

Carnegie Institution of Washington
Department of Terrestrial Magnetism
Washington, DC 20015-1305

This report covers astronomical research carried out during the period July 1, 1994 – June 30, 1995. Astronomical studies at the Department of Terrestrial Magnetism (DTM) of the Carnegie Institution of Washington encompass observational and theoretical fields of solar system and planet formation and evolution, stars and star formation, galaxy kinematics and evolution, and various areas where these fields intersect.

1. PERSONNEL

Staff Members: Sean C. Solomon (Director), Conel M. O'D. Alexander, Alan P. Boss, John A. Graham, Vera C. Rubin, François Schweizer, George W. Wetherill

Postdoctoral Fellows: Harold M. Butner, John E. Chambers, Prudence N. Foster, Munir Humayun, Stacy S. McGaugh, Bryan W. Miller, Elizabeth A. Myhill, David L. Rabinowitz

Predocutorial Fellow: Lori K. Herold

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2. RESEARCH PROGRAMS

2.1 Planetary System Formation

Prudence Foster and Alan Boss have continued their study of triggered collapse of the solar system and of low mass stars. Using numerical models, they are examining the viability of scenarios where a shock wave impacts a molecular cloud, triggers collapse, and injects particles from the shock wave into the collapsing molecular cloud. Such a scenario can solve the problem of having live ^{26}Al present in the solar system at the time of formation of certain meteoritical inclusions (CAIs). This year Foster completed the code development. The major programming accomplishment was to develop and test a Poisson solver in cylindrical coordinates, the preferred coordinate system for the problem. The solution of the Poisson equation gives the self-gravity of the gas which undergoes collapse.

With the new code, Foster and Boss examined a suite of models, and found that merely changing the adiabatic index, γ , could drastically alter the results. Previous simulations of supernovae (SN) impacting clouds have shown that the clouds are usually destroyed. Foster & Boss found that if the supernova is distant, such that γ is effectively reduced from $5/3$ to 1 , the cloud is not destroyed, but instead undergoes sustained gravitational collapse. Foster & Boss also found that a good criterion for shock-induced collapse is the momentum of the shock. Below a critical value, $0.2 M_{\odot} \text{ km/s}$, the shock will not instigate collapse. Both supernova and

protostellar outflows have this much momentum out to relatively large distances. Planetary nebulae do not, but with their characteristic high post-shock temperatures, collapse again occurs. Hence all three outflows appear to be able to trigger the collapse of molecular clouds to form stars.

Foster and Boss are continuing this work and examining the possibility of introducing ^{26}Al into the early solar system in a heterogeneous manner. Some meteoritical inclusions (chondrules) show no evidence for live ^{26}Al at the time of their formation. So either the chondrules formed after the aluminium had decayed away, or the solar nebula was not uniformly populated with the isotope. Foster & Boss are exploring the injection of shock wave particles into the collapsing solar system. Preliminary results are that $\sim 40\%$ of the incident shock particles are swallowed by the collapsing disk/star system, with the particles arriving at the collapsing star in two bursts separated by about 80,000 years.

Boss used a two-dimensional radiative hydrodynamics code to calculate steady state models of the thermal structure of low mass protoplanetary disks undergoing mass accretion from their molecular cloud envelopes. The standard model consists of a $0.02 M_{\odot}$ disk in Keplerian orbit about a $1 M_{\odot}$ central protostar, accreting mass at a rate of $\sim 10^{-6}$ to $10^{-5} M_{\odot}/\text{yr}$. With these assumptions, the midplane temperatures in the disk are above 1000 K inside about 2 AU, and fall to the ice condensation point (~ 160 K) around 6 AU. This particular model predicts that the icy cores necessary for giant planet formation could not form inside about 6 AU, which is only slightly larger than Jupiter's orbital radius of 5.2 AU. When the models are extended to study the structures of lower mass protostars (for fixed disk mass), the midplane temperature profiles shift inwards, but not greatly: the ice condensation point falls around 5 AU for a $0.5 M_{\odot}$ star and at ~ 4.5 AU for a $0.1 M_{\odot}$ star. This weak dependence on stellar mass is contrary to what would be predicted based on the main sequence luminosities, and is due to the fact that the disks largely determine their own temperature distribution, which is fixed by the disk mass and the mass accretion rate. These models imply that Jupiter-like planets orbiting low-mass stars may be found at distances only slightly closer to their stars than Jupiter is to the sun.

