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Department of Terrestrial Magnetism
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This report covers astronomical research carried out during the period July 1, 2001 – June 30, 2002. Astronomical studies at the Department of Terrestrial Magnetism (DTM) of the Carnegie Institution of Washington encompass observational and theoretical fields of star formation and stellar evolution, meteoritics, planetary system formation, terrestrial planetary evolution, extrasolar planet detection, and galaxy dynamics and evolution.

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, Sara Seager, Alycia J. Weinberger, George W. Wetherill
•Postdoctoral Fellows: Jonathan Aurnou, Steven Desch, Andrew Dombard, Kathleen Flint, Nader Haghighipour, Steven Hauck, Satoshi Inaba, Chris McCarthy, Sujoy Mukhopadhyay, Eugenio Rivera, Aki Roberge, Rob Swaters
•Computer and Support Staff: Michael J. Acierno, Mary M. Coder, Janice S. Dunlap, Rosa Maria Torres, Shaun J. Hardy, Sandra A. Keiser, Jianhua Wang, Merri Wolf

2. HONORS

Alan P. Boss — Fellow, American Association for the Advancement of Science (2001); **Paul Butler** — Beatrice M. Tinsley Prize of the American Astronomical Society (2002); **Larry Nittler** — Alfred O. Nier Prize of The Meteoritical Society (2001); **Vera Rubin** — John Scott Medal (2001); honorary D.Sc. from Grinnell College (2002); **Alycia Weinberger** — Vainu Bappu Gold Medal of Astronomical Society of India (2000).

3. RESEARCH PROGRAMS

3.1 Stars and Star Formation

Boss published the results of a major survey of three-dimensional (3D) radiative hydrodynamics models of the fragmentation mechanism in magnetic molecular clouds. Fragmentation, the break-up of molecular cloud cores during their self-gravitational collapse to form stars, is by far the leading explanation for the formation of binary and multiple protostars. Boss's models include many of 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 actually enhance fragmentation of collapsing magnetic cloud cores. Initially oblate magnetic clouds collapse and fragment into multiple protostar systems, while initially prolate magnetic clouds fragment into binary protostars.

These calculations, as well as Boss's work on disk instabilities, have been enabled by the Carnegie Alpha Cluster, supported in large part by the National Science Foundation. The most recent additions to the cluster include eight dual node machines with the 667 MHz Compaq Alpha 21264 processor, with a 4 MB cache, crucial for fast execution of 3D hydro codes, as well as eight dual node machines with the 2.2 GHz Intel Xeon processor, with a 512 KB cache, ideal for orbital dynamics calculations.

3.2 Planetary System Formation

A proper theory of the processes by which the giant planets of our Solar System formed is essential for understanding the formation of all the other companions of our Sun. Inaba and Wetherill are continuing their extension of previous work on the origin of Jupiter and Saturn in the framework of the present "standard model" in which planet formation is a two stage process by which "cores," more similar in composition to the terrestrial planets form first, and may lead to a gravitational instability in the surrounding hydrogen-helium atmosphere. Emphasis is placed on consistency with their earlier models of terrestrial planet formation. Only under certain conditions can this lead to an atmospheric instability, and thereby to formation of the much more massive gaseous envelopes observed in our gas giant planets. The circumstances under which this may or may not occur are open questions. At present, they are extending their calculations to include the capture of gas during the stage in which primarily solid planetesimals are formed, an effect that is of more importance than it is in the terrestrial planet region, as pointed out by M. Podalak. The goal of this work is not necessarily to support the standard model, but rather to understand better the conditions under which the alternative "disk instability" model, proposed by Boss, may or may not be a more adequate one.

In general, the roughly 100 extrasolar planets discovered by radial velocity searches are quite different than Jupiter and Saturn, with shorter orbital periods, more eccentric orbits, and considerably higher masses. Recently, Boss has proposed an alternative mechanism to core accretion, disk instability, that appears to be able to form gas giant planets rapidly enough to be able to account for the apparently high frequency of extrasolar giant planets.

