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This report covers astronomical research carried out during the period July 1, 2000 – June 30, 2001. Astronomical studies at the Department of Terrestrial Magnetism (DTM) of the Carnegie Institution of Washington include observational and theoretical fields of planet structure, detection, and formation, the formation of stars and stellar evolution, the structure, dynamics, and evolution of galaxies.

1. PERSONNEL

Staff Members: Sean C. Solomon (Director), Conel M. O'D. Alexander, Alan P. Boss, R. Paul Butler, John A. Graham, Larry R. Nittler, Vera C. Rubin, Alycia J. Weinberger, George W. Wetherill

Postdoctoral Fellows: Kenneth M. Chick, Steven Desch, Andrew M. Freed, Nader Haghighipour, Satoshi Inaba, Stephen J. Kortenkamp, Patrick J. McGovern, Chris McCarthy, Rob A. Swaters, Harri A. T. Vanhala

Visiting Investigators: Hugh M. Van Horn, Steven S. Vogt

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2. RESEARCH PROGRAMS

2.1 Extrasolar Planet Detection

Geoff Marcy (UC Berkeley) and Paul Butler are surveying the nearest 1,200 Sun–like stars (F8 – M5) with the precision Doppler technique at the Lick 3 m, Keck 10 m, and Anglo-Australian 3.9 m telescopes. Over the past 6 years, these surveys have led to the discovery of two-thirds of the known extrasolar planets. Within just the last two years, roughly 30 new planets have emerged from this work, including the only known transit planet, the first two sub–Saturn mass planets, and the first 4 published multiple planet systems.

Of the $\sim$75 known substellar companions found from precision Doppler surveys, only 4 have $M \sin i$ mass greater than 12 Jupiter-masses. The substellar companion mass function is rises sharply toward the smallest detectable planets, near 1 Jupiter-mass. Brown dwarf companions orbiting within 5 AU of solar-type stars are rare.

Previously, all known extrasolar planets have either been of the ''51 Peg–type'' in circular orbits with periods of 3 to 5 days, or they have been in larger eccentric orbits. Over the last year a new class of planets has been uncovered with orbital characteristics similar to Earth and Mars, with orbital periods of 1 to 2 years and circular orbits ($e<0.1$). These new planets stimulate the long term search for true Solar System analogs, circular systems with Saturn–to–Jupiter masses planets in 10 to 30 year orbits.

The long term goal of this work is to maintain Doppler precision of 3 m s^{-1} over the next two decades, sufficient to make 4σ detections of Solar System analogs. Over the next decade these surveys will provide the raw data needed to construct the substellar mass function and the distributions of orbital radii and eccentricity needed for further development of planet formation theory. In addition, these surveys will provide target lists for the next generation of techniques, such as the Keck Interferometer, the Space Interferometry Mission, and the Terrestrial Planet Finder. By 2010 these surveys will provide a first planetary census of nearby stars and allow us to estimate the ubiquity of planetary systems and of ''Solar System''analogs.

Chris McCarthy began a postdoctoral fellowship at DTM in April, working with Butler on searches for extrasolar planets. As these searches continue, future discoveries will depend on achieving greater sensitivity to Doppler signals. In this regard McCarthy has worked on improving corrections for the motion of the Earth-bound observatory. He has also obtained data at the Anglo Australian Observatory (AAT) in New South Wales, Australia, and participated in the installation and testing of a new CCD detector there which will improve the precision with which Doppler velocities can be measured.

2.2 Planetary System Formation

Radial velocity searches have discovered over 70 gas giant planets in orbit around nearby stars, with most of them having been discovered by Butler and his colleagues. These discoveries have shown that extrasolar gas giant planets may have quite different characteristics compared to Jupiter and Saturn, such as very short orbital periods, eccentric orbits, and minimum masses a factor of 10 times larger, or more. In this fluid situation, it is unclear if the conventional mechanism of gas giant planet formation, core accretion, is robust enough to account for the formation of all of the extrasolar gas giant planets. Alternative mechanisms deserve further scrutiny. Alan Boss has been investigating one promising alternative, the disk instability mechanism.

