

**Carnegie Institution of Washington**  
**Department of Terrestrial Magnetism**  
*Washington, District of Columbia 20015-1305*

This report covers astronomical research carried out during the period July 1, 2002 – June 30, 2003. Astronomical studies at the Department of Terrestrial Magnetism (DTM) of the Carnegie Institution of Washington include observational and theoretical fields of planet detection, formation, structure, evolution, and atmospheres, the formation of stars and stellar evolution, meteoritics, and 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 (Emeritus), Larry R. Nittler, Vera C. Rubin (Senior Fellow), Sara Seager, Alycia J. Weinberger, George W. Wetherill (Director Emeritus).
- Research Scientist: James Cho.
- Postdoctoral Fellows: Steven Desch, Kathleen Flint, Nader Haghighipour, Christopher McCarthy, Eugenio Rivera, Aki Roberge.
- Computer and Support Staff: Michael J. Acierno, Alexis Clements, Janice S. Dunlap, Brooke Hunter, Shaun J. Hardy, Sandra A. Keiser, Jianhua Wang, Merri Wolf.

## 2. HONORS

**Alan P. Boss** — Fellow, American Academy of Arts and Sciences (2002); **R. Paul Butler** — Carl Sagan Memorial Award (2003); **Steven Desch** — Alfred O. Nier Prize of the Meteoritical Society (2003); **Vera C. Rubin** — Peter Gruber International Cosmology Prize (2002), ASP Catherine Wolfe Bruce Gold Medal (2003), Thomas Gold Visiting Lecturer, Cornell (2003); **George Wetherill** — AAS Henry Norris Russell Lectureship (2003).

## 3. RESEARCH PROGRAMS

### 3.1 Extrasolar Planet Detection

The California & Carnegie Extrasolar Planet Search (Geoff Marcy & Debra Fischer – UC Berkeley, Steve Vogt – UC Santa Cruz, Paul Butler – Carnegie DTM) are surveying the nearest 1,700 Sun-like stars (F8 - M5) with the *precision Doppler technique* at the Lick 3-m, Keck 10-m, Anglo-Australian 3.9-m and the Magellan 6.5-m telescopes. Nearly all suitable stars out to 50 parsecs are now being monitored. Over the past 8 years, these surveys have led to the discovery of two-thirds of the known extrasolar planets, including the first extrasolar transiting planet, all 8 published multiple planet systems, and 5 of the 6 published sub-saturn mass planets.

Of the ~100 known substellar companions found from precision Doppler surveys, only 3 have  $M \sin i$  masses greater than 8 Jupiter-masses. The substellar companion mass function rises sharply toward the smallest detectable planets, near 1 Jupiter-mass. Brown dwarf companions to solar type stars are rare.

More than 90% of the planets found orbiting beyond 0.2 AU are in eccentric ( $e > 0.1$ ) orbits, suggesting that systems of planets in circular orbits may be rare. These discoveries have stimulated the development of planet formation and evolution theories, including disk-planet and planet-planet interactions, capable of producing planets in eccentric orbits and in very short period orbits.

The long term goals of this work include improving Doppler precision from 3 to 2 m/s, maintaining this precision over the next two decades, detecting many hundreds of giant planets, and detecting planets as small as 10 earth-masses in short period orbits. 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, to be used on such telescopes 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.

Alan Boss and Alycia Weinberger have undertaken a new *astrometric planet search* program with the 2.5-m du Pont telescope at Carnegie's Las Campanas Observatory. Along with the Observatory's Ian Thompson, Allegheny's George Gatewood, and Virginia's Steven Majewski and Richard Patterson, Boss and Weinberger plan to begin a long-term search for Jupiter-mass planets and brown dwarfs on long-period orbits (10 years or more) around nearby low mass stars (G,K,M dwarfs). Observations have been underway for two years now to demonstrate the astrometric stability of the du Pont, and to begin to characterize the target stars and their background reference stars. For the latter stars, photometry is underway in order to determine their colors, so that the effects of differential chromatic refraction can be removed from the astrometric solutions. While the current work is being undertaken with the existing Tek5 camera on the du Pont, the hope is to develop a specialized astrometric camera, capable of handling the extreme brightness ratios between the nearby target stars and the more distant reference stars.

