO – dust system is followed on a supercomputer by detailed quantum mechanical means. In the latest calculation, F. Dzegilenko (Emory U.) and Herbst studied the effect of translational energy, finding that sufficient translational energy can lead to desorption of CO molecules from dust particles, by a rather complex mechanism involving the transfer of energy through a hindered rotational mode known as 'libration'.

In order to understand inelastic collisions between the important interstellar species HCO^+ and H_2, Q. Liao (OSU Physics) and Herbst used several theories to try to duplicate the laboratory pressure broadening of rotational lines of HCO^+ by collisions with H_2 in the $10 - 30$ K range. The most successful theory utilized is a so-called simple capture theory, but its surprising success raises questions concerning the true detailed quantum mechanics of the scattering process. More detailed quantum scattering calculations are currently being undertaken.

J. Pearson (OSU Physics; now JPL), K. Sastry (New Brunswick), F. De Lucia (OSU Physics), and Herbst have measured the millimeter-wave and submillimeter-wave spectrum of the known interstellar molecule ethyl alcohol (ethanol) in its first excited gauche state. This state, which lies only 60 K above the ground trans state, is certain to be populated in warm interstellar clouds. Some of the measured frequencies have already been found to correspond with previously unknown 'U' lines from interstellar hot core-like sources. In another laboratory study, Herbst collaborated with G. Winnewisser and S. Belov (U. Köln) to extend the known submillimeter-wave spectrum of methanol up to 1.2 THz.

Ryden analyzed the apparent shapes of Bok globules and dense molecular cloud cores, as reported in the literature, under the alternative hypotheses that they are randomly oriented oblate objects or randomly oriented prolate objects. For all the data sets examined, the prolate hypothesis provides a better fit to the data. If Bok globules and dense cores are prolate, then their mean intrinsic axis ratio is $\gamma \approx 0.5$.

Berlind, Quillen, Pogge, and Sellgren have measured the extinction law in a galaxy's spiral arm and interarm regions using a visual and infrared imaging study of the overlapping galaxy pair NGC 2207 and IC 2163. They measure the extinction as a function of wavelength and find that there is less extinction in the optical bands than expected from a normal Galactic extinction law. This deviation is significantly larger in the interarm region than in the spiral arm. The extinction curve in the spiral arm resembles a Milky Way $R = 5.0$ dust model and the interarm extinction curve is flatter still. Scattering effects are negligible. Examining the effect of an unresolved patchy dust distribution, they found that even a simple two-component dust model can flatten the extinction curve significantly.

5 Our Galaxy

Terndrup, in collaboration with E. Sadler (U. Sydney) and R. M. Rich (Columbia), has completed an analysis of the metallicity distribution in the Baade's Window field of the nuclear bulge. They presented [Fe/H] and distance estimates for over 300 stars and discussed trends in the CN strengths and [Mg/Fe] ratio as a function of [Fe/H]. Using two different analysis techniques, they demonstrated that the bulge stars show, on average, [Mg/Fe] > 0 up to solar [Fe/H], but [Mg/Fe] ≈ 0 at higher abundances. This is consistent with recent work at high resolution, and suggests that the initial formation of the bulge was fairly rapid ($\leq$ 1 Gyr). The CN strengths are fairly normal at low [Fe/H] but are surprisingly weak at high abundance, which may indicate that bulge stars have low or absent core/envelope mixing at high [Fe/H]. A paper on the three-dimensional kinematics of the bulge is in preparation.

Tiede, Frogel, and Terndrup have completed an extensive survey on the near-IR color-magnitude diagram in the nuclear bulge. They confirm previous estimates of a metallicity gradient in the inner Galaxy and provide a discussion of the bolometric corrections in the visual and near-IR for bulge stars. Tiede has now commenced his dissertation research on the kinematics of the inner bulge and disk of the Galaxy.

R. Blum (JILA), J. Carr (NRL), Sellgren, and Terndrup have investigated the mass distribution of the inner 600 pc of the Galaxy, by measuring radial velocities for ~40 stars in each of four optically obscured, off-axis fields toward the Galactic bulge. Their four fields lie nearly along an axis whose position angle from the major axis of the Galaxy is 55 degrees. The observed kinematics generally match both axisymmetric and barred dynamical model predictions, but are marginally better described by a barred model. The velocity dispersion in the innermost field is high, which suggests, when combined with data from previous studies at larger radii, that the stellar velocity dispersion is flat or still rising at a projected radius of about 150 pc.

