

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

[S0002-7537(90)02101-1]

This report covers astronomical research carried out during the period July 1, 1998 – June 30, 1999. 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, and the extragalactic distance scale.

1. PERSONNEL

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

Postdoctoral Fellows: Kenneth M. Chick, Andrew M. Freed, Satoshi Inaba, Daniel D. Kelson, Stephen J. Kortenkamp, Patrick J. McGovern, Larry Nittler, Michael W. Regan, Harri A. T. Vanhala

Computer and Support Staff: Michael J. Acierno, Mary M. Coder, Janice S. Dunlap, Rosa Maria Esparza, Shaun J. Hardy, Sandra A. Keiser, Jianhua Wang, Merri Wolf

2. RESEARCH PROGRAMS

2.1 Extrasolar Planet Detection

Over the past year, Geoff Marcy (UC Berkeley) and Butler have expanded their precision Doppler search for extrasolar planets to include the 1,100 nearest Sun-like stars (F8 - M5) with the Lick 3-m, Keck 10-m, and Anglo-Australian 3.9-m telescopes. Over the past 4 years, these surveys have led to the discovery of two-thirds of the known extrasolar planets. Within just the last year, 7 new planets have emerged from this work, including the only known system of multiple planets orbiting a normal Sun-like star – Upsilon Andromedae.

Of the ~ 400 stars surveyed for 4 years or longer, no companions have been found with “Msini” mass greater than 6.6 Jupiter-masses. The substellar companion mass function is strongly peaked at less than 5 Jupiter-masses. Brown dwarf companions to solar type stars are rare.

All 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 goal of this work is to maintain Doppler precision of 3 m/s over the next two decades, sufficient to make 4 sigma detections of Solar System analogs (Jupiter-mass companions out to 5 AU). 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.

2.2 Planetary System Formation

Alexander and Wang are using trace element and isotopic measurements, in conjunction with theoretical models, to determine the extent to which evaporation played a role in the formation of chondrules, rims and matrix in primitive meteorites. Chondrules, rims and matrix are the major components in these ancient meteorites which provide glimpses of the early history of the Solar System. Chondrules, at least, formed a few million years after the formation of the Solar System as isolated molten droplets in the Solar Nebula. At the low pressures of the Solar Nebula and the high temperatures needed to form chondrules, many elements, including K, Fe, and Si, would have been relatively volatile. The degree of evaporation these elements experienced will constrain conditions during this important epoch in the evolution of the Solar Nebula just prior to or during the formation of the terrestrial planets. Initial results suggest they must have formed in a dust enriched environment with $p(H_2) = 10^{-5}$ atm.

The discovery of presolar grains in primitive meteorites, some of which are large enough for precise isotopic measurements on individual particles, provides a novel means of probing both stellar and Galactic evolution. Alexander, Nittler and Wang have recently developed a new, highly automated technique, utilizing the Carnegie ion microprobe, for making large scale surveys of various types of presolar grain. These grains come from a large number of stellar sources. Large, unbiased surveys will provide information on (1) the relative dust production rates of various types of source, (2) the details of the nucleosynthesis in these stars, (3) identify rare subtypes, and (4) the Galactic chemical evolution (GCE) of some elements. They have recently reported the first detection of a presolar supernova oxide grain, as well as detailed analyses of the GCE of Si, Ti and O as recorded in presolar grains and the possible influence of stellar diffusion on the compositions of presolar grains.

Kortenkamp has been working with Scott Messenger (NIST) on a method for identifying the specific parent bodies of some interplanetary dust particles collected in Earth's stratosphere. Parent body identification is possible for dust particles from debris trails associated with certain Earth-crossing asteroids and short-period comets. For a limited range of parent body orbital parameters, dust particles gen-

erated by debris collisions can be directly injected into Earth-encountering orbits through the action of radiation pressure. Fresh dust particles from such sources can be recognized by their short space exposure ages (tens of years), indicated by a low abundance of implanted solar wind noble gases and/or lack of solar flare tracks. Space exposure age serves to distinguish between dust particles which share orbital characteristics of their parent body debris trail (age < 100 years) and dust particles which became Earth-crossing after their orbits were significantly modified through Poynting-Robertson drag and gravitational perturbations (age ≥ 100 years). The time of year that the dust particles are collected provides the approximate longitude of one of the ecliptic nodes of the parent body's debris trail. An estimate of the peak temperature reached by the dust particles during atmospheric entry provides a constraint on their atmospheric entry velocity, which further limits the range of possible orbits for the parent body's debris trail. There are presently 50 Earth-crossing asteroids and 4 short-period comets which may produce dust identifiable with these orbital constraints. It is particularly notable that some asteroidal and cometary dust is accreted with low Earth-encounter velocities, and will thus suffer minimal alteration from atmospheric entry heating.

On the basis of earlier work by Wetherill and Glen Stewart (U. Colorado), Inaba and his colleagues at the University of Tokyo constructed a highly accurate statistical method for the calculation of planetary accumulation, using the latest results of planetary dynamics. Inaba tested the statistical method by comparing carefully with N -body simulations. As a result, they found that the statistical method can reproduce results of N -body simulations with high accuracy. This means that the statistical method describes the accumulation process correctly. The statistical method is a powerful device for simulating the early stage of planetary accumulation where a large number of bodies exist.