Sara Seager has continued to work on the EXPLORE *planet transit search* together with DTM visiting investigator Gabriela Mallen-Ornelas (CfA) and Howard Yee (University of Toronto). Also involved are DTM Carnegie Fellow Kaspar von Braun, Carnegie Observatories Fellow Michael Gladders and graduate student Brian Lee (University of Toronto). The EXPLORE project is a search for planetary transits around Galactic field stars using large-format mosaic CCD cameras on 4m-class telescopes. Out of 50,000 stars with high photometric precision light curves from two different fields, radial velocity followup data of three planet candidates is currently being analyzed.

Kaspar von Braun arrived as a Carnegie Fellow at DTM to initiate a search for planet transits around stars in Galactic open clusters (EXPLORE/OC). By making use of the fact that all stars in open clusters have the same age, metallicity, and distance, specific stellar spectral types and radii may be targeted. Furthermore, astrophysical properties of parent stars of detected planets will readily be available from studying the cluster as a whole, rather than studying individual field stars. Finally, the analysis of two separate environments may enable the EXPLORE project to compare planet frequencies, and thus constraints on planet formation mechanisms, in the Galactic disk as well as in open clusters. Along with Brian Lee and other EXPLORE collaborators von Braun used the Swope 1m Telescope at Las Campanas Observatory for the bulk of the monitoring studies of the two open cluster NGC 2660 and NGC 6208, both of which were selected based on properties such as the ones described above, and on richness estimates based on test data obtained in early 2002. A total of approximately 10000 stars were monitored with a precision of 1% or better (corresponding to around 15% of the total number of stars in both fields), and four systems were flagged as being planetary candidates. Along with Eugenio Rivera (DTM), von Braun set up a DTM computer cluster to handle the immense data flow created by the EXPLORE Field Searches conducted using  $8k \times 8k$  mosaic cameras on the KPNO and CTIO 4 m Telescopes.

### 3.2 Stars and Star Formation

Boss is working on a new major survey of 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 have shown 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. The new models involve the collapse of initially sheet-like clouds, and it is found that such clouds have three possible outcomes: formation of one or two protostars near the edge of the computational volume, a single protostar near the center of the volume, or formation of a rotating disk near the center of the volume which appears likely to fragment into two or more 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 833 MHz Compaq Alpha 21264 processor, with a 4 MB cache, crucial for fast execution of 3D hydro codes, as well as forty-eight dual node machines with the 2.8 GHz Intel Xeon processor, with a 512 KB cache, ideal for orbital dynamics calculations.

### 3.3 Planetary System Formation

Boss continues to calculate the evolution of three dimensional (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 latest 3D models include the gravitational effects of a binary star companion to the protostar and disk system under consideration. Previous work had suggested that binary protostars with separations of order 50 AU would be unable to form planetary systems, because the tidal heating generated at each close encounter would heat the disk to such high temperatures that solids would evaporate and the disk gas would be too hot for a gravitational instability to occur. The new models, however, find that a binary star companion can actually help to trigger the formation of gas giant protoplanets by the disk instability scenario by gathering disk gas into tidally-forced spiral arms. The disk gas remains cool enough for self-gravitating clumps to form, as well as for solids to remain solids and therefore form planets by collisional accumulation. The reason for this new result compared to the previous work seems to be the inclusion of the third (vertical) dimension in the new models, allowing the disk to cool by vertically-driven thermal convection.

Nader Haghighipour continued his research on the effect of gas drag and pressure gradients on rapid formation of solids in the vicinity of local density enhancement of a non-uniform solar nebula. He had previously shown that in a two-dimensional model, where solid objects were constrained to the midplane of a nebula, the combined effect of gas drag and pressure gradients could cause objects to rapidly migrate toward the location of local maximum density. Haghighipour extended his work to three dimensions and studied rapid vertical and radial migrations of solids, ranging from micron-sized particles to kilometer-sized objects. In this work, Haghighipour has shown that in the vicinity of local density enhancements, objects undergo rapid radial migration while approaching the midplane. He has also presented analytical analysis of the motions of objects in the vicinity of the midplane and has shown that solid bodies can undergo over-damped, under-damped and critically-damped oscillatory motions. The frequencies of such oscillations vary with the physical properties of the particle and also the temperature of the gas.