Boss examined a large number of models that have been proposed for the formation of the chondrules that dominate the composition of the most primitive meteorites. Meteoritical constraints such as the need for rapid heating to the melting point followed by cooling at rates on the order of a 1000 K per hour imply that a flash heating mechanism was responsible for the thermal processing of chondrules. Astrophysical constraints on the likely energy sources available for providing this heating seem to point to nebula shock waves as the most likely mechanism. However, the source of such shock waves remains to be elucidated – Boss and John Graham

proposed that the impact of distinct clumps of infalling molecular cloud gas on the surface of the solar nebula may have launched shock waves capable of thermally processing chondrule precursors. While this hypothesis is difficult to test, ongoing observations by others of the variable luminosity of young stars imply the presence of nearby dust clouds moving at high velocities, consistent with the hypothesis of chondrule formation by clump impact.

Primitive meteorites retain evidence of the conditions in the early solar nebula. C.M.O'D. Alexander has used the Washington University ion probe to measure trace element abundances in the various major constituents of ordinary chondrite meteorites. Many of these components, particularly chondrules, have been heated to 1800K to 2100K. Given the low pressures that existed in the solar nebula, significant evaporation during heating and recondensation during cooling may have occurred. The possibility that evaporation-recondensation may explain the major and trace element compositions of ordinary chondrite components is being explored through numerical simulations. Primitive meteorites also contain grains that formed in the atmospheres of other stars, primarily AGB stars and supernovae. C.M.O'D. Alexander has continued his collaboration with E. Zinner and L. Nittler in the search for and isotopic analysis of these presolar grains.

Laboratory-based investigations of the chemical and isotopic compositions of 5d transition metals (W, Re, Os, Ir and Pt) in meteorites and planetary samples in order to elucidate the nature and timing of formation of planets and asteroids are being carried out by Munir Humayun. Chemical processes involved in the formation of asteroids and planets separate the 5d transition metals from an initial solar abundance distribution of these elements. A long-lived radioisotope, ^{187}Re ($t_{1/2}=42.3$ billion years), decays to ^{187}Os , providing a cosmochronometer for processes separating Re from Os, which has yielded meaningful ages for iron meteorites. A potential test of the fidelity of $^{187}\text{Re}/^{187}\text{Os}$ dating of iron meteorites is provided by a short-lived radioisotope, ^{182}Hf ($t_{1/2}=9$ million years), decaying to ^{182}W , with a residence time comparable to the timescale between nebula formation and accretion of planetesimals to form embryonic planets. A search for this short-lived radioisotope is being carried out at DTM's isotope laboratories by performing isotopic analyses of W in meteorites with a precision of about 1 part in 10,000. A useful by-product of this investigation is a measurement of (or a limit on) the initial ratio of $^{182}\text{Hf}/^{180}\text{Hf}$ (a stable Hf isotope). The radioisotope ^{182}Hf is produced by two nucleosynthetic processes: 1) r-process from rapid neutron capture on lanthanides, followed by a β^- decay chain terminating at stable ^{182}W , and 2) fast s-process by neutron capture on ^{180}Hf , via ^{181}Hf ($t_{1/2}=42.4$ days, decaying to ^{181}Ta , the principal Ta isotope), to ^{182}Hf . The initial solar system $^{182}\text{Hf}/^{180}\text{Hf}$ ratio provides insights into the nucleosynthetic mixture of the sun's parental molecular cloud, and particularly into deciphering the nature of its last contributor (an AGB star or a supernova) providing live radioisotopes with half lives from 0.1 to 10 million years, including ^{26}Al (0.7 million years), ^{41}Ca (0.1 million years), ^{60}Fe (1.5 million years), and ^{107}Pd (6.5 million years).