Boss continues to calculate the evolution of 3D, gravitational, radiative hydrodynamical models of protoplanetary disks, in order to learn the outcome of a phase of gravitational instability. Computing these 3D models requires round-the-clock usage of the growing Carnegie Alpha Cluster of workstations. The 3D 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. The similarity of the results for models calculated with detailed disk thermodynamics (including the solution of the energy equation and radiative transfer in the diffusion approximation) to those with the "locally isothermal" approximation is due to the fact that convective motions are able to carry heat away from the hot, dense midplane to the disk surface, where this heat can be radiated away on a time scale comparable to the dynamical time scale for clumps to form. Because vertical convective transport is critical for cooling these disks, rather than radiative transport, 3D models calculated with opacities varied by factors of 10 greater than or less than the standard dust grain opacity show that clump formation is insensitive to the opacity at this level of variation. This result suggests that if disk instability is able to form gas giant planets, the primordial metallicity of the host star should not matter. This simple prediction can be tested by searching low metallicity (e.g., halo) stars for the presence of gas giant planets.

Boss, Wetherill, and Haghighipour have extended the disk instability hypothesis to the question of the formation of the gas and ice giant planets of our Solar System. 3D models show that it is possible for a disk to break up into four clumps with masses of order twice that of Jupiter, on initial orbits inside about 30 AU. If an O star should then form nearby (as in the Orion nebula cluster), the disk gas beyond about 10 AU would be removed by EUV radiation from the O star, exposing the outermost gas giant protoplanets to EUV radiation which removes their gaseous envelopes and leaves behind ice and rock cores, similar to the ice giant planets. The innermost protoplanets would be protected by the Sun's gravitational potential well from losing their gaseous envelopes, leading to gas giant planet formation. Haghighipour's work on this five body system indicates that such a system can be stable for a million years or longer, a time scale that is long enough to allow the formation of giant planets through the disk instability mechanism. The inner Solar System would be largely unaffected by the EUV radiation field, and the terrestrial planets could then form much later by the usual process of collisional accumulation of solids, a process which has been studied in great detail by Wetherill and his colleagues.

Haghighipour has shown that the combination of pressure gradients, gas drag, and gravitational attraction of a gaseous disk can enhance the growth rate of planetesimals in a solar nebula capable of forming giant planets. His work indicates that it is possible for centimeter-sized particles and meter-sized objects to migrate rapidly (within 1000 years) toward the location of local density enhancements in a non-uniform circumstellar disk. The results of a two dimensional model of Haghighipour's work were presented at the Lunar and Planetary Science Conference in March 2001 and are to be published in the February 2003 issue of ApJ. Recently he extended his study to 3D models. The results of his work, which were presented in the annual meeting of the Division for Planetary Sciences and are at the last stage of preparation for submission to ApJ, indicate that centimeter- to meter-sized objects undergo rapid migration both vertically and radially. The rate of vertical migration toward the mid-plane of the disk is much larger than the rate of radial migration which implies in/outward migrations toward the location of the local density enhancement occur mainly on the mid-plane of the nebula.

3.3 Circumstellar Disks

For studies of disk evolution, it is imperative to have samples of stars that are believed to have formed simultaneously in the same parent clouds, in order to control as much as possible for initial conditions. Weinberger has ongoing programs to identify young stars within 100 pc. For every candidate from catalog searches, she obtains high resolution spectroscopy, to measure equivalent widths of important age signifiers such as Hα and Li I, and radial velocity, for dynamical confirmation of membership in the young association. Observations are made at the Las Campanas Observatory. Young star targets are then followed up with mid-infrared observations at the W. M. Keck Observatory and at the Magellan Telescopes of the Las Campanas Observatory (e.g. Song *et al.* 2002). Large ground based telescopes, thanks to their large collecting apertures, low emissivities, state-of-the-art detectors and wide passband filters are more sensitive than any past space or ground mid-infrared instrument. The improvement over IRAS for observations at 12 microns is a factor of 50 and comes along with spatial resolution of $0.''25$. Weinberger worked with NSF summer intern Anna Haugsjaa (University of Montana) on limiting the amount of dust in 15 members of the TW Hydra association. They identified two new candidates for stars with hot, close-in circumstellar dust.