Blum, Sellgren, and DePoy have obtained J, H, K, and L photometry for the stars in the central $2'$ (5 pc) of the Galaxy. Using the observed $J-H$, $H-K$, and $K-L$ colors and assumed intrinsic colors, they determine the interstellar extinction at 2.2 μm (A_K) for ~1100 individual stars. The mean A_K of 3.3 mag is similar to previous results, but they find that the reddening is highly variable, and some stars are likely to be seen through A_K > 6 mag. The de-reddened K-band luminosity function points to a significantly brighter component to the stellar population (> 1.5 mag at K) than found in Baade's window, confirming previous work done at lower spatial resolution. The observed flux of all Galactic center stars with estimated K_0 (de-reddened magnitude) $\leq$ 7 mag is ~25% of the total. Their observations confirm the recent finding that several bright M stars in the Galactic center are variable. Their photometry also establishes the near-IR variability of the M1–2 supergiant, IRS 7.

Gould, C. Flynn (Tuorla Obs.), and J. Bahcall (IAS) used the Hubble Deep Field to strongly constrain the baryonic content of the Galactic dark halo.

Wing has obtained classification photometry on his eight-color narrow-band system for 8 supergiant stars of types G, K, and M belonging to Westerlund's heavily reddened cluster in Ara. The aim is to obtain improved measures of CN strength (and hence luminosity) and reddening in order to determine the cluster distance. It appears that the cluster – which is seen through the dusty Sagittarius Arm – lies at a distance of 4-5 kpc and is a major feature of a little-known interior arm.

6 Extragalactic Astronomy

A relatively small number of luminous stars dominate the bolometric luminosity and near-IR light of many star clusters – M supergiants in young clusters, and AGB stars in intermediate age clusters. To interpret integrated light observations of galaxies in terms of simple stellar populations, such as those of star clusters, the effects of stochastic variations in the number of luminous stars must be evaluated. Santos and Frogel have examined the influence of such stochastic effects on the integrated near-IR light of star clusters with ages $7.5 < \log t < 9.25$. They used stellar evolution models and a Monte Carlo technique to simulate the effects of stochastic variation on the number of main sequence, giant, and supergiant stars for single-generation stellar populations. The fluctuations in the integrated light produced by such variations were evaluated for the $VJHK$ bands. They demonstrated that the observed scatter in the integrated colors of clusters of a given SWB type in the Magellanic Clouds can be largely accounted for by such stochastic variations. Implications of this analysis are important for studies of the integrated light of stellar populations where it is not possible to resolve individual stars.

Using the IRAM Plateau de Bure Interferometer, Kaufman, N. Brouillet (Bordeaux), F. Combes (Paris), A. Baudry (Bordeaux), and F. Bash (U. Texas) have detected CO J = 1-0 line emission from 6 molecular cloud complexes in M81, with viral masses $\sim 10^6\,M_\odot$ and radii ~ 100 pc. They find that the ratio of $N(H_2)/I(CO)$ in these clouds is consistent with the standard Galactic value, within an uncertainty of 50%.

Kaufman, E. Brinks (NRAO), M. Thomasson (Onsala), D. Elmegreen (Vassar), B. Elmegreen (IBM), C. Struck (Iowa St.), and M. Klaric (Midlands Tech) have taken VLA H I and radio continuum observations, CO J = 1-0 data, and B, I, J, and K-band images of the ocular galaxy NGC 2535 interacting with its smaller starburst companion NGC 2536. There are unusually massive H I clouds on the tidal arms of NGC 2535; these do not coincide with the most luminous blue knots, and most are not detected in CO emission. The data in the H I cube imply that NGC 2536 is presently passing through the outer part of the tidal bridge of NGC 2535; this is consistent with Klaric's galaxy encounter simulation of the system. In addition to tidal arms, NGC 2535 has an outer elliptical H I arc, which may be a gravitational wake produced by the passage of NGC 2536 within or close to the extended H I envelope of NGC 2535. In radio continuum emission, NGC 2535 has a bar-like feature that leads the stellar bar, as seen in the near infrared, by 50 degrees.

Kuchinski and Terndrup have presented an initial analysis of their work on the opacity of highly-inclined spiral galaxies, many of which show a boxy or peanut-shaped bulge, as does the Milky Way. In their first paper, they demonstrated that the corrections for dust are strongly dependent on the assumed geometry of the extinction, and even in the K band the galaxies can be optically thick near the plane. Kuchinski is now pursuing a more extensive analysis of these galaxies, in collaboration with A. Witt (U. Toledo) and his research group.