Rapid migration of solids toward local maximum density results in the accumulation of these objects at such locations in a short time. Haghighipour has shown that 1-1000 micron-sized particles can rapidly grow to 1 centimeter in radius sweeping smaller particles of the background material of a nebula while undergoing radial and vertical migrations. These results indicate that appearance of density enhancements in a nebula, at any stage of its evolution and planet formation, will have a considerable effect on enhancing the rate of growth of small solids to larger objects. Haghighipour is currently continuing his research on rapid growth of centimeter-sized particles to meter-sized and kilometer-sized bodies in non-uniform nebulae.

### 3.4 Circumstellar Disks

Weinberger studied young circumstellar disks as the sites of planet formation and evolution. She has been conducting a ground-based search for warm dust around young stars in nearby associations. She completed a study of the TW Hydrae Association (TWA) in collaboration with E. Becklin, B. Zuckerman, and I. Song of UCLA. In a survey of sixteen TWA stars with sensitive 12 and 18  $\mu\text{m}$  photometry from the W. M. Keck Observatory, she could detect small amounts of dust, similar to that found around the well studied A-type member star HR 4796A, around the late-type members. The measurements constrained the amount of dust at temperatures of  $\sim 200$  K. For the TWA stars, this corresponds to distances of 1–5 AU, depending on the luminosity of the star and the emissivity of the grains. Primordial, i.e. interstellar, dust distributions, are dominated by small ( $< 1 \mu\text{m}$ ) grains. So, these observations would be very sensitive to primordial dust. In addition, copious dust is produced during an epoch where large bodies perturb each other and generate many collisions. However, no new stars with infrared excess at 12 or 18  $\mu\text{m}$  were positively discovered in this most sensitive survey to date.

It is remarkable that of the 24 star systems now known in the TW Hydrae association, all of those with dust were discovered by IRAS despite the ten times better sensitivity of this survey. Dust content in TWA is bimodal, with a few stars possessing much dust and most largely devoid of material. In regions analogous to the terrestrial planet region, even at the young age of 5–10 Myr, little material remains or is being generated in collisions around these late-type stars. Any planet formation in the terrestrial planet region was evidently completed very quickly. Other work has shown that not all star clusters may have the same disk lifetime, and Weinberger would like to tease out the reasons for this by studying different cluster environments. Weinberger's disk survey is ongoing in the 12 Myr old  $\beta$  Pictoris Association. Three disks with 12  $\mu\text{m}$  excess are known in that association from IRAS data. Weinberger has surveyed 19 more stars and detected photospheres for stars as late as M3. Preliminary analysis suggests that no significant infrared excesses were detected around the sample stars, although hints of excess appear in a few.

Once disks are identified, Weinberger will apply space and ground-based imaging and spectroscopy to understand their geometries and compositions. She is continuing her detailed analyses of imaging data for the disks around HD 141569A, HR 4796A, and TW Hydrae taken with the Space Telescope Imaging Spectrograph (STIS) aboard HST.

Barbara McClintock fellow Aki Roberge works on multi-wavelength studies of gas and dust in circumstellar (CS) disks around young stars. Her Ph.D. thesis was a far-UV spectroscopic study of gas in these planet-forming disks, focusing on CS molecular gases. Her work with the *Far Ultraviolet Spectroscopic Explorer (FUSE)* Science Team CS disks project has produced indications that primordial interstellar gas dissipates faster than most theoretical timescales for giant planet formation which involve gravitational accretion of disk gasses onto a solid core. In 2003, Roberge was awarded a funded proposal to obtain *FUSE* observations of

additional planetary debris disk systems, which will attempt to set a more accurate limit on the lifetime of primordial gas in CS disks.