Once disks are known, Weinberger applies space and ground-based imaging and spectroscopy to understand their geometries and compositions. In the first spatially resolved spectroscopy of β Pictoris, Weinberger and colleagues E. Becklin and B. Zuckerman of UCLA showed that dust very close to the star shows silicate emission features, including amorphous and crystalline species. Further out, the disk spectra are featureless and are entirely dominated by dust thermal continuum emission. Imaging of β Pictoris reveals spatial asymmetries in its dusty circumstellar disk at a spatial resolution of $0.''5$. Visible for the first time is an inner ($r<20$ AU) warp in the disk that is aligned differently from a larger scale warp observed in scattered light by HST. At 12 μm, as has been observed before, the southwest extension of the disk is brighter than the northeast side. This asymmetry appears to be not as significant at 18 μm. The spatially resolved spectra show that this asymmetry cannot be accounted for by small dust grains that have a spectral feature (Weinberger, Becklin, & Zuckerman 2002). For the three spectra at radii $<1''$, the flux to continuum ratios are equal to within the uncertainties. At radii $> 1''$, although flux from the disk is present at a significant level in the spectra, it appears to be composed only of continuum. The shape of the silicate peak does not change significantly over the radii where it can be seen. This implies that the relative abundances of amorphous and crystalline grains remains approximately constant with radius.

Roberge began a Barbara McClintock fellowship in July 2002, working with Weinberger on multi-wavelength studies of circumstellar (CS) disks around young stars. Her recently completed Ph.D. thesis was a far-UV spectroscopic study of gas in these young planet-forming disks, focusing on CS molecular gasses. This has been the subject of recent intensive study, since the timescale for dissipation of primordial interstellar gas left over from star formation limits theoretical timescales for gas giant planet formation. Her work with the *Far Ultraviolet Spectroscopic Explorer* (*FUSE*) Science Team CS disks project has produced indications that primordial molecular hydrogen gas dissipates faster than most theoretical timescales for giant planet formation that involve gravitational accretion of disk gasses onto a solid terrestrial planet sized core (Roberge *et al.* 2001; Lecavelier des Etangs *et al.* 2001). Since coming to DTM, she has written a proposal to obtain observations of additional planetary debris disk systems with *FUSE*, which will attempt to confirm this preliminary suggestion by setting a more accurate limit on the lifetime of primordial gas in CS disks.

She has also studied secondary gasses in CS disks with *HST*-STIS and *FUSE* and provided additional evidence that they are produced by the destruction of planetary material, i.e., the sublimation of icy comet-like bodies and the vaporization of star-grazing planetesimals (Roberge *et al.* 2000; Roberge *et al.* 2002). Recently, she has been involved with Weinberger's Magellan mid-IR observations of young stellar systems, looking for small IR excesses from CS dust and attempting to spatially resolve some known CS disk systems. In addition to her studies of CS disks, she has been involved with research on the problem of stellar activity in A-stars (Deleuil *et al.* 2001; Bouret *et al.* 2002). This activity is not explained by standard theories of stellar structure, which predict that such stars do not possess outer convective layers that could drive magnetic dynamo activity.

3.4 Meteorites and Interplanetary Dust Particles

Presolar dust grains in meteorites, whose isotopic compositions indicate 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. Alexander and Nittler used a new highly automated isotopic analysis technique to determine Si and C isotopic compositions of $\sim$3,000 individual presolar SiC grains from the Murchison meteorite, more than tripling the available dataset. This large database is being used to better determine the abundances and compositions of rare isotopic sub-populations, including grains from supernovae and novae, in addition to the more abundant grains from red giant stars.

All known types of presolar grains in meteorites 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 a presumed presolar carrier of ^{54}Cr enrichments is preserved. Ion probe studies of individual grains in the sample are planned.

Some isotopic signatures in presolar grains are believed to reflect compositional changes associated with galactic chemical evolution. Nittler used a Monte Carlo model to test the hypothesis that inhomogeneous mixing of supernova ejecta into the interstellar medium can explain the distribution of Si and Ti isotopic ratios in presolar SiC, as previously suggested. He found that while the range of silicon isotopes is well explained, an observed correlation between Si and Ti isotopes is not. Nor is the range of $^{16}O/^{18}O$ ratios observed in presolar oxide grains reproduced. These results can put tight constraints on the level of compositional heterogeneity in the ISM 4.6 Gyr ago.

Nittler, Alexander, and NSF 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 an 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 (FIB) technique in collaboration with R. Stroud (Naval Research Laboratory). Subsequent transmission electron microscopy (TEM) of the grain indicated that it contains sub-grains of graphite, in agreement with models of dust condensation around AGB stars, but not previously observed. Stroud also used the FIB technique to prepare a TEM section of a presolar Al_2O_3 grain identified by Nittler and Alexander. Analysis indicated the grain is a single crystal with the α (corundum) structure, not amorphous as suggested by some observations of O-rich red giants.