Thakar, with Ryden, K. Jore (Cornell), and A. Broeils (Cornell), has modeled the formation of the counterrotating disk recently discovered within the Sa(r) galaxy NGC 4138. Both continuous retrograde infall of gas and a retrograde merger with a gas-rich dwarf are successful in producing a counterrotating disk of the observed mass and dimensions without overheated the primary disk. It is possible that the Hα ring seen in the inner half of the disk is a consequence of counterrotating gas colliding with pre-existing corotating gas, forming stars in the process.

Ryden, Terndrup, Pogge, and T. Lauer (KPNO) made a study of dwarf elliptical and dwarf S0 galaxies in the Virgo cluster. For each of 81 dwarf ellipticals and 14 dwarf S0's, they computed the mean ellipticity, the boxiness or diskiness, the shape of the luminosity profile, and a newly defined 'twistiness' parameter T, which quantifies the twist of the isophotes as a function of semi-major axis. In none of these parameters do the dwarf S0 galaxies differ greatly from the dwarf elliptical galaxies. Kinematic data will be needed to determine whether, in fact, there exists a class of pressure-supported dwarf ellipticals and a class of rotationally-supported dwarf S0's.

Work continues on the OSU survey of spiral galaxies. The immediate objective of obtaining $BVRJHK$ images of about 230 spiral galaxies is nearing completion; analysis of the data on hand continues. Frogel spent 9 months at the University of Durham working with R. Davies and R. de Jong developing the tools needed to analyze the large data base. One paper that resulted from the analysis carried out this year concerns the existence of spiral bulges with boxy or peanut-shaped morphology. Several mechanisms have been proposed to explain these structures, including resonant heating by bars, bending instabilities in the disk, and accretion of small satellites. Kinematic studies of spectra in a few edge-on peanut-shaped bulges have provided strong evidence that these bulges are indeed barred. The advent of large format infrared array detectors makes it possible to carry out surveys of galaxy morphology in the near-IR and to search for structures that at visible wavelengths would be obscured by dust or hidden by the presence of young stars. Quillen, Kuchinski, Frogel, and DePoy now report the discovery in the near-IR of a peanut-shaped bulge in the highly inclined Seyfert 2 galaxy NGC 7582. The peanut shape is clearly evident in JHK images, but obscured by extinction from dust in BVR images. This suggests that near-IR imaging surveys will discover a larger number of boxy/peanut morphologies than visible surveys, particularly in galaxies with heavy extinction such as NGC 7582.

Quillen and Frogel have studied the ringed galaxy NGC 6782 as another example of how imaging data from the galaxy survey can be used in a study of galactic dynamics. Outer rings are located at the greatest distance from the galaxy center of any feature resonant with a bar; because of their large scale, their morphology is sensitive to the distribution of dark matter in the galaxy. Quillen and Frogel compared periodic orbits integrated in the NGC 6782 potential near the outer Lindblad resonance to the shape of the outer ring. The non-axisymmetric component of the potential was derived from a near-IR image of the galaxy. The axisymmetric component was derived assuming a flat rotation curve. The maximally pinched non-self-interacting periodic orbits were found to be more elongated for high bar mass-to-light ratios. For the orbits to be consistent with the observed ring morphology, the mass-to-light ratio of the bar must be high, and so a maximal disk value is preferred. This implies that either there is little dark matter within the bar, or that the dark matter contained in the disk of the galaxy is non-axisymmetric and rotates with the bar.

7 Active Galactic Nuclei and Quasars

Peterson, Pogge, Wanders, Wagner, and Bertram are continuing a long-term program of spectroscopic monitoring of selected Seyfert galaxies. Their data are being used in 'reverberation mapping' studies of the broad-line region in active galactic nuclei (AGN). Spectroscopic observations of these galaxies are obtained with the CCD spectrograph on the Perkins 1.8m telescope, on an approximately weekly basis. Much of this monitoring is carried out in support of multiwavelength monitoring campaigns undertaken by the International AGN Watch, a large informal consortium of AGN observers; Peterson is one of the organizers of AGN Watch activities. In the last year, analysis of optical spectroscopic monitoring data has been completed for two Seyfert 1 galaxies, Mrk 509 and Mrk 335. In Mrk 335, the Hβ emission line responds to continuum variations on a time scales of 17 days, and He II λ4686 responds with a delay of only 2 days. In the case of the more luminous source Mrk 509, the time delays are about 80 days and 60 days for Hβ and He II, respectively. The Mrk 509 result is based on several years of monitoring by several groups. Similar data on other sources are currently being analyzed.