In order to learn whether the disk instability mechanism is plausible, Boss has calculated the evolution of a number of three dimensional (3D), gravitational hydrodynamical models of protoplanetary disks starting from realistic initial temperature and density profiles, and with an unprecedented degree of spatial resolution permitted by the use of the Carnegie Alpha Cluster of state-of-the-art workstations. The models show that a clump-forming disk instability could occur in a marginally gravitationally unstable disk with a mass as low as 10% of a solar mass inside a radius of 20 AU. This result holds even with detailed disk thermodynamics in the models, including the solution of a full energy equation and radiative transfer in the diffusion approximation. These results are roughly similar to previous ''locally isothermal'' models, because the time scale for cooling at the disk midplane is comparable to the time scale for growth of the instability. These models have also shown the need for exceptionally high spatial resolution (over 1 million active grid points) in order to allow self-gravitating clumps to form and survive. A number of other disk models are currently in progress, including variations in the assumed opacity, the presence of binary companions, the disk size, and the transport of color fields in a disk evolving by gravitational torques.

These models imply that a disk instability may be possible in disks with total masses comparable to that which seems to be required in order for core accretion to produce giant planets in a few million years. Because a disk instability occurs in a few thousand years, it should occur well before core accretion gets started. If a massive OB star should form nearby (as in the Orion nebula cluster), the outermost disk gas will be removed by UV radiation, possibly exposing the outermost gas giant protoplanets to the UV radiation which could remove their gaseous envelopes and leave behind ice and rock cores, similar to the ice giant planets, a process which has been investigated by Boss, Wetherill, and Haghighipour. The terrestrial planets could then form much later by the usual process of collisional accumulation of solids, a process which has been studied in most detail by Wetherill and his colleagues.

Nader Haghighipour recently arrived at DTM as a Postdoctoral Fellow. The focus of his research is on dynamics of planetary systems. His research activities include computational simulations and analytical analysis. During the past year he has been working on two computational projects, one in collaboration with Ferenc Varadi at UC-Los Angeles on developing an inventory of resonant periodic orbits for a three-body planetary system, and one on the effect of dynamical friction of a disk of planetesimals on migration of planets in their early stages of their formation and possibly, their capture into a mean-motion resonance. The former project was initiated when he was at UC-Irvine and was carried on after he moved to Northwestern University. He has presented preliminary results for the case of (1:2) resonances, in an oral presentation in the annual meeting of Division of Planetary Sciences, last year in Pasadena.

He has also been working on application of the method of partial averaging to analytical study of the dynamics of planets while captured in a resonance. One paper has already been published in Monthly Notices on this subject and earlier this year in July, he submitted another paper to the same journal on partial averaging and resonance trapping in a restricted three-body system. In this work, as an example of the applicability of the method of partial averaging to the study of the dynamics of planetary systems, Haghighipour has followed a new approach to study of the (1:1) resonance capture of Trojan asteroids. Currently the focus of his analytical work is on investigation of the regions of stability and instability of binary-planetary systems, in particular P-type binaries.

Satoshi Inaba, Stephen Kortenkamp,and George Wetherill continued to address serious difficulties in coordinating present theoretical models of the formation of the terrestrial planets, the asteroids, and the outer planets. Roughly speaking, based on previous work, these models can be placed in two categories: (1) The ''Standard'' model in which primarily solid planetary bodies were at first formed from small (e.g., 1 km) bodies throughout the entire planetary system. Extensive calculations by many other workers, as well as this group, have led to the expectation that a combination of mutual gravitational forces, collisions, and gas drag, will lead to growth of a hierarchy of ''planetary embryos'' throughout the entire planetary system at least as far out as Saturn. The time scales for this range from less than 10^5 years in the terrestrial planet region to more than 10^6 years at Saturn's distance. The mass of these ''embryos'' varies from about 10^{26}g at 1 AU to about 10^{28}g at 10 AU. In the terrestrial planet region, cumulative collisions between embryos lead to formation of the terrestrial planets, whereas in the outer Solar system, gas giants are formed by a hydrodynamical instability in the gaseous disk that causes gas to accumulate on the embryos to form large gaseous ''envelopes'' that are needed to complete the growth of gas giant planets on a time scale of about 10^7 years. (2) The ''Gas Instability'' model in which the gas giant planets form directly from the protosolar disk without prior formation of solid planetary embryos. As a result, gas giant planets in the outer Solar System can form much earlier than in the time consuming process of first forming the large embryos and then accumulating the gas mantle, as in the Standard model. This has the advantage that the gas giant planets can avoid the ''type I drift'' that in the standard model is expected to cause them to drift deeply into the inner Solar System before completion of their growth. We are carrying out simulations that bear on both of these models in order to understand more clearly their consequences regarding the real processes by which planetary systems form.