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 and postdoctoral fellow Mukhopadhyay have initiated a study of isotopic heterogeneity in IDPs, using the micron resolution isotopic imaging capabilities of the ion probe. They have 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. Sulfides are ubiquitous in IDPs and it has been suggested that interstellar sulfides with unusual isotopic compositions might be preserved. Mukhopadhyay and Nittler have performed the first S isotopic measurements of IDPs. Thus far, no anomalous signatures have been found.

Desch has pursued his research goals of applying astrophysical modeling techniques to problems in the fields of meteoritics. One major avenue of research was the melting of chondrules, millimeter-sized spheres of melted rocks found in abundance in chondrites. Work finished this year by Desch and Connolly (Kingsborough College), along with 2001 NSF summer intern student Danielle Moser (University of Illinois), strongly suggests that chondrules were melted when shock waves passed through the gas of the solar nebula. The physical conditions experienced by chondrules also strongly implicate gravitational instabilities as the triggers of the shock waves. These same shocks also may have initiated astrobiologically important nitrogen chemistry in the solar nebula gas, as seen in a preliminary exploration by M. Kress (University of Washington), Desch, and collaborators. With

D. Harker (NASA Ames Research Center), the same shocks that melt chondrules were also shown to explain the crystalline mineralogy of silicate dust in comets.

Further research into the mineralogy of silicate dust in other protoplanetary disks was undertaken with 2002 NSF summer intern student Leah Hutchison (Massachusetts Institute of Technology). Using a radiative transfer code written by Desch, they were able to show that dust in the TW Hydrae disk most closely resembles 1 to 2 micron radius, Fe-rich amorphous olivine grains. Desch also completed a review of planetary lightning that summarized the theories of lightning on Venus, Jupiter, and Titan, and the Galileo observations of Jovian lightning.

3.5 Terrestrial Planetary Evolution

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 been divided between the analysis of data from the Mars Global Surveyor (MGS) spacecraft still operating in Martian orbit and oversight of the development of the MESSENGER spacecraft scheduled 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 topography data and its relationship to the planetary gravity field to formulate new constraints on lithospheric loading, planetary heat flow, and interior evolution on Mars. For the most ancient regions of the planet, gravity-topography relations preserve evidence from early in Martian history for comparatively high heat flow and thickness values for the mechanical lithosphere much less than the local crustal thickness, implying that lower crustal flow operated for at least some interval to help reduce lateral variations in crustal thickness at shorter wavelengths. Gravity-topography relations for areas with younger surfaces indicate that the Martian lithosphere thickened rapidly over the first several hundred million years of the planet's history, on the grounds that the stress differences imparted by the formation of the youngest large impact features and by contemporaneous volcanic deposits have not relaxed substantially with time. Rapid early cooling of the Martian lower crust and mantle, possibly enabled by deep penetration of hydrothermal circulation, must have led to a sharp decline in internal heat flow, stabilization of a thick lithosphere, and retention of ancient lateral variations in topography and crustal thickness.

Mercury has been viewed at close range by only a single spacecraft, Mariner 10, in 1974-75. 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 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. 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.

Hauck and Dombard worked with Solomon to develop models of the internal evolution of modestly-sized, solid planetary bodies. In anticipation of results from MESSENGER, they collaborated with R. Phillips (Washington University) to update current understanding of Mercury's internal and tectonic evolution. The goal is to provide context for data to be returned by the MESSENGER spacecraft concerning Mercury's geologic history and magnetic field and their implications for the planet's internal history and constitution. Hauck, Dombard, Aurnou, and Solomon have also been developing models of Ganymede's interior with the aim of understanding the mechanism responsible for the operation of its magnetic field. In particular, their proposed model suggests that convection in Ganymede's metallic core, necessary to drive a dynamo, may have been driven by ''snowing'' of solid Fe through the core.

Dombard also continued his work investigating the Galilean satellites of Jupiter, modeling the development of the grooved terrain on Ganymede, and constraining the thickness and thermal structure of the outer ice shell of Europa. He further developed his models of the long-term relaxation of impact crater topography and worked with former DTM postdoctoral associate A. Freed on the generation of thermal stresses in asteroids undergoing chaotic orbit transfer. With former DTM postdoctoral associate C. Johnson, DTM visiting scientist M. Richards (UC Berkeley), and Solomon, he examined the origin of coronae, enigmatic volcanotectonic features found exclusively on Venus, and again with Richards he considered the earliest mantle dynamics of Mars and implications for true polar wander.