John Chambers in collaboration with George Wetherill has begun a project to study a poorly-understood stage of the formation of the terrestrial planets, namely the transition from ordered accretion of material onto planetary embryos to a regime in which the embryos move on highly-eccentric crossing orbits, interacting strongly and colliding with one another. Several authors have previously noted that a pair of embryos in isolation are prevented from accreting one another if their orbital separation exceeds a critical value. Conversely, Chambers finds that in more realistic systems consisting of at least three embryos, close encounters occur even when the initial separation exceeds this critical value, allowing further accretion to occur. In addition, Chambers finds a robust relation between the initial orbital separation and the logarithm of the time of first close encounter in such systems. This relation appears to be very general and has implications for the stability of planetary and satellite systems.

Wetherill has extended the modelling of the final stage of planet formation to include variations that may be expected to occur in extrasolar planetary systems. These variations include differences in stellar mass, surface density of the protoplanetary disk, and absence of gas giant planets in the outer part of the planetary system. It is found that the general characteristics of these planetary systems are insensitive to variation in stellar mass. Because the position of zones habitable for living organisms are sensitive to stellar mass, planets associated with stars smaller than $0.5M_{\odot}$ tend to be too cold to be habitable, whereas those associated with stars larger than $1.5M_{\odot}$ tend to be too hot. The mass of the final planets is roughly proportional to the solid matter surface density of the disk. The effect of gas giant planets is to clear the region of the planetary system in the vicinity of their stronger commensurability and secular resonances. Planetary systems in which such bodies are more distant or absent may be expected to have terrestrial planets at the distance of our asteroid belt.

2.2 Solar System Evolution

David Rabinowitz and Wetherill worked together to model the origin of Earth-approaching asteroids, extending Wetherill's previous calculations in order to predict the size and orbital distribution of asteroids with diameters in the range 10 m to 1 km. Using Monte Carlo methods to model the effects of planetary encounters, and using analytic theory to predict the effects of resonant gravitational perturbations by the planets, Rabinowitz and Wetherill have shown that the collisional fragments of main-belt asteroids are sufficient to explain the observed number and orbit distribution of km-sized Earth approachers, but are not sufficient to explain the orbits of small Earth approachers (SEAs) with diameters less than ~ 50 m. Too many of the SEAs have low eccentricity, Earth-like orbits that are not predicted by the calculation. This result supports the earlier suggestion by Rabinowitz that $\sim 5\%$ or more of the SEAs originate from a local source, such as ejecta from the Moon, Mars, or an undiscovered population of small asteroids at the Earth's L4 and L5 Lagrange points.

Rabinowitz returned to Kitt Peak in April, May, and June to continue ongoing searches for SEAs at the Spacewatch

Telescope of the University of Arizona. These efforts resulted in the discovery of several new Earth approachers. He also participated in a NASA working group, headed by Gene Shoemaker at Lowell Observatory, and formed at the request of the U.S. Congress, with the task of preparing a 10 year plan to detect all Earth-crossing asteroids and comets with diameters larger than 1 km. The resulting plan calls for the construction of two dedicated search telescopes of ~ 2 m aperture, with state of the art focal-plane detector arrays, as well as investments to boost the capabilities of smaller, existing telescopes. Such a system could discover 60-70 % of the Earth-crossing asteroids larger than 1 km in a 10 year period.

Chambers has completed work on a study of the long-term orbital evolution of comet P/Swift-Tuttle, the largest known Halley-type comet. Results include the discovery that this comet librates about the 1:11 mean-motion resonance – the most distant resonance yet found for a comet, and a correlation between resonant/non-resonant motion and the value of the orbit's Lyapunov exponent, which has implications for long-term studies of the orbital motion of comets.

Sean Solomon continued his studies of the tectonic and volcanic evolution of Venus. Important clues to the interior structure and dynamics of Venus come from the relationship between variations in the planet's gravity field, recently measured by the Magellan spacecraft, and variations in surface elevation. The distribution and state of preservation of impact craters on Venus have been taken to indicate that most of the surface dates from the end of a global resurfacing event that ceased at about 500 million years ago. An important class of features, however, is younger. Solomon and Noriyuki Namiki of M.I.T. showed that the density of impact craters on the largest volcanoes on Venus, as a group, is half that of the planet as a whole. The most straightforward explanation is that large volcanoes have an approximately uniform age distribution over the last 500 million years.