Inaba and Wetherill have made a more complete treatment of the Standard model in the Jupiter and Saturn region. In addition to use of more advanced dynamic algorithms, these calculations now include for the first time the effects of collisional fragmentation of the planetary embryos and the consequences of variation in the grain opacity of the gaseous envelope. It is found that during the formation of these embryos, the strong gravitational perturbations between these bodies and the residual planetesimals result in depletion of the mass needed to form large planetary embryos. As a consequence, these embryos are not large enough to initiate the gravitational instability required to form the gaseous envelopes of the gas giant planets in our Solar System. This problem is in addition to that mentioned earlier regarding inward drift of the planets.

Because of such difficulties with the Standard model, an effort is being made to also model the consequences of the alternative Gas Instability model, as developed by our colleague Alan Boss, and briefly described earlier in this report. This work has primarily been carried out by Stephen Kortenkamp, but with involvement of the rest of us, as well as valuable help from David Trilling of the University of Pennsylvania. In this model the gas giant planets are assumed to have rapidly formed directly from the protosolar disk (Boss, Astrophys J. Letters 536, L101, 2000). As a result of this, the gravitational effects of these planets will be present at an early stage of formation of the Solar System, prior to the principal growth of bodies in the terrestrial planet and asteroidal regions. During this stage, the mutual perturbations of the planetesimals will be negligible. Planetesimal velocities will be reduced by gas drag, and the relative velocities of bodies similar in mass to one another will be small as a consequence of the synchronism in the phasing of their orbital orientation angles (e.g., Kortenkamp and Wetherill, Icarus, 143, 60, 2000). In the case of the terrestrial planets, this results in a type of runaway growth that is quite different from that associated with planetary formation in the absence of giant planets, but nevertheless has a similar effect in permitting the formation of ‘‘planetary embryos’’ that can evolve to form terrestrial planets on a time scale similar to that found in the standard model. Extension of this effect to the asteroid belt may be more difficult. Because of their proximity to the gas giant planets they may not be able to form unless the formation of the the giant planets is delayed by about 10^5 years, in order to avoid premature collisional destruction of the asteroidal bodies.

Larry Nittler, in collaboration with J. Trombka (NASA-GSFC) and T. McCoy (Smithsonian) has been responsible for reducing and interpreting data from the x-ray spectrometer (XRS) aboard NASA’s Near Earth Asteroid Rendezvous (NEAR). The NEAR Shoemaker mission orbited the S-class asteroid 433 Eros for one year, ending in February 2001. A major question in Solar System science is whether S-class asteroids, the most abundant class in the inner asteroid belt, are the parent bodies of ordinary chondrites, which dominate the meteorite flux on Earth. Dynamical calculations suggest such a link, but there are important differences in reflectance spectra between the asteroids and meteorites. X-ray remote-sensing uses solar x-rays as the excitation source for characteristic fluorescence emissions from the asteroid’s surface. Analysis of data acquired during five solar flares confirmed that Eros is largely a primitive, undifferentiated body. Inferred Mg/Si, Al/Si, Ca/Si and Fe/Si ratios are consistent with those measured in ordinary chondrites, but sulfur is greatly depleted. This probably reflects the effects of micrometeorite, particle and photon bombardment of the surface with consequent devolatization and loss of sulfur.

2.3 Meteorites and Interplanetary Dust Particles

Presolar dust grains in meteorites, whose isotopic compositions indicate a formation in stellar outflows and supernova explosions, provide a novel means of probing stellar and galactic evolution as well as processes in the interstellar medium and early solar system. Conel Alexander and Larry Nittler have completed development of a new highly automated technique for isotopically analyzing individual micron-sized dust grains. They have begun to use this system to pursue a number of lines of research.