Recently, the *FUSE* CS disks team found unusual hot  $\text{H}_2$  near two intermediate age CS disks. Two possibilities for the nature of this gas have been suggested, 1) that the gas lies in hot dense surface layers on the disks, or 2) that the relatively old stars are still driving unseen bipolar outflows which create weak Herbig Haro flows. Roberge has begun a project using the Magellan telescopes at Las Campanas Observatory to try to determine the origin of this hot gas using narrow-band near-IR imaging of  $\text{H}_2$  emission.

Roberge is nearing completion of a project with Dr. Weinberger involving it HST-STIS imaging spectroscopy of light scattered off dust grains in the TW Hydrae CS disk, a dense face-on disk surrounding a classical T Tauri star. This work has confirmed earlier suggestions based on broad-band photometry that the bulk of the CS dust shows wavelength-independent scattering in the optical. This likely indicates either that the dust grains are large ( $> 1 \mu\text{m}$ ) compared to typical interstellar grains or that the disk is very optically thick to large radii. Spatially resolved spectra of this kind will be an important new constraint on theoretical models of grain growth and disk structure.

Weinberger and Roberge worked with NSF summer intern Matthew Peck (UMBC) on a compositional analysis of infalling gas around  $\beta$  Pic, which has been attributed to the evaporation of star-grazing planetesimals. Using high resolution ultraviolet spectroscopy from STIS, they identified variable lines in four distinct velocity ranges from the elements Fe, C, Si, Ni, S, Cr, Mn, and Al. With additional data, they will make a comparison between the composition of this infalling material and the stellar composition, to try to understand how material in a 12 Myr old disk has been processed.

### 3.5 Planetary Dynamics and Celestial Mechanics

Haghighipour, in collaboration with F. Varadi and W. B. Moore from IGPP/NAI at UCLA, has worked on mapping the parameter-space of a restricted elliptical three-body system in an exterior 1:2 resonance. The results indicate that the parameter-space of such systems can be separated into two distinct regions corresponding to stable and unstable resonant periodic orbits. An approximate application of these results to the extrasolar planetary system of GJ 876, where two planets are in a near 1:2 resonance, indicate that this system is well within the stable region.

Eugenio Rivera performs fits to the radial velocity data of stars, and he studies the stability of extrasolar planetary systems. He has developed an algorithm which models the radial velocity observations of stars and which accounts for the planet-planet perturbations. The algorithm can be used to fit for 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,  $P$ ,  $e$ ,  $\varpi$ ,  $T_{\text{peri}}$ , 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. For GJ 876, the quantity used to measure the goodness of a fit,  $\sqrt{\chi^2_{\nu}}$ , drops from a value above 2.8 for fits without the planet-planet perturbations to a value of about 1.6 for fits with it. Note that the best models would result in  $\sqrt{\chi^2_{\nu}} \sim 1.0$ . 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 can be used to fit the radial velocity data, obtained at one or more telescopes, for any star which has at least two planets in orbit about it (in general). It has been used to generate fits for 47 Uma and 55 Cancri. A study which looks at the differences between these Newtonian fits and the usual Keplerian fits, in which the planet-planet perturbations are not modeled, for all the multi-planet systems is ongoing. Future improvements are planned. These improvements include fitting for parameters such that the correlations between parameters are minimized and fitting for (linear) trends.

The code has been used to generate initial conditions for N-body simulations performed by Rivera and Haghighipour. They have looked at the long-term stability of the planetary systems of Upsilon Andromedae, GJ 876, 47 Uma, and 55 Cancri. They have also simulated hundreds of test particles within these four systems to look for stable regions, which could harbor terrestrial planets, as well as unstable regions. In addition to broad stable and unstable regions they have found islands of stability and instability which correspond with mean motion resonances with the planets. The results of their work on 47 UMa and 55 Cnc indicates the former is most likely in a near 5:2 resonance.

Haghighipour and Jared Crossley, an undergraduate summer intern from the New Mexico State University, studied the long term stability of a planetary system embedded in the debris disk of Beta Pic. Such a system has been suggested to account for the observed warps in the Beta Pic. disk. This is a five-body system with 4 planets at locations of the warps. The mass of the planets were randomly chosen between 1 – 3 Jupiter-mass. Haghighipour and Crossley simulated the stability of 20000 systems and discovered that only 40% of these systems will stay stable for as long as the age of the disk and longer.