2.3 Star Formation and Stars

Recent radio wave observations have shown that the density distributions toward the center of suspected pre-collapse molecular cloud cores appear to turn over and flatten out, compared to the power-law behaviors previously inferred. Thus Gaussian density profiles appear to be better approximations for pre-collapse clouds than power-laws. Boss pointed out the importance of this discovery for the question of binary star formation. Molecular cloud cores with power-law profiles are highly resistant to fragmentation into binary protostars during their collapse, whereas Gaussian profile clouds fragment much more readily. For the thermal and gravitational energies appropriate for a magnetically-supported cloud on the verge of dynamical collapse, a Gaussian cloud should collapse and fragment into a binary or higher order protostellar system, implying that binary protostars should be the rule rather than the exception. This prediction appears to be in the process of being validated by observations of suspected protostellar objects, and has already been demonstrated for pre-main-sequence stars – single T Tauri stars are relatively rare. Observations of pre-

collapse clouds and of T Tauri star companions thus seem to point toward fragmentation as the dominant mechanism for binary star formation.

Lee Hartmann (CfA), Nuria Calvet (CfA), and Boss have explored the implications of protostellar collapse starting from an infinite sheet rather than a sphere, finding that disk-like structures develop in this case, even in the absence of rotation or magnetic fields. Radiative transfer calculations of the expected appearance of disks formed by sheet collapse show that such models provide a better match to observations than initially spherical models; e.g., such models allow the accreting protostars to be optically visible from certain angles while still being surrounded by reflection nebulae.

Boss and Elizabeth Myhill completed a major survey with the three-dimensional radiative hydrodynamics code of the collapse of molecular cloud cores with initial differential rotation. Boss and Myhill found that when clouds with initial Gaussian density profiles were given an initial angular velocity profile consist with a prior phase of contraction with conserved angular momentum (i.e., the maximum degree of differential rotation likely), the range of initial conditions leading to binary fragmentation expanded. That is, clouds that previously collapsed without undergoing binary fragmentation were found to be susceptible to fragmentation when differential rotation was introduced (while holding the ratios of thermal and rotational to gravitational energies fixed). Initial configurations with centers rotating more rapidly than the boundaries are clearly conducive to fragmentation. In fact, differentially-rotating clouds with ratios of thermal to gravitational energy close to that characterizing virial equilibrium ($1/2$) are expected to collapse and undergo fragmentation. Clouds contracting under the influence of magnetic fields develop differential rotation, and the present models imply that such clouds should readily form binary protostars.

Boss and Harold W. Yorke (U. Würzburg) calculated the spectral energy distribution (SED) of single and binary protostars at an early phase of evolution, prior to the formation of the final protostellar core associated with embedded protostellar objects (class 0 and I objects) and with the slightly older pre-main-sequence stars (class II and III objects). These earlier objects are so-called first protostellar cores, with radii on the order of 10 AU, and are supported primarily by molecular rather than atomic hydrogen. In keeping with the established nomenclature, Boss and Yorke proposed calling these protostars 'class -I objects'. Spherically symmetrical models of class -I objects imply that their SEDs would be similar to those of black bodies with temperatures of order 10 K, because the protostar's radiation must filter its way out of an intervening cloud of infalling dust. However, Boss and Yorke showed that in the more realistic case of rotating, asymmetrical protostars, certain lines of sight permit the radiation to escape more freely, adding shorter-wavelength shoulders to the black body SEDs. Interestingly, the predicted shoulder fluxes for nearby star-forming regions are too low for *IRAS* to have detected class -I objects, but high enough for *ISO* and *SIRTF* to find these protostars.