All known types of presolar grains are acid-resistant phases such as SiC, graphite and aluminum oxide. However, most circumstellar and interstellar dust is believed to be silicate material. Alexander and Nittler have used a new chemical dissolution technique to prepare meteorite residues enriched in refractory iron-poor silicates in order to search for presolar silicates. Preliminary automated analysis of $\sim$2,000 micron-sized enstatite grains from the Murchison meteorite did not identify any grains with isotopic anomalies indicating a presolar origin, but further measurements are planned. Inductively-coupled Plasma Mass Spectrometric measurements of meteorite residues prepared with the new technique also indicate that the presumed presolar carrier of ^{54}Cr enrichments is preserved. Ion probe studies of individual grains in the sample are planned. Nittler and Alexander also used the automated system to identify 30 presolar oxide grains in a new residue of the Tieschitz meteorite. This builds on initial work that included the first discovery of presolar TiO_2. The new data increase the known oxide data set by $\sim$20% and includes the discovery of a grain very highly enriched in ^{17}O. This grain cannot be explained by current models of stellar nucleosynthesis and might require an origin in a binary star system.

Nittler, Alexander and summer intern Megan O’Grady (Vanderbilt University) implemented a method to identify presolar silicon carbide grains *in situ* in meteorite sections, using x-ray mapping with the electron microprobe. They identified a 2 μm diameter SiC grain in the matrix of the Cold Bokkeveld carbonaceous chondrite. Ultrathin slices of this grain and surrounding material were subsequently extracted using a new focused ion beam technique in collaboration with R. Stroud of the Naval Research Laboratory. Planned transmission electron microscopy of the SiC sections should provide new information about the origin and history of these grains.

Interplanetary dust particles (IDPs) are small (tens of microns) particles collected by aircraft in the Earth’s stratosphere. They are among the most primitive material available for laboratory study and are known to contain preserved presolar interstellar cloud material in the form of D and ^{15}N enrichments. The chemical form of the carriers of the isotopic anomalies is poorly constrained, however. Nittler has initiated a study of isotopic heterogeneity in IDPs, using the micron resolution isotopic imaging capabilities of the ion probe. He has measured the spatial distribution of H and N isotopes in ten IDPs and identified heterogeneous concentrations of isotopically unusual material. It is planned to extract remaining material from the sample mounts for complementary studies to better constrain the origin of the isotopically anomalous material.

Steven Desch has been directing his research efforts towards restricting possible astrophysical models of the solar nebula based on meteoritic data and other observational constraints. A major effort has gone into the completion of a paper with Harold Connolly Jr. (Kingsborough College, CUNY) in which the thermal histories have been calculated for particles passing through shock waves in the solar nebula. This has now been accepted for publication in *Meteoritics and Planetary Science*. It is shown how the igneous textures of chondrules and (type B) CAIs can be produced by a shock wave model. The model explains other, previously unrecognized aspects of chondrules, and leads to the conclusion that shock wave heating is the most likely mechanism for melting chondrules. It implies that chondrule formation must have taken place in the first few Myr of the nebula, and that gravitational instabilities played an active role in the evolution of the protoplanetary disk.

Shocks will also lead to disequilibrium chemical products, traces of which may be found in carbonaceous meteorites.

Together with Monika Kress, (University of Washington), Desch is calculating which observable chemical products might be produced by nebular shocks. He is also working on constraining the mechanisms leading to turbulence or mass and angular momentum transport in the nebula. A paper submitted to the *Astrophysical Journal* brings astronomical and meteoritic evidence together to show that the solar nebula was too dusty, and therefore had too few free electrons and ions, for the gas to couple to the magnetic field. This work indicates that the so-called ''Balbus-Hawley'' instability cannot be relevant to the evolution of protoplanetary disks, and suggests again that gravitational instabilities play an important role in disk evolution.

2.4 Terrestrial Planetary Evolution

Sean Solomon is utilizing spacecraft observations to address aspects of the internal and geological evolution of the terrestrial planets. His scientific efforts during the past year have focused on Mars, motivated in large part by the data from the Mars Global Surveyor (MGS) spacecraft still operating in Martian orbit. He is also leading the Phase C/D development of the MESSENGER mission to fly by and orbit the planet Mercury.

Altimetry data from the Mars Orbital Laser Altimeter (MOLA) on MGS have stimulated a significant increase in understanding of all phenomena that affect the Martian surface, from cratering and deformation, to volcanism and atmospheric circulation, to the erosional and depositional action of water and ice. As a Co-Investigator on the MOLA team, Solomon worked with recent DTM Postdoctoral Associate Patrick McGovern on the application of MOLA data to formulate new constraints on lithospheric loading, planetary heat flow, and volcanic processes on Mars. Gravity and topography relations throughout Mars document variations in lithospheric thickness and implied heat flow versus time, both globally and within major volcanic provinces. Analysis of the topography and gravity signatures of individual volcanos, coupled with numerical models for stress and strain within a growing volcano, have given fresh insight into the roles of extrusion and intrusion at Martian volcanic centers.