Pogge and M. DeRobertis (York U.) obtained Integral Field spectroscopy of the circumnuclear regions of seven Seyfert galaxies using the ARGUS spectrograph on the 3.6m CFHT. The target galaxies all have previously known extended emission-line regions surrounding the nucleus, and evidence of ionization cones or shock-like features from previous CFHT and HST imaging work. Pogge and DeRobertis find multiple velocity components in the circumnuclear ionized gas of all the target galaxies: a general rotation pattern upon which additional components with peculiar motions are superimposed. These peculiar motions are generally associated with the location of radio plasma 'lobes' seen in VLA maps, confirming previous suggestions of shocked components in the ionized gas where the outflowing radio plasma is ramming into the circumnuclear ISM. In one of the galaxies (NGC 1068), the high-ionization coronal [Fe VII]λ6087 emission line is spatially extended on 2–3$''$ scales, and shows multiple velocity components that appear to be the extension of the larger-scale peculiar motions seen in lower-ionization species.

Kennefick, Osmer, M. Smith (CTIO), and R. de Carvalho (Observatório Nacional, Brazil) are conducting a search for quasars at $4.8 < z < 6.5$ for the purpose of determining quasar space densities at these redshifts. The survey relies on a multicolor technique, using object catalogs from the Second Palomar Observatory Sky Survey with the addition of z-band CCD data acquired at the Curtis Schmidt at CTIO and the Burrell Schmidt at KPNO. So far the survey covers ~ 300 deg^2; it is hoped that another 500 deg^2 will be added during the coming year.

Kennefick, as part of her Caltech PhD thesis, conducted a survey for, and computed space densities of, quasars at $z > 4$. Last year, Kennefick, Osmer, M. Pahre (Caltech), and S. Djorgovski (Caltech) obtained K-band magnitudes for the quasars in the Kennefick thesis sample. These K-band magnitudes measure the flux of the $z \sim 4$ quasars at restframe B, allowing for a more direct measure of their absolute M_B, and, when combined with their optical spectra, an estimation of their true spectral indices. They computed a median spectral index of -0.87 for the sample, and values of M_B that are on average ~ 0.5 mag brighter than previously computed.

Osmer, Kennefick, Pogge, Weinberg, Conti, and Martini have been undertaking a project to determine the abundance of faint quasars and AGN in the Hubble Deep Field. The data were taken in the $UBVI$ bands, making them suitable for a multicolor survey for quasars and AGN over a wide range of redshifts. Most of the work so far has been in constructing object catalogs and determining their completeness through Monte Carlo simulations. In the coming year, Osmer and collaborators will develop rigorous candidate selection procedures for quasars and AGN, making both the catalogs and candidate lists available to the public.

Osmer continued his work on a deep multicolor survey for quasars with P. Hall (Arizona), R. Green (NOAO), A. Porter (deceased), and S. Warren (Imperial College). Kennefick joined the project during the year and worked on spectroscopic observations of additional candidates from the survey, which are now being prepared for publication. The data confirm 13 new quasars with $0.3 < z < 2.8$. These results increase the total number of quasars in the 0.83 deg^2 area to 58. The results also suggest that the excess of quasars at $z > 3$ in the survey will be less than indicated by the first spectroscopic observations. The plan for the coming year is to complete the spectroscopy of the high redshift candidates and publish the first catalog of positions and magnitudes for the 21,375 'stellar' objects in the survey.

Anomalously high optical and UV fluxes are observed in some quasars and AGN, particularly from Fe II spectra; this is the so-called "Fe II problem". A. Sigut (U. Toronto) and Pradhan are developing a new code, based on an extensive atomic model with radiative transfer, that would test various physical mechanisms potentially responsible for the Fe II problem. X-ray spectra from highly ionized iron ions are also being studied, with a view to understanding the gravitational redshifts of the Kα lines and testing the paradigm of a supermassive black hole with an accretion disk.

8 Atomic Processes

Heavy elements of the iron-peak group, such as iron, cobalt, and nickel, are of great importance as end products of stellar nucleosynthesis. As part of the ongoing Iron Project, Zhang and Pradhan finished, and submitted for publication, electron impact excitation collision strengths for Fe III and Fe XXII. The latter is an improved calculation with relativistic effects and radiative damping included. Calculation of collision strengths for Fe IV has also been included.