### 3.6 Planet Atmospheres

Seager has continued to model extrasolar planet atmospheres with a focus on the close-in extrasolar giant planets (CEGPs). The CEGPs have  $\sim 4$  day orbits and are therefore intensely irradiated by their parent stars. They are potentially bright in both thermal emission and scattered light, in comparison with giant planets at larger orbital semi-major axes,

and so should be the first class of extrasolar planets to be successfully studied observationally. In particular, Seager has been preparing for interpretation of upcoming results from the Microvariability and Oscillations of STars (MOST) mission for which she is a support scientist. MOST is a Canadian Space Agency microsatellite (PI Jaymie Matthews at the University of British Columbia) that launched successfully on June 30 2003. MOST will study several stars with known CEGPs, observing the stars for 30 to 60 days, and folding the data on the planet period to reach par-per-million photometric precision. For the transiting planet HD209458b, this will enable for the first time ever the measurement of the planet albedo and the planetary illumination phase curve. For non-transiting CEGPs the phase curve will be measured. In order to understand the reflective nature of the CEGP atmospheres, Seager has embarked on a theoretical investigation on photochemistry in the CEGP atmospheres with Caltech collaborators and Yuk Yung and graduate student Mao-Chang Liang. Seager has also been collaborating with observers Drake Deming (GSFC) and Jeremy Richardson (U. Colorado and GSFC) to narrow down the parameter space of theoretical models using near-infrared IRTF data of the transiting CEGP HD209458b.

Research scientist James Cho arrived at DTM in 2002 and is currently leading a collaboration between scientists at DTM, University of Virginia, UCLA, Harvard, and Caltech in atmospheric dynamics and circulation modeling of solar and extrasolar planets. Cho is focusing on both giant and terrestrial-type planets. The scientific problems that have been investigated range from the transport and mixing of heat and tracers (e.g., cloud, dust, and moisture) to the formation of persistent structures (e.g., vortices, jets, waves, and localizations of tracers), under a variety of external conditions (e.g., spin-orbit synchronized heating, high eccentricity and obliquity, and bolide impacts). The progress in these efforts have not only been useful for theoretical understanding of specific mechanisms, but have also been guiding observer in planning their runs, interpreting acquired data, and designing future instruments. Currently, the effort is underway to use large-scale general circulation models to generate specific spectra and phase curves for extrasolar planets, as well as seasonal and annual flow predictions for Mars and Saturn.

Seager and Cho, in collaboration with summer intern Karen Horning (Florida Institute of Technology), started a project on ‘‘Jupiter as an Extrasolar Planet.’’ Although Jupiter has been observed in great detail with high spatial and spectral resolution from Earth and from spacecraft, spatially integrated data as a function of phase and time with a broad wavelength coverage is not readily available. The goal is to compile such data and then use it together with Seager’s and Cho’s extrasolar planet atmosphere models to interpret Jupiter as a point source. In this way they will be able to answer the questions, what would we learn, what would we miss and what would we misinterpret if Jupiter were an extrasolar planet?

Seager is leading an effort to study the transit of Venus in June 2004 as an extrasolar planet. Collaborators include Jian Ge (Penn State) who is leading the instrumentation develop-

ment and Kaspar von Braun (DTM). The results will be used as a calibration tool for the astronomical community to interpret transit transmission spectra of extrasolar planets.

### 3.7 Dynamics and Evolution of Galaxies

Last year, Vera Rubin and former post-doctoral fellow Stacy McGaugh (now at University of Maryland) and former post-doctoral fellow Rob Swaters (now at Johns Hopkins University) described their program to obtain high resolution spectra for low surface brightness (LSB) galaxies. 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 Dr. Erwin de Blok (Australia Telescope National Facility) and Dr. Albert Bosma (Observatoire de Marseille), spectra from the 4-m telescope at Kitt Peak National Observatory, and the 2.5-meter DuPont telescope at Las Campanas, Chile, were analyzed and the results published. For many LSBs, the mass distribution at small radii is dominated by a nearly constant density core. This result conflicts significantly with the sharply rising nuclear density cusp predicted from models calculated on the basis of Cold Dark Matter cosmology.