Mercury has been viewed at close range by only a single spacecraft, Mariner 10, which flew by the planet three times in 1974-75. Mariner 10 discovered Mercury's global magnetic field, documented the presence of several species in Mercury's exosphere, and imaged about 45% of the surface. In part because of this limited history of exploration, and in part because of several unusual characteristics of the planet, Mercury holds special promise for elucidating general Solar System processes. Determining the surface composition of Mercury, a body with an anomalously high ratio of metal to silicate, will provide a unique window on the mechanisms by which planetesimals in the primitive solar nebula accreted to form planets. Documenting the global geological history will elucidate the role of terrestrial planet size as a governor of magmatic and tectonic history. Characterizing the magnetic field and the size and state of Mercury's core will advance our understanding of the energetics and lifetimes of magnetic dynamos in solar system bodies. Determining the full range of volatile species in Mercury's polar deposits, exosphere, and magnetosphere will provide insight into volatile inventories, sources, and sinks in the inner solar system.

The MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) mission to fly by and orbit Mercury, selected in July 1999 under NASA's Discovery Program and confirmed for flight in June 2001, will accomplish all of these key objectives. After launch by a Delta 2925H in March 2004, two flybys of Venus (in 2004 and 2006), and two flybys of Mercury (in 2007 and 2008), orbit insertion is accomplished at the third Mercury encounter. The instrument payload includes a dual imaging system for wide and narrow fields-of-view, monochrome and color imaging, and stereo; X-ray and combined gamma-ray and neutron spectrometers for surface chemical mapping; a magnetometer; a laser altimeter; a combined ultraviolet-visible and visible-near-infrared spectrometer to survey both exospheric species and surface mineralogy; and an energetic particle and plasma spectrometer to sample charged species in the magnetosphere. During the flybys of Mercury, regions unexplored by Mariner 10 will be seen for the first time, and new data will be gathered on Mercury's exosphere, magnetosphere, and surface composition. During the orbital phase of the mission, one Earth year in duration, MESSENGER will complete global mapping and the detailed characterization of the exosphere, magnetosphere, surface, and interior.

2.5 Stars and Star Formation

Harri Vanhala (now at Arizona State University) and Boss have continued calculating detailed hydrodynamical models of the interaction of interstellar shock waves with target dense cloud cores, in order to determine under which circumstances a cloud can be shocked into collapsing and forming a protostar. They have examined the viability of this scenario by performing two-dimensional piecewise-parabolic method simulations at high spatial resolution. The calculations show that in isothermal shock waves, material can be injected into the collapsing system through Rayleigh-Taylor fingers developing at the surface of the compressed molecular cloud core with an efficiency of approximately 10%. The amount of injected material in the central parts of the collapsing system is typically 0.7% of the total mass contained in that region. The results also suggest that the abundances of the shock wave material mixed into the forming solar system may have experienced temporal and spatial heterogeneities. The models support the hypothesis that short-lived radioactivities found in certain primitive meteoritical inclusions may have been synthesized in a supernova, ejected by the supernova explosion, and then injected into the presolar cloud prior to their radioactive decay.

Boss continues to calculate 3D radiative hydrodynamics models of the fragmentation mechanism. Fragmentation, the break-up of molecular cloud cores during their self-gravitational collapse to form stars, is the leading explanation for the formation of binary and multiple protostars. In his most recent calculations, Boss has been including the effects of magnetic fields, using certain simple approximations. These calculations show that because magnetic tension forces help in avoiding a central density singularity during protostellar collapse, magnetic fields enhance fragmentation of collapsing magnetic cloud cores. Magnetic clouds can thereby fragment into multiple protostar systems. During the central rebound caused by magnetic tension forces, the Jeans mass drops significantly compared to a non-magnetic cloud, permitting fragmentation to proceed to masses as low as a Jupiter mass. If such very low mass objects form in a multiple system which is unstable to orbital decay, the system may eject objects with masses in the range (roughly 5 to 15 Jupiter masses) previously reserved for gas giant planets. Free-floating objects with masses in this range which form by the fragmentation mechanism might best be termed ‘‘sub-brown dwarfs.’’