Zhang and Pradhan extended the unified method for calculating photorecombination cross sections, including both the direct recombination and di-electronic recombination, from LS coupling to fine structure, for applications in highly charged ions. Using this method, di-electronic satellite lines for highly charged He-like and H-like iron were calculated for explanation of some observed x-ray spectra. Photorecombination spectra for Ar XIV, as well as for Fe XXV, were also calculated and compared with experiments. It is now also possible to calculate photoionization cross sections for high-energy and highly-charged ions, including the relativistic effects, using either the Breit-Pauli R-matrix or the relativistic distorted wave codes.

Nahar continues her large-scale calculations of photoionization and recombination cross sections for astrophysically abundant elements. Nahar and Pradhan have implemented their new, unified recombination rates of the carbon ions, C I–C VI, and nitrogen ions, N I–N VII, for the determination of ionization fractions of these ions in thin, coronal plasmas. The new results differ significantly from the earlier values. However, the main point of this work is to provide, for the first time, completely self-consistent rates for photoionization and recombination for photoionization models. The rates are calculated using an identical set of atomic eigenfunctions for both photoionization and recombination, and are therefore self-consistent in an *ab initio* manner. Nahar has also calculated an extensive set of fine structure radiative transition probabilities for Fe III.

9 Nuclear Astrophysics

The inability of the standard model of big bang nucleosynthesis to reproduce the primordial abundances has led Boyd and his collaborators to pursue several efforts associated with inhomogeneous models. (1) G. Raimann (OSU Physics), F. Chloupek (OSU Physics), Boyd, and their Japanese collaborators have completed two experimental papers on reactions of possible interest to inhomogeneous models. These involve studies of states in very short-lived neutron-rich resonances that would affect the (n,γ) rates on nuclides such as ^{16}C and ^{18}N. Experiments were done at RIKEN, in Japan, to produce beams of ^{17}B and ^{19}C, and then look for the β-delayed neutron emission from these nuclides. No neutron groups were observed that would affect the low energy (n,γ) cross sections, suggesting that the neutron captures on ^{16}C and ^{18}N are dominated by direct processes. (2) A study of the apparent inconsistencies among the various experiments designed to yield the ^{8}Li(α,n)^{11}B cross section, which is crucial to inhomogeneous models, was performed by Boyd, T. Paradellis (Inst. Nucl. Phys., Greece), and C. Rolfs (Ruhr-Universitäa Bochum). The inconsistencies between the measurements may be related to overlapping states, and those experiments in question might then be consistent with the direct ^{8}Li(α,n)^{11}B cross section measurements made by Boyd and his collaborators over the past several years. (3) A theoretical study by Boyd, M. Orito (National Astronomical Obs., Tokyo), T. Kajino (N.A.O., Tokyo), and G. Mathews (Notre Dame) has been completed on geometry dependent effects of inhomogeneities on big bang nucleosynthesis. It was found that cylindrical shell inhomogeneities (produced by cosmic strings, for instance) produces the best correspondence with the observations, and allow a somewhat higher baryon-to-photon ratio than can be obtained with the standard model. However, that ratio is still well below the closure density. (4) M. Balbes (OSU Physics), Boyd, Stegiman, and D. Thomas (OSU Physics) studied a scenario, suggested by Gnedin and Ostriker, in which postprocessing of primordial nuclides, by radiation from primordial black holes, would modify the abundances predicted by the standard model. They found that when the abundances were studied in detail as a function of the amount of material processed, there were no solutions that even came close to reproducing the observed primordial abundances.

M. Balbes, M. Hencheck, J. Vandegriff, J. Kalen, E. Sugarbaker (all OSU Physics), and Boyd, with other collaborators, have completed measurements of the neutron background in a possible underground site for the Supernova Neutrino Burst Observatory, which will allow detection of μ- and τ-neutrinos from a Galactic supernova via their neutron-producing interactions with rock. They performed measurements both with a bare neutron detector in the underground site, and with the detector enclosed in a neutron absorber. They found that most of the observed events originated within the detector, so that when low-background materials are used for detectors the backgrounds should be reduced appreciably.

Raimann, Balbes, Hencheck, and Boyd, with a number of German collaborators, have studied properties of nuclei at the proton drip line, using an accelerator in Germany. These nuclei may be important for production of light p-process nuclides, from mass 74 to $\sim$100, via high temperature stellar hydrogen burning. Since the seed nuclei in such burning scenarios are driven to the proton drip line, nuclei at the proton drip line are the progenitors of the final nuclei observed. The half-lives and decay modes of ^{96}Ag, ^{98}Ag, and ^{98}Cd have thus been studied.