Aurnou focused on numerical models for planetary magnetic field generation and its dependence on the relative size of the planet's solid inner core. In collaboration with M. Heimpel and F. Shamali (University of Alberta) he is carrying out massively-parallel numerical simulations of planetary dynamo action. These simulations have been made using J. Wicht's (Gottingen University) rotating, magnetohydrodynamic, spherical, thermal convection code. Their results for Boussinesq spherical shells of convecting fluid, subject to non-slip, isothermal boundary conditions, demonstrate that dynamo action occurs for the weakest non-dimensional thermal forcing with inner core sizes that are comparable to half the radius of the entire core.

Aurnou has also taken part in two experimental studies of rapidly rotating convection relevant to planetary core dynamics. The first study was made in collaboration with workers at Johns Hopkins University and focuses on core convection at high latitudes inside the Earth's core tangent cylinder (Aurnou *et al.* 2002). This tangent cylinder is the imaginary, right cylinder that is aligned with the rotation axis and circumscribes the inner core equator. Their experiments, which are the first made to focus specifically on high-latitude core processes, support the idea that large-scale polar vortices exist within each hemisphere of Earth's core tangent cylinder. The second experimental study was made in collaboration with workers at the Observatoire de Grenoble, France. They were able to make the first experimental measurements of turbulent viscosity in a rapidly rotating spherical shell and apply these measurements to coupling processes in planetary cores (Brito *et al.* 2002).

3.6 Extrasolar Planet Detection

The California & Carnegie Extrasolar Planet Search (Geoff Marcy & Debra Fischer – UC Berkeley, Steve Vogt – UC Santa Cruz, Chris McCarthy & Paul Butler – Carnegie DTM) are surveying the nearest 1,300 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. McCarthy made several observing trips to Australia working with international partners in the Anglo Australian Planet Search (AAPS). Over the past seven years, these surveys have led to the discovery of two-thirds of the known extrasolar planets, including the only known transit planet, all five published multiple planet systems, and all five published sub-Saturn mass planets.

Most of the known planets orbit beyond 0.2 AU in eccentric ($e > 0.1$) orbits, while a surprising class of Jupiter-mass planets is found in circular orbits with periods of 3 to 5 days. These discoveries have stimulated the development of planet formation and evolution theories, including disk-planet and planet-planet interactions. Within the last year a handful of planets have been found orbiting beyond 1 AU in relatively circular orbits, suggesting that "circular planets" may be more common among systems in which giant planets orbit in distant Jupiter–like orbits.

In June, McCarthy presented the collaboration's discovery of "the 100th extrasolar planet" at a conference at Carnegie's headquarters in in Washington. The mass function of the $\sim$100 substellar companions found from precision Doppler surveys begins rising abruptly below 8 Jupiter-masses, and continues to rise all the way down to the detection limit below 1 Jupiter-mass. Above 8 Jupiter-masses the mass function is flat, empirically motivating a 10 Jupiter-mass limit between planets and brown dwarfs. Brown dwarf companions to solar type stars are rare. At an International Astronomical Union Symposium on Brown Dwarfs in May, 2002, McCarthy presented a paper on the surprising lack of brown dwarf companions to stars, the so-called "brown dwarf desert."

The long term goal of this work is to survey all 2,000 nearby Sun-like stars out to 50 parsecs. The team will begin adding most of the remaining stars to their survey this year with the addition of time on the Carnegie 6.5-m Magellan telescopes. They currently achieve long term precision of 3 m s^{-1}, sufficient to make 4σ detections of Solar System analogs (Jupiter-mass companions out to 5 AU), but are working to improve their precision to 2 m s^{-1}. McCarthy will travel again to Australia to install new instrumentation aimed at refining Doppler precision. 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.

Rivera performs fits to the team's radial velocity data. He has developed an algorithm that models the radial velocity observations of stars and accounts for the planet-planet perturbations. The algorithm can be used to find the semi-major axes (or periods), eccentricities, longitudes of periastron, and mean anomalies of each planet. Additionally, an osculating radial velocity amplitude for each planet may be determined. Thus, the five radial velocity parameters for each planet, P, e, ϖ, $T_{\rm peri}$, and K, can be fitted. Ideally, with the inclusion of the planet-planet perturbations, the planetary masses, inclinations, and the longitudes of the ascending node may also be determined. Currently, this improved fitting method can be used to place constraints on planetary masses and inclinations, although the fits change as more data is obtained.