John Graham used the Las Campanas 100-inch telescope in May 1995 to discover two extended regions of line-

emitting gas, one on each side of the deeply embedded IR source IRAS 18595-3712 in the Corona Australis area of star formation. The excited gas, observed so far only in H-alpha, extends NW and SE of the probable protostar over a total length of 20 arcmin (corresponding to a transverse distance of approx 0.8 pc). Although no detailed spectroscopy or velocity measurements are available, it seems most likely that the gas is tracing a major material outflow for this heavily obscured object.

High resolution observations of the ice-band profile seen against selected young stellar objects were acquired at Cerro Tololo Inter-American Observatory by Graham with the recently refurbished IR spectrometer at the 4 meter telescope. Observations were most complete for the FU Orionis star V346 Nor and for HH100-IR and TS2.4, two embedded pre-main sequence stars in the Corona Australis cloud. Reductions of the data are proceeding.

During a series of observing runs in 1994 and 1995, Harold Butner and collaborators Helen Walker (RAL), Diane Wooden (NASA Ames) and Fred Witteborn (NASA Ames), obtained moderate resolution 8-13 micron spectra for a number of Vega-like stars from the NASA IRTF 3 meter telescope, using the NASA Ames HIFOGS spectrometer. These stars revealed a range of spectra features, from classic ISM silicate features to others much more comet-like in character. Several papers are in preparation.

Butner, Lynne Deutsch (FCAD), Bill Hoffmann (Steward Observatory) and Joe Hora (IfA) mapped a number of young stars in Taurus with the MIRAC2 camera at UKIRT in November 1994. The purpose was to look for both extended 10 and 20 micron emission as well as additional sources in the vicinity of the known IR source. Data is currently being reduced.

Wooden and Butner continued a monitoring program of T Tauri stars at 10 microns in February 1995. No obvious variations were detected, though the project was hampered by bad weather at Mount Lemmon.

Butner and Gerald Moriarty-Schieven (DRAO) studied the emission from pre-protostellar cores using the molecule DCO+ and the JCMT 15 meter telescope. Initial maps suggest that the DCO+ J=3-2 emission does not peak at the same location as the submillimeter continuum maps. In addition, some sources for which DCO+ emission might have been expected were not detected, indicating either higher temperatures or lower densities than previously suggested in studies of these regions.

Butner and Steven Charnley (NASA Ames) used the NRAO 12 meter telescope to look for evidence of Alfvén waves, using deuteration chemistry as a tracer for the presence of the waves. They found evidence consistent with the predictions of Charnley and Roberge, suggesting that the waves are present and affecting the abundances of deuterated species in the way expected by theory. Other projects that were pursued by Butner included including finishing a survey of 450 micron emission around a sample of low mass embedded YSOs in Taurus. In addition, CS 5-4 and 7-6 maps were taken for many of the same objects. Modeling of these regions is currently underway.

2.4 Galaxies and Extragalactic Research

John A. Graham is a co-investigator in the Hubble Space Telescope Key Project "Determination of the Extragalactic Distance Scale." He is currently the lead investigator for the observations which have been obtained of the barred spiral galaxy NGC 3351 in the Leo I group. This group also contains the closest normal elliptical galaxies. Distances to the galaxies in the Leo I group have been estimated until now by using several secondary techniques including the Tully-Fisher relation. Thus, the determination of the distance to this early type galaxy using a primary distance indicator such as its Cepheid variable stars will provide a powerful way of calibrating the secondary methods and of refining the distance scale as a whole. The new data set spans nearly 2 months and incorporates 12 separate visits to NGC 3351. 50 Cepheid variables have been discovered with periods ranging from 10 to 43 days. Magnitudes for these stars at each epoch are now being finalized.

Graham used the Las Campanas 100-inch telescope to obtain large format UBV images of a field containing a group of young, blue stars in the NE radio lobe of the active galaxy NGC 5128 (CenA). The field includes also a previously determined magnitude sequence which extends to magnitude 22. Preliminary results show that the brightest blue stars are at visual magnitude 20 and thus, with modulus 27.7, are comparable to the blue supergiant stars in the Magellanic Clouds. The blue stars lie in loose chains along the edge of a recently discovered cloud of neutral hydrogen and are probably a consequence of the compression of this cloud by shocks arising from the neighboring radio jet. This unusual mode of star formation may relate to the origin of the faint, aligned and relatively blue extensions which are seen in more distant radio galaxies.