The ^{12}C(α,γ)^{16}O reaction is critical for nuclear astrophysics. It directly determines the abundances of all the nuclides up to ^{56}Fe produced in the final phases of stellar evolution, and it determines the size of the iron core which a star must overcome in order to undergo a supernova explosion. Unfortunately, its cross section decreases by about 7 orders of magnitude from the lowest energy at which it has been measured to the energy relevant for helium burning. The low energy cross section is dominated by resonances associated with two subthreshold states in ^{16}O. Boyd, Raimann, and B. Chwieroth (OSU Physics), with Canadian collaborators, are studying the β-decay of ^{17}Ne to ^{17}F, which then proton-decays to states in ^{16}O. They have shown that there are states in ^{17}F populated in this decay sequence that populate the 6.917 MeV state in ^{16}O, from which one could hope to determine the resonant contribution from the 6.917 MeV state to the cross section for ^{12}C(α,γ)^{16}O.

A recent surprise from gamma-ray astronomy is the detection in Cas A of decays from ^{44}Ti, a nuclide produced in supernovae, but generally thought to be produced in insufficient quantities to be observed. Measurements of the half-life of ^{44}Ti have yielded values either around 45 years or around 65 years. The longer value would require production of ^{44}Ti in supernovae slightly beyond what present models appear capable of yielding, but the shorter value would demand large changes in the present ^{44}Ti production scenarios. Boyd, with collaborators from Notre Dame and Michigan State, has remeasured the half-life. The measurement appears to yield a value consistent with the shorter half-life, but the experiment is scheduled to be rerun early in 1997.

Over the last few years, increasingly accurate observational data have led to meaningful bounds on the primordial abundances of D, ^{3}He, ^{4}He, and ^{7}Li, which have begun to challenge the consistency of the predictions of standard big bang nucleosynthesis (SBBN). To explore this question, the OSU group of N. Hata, Scherrer, Steigman, D. Thomas, and Walker has performed a statistical analysis of the confrontation between theory and observations. Deuterium and ^{3}He provide the lower bound to the nucleon-to-photon ratio η, and ^{4}He, ^{7}Li and D provide upper bounds to η. The inferred primordial abundance of deuterium is low, suggesting that η and the ^{4}He abundance (mass fraction Y_P) should be high. In contrast, the derived value of Y_P is low, requiring (for SBBN) a low value of η and a high abundance of primordial deuterium. These two conflicting demands constitute the crisis for SBBN. Hata and collaborators identify several ways in which the crisis may be ameliorated. Perhaps the derived bound on the primordial abundance of D is overly restrictive; perhaps unidentified systematic effects have led to an inferred value of Y_P which is too small. If the tau neutrino were massive ($\sim 10-24$ MeV) and unstable (lifetime $\sim 0.01-0.1$ sec) the tension between D and ^{4}He would be relieved.

The predicted SBBN primordial abundances of D and ^{3}He depend sensitively on η, providing, thereby, an ideal 'baryometer'. Unfortunately, for the most part these light elements are observed 'here and now'. It is necessary to employ a chemical evolution model to infer the primordial abundances of D and ^{3}He. In an attempt to finesse the model dependent uncertainties, Steigman and M. Tosi (Bologna) have developed a generic approach to D and ^{3}He evolution which avoids specific evolution models by relegating all the model dependence to a single parameter g_3, the ^{3}He survival fraction. Hata, Scherrer, Steigman, Thomas, and Walker have extended the generic analysis in a statistical survey; this work uses both solar system and interstellar data to derive a new upper bound to primordial D and ^{3}He.

Nonetheless, it is also important to explore the predictions of detailed models of stellar and Galactic evolution. M. Tosi, D. Dearborn (LLNL), and Steigman have used a new grid of stellar models which track both D and ^{3}He, in concert with chemical evolution models to follow the Galactic evolution of D and ^{3}He as a function of time and location. The stellar models confirm the production of significant amounts of new ^{3}He by low mass stars. Indeed, stellar ^{3}He production is so overwhelming that even in the absence of any primordial D or ^{3}He all evolution models predict ^{3}He abundances in excess of those observed in the solar system and in Galactic H II regions. To reconcile this apparent contradiction, Dearborn, Steigman, and Tosi have explored a series of non-standard stellar models in which the ^{3}He yields are modified.

Claims of detection of deuterium in a handful of high-redshift, low-metallicity QSO absorption systems have stimulated the hope that the primordial abundance of D may be derived directly from the data, without recourse to chemical evolution models. However, the few observations available appear contradictory: two systems of high-redshift, low-metallicity absorbers seem to have high D; two others have low D. Hata, Steigman, S. Bludman (U. Penn.), and P. Langacker (U. Penn.) have considered the implications for SBBN of each case. High D is consistent with SBBN, but implies a very low nucleon density, and challenges models of Galactic chemical evolution. In contrast, low D is in conflict with SBBN, but suggests a more reasonable nucleon density, and is consistent with 'normal' Galactic evolution.