This method has been used primarily to fit the radial velocity data for the star GJ 876. Thus far, the GJ 876 planetary system is the only system for which the inclusion of the planet-planet perturbations produces a very significant improvement in the fits to the radial velocity data. The fit is significantly improved because the planets in GJ 876, which are in a 2:1 mean motion resonance, strongly perturb each other.

The code has been generalized so that it can be used to fit the radial velocity data, obtained at one or more telescopes, for any star that has at least two orbiting planets. It has been used to generate fits for 47 Ursa Majoris and 55 Cancri, with results in rough agreement with those of Fischer *et al.* (2002) and Marcy *et al.* (2002). Future improvements are planned including fitting for parameters such that the correlations between parameters are minimized and fitting for linear trends.

3.7 Planetary Dynamics and Celestial Mechanics

Haghighipour extended his previous work on the application of the method of partial averaging to the dynamics of planetary systems at resonance as an alternative to the traditional pundulum and Hamiltonian methods. He is applying his method to the study of the dynamics of objects trapped in (1:1) resonances in Lagrangian points of extrasolar planetary systems, to the dynamical evolution of planets of 47 Uma while captured in a (5:2) resonance and also to the dynamics of GJ 876 extrasolar planetary system where two planets are locked in a (2:1) commensurability.

Haghighipour and Rivera have been studying the dynamical evolution and also the long-term stability of multi-planet systems such as Upsilon Andromedae, 47 Uma, GJ 876, and 55 Cnc. They have shown that the extrasolar planetary system of 47 Uma may be in a (5:2) resonance, similar to the resonance state of Jupiter and Saturn, and that the apparent (3:1) commensurability between the two inner planets of 55 Cnc may not be an actual resonance. Rivera's code has been used to generate initial conditions for N-body simulations. They have also simulated the motions of hundreds of test particles within these four systems to look for stable regions, where terrestrial planets can be harbored. In addition to broad stable and unstable regions, they have found islands of stability and instability that correspond with mean motion resonances with the planets.

Two NSF summer interns worked with Haghighipour in 2002. Jim Norwood (Harvey Mudd College) studied the effect of the distant binary companion on the stability of the Ups And planetary system. His results, which were presented at the 2002 meeting of the Division for Planetary Science, map the stable and unstable regions of this planetary system. Eric Nadal (University of British Columbia) worked on the role of the dynamical friction as a stopping mechanism for migrating planets in a disk of planetesimals. He was able to show that it is possible for the planets of a three-body planetary system to migrate and become captured in a resonant state. His results will be presented in the annual meeting of the Division on Dynamical Astronomy next April.

3.8 Dynamics and Evolution of Galaxies

Last year, Rubin and former postdoctoral fellow Stacy McGaugh (University of Maryland) described their program to obtain 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 rotation curve directly probes the invisible mass component, for the dark matter dominates the observed rotation at essentially all radii. 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 E. de Blok (Australia Telescope National Facility) and A. Bosma (Observatoire de Marseille), rotation curves from the 4-m and 2.5-m telescope data have been analyzed and published. For many LSBs, the mass distribution at small radii is dominated by a nearly constant density core. 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, McGaugh, and Swaters (now at Johns Hopkins University) are presently analyzing observations of additional LSB galaxies obtained with the Magellan 6.5-m telescope. In general, the analysis of the newer data supports the earlier conclusion that halos based on Cold Dark Matter cosmology are not as good a fit as are models with an isothermal halo. Rubin and collaborators are presently investigating to what extent systematic effects could play a role in the conclusions.

Deidre Hunter (a former DTM postdoctoral fellow now on the staff of Lowell Observatory) and Rubin have obtained long-slit spectra of irregular galaxies NGC 1156 and NGC 4449 with the Kitt Peak 4-m telescope. In collaboration with Swaters, they have determined velocities from both 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. In NGC 1156, they detect a small stellar linear velocity gradient of $(5\pm1/\sin i)$ km s^{-1} kpc^{-1} to a radius of 1.6 kpc. The stars and gas rotate about the same axis, which is different from the major axis of the prominent stellar bar. For NGC 4449 they detect no organized stellar rotation greater than $(3/\sin i)$ km s^{-1} kpc^{-1}. A model that reproduces the observed velocities, produced in collaboration with L. Sparke (University of Wisconsin) and S. Levine (USNO), suggests that the rotating stellar component is viewed almost face on, while the gas is in a tilted disk with orbits whose planes precess. The peculiar gas orbits are presumed to arise from gas acquired in an past interaction.