Vera Rubin, in collaboration with Jeffrey Kenney (Yale University), has completed an observing program to obtain spectra and measure rotation curves for about 100 galaxies in the Virgo cluster. This year, studies have been completed for the highly disturbed Virgo pair, NGC 4438 (Sb) and NGC 4435 (SB0). Kenney, Rubin, Pere Planesas (Yebes, Spain), and Judith Young (Univ. Mass. Amherst) have combined high resolution long slit spectroscopy, high resolution CO interferometry, and optical line images to interpret the complex morphology and kinematics in terms of a high-velocity (900 km/s) ISM-ISM collision between the massive gas-rich NGC 4438 and the less massive, less gas-rich NGC 4435.

Kenney, Rebecca Koopmann, a Yale graduate student, and Rubin have also studied NGC 4424 (Sa), a little noted galaxy in Virgo. The twisted morphology and the complex inner gas kinematics are consistent with a recent merger. They predict that the galaxy will become a small-bulge S0 within ≈ 1 Gyr.

Rubin, Kenney, and Young have completed a study of fourteen Virgo galaxies, types E/S0 to Sc, whose motions in their near-nuclear regions suggest disconnected, rapidly-rotating core components of radius ≈ 500 pc, mass $\approx 3 \times 10^9 M_{\odot}$ (ranging up to $10^{10} M_{\odot}$). There is a good correlation of radius, mass, and peak rotation of a core with radius, mass, and peak rotation within the corresponding optical disk. A core extends to about 3 or 4% of the outer disk isophotal (R_{25}) radius, with a mass of about 4% of the mass

interior to R_{25} , and a rotation velocity approximately that of the outer disk.

Rubin, Bradley Whitmore (STScI) and Bryan Miller are using the Hubble Space Telescope to investigate the dust and nuclear properties of galaxies in the Virgo clusters with kinematically distinct cores. The morphology of the dust ranges from very orderly disks to very chaotic with structures seeming to extend out of the plane of the galaxy.

Stacy McGaugh made a detailed investigation of the morphologies of a sample of Low Surface Brightness (LSB) galaxies in all optical (UBVI and $H\alpha$) bands. Generally late types, LSB galaxies extend the classic Hubble sequence in a number of directions. In addition to classic dwarfs of smooth and irregular nature, there also exist many larger systems with erratic and feeble but definite spiral structure. With collaborators J. Schombert (NASA/IPAC) and G. Bothun (U. Oregon), some indication was also found of a binary distribution of bulge to disk ratios, with most LSB galaxies lacking any significant bulge at all but some subset having quite prominent bulges with no obvious transition population between the two. Another conclusion is that the morphology varies less from the U to I bands than in higher surface brightness spirals, indicating a more homogeneous stellar population. More generally, it was found that the volume of parameter space occupied by galaxies continues to grow towards later morphological types, with the result that galaxies which are very different physically can be lumped into the same late-type bin (e.g., Sd) while rather fine distinctions (e.g., that between Sb and Sc) are made between high surface brightness galaxies since the classification scheme gives much weight to high contrast features.

McGaugh also revisited the long standing debate over the number density of LSB galaxies. Though fraught with differences of definition and arguments over the nature of selection effects, it appears clear now that LSB galaxies do exist in substantial numbers, much higher than previously believed. However, number density is not the same as luminosity density, and it seems unlikely that LSB galaxies are major contributors to the integrated luminosity density of the universe. Nevertheless, they can have a significant impact on the shape of the galaxy luminosity function. Possible scenarios and their implications for the faint blue galaxy problem were investigated in collaboration with H. Ferguson (STScI), but the true form of the luminosity function remains to be quantified.