These calculations, as well as Boss's work on disk instabilities, have been greatly enhanced by the Carnegie Alpha Cluster, supported in large part by the National Science Foundation. The initial cluster consists of eight nodes with dual 667 MHz Alpha 21264 chips with 4 MB of cache for each processor and 1 GB of memory. Another nine older nodes were added to the cluster this year, containing 500 or 533 MHz Alpha 21164 chips and varied memory sizes. A second installment of eight dual node 667 MHz Alpha 21264 chips has been ordered. The cluster machines are kept busy 24/7, in order to provide the computational horsepower required by high spatial resolution 3D hydrodynamical simulations.

Boss and Lee Hartmann (Center for Astrophysics) completed their calculations of the axisymmetric collapse of rotating, dense cloud cores which start from sheet-like initial configurations, rather than the traditional spherical clouds. Such clouds develop large-scale infall motions during the first several free fall times of evolution, prior to the onset of rapid dynamical collapse, and have spherically-averaged density profiles which strongly resemble that of the critical Bonnor-Ebert sphere. These results are in basic agreement with several observations of large-scale motions and density profiles for pre-collapse dense cloud cores.

Alycia Weinberger, who has recently joined the staff at DTM, is currently engaged in an extensive program of disk investigations aimed at finding protostellar disks and determining their physical conditions. Observations of TW Hydrae showed a face-on disk in scattered near-infrared light extending from 20–230 AU. The disk, while spatially unresolved in thermal radiation at 12 and 18 μm in observations from the W. M. Keck Observatory, shows amorphous and crystalline silicate emission in its spectrum. TW Hya may be in an active planetesimal building phase – centimeter sized grains are needed to fit its spectral energy distribution, and a ripple in the surface brightness at 85 AU and a steep decline in surface brightness beyond 150 AU could be due to thermal instabilities or dynamical effects (Weinberger *et al.* 2002). She is using the Keck Observatory for mid-infrared spectroscopy of known disks. The first spatially resolved mid-infrared spectroscopy of a disk, around the canonical infrared excess star β Pictoris, shows that as distance from the star increases, the continuum flux from the disk shifts to longer wavelengths. In the 8–13 μm window, the silicate emission arises mainly in an unresolved region very close to the star.

Hugh Van Horn, formerly the Director of the Division of Astronomical Sciences at the National Science Foundation, has been on a two-year leave of absence at DTM since June, 2000. He has been primarily engaged in completing a book on the white dwarf stars in collaboration with James Liebert of the University of Arizona. In addition, Van Horn has continued to collaborate with his colleagues Eric Blackman, Adam Frank, and John H. Thomas of the University of Rochester on research concerning both dynamo generation of magnetic fields and relaxation oscillations in pre-white-dwarf phases of stellar evolution.

2.6 Dynamics and Evolution of Galaxies

Vera Rubin and former post-doctoral fellow Stacy McGaugh (now at University of Maryland) have obtained high resolution spectra for about 60 low surface brightness (LSB) galaxies, using the 4 m telescope at Kitt Peak National Observatory, and the 2.5 m and the 6.5 m Carnegie telescopes at Las Campanas, Chile. In an LSB galaxy, the stellar population makes only a small contribution to the mass, so dark matter dominates the observed rotation at essentially all radii. Hence the rotation curve directly probes the invisible mass component. Moreover, the derived inner mass distribution is a discriminant among various models for the formation and evolution of the dark matter halo.

In collaboration with Erwin de Blok (Australia Telescope National Facility) and Albert Bosma (Observatoire de Marseille), the rotation curves from the 4 m and 2.5 m telescopes have been analyzed in detail. In an LSB galaxy the neutral hydrogen disk extends beyond the optical disk, but the optical velocities have an order of magnitude higher spatial resolution than the 21-cm observations. These collaborators have produced accurate hybrid curves by appending the outer 21-cm velocities at radii beyond the optical observations. Their analysis indicates that at small radii, the mass distribution in most LSBs is dominated by a nearly constant density core. Only in a few LSB galaxies does the mass distribution appear more cuspy. This result conflicts significantly with the predictions from models calculated on the basis of Cold Dark Matter cosmology. Cold Dark Matter models predict the existence of a sharply rising density (a cusp) with decreasing distance from the nucleus. Rubin and McGaugh are presently analyzing new data from the Magellan 6.5 m telescope. They are also extending the analysis in an effort to put limits on the density of the universe as well as constraints on other cosmological parameters which enter into the analysis.