As the second most abundant nuclide in the universe, ^{4}He plays a key role in testing SBBN and in probing for new physics beyond the standard model. K. Olive (Minnesota) and Steigman have included new data on ^{4}He in low metallicity extragalactic H II regions to infer the primordial helium abundance ($Y_P = 0.230 \pm 0.003$). The large number of independent measurements of high statistical accuracy is responsible for the very small uncertainty in Y_P. This relatively low value for Y_P exacerbates the challenge to SBBN. Olive and Steigman have also used the data in a semi-empirical approach to bounding a large class of possible contributions to systematic offsets in Y_P. In a parallel effort to pin down Y_P, Steigman is collaborating with S. Viegas (IAG/USP Brazil) in modeling the low metallicity H II regions with the goal of estimating the size of several potential sources of uncertainty, such as ionization corrections and temperature fluctuations.

X-ray observations of rich clusters of galaxies reveal that baryons in the hot intracluster gas dominate those in the visible galaxies. The fraction of the total mass in hot gas is $f \approx 0.20h^{-3/2}$. If such clusters provide a fair sample of the universal fraction of baryons, these data may be used in concert with observational estimates of $\Omega_{\rm tot}$ to infer $\Omega_{\rm bary}$ (and, equivalently, η). Steigman, J. Felten (NASA/GSFC), and Hata have begun to explore this alternate approach to the universal density of baryons. The large cluster baryon fraction drives this approach to inferring a large baryon density ($\eta_{10} \approx 7 \pm 2$), favoring the high-D option for QSO absorption systems.

Scherrer and R. Leonard (OSU Physics) examined primordial element production for the case where the early universe is inhomogeneous. This problem has been examined, on and off, for twenty years, but all previous investigations have used specific functions for the distribution of densities in the early universe. Scherrer and Leonard we able to treat the most general case of arbitrary inhomogeneity using linear programming, essentially bringing to a close the investigation of inhomogeneous models.

10 Cosmology & Large Scale Structure

In collaboration with N. Katz (U. Washington), L. Hernquist (UC Santa Cruz), J. Miralda-Escudé (IAS),

R. Davé (UC Santa Cruz), and J. Gardner (U. Washington), Weinberg has been using cosmological simulations with gas dynamics to study the formation of Lyman-α quasar absorption systems at $z \geq 2$. The simulations show that the Lyα forest arises naturally in cold dark matter (CDM) cosmogonies as photoionized gas falls into dark matter potential wells. The low column density absorption systems are extended, anisotropic, low-overdensity structures, far from dynamical or thermal equilibrium. These structures are scaled-down versions of the galaxy superclusters observed today. When the simulated spectra are analyzed using the traditional technique of Voigt-profile decomposition, they reproduce the large number of low column density lines found in Keck HIRES spectra. Weinberg and collaborators are developing new methods for analyzing simulated and observed spectra that correspond more closely to the physical picture that emerges from the simulations and that may have more power to discriminate between competing cosmological scenarios. Croft, Weinberg, Hernquist, and Katz have been analyzing helium absorption in these simulations, considering several different CDM cosmogonies. Absorption of quasar light by intergalactic helium is the only known way of directly probing truly underdense regions of the universe. Space-based observations reveal the same basic trend of mean optical depth with redshift predicted by the combination of CDM models and the UV radiation background from quasars. The high value of the optical depth, however, indicates a higher baryon content than is predicted by standard big bang nucleosynthesis.

Owen, in collaboration with Weinberg, Katz, Hernquist, and A. Evrard (U. Michigan), has analyzed hydrodynamic cosmological simulations that start from scale-free initial conditions. Because the initial conditions have no preferred scale and the simulations do not include radiative cooling, the properties of collapsed objects should evolve according to self-similar scaling laws. This study tests the ability of the numerical simulations to reproduce this self-similar scaling, finding significant but not complete success; it shows that two different implementations of cosmological hydrodynamics yield similar results for well resolved systems. Owen is currently performing a set of experiments that have scale-free initial conditions and radiative cooling, with a cooling law chosen so that it preserves self-similar evolution. This study will illustrate the role of radiative cooling in cosmological simulations, and it will test the ability of such simulations to achieve reliable results for galaxy formation.