Bryan Miller used $H\alpha$ imaging, nebular spectroscopy, and BVI photometry to investigate the recent star formation histories of eight dwarf galaxies in the Sculptor Group. Only two of the eight galaxies have current star formation, and the oxygen abundances in their HII regions are typically low. However, distance estimates place these two galaxies in the field behind the Sculptor Group. Of the remaining six galaxies, the four dwarf irregular galaxies have blue supergiants, indicative of star formation within the last 100 Myr, and the two dwarf elliptical galaxies have not had a significant episode of star formation for 1–3 Gyr. The general star formation activity of the Sculptor Group dwarfs is less than in dwarf galaxies in the Local Group or M81 Group. Since the mass density in the Sculptor Group is less than in either the

Local or M81 Groups, large-range gravitational interactions may play a role in regulating star formation in dwarf galaxies.

Miller and P. Hodge (U. Washington) have determined oxygen and nitrogen abundances for HII region in the M81 Group dwarf galaxies IC 2574, Holmberg I, and M81dB. The empirical, or bright line method, is used to determine the oxygen abundances and ionization parameters. When the [OIII]4363 line is detected the directly calculated oxygen abundances agree with the empirical values within the uncertainties. The oxygen abundances are typically 0.12 solar and are consistent with the $\log(O/H)-M_B$ relation. Nitrogen abundances are also normal for irregular galaxies.

Hodge and Miller have continued their work on current star formation rates and abundances in dwarf galaxies near the Local Group. HII regions have been detected in WLM, UGC-A 86, and EGB 0427+63, but no $H\alpha$ emission was detected from LGS 3. Previous work had suggested that UGC-A 86 could be a pair of dwarf galaxies but the new data suggest that it is one galaxy, the disjoint appearance being caused by several star forming regions of different ages. The bright end of the HII region luminosity functions is fit by a power law and the size distributions are reasonably well described by exponential functions. Oxygen abundances are 7% of solar, typical of dwarf galaxies of this absolute magnitude.

Miller discovered $H\alpha$ emission in a shell around a very luminous X-ray source near the dwarf galaxy Holmberg IX in the M81 Group. Spectroscopy of the nebular gas revealed [OI]6300 emission and $[SII]/H\alpha > 0.4$, indicating that the shell is shock heated. With a diameter of 250x400 pc this shell is likely to be the result of winds from massive stars or multiple supernovae explosions. It may be in the process of becoming a supershell like those observed in the LMC or several edge-on spiral galaxies. With a luminosity of $\sim 10^{40}$ erg/sec, the X-ray source is 100–1000 times more luminous than most supernovae remnants and is slightly brighter than even young supernovae remnants expanding into dense gas. The X-ray flux may originate from a combination of shocks in the expanding shell and a massive X-ray binary or other compact source.

E. Wilcots (U. Wisconsin), C. Lehman (Rensselaer Polytechnic), and Miller have analyzed the HI distribution of a sample of barred Magellanic irregular galaxies using the VLA. The bars are evident in both the HI morphology and the kinematics. Four of the five galaxies have small ($10^7 M_{\odot}$) HI companions. Three of these clouds have no optical counterparts on Palomar Sky Survey plates and the clouds appear to be interacting with their primary galaxy. Therefore, we expect that the bars may be due to these interactions. The presence of these clouds is also significant because they imply that galaxy building continues in the present epoch.

Miller and Rubin obtained $H\alpha$ spectroscopy of the edge on galaxy NGC 5907. The rotation curve is double-valued in the nuclear region: outer disk gas has a low line-of-sight velocity seen in projection against the nucleus and high-velocity gas originates closer to the nucleus. The high velocity gas shows that the rotation curve rises much more quickly than had previously been known. Mass models put a lower-

limit on the mass-to-light ratio of the bulge and suggest that the mass density of the halo goes as r^{-2} or $r^{-2.25}$, consistent with the faint light detected by Morrison and colleagues in 1993.

François Schweizer continued his observational studies of stellar populations and globular clusters in merger remnants and in elliptical galaxies rich in fine structure. These studies aim principally at addressing the issue whether the two kinds of galaxies are related and form an evolutionary sequence. In addition, they also yield valuable information concerning the formation and evolution of globular-cluster systems.