Deidre Hunter (a former DTM post-doctoral Fellow now on the staff of Lowell Observatory) and Rubin have obtained long-slit spectra of irregular galaxies with the Kitt Peak 4 m telescope. Spectra in four position angles have been obtained for both NGC 1156 and 4449. In collaboration with Rob Swaters (DTM Carnegie post-doctoral fellow), velocities have been measured from stellar absorption lines and from ionized gas emission lines. Hence NGC 1156 and 4449 are the first irregular galaxies for which *stellar* velocities are known. For NGC 2366, observing time permitted only short exposures, so only HII velocities have been measured. The authors will compare the kinematics of the old stellar component to that of the gas which has a higher likelihood of having been perturbed by outside forces. They hope to put limits on the amount and the distribution of dark matter in these galaxies. These data will help to determine whether irregulars are disks or triaxial in shape, and what contribution the stellar velocity dispersion makes to the dynamical support of the galaxy as a whole.

Rob Swaters and Barry Madore (OCIW) have analyzed high-resolution rotation curves obtained with the Palomar 5 m telescope of a sample of 15 dwarf and low-surface brightness galaxies. Because these galaxies are dominated by dark matter, they provide ideal laboratories to test the predictions for the shape of the dark matter halos made by theories of hierarchical galaxy formation. Previous studies often found the rotation curves of these galaxies to be inconsistent with the steep inner rotation curve slopes predicted from models based on cold and warm dark matter. Swaters and Madore investigated the influence of systematic effects, such as seeing, slit-width and misplacement of the slit, on the derived rotation curve shape, and they find that these systematic effects may well lead to significantly shallower observed slopes. The distribution of observed slopes of the galaxies in their sample is consistent with dwarf and low surface brightness galaxies having steep inner slopes. However, they note that the observed rotation curves are also consistent with these galaxies having halos with constant density cores.

Swaters, Matthew Bershady and Marc Verheijen (University of Wisconsin), have used the newly commissioned Sparsepak on the WIYN telescope to obtain high-resolution, two-dimensional velocity fields for two low surface brightness galaxies. The initial analysis of these data show that non-circular motions may play an important role in the kinematics of these galaxies. This is of great importance for studies of the rotation curves of these galaxies that are based on long-slit spectroscopy, because the effects of non-circular motions cannot be assessed from these observations alone. Taking the effects of non-circular motions into account is essential when comparing the rotation curves of these galaxies to predictions from theories of galaxy formation.

Frank van den Bosch (Max Planck Institut für Astrophysik), Andy Burkert (Max Planck Institut für Astronomie) and Swaters have used the data from Swaters' thesis sample to compute the specific angular momentum distributions for these galaxies. These have been compared to the distributions obtained from published N-body simulations. They found that the disk mass fractions are lower than the universal baryon fraction, but that the total specific angular momenta of the disks are in good agreement with those of the dark matter halos in the simulations. This suggests that the disks form out of only a small fraction of the baryons, but yet manage to draw most of the available angular momentum. The angular momentum distributions of the dwarf galaxy disks are different from those of the dark halos; the disks lack both the low and high specific angular momenta, presenting an important challenge for theories of galaxy formation.

Swaters and Roelof de Jong (Space Telescope Science Institute) have continued their project to obtain stellar velocity dispersions of a sample of disk galaxies. From these measurements, it is possible to derive an independent estimate of the stellar mass-to-light ratio. With the contribution of the stellar disk constrained, it is possible to derive the properties of the dark halo with much higher accuracy, and to get information on the nature of dark matter.

John Graham was on leave for almost all of the report year at the National Science Foundation, serving as Director of the Stellar Astronomy and Astrophysics Program. Following the publication of a study of the loose groups of blue stars associated with the NE radio lobe of the giant radio galaxy Centaurus A, he is continuing this work by examining a second field which contains blue stars apparently associated with the recently discovered X-ray jet. The diffuse region, DF6, originally cataloged by Dufour and van den Bergh, is resolved into a small cluster of young, luminous stars. Small dust clouds in the area, visible as globule-like patches against the extended galaxy, apparently contain sufficient material for gravitational collapse to be triggered by shocks associated with the X-ray jet. The work is being done in collaboration with Caleb Fassett (Williams College) and a paper is in preparation.

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