Rubin, McGaugh, and Swaters are presently completing the analysis of spectra of mostly fainter LSB galaxies, obtained with the Magellan 6.5-m telescope at Las Campanas. 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.

To extend their study of stellar orbits in the rings of polar ring galaxies, Rubin and Swaters have obtained additional spectra of 4650A and a few other polar ring galaxies with the Baade 6.5 telescope at Las Campanas. Last year, their observations showed that stellar orbits in the ring of NGC 4650A matched the unidirectional motion of the ring gas. This result contradicts the novel model of Tremaine and Yu (2002) which predicted that a polar ring contains two equal, counterrotating star streams. From a comparison of the lenticular and the polar ring velocities of several galaxies, Rubin and Swaters hope to put meaningful constraints on the three dimensional shapes of the dark halos.

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 NGC 1156 and NGC 4449 with the Kitt Peak 4-m telescope. 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 out to a radius of 1.6 kpc. The stars and gas rotate about the same axis, which differs from the major axis of the prominent stellar bar. For NGC 4449 they detect no organized stellar rotation greater than  $(3 \sin i) \text{ km s}^{-1} \text{ kpc}^{-1}$ . A model which reproduces the observed velocities, produced in collaboration with Linda Sparke (U. Wisc.)

and Stephen 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 a past interaction. Hunter and Rubin will extend their observations of stellar velocities in irregulars with the new IMACS spectrograph on the Baade 6.5 m telescope.

Kathleen Flint has continued her work on dwarf galaxies and galaxy groups in the nearby Universe. Her extensive survey of the Leo I group and her follow-up spectroscopic program with collaborators Mike Bolte (UCO/Lick Observatory) and Claudia Mendes de Oliveira (University of São Paulo) nears completion. With the resulting dwarf galaxy sample complete to sensitive luminosity and surface brightness limits,  $M_R \lesssim -11$ ,  $\mu_R(0) \lesssim 24.5$ , they find the dwarf luminosity distribution to be roughly 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. Flint has begun to extend her imaging survey coverage to the outskirts of the group, where there is evidence for group members with magnitudes falling in this gap region.

Flint also has a project underway to look at the neutral hydrogen distribution in the group. Deep Arecibo observations with Bolte and Chris Impey (University of Arizona) of the H I in optically-selected Leo I dwarfs (down to  $M_{HI}^{lim} \approx 10^6 M_\odot$ ) suggests a distribution unusually skewed toward gas-poor dwarf spheroidals. They are following up this work with a blind H I survey of the group core, covering an area commensurate with that of Flint's deep optical survey in Leo I. REU summer student Martha Buckley (MIT) has constructed an integrated H I-flux map of the group from these data, reaching a low-mass limit of  $M_{HI} \approx 10^7 M_\odot$ . While they re-detect the known H I ring in the center of the group, they find the H I galaxy mass function to be unusually sparse down to their limits. This is consistent with the lack of intermediate luminosity galaxies seen, and confirms that no previously undetected, low-surface brightness gas-rich galaxies fill this gap in the luminosity function.

To further examine the relationship between local galaxy evolution and the luminosity function, Flint and Jason Harris (Space Telescope Science Institution) have modeled the luminosity evolution of the Local Group over the age of the Universe. Using published star-formation histories and population synthesis models, they empirically reconstructed the Local Group optical luminosity function as a function of time. 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. They find that the Schechter formulation of the luminosity function is surprisingly robust to local bursts of star formation, and that the faint-end slope of the function is relatively constant over a Hubble time. While uncorrelated bursts have no real effect on the ensemble luminosity properties of the Local Group, the coincidence of the initial epochs of star formation observed in dwarf galax-

ies causes an excess of  $M_V \geq -15$  galaxies at early epochs ( $> 10$  Gyr ago).

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