The detailed study of the merger remnant NGC 3921 begun a year earlier and based on groundbased data gathered over more than a decade was finished, and a paper is in press. This luminous galaxy at a redshift of $z \approx 0.02$ features a single nucleus, a main body with complex fine structure, and a pair of ~ 100 kpc long, crossed tidal tails indicative of two major former disk galaxies that have essentially merged. The main body of the remnant shows a typical post-starburst spectrum dominated in the blue by A3V – A5V stars, leading to an estimated burst age of 0.5–1 Gyr and burst strength of $\sim 10\%$ by mass. Analysis of the Balmer absorption lines and *UBV*-colors shows that NGC 3921, like its more famous kin NGC 7252, is a nearby analog of distant galaxies with “E+A”-type spectra in Butcher-Oemler clusters. Remarkably, its radial luminosity distribution, *UBV*-colors, color gradients, velocity dispersion, spectroscopic line strengths, and fine-structure index all agree with the notion that NGC 3921 is a 0.7 ± 0.3 Gyr old protoelliptical. This finding lends support to the hypothesis that “E+A”-type galaxies in distant clusters, too, are merger remnants in the process of becoming E and S0 galaxies. Since NGC 3921 itself is a member of a small, tight group of four galaxies, it also presents direct evidence that mergers resulting in elliptical formation occur in such nearby groups to the present day.

The study of young globular clusters formed during mergers of gas-rich disk galaxies continues to generate great interest since it holds the promise of relatively simple age-dating of the last major starbursts in merger remnants. In collaboration with Patrick Seitzer (U. Michigan), Schweizer obtained spectra of 10 candidate young globular clusters in NGC 7252 with the CTIO 4-m telescope. Though for the fainter objects the signal-to-noise ratio of this first set of spectra leaves much to be desired, all objects seem to show strong Balmer absorption lines indicative of ages in the range 20–1000 Myr. Thus, at least these brightest clusters seem to all have formed during the merger, which from the kinematics of the tidal tails is estimated to have begun $1.0_{-0.5}^{+1.0}$ Gyr ago. Work is in progress to measure metallicities for the brightest two or three clusters.

In collaboration with Bradley Whitmore and his team at STScI, Miller and Schweizer used the refurbished *Hubble Space Telescope* to image the merger remnants NGC 3921 and 7252 and the two ellipticals NGC 1700 and 3610 suspected to be dynamically young. In all four galaxies, extensive systems of candidate globular clusters were found. In NGC 7252, the new, deeper observations reveal hundreds of clusters down to the peak of the old-globular-cluster luminosity function. In NGC 3921, observed with *HST* for the

first time, there are now over 100 luminous candidate globular clusters, where only a handful had been tentatively identified from the ground. Their *V–I* colors yield ages of a few 100 Myr, showing that like those in NGC 7252 these clusters formed during the recent merger. In the two ellipticals, the cluster systems appear redder and older, and accurate age estimates will have to await spectroscopic abundance determinations. However, assuming cluster abundances of at least 1/10-th solar in these fine-structure rich ellipticals and likely recent merger remnants, the cluster colors suggest that at least a fair fraction of these globular clusters are only a few Gyr old, again in tentative agreement with the estimated merger ages of their host galaxies. Also, the color distribution of the NGC 1700 clusters seems to be bimodal. Thus, these observations all reinforce the view that globular-cluster systems in ellipticals may have formed during merger episodes.

Lori Herold, a graduate student from MIT, continued her thesis work (with Bernard Burke as advisor) on close double radio sources in the MIT–Green Bank–VLA Gravitational Lens Search program. Close double radio sources are a subset of the class of compact steep spectrum radio sources, which appear unresolved in VLA maps with total angular sizes of $< 2''$. These objects are not well understood, but appear to be intrinsically small sources, most likely radio galaxies at large redshifts. As such they may represent an early stage in radio source evolution. Herold has been using the 1.3-m McGraw-Hill telescope on Kitt Peak to search for optical counterparts and obtain color information on these sources, which she has previously observed with MERLIN and the VLA. This fall, Herold and her MIT colleagues will use the MDM 2.4-m Hiltner telescope to obtain spectra and redshifts for a subset of close double sources.

PUBLICATIONS

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