Rubin and Swaters observed the polar ring galaxy NGC4650A with the Baade 6.5-m telescope at Las Campanas to test a novel model of polar ring formation (Tremaine and Yu 2002). The model predicts that a polar ring contains two equal, counter-rotating star streams. From relatively high resolution *stellar* velocities in the polar ring and in the central lenticular of the galaxy NGC 4650A, Rubin and Swaters detect only a single sense of rotation in each. These may be the first stellar velocities in a polar ring. Rubin and Swaters are presently attempting to put limits on the fraction of the polar population that may be counter-rotating. From a comparison of the lenticular and the polar ring velocities, they hope to put meaningful constraints on the three dimensional shape of the dark halo in this remarkable object.

Swaters, B. Madore (OCIW), F. van den Bosch (MPA, Garching), and M. Balcells (IAC, Tenerife) continued their study of high-resolution rotation curves obtained with the Palomar 200″ 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 *et al.* investigated the influence of systematic effects, such as seeing, slit-width and misplacement of the slit, on the derived rotation curve shape, and they found 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.

Graham concluded his work on the recently formed blue stars in the NE radio lobe of the Centaurus A radio galaxy. In a paper co-authored with NSF summer intern Caleb Fassett (Williams College), blue stars were identified close to the X-ray jet that extends NE of the galaxy nucleus. Positions, photometry, and finding charts were given. The formation of the stars was apparently triggered by the impact of the jet on ambient, adjacent clouds of dust and gas that may be remnants of a former merger event. Observations made with the 2.5-m du Pont telescope at Las Campanas Observatory were used for this project.

Flint joined DTM as a Carnegie fellow in December 2001. She is continuing her work on the Leo I group survey that was the basis of her thesis at UC Santa Cruz. Flint's work in Leo is one of the deepest large-scale surveys of a nearby group, providing insight into the luminosity function of galaxies in low-density environments down to dwarf luminosities, $M_R \leqslant -11$. She finds the faint-end of the luminosity function appears consistent with that of the Local Group, without the excess of dwarf galaxies seen in denser cluster environments like Virgo. At the bright end, however, the group core is completely devoid of intermediate luminosity galaxies $-19.5 < M_R < -16$, suggesting evolutionary processes might be at work more akin to those in dense clusters. She also has a project underway to look at the HI-mass function of the group in collaboration with M. Bolte (UCO/Lick Observatory) and C. Impey (University of Arizona). A sensitive survey with Arecibo from January 2002 of optically-selected dwarf galaxies suggests a distribution unusually skewed toward gas-poor dwarf spheroidals. A blind HI survey of the group core, which is currently in the queue to be scheduled at Arecibo, will provide a complete picture of the mass function down to $M_{HI} \simeq 10^7 M_\odot$, and possibly shed light on the relationship of the dwarf galaxy population and the quiescent intergalactic gas ring in the group's center.

While expected to be the dominant galaxy population in the Universe *by number*, dwarf galaxies are elusive to detect due to their low surface brightnesses and luminosities. Yet, these low-mass galaxies can be an important indicator of environmental influences on galaxy evolution. Flint and A. Gonzalez (University of Florida) have begun a study to identify the first field population of dwarf spheroidal galaxies, with a sample of low-surface brightness candidates drawn from the extensive drift-scan data of the Las Campanas Distant Cluster Survey. They have begun analyzing images taken with the Magellan 6.5-m and the du Pont 2.5-m telescopes at Las Campanas, to measure a distance via surface-brightness fluctuations and establish an intrinsic luminosity for these objects. Flint and J. Harris (Space Telescope Science Institute) are examining dwarf evolution within the Local Group by empirically reconstructing the Local Group optical luminosity function as a function of time, using published star-formation histories and population synthesis models. By characterizing the extremes of the luminosity function shape due to local evolutionary processes, they can examine the utility of using the luminosity function as a proxy for the mass distribution.

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