Owen and J. Villumsen (MPA Garching) have completed an investigation on the effects of a minimum temperature in hydrodynamical cosmological simulations. This study shows that a globally defined Jeans mass, set by this minimum temperature, constitutes a minimal resolution requirement for the hydrodynamical cosmological experiments to converge. Owen has also continued work, with Villumsen, P. Shapiro (U. Texas), and H. Martel (U. Texas), on the technique of Adaptive Smoothed Particle Hydrodynamics, publishing one paper and completing a second. These papers show that the use of geometrically adaptive kernels can substantially improve the spatial resolution of SPH for a fixed number of particles.

Weinberg continued work on a variety of problems in large scale structure, including methods for reconstructing initial fluctuations from galaxy redshift data (with Narayanan), using the anisotropy of the quasar correlation function as a method for constraining the cosmological constant (with Popowski, Ryden, and Osmer), computing the abundance of galaxy clusters in COBE-normalized CDM models (with S. Cole and C. Frenk, Durham U., and B. Ratra, Kansas State), and simulating the redshift sample of the Sloan Digital Sky Survey (with R. Gott, Princeton, and C. Park, Seoul National U.). He continued work on galaxy target selection algorithms for the Sloan Survey and joined the project's Science Advisory Committee.

Croft and E. Gaztañaga (Barcelona) have been working on reconstructing the initial density and velocity fields of the universe. One method involves reversing gravitational dynamics under the assumption that mass elements move in straight lines (the Zel'dovich approximation). The algorithm has been extensively tested on numerical simulations, where it performs well. An application to data from the IRAS 1.2 Jy redshift survey is in progress. The second reconstruction method is based on quantitatively identifying features of a density field which are preserved under gravitational evolution and with galaxy biasing. To this end, the number density of peaks in the density field has been studied. Numerical simulations show that this is a preserved quantity if large enough smoothing ($> 5\,$Mpc) is applied. As the peak density can be directly related to the slope of the power spectrum on the filter scale, this provides a method of recovering the initial mass power spectrum. Again, an application to the IRAS 1.2 Jy survey is underway.

Croft, G. Dalton, and G. Efstathiou (Oxford) have been measuring the clustering of galaxy clusters measured from a recent extension of the APM cluster redshift survey to high richness objects. They find that the clustering strength of these rare peaks in the galaxy distribution ($n < 2 \times 10^{-6}\,\mathrm{Mpc}^{-3}$) is consistent with that of lower richness clusters. This is predicted by currently favored Gaussian models of structure formation, and means that more exotic non-Gaussian or fractal scaling models need not be invoked to explain clustering on extremely large scales.

A. de Laix (OSU Physics) and Scherrer investigated isocurvature hot dark matter models, in which massive neutrinos are the dark matter in the universe. Their results indicate that certain versions of this model may give a distribution of galaxies which agrees with observations; the model may also provide a natural mechanism to enhance the production of hydrogen gas clouds at high redshift.

Scherrer and Z. Protogeros (OSU Physics) completed work on models for the evolution of the density distribution function due to gravitational clustering. They developed several approximations for the evolution of the density field and tested their approximations against numerical simulations, finding remarkable agreement using very simple arguments. Scherrer and Protogeros have also finished investigating the evolution of the skewness of the divergence of the peculiar velocity field for non-Gaussian initial conditions. While the calculations were straightforward, they found interesting results concerning linear combinations of the density skewness and velocity skewness which may be interesting for the analysis of large scale structure.

Scherrer and A. Vilenkin (Tufts) are examining the initial conditions for the formation of cosmic strings in the early universe with a variety of initial field configurations. They found that for power spectra of the form $P(k) \propto k^n$, a phase transition occurs, with the disappearance of infinite strings, at $n = -2$. They are planning to follow up this project with a similar study of monopole formation in the early universe; this work may also be useful in areas outside cosmology.

Gould continues to work on applications of gravitational microlensing. He developed a general theoretical treatment of 'pixel microlensing' (the microlensing of unresolved stars) and suggested several new applications of microlensing, including a search for intracluster dark matter. Together with Gaudi and T. Boutreux (Saclay), he made a systematic study of satellite parallaxes of microlensing events. Working with Han, Narayan, R. Nemiroff (NASA/GSFC), and D. Welch (McMaster U.), he developed new techniques for detecting microlensing events and extracting additional information from these events.

Weinberg and Gould analyzed the possibility of detecting the Lyman-alpha forest in three dimensions in emission. By taking a series of spectra, it will be possible to map optically thick Lyα clouds in three dimensions.

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