Over a number of years Wetherill has carried out theoretical studies regarding the formation of the asteroid belt and its equivalents in other planetary systems, and with different assumptions regarding the formation of the giant planets and their extrasolar counterparts. Asteroidal samples, in the form of meteorites, are our only samples of materials that have preserved a chemical and isotopic record of the first several hundred million years in the history of a planetary system. For this reason it is important to develop alternative models of the formation of asteroids that can link this laboratory and observational data to models of planet formation.

During the past year an investigation of this kind has been carried out in collaboration with former DTM postdoctoral associate John Chambers (now at the Armagh Observatory in Northern Ireland), and submitted for publication. This makes use of numerical integration to address the question of how an originally smooth radial distribution of matter in the early Solar System may have evolved into the present sparsely populated region observed today. It is found that after formation of Jupiter and Saturn, an earlier population of planets as large as two lunar masses or more will perturb one another into giant planet resonances, and on a time scale of a few hundred million years will be transported into the Sun, beyond the giant planets, or collide with a large planet, e.g.

Earth. As a result, frequently all these bodies will be removed from the asteroidal regions, as well as most of the smaller bodies. All that may be left is a population of "asteroid size" bodies that are not far more numerous than the present asteroid population.

An alternative approach to evolution of asteroid regions is being studied in collaboration with Kortenkamp. In this case, it is assumed that giant planets were rapidly formed during the latter stage of formation of the central star, as proposed by Boss. Growth of planets in the terrestrial planet and asteroid region is slowed markedly by the strong perturbations in eccentricity and inclination by the giant planets. Nevertheless preliminary results seem to show that planets are likely to form in the present terrestrial planet region, whereas it is unclear if this is possible in the asteroidal region. If bodies of significant size can form, it will be a consequence of the tendency of the perturbations by the giant planets to be in phase with one another when the colliding bodies are of similar mass. As a consequence, the relative velocities of these bodies will be similar to one another at the time of their collision, increasing the probability that they will merge, rather than shatter one another. Conventional statistical mechanical techniques for calculating the evolution of systems of this kind are not applicable because they assume a random distribution of the angular orbital elements, but this tendency is reduced by the synchronicity mentioned above. We have recently acquired improved computational facilities, use of which we expect will make it possible to see if a planetary growth process of this kind will permit formation of an asteroid population that is small enough to evolve into that observed by ordinary asteroidal collisional mechanisms.

Boss has been examining the formation of gas giant planets. Two mechanisms have been suggested, core accretion and disk instability. Core accretion presumes the collisional accumulation of a roughly 15 Earth mass core of ice and rock, which then accretes hydrodynamically an envelope of H and He gas. However, recent models of the interiors of Jupiter and Saturn require considerably smaller core masses than were previously thought to be the case, or even no core at all. Core accretion also has a difficulty with growing a Jovian-mass planet within the expected lifetime of the solar nebula (a few million years at most). Core accretion is the generally accepted mechanism, but if a disk instability is possible, as proposed by Boss, it will occur well before core accretion can even get started.

In the disk instability mechanism, a gravitationally-unstable disk breaks up into clumps of gas and dust that can contract and become giant gaseous protoplanets. The disk instability mechanism can lead to core formation by rapid sedimentation of dust grains as the protoplanet slowly contracts toward planetary densities. Because the instability occurs over a time scale of order about 1000 years, there is no danger of losing the disk gas before the giant gaseous protoplanets form. However, the instability requires a disk that is massive enough and cold enough to become gravitationally unstable. Disk instability may be able to explain the formation of massive giant planet systems like that of Upsilon Andromedae, recently found by Butler and his colleagues.

In order to further study the disk instability mechanism, 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. The 3D models show that a clump-forming disk instability can occur in marginally unstable disks with masses as low as 4% of a solar mass inside a radius of 10 AU, and perhaps even in somewhat lower disk masses, though the disk mass seems to need to be greater than about 1% of a solar mass inside 10 AU. Models with doubled radial extent show that the outer boundary conditions on the calculations have little effect on the results, and imply that clump formation may be limited to an annulus in orbital radius between about 5 AU and 12 AU, with the usual outcome being two multiple-Jupiter-mass clumps within this annulus. These 3D models suggest that a protoplanetary disk with a mass at the high end of the range (1% to 7% of a solar mass) considered possible for the minimum mass solar nebula could quickly lead to the formation of two giant gaseous protoplanets, one at about 6 AU and one at about 12 AU. The terrestrial and outer planets could then form much later by the usual process of collisional accumulation of solids.

Chick has continued the development of a computer code to simulate the hydrodynamic behavior of gas accretion disks surrounding protostars. The ultimate goal is to explore whether density concentrations, which form rapidly and spontaneously in a self-gravitating disk, may coalesce into protoplanets over long periods of time, on the order of 10^6 yr.

Initial testing of Chick's code has focussed on the simpler problem of determining the disturbances in a non-self-gravitating disk which are induced by a small secondary body, such as a planet, which orbits the primary star. The secondary body is located outside the disk. Interest in this problem is twofold. On one hand, since substantial analytical and numerical work on this problem exists in astrophysical literature, it is a good benchmark case. On the other hand, the problem arises in a wide range of astrophysical phenomena, is not fully understood, and thus merits further research.

The particular numerical approach selected by Chick, the Beam-Warming implicit scheme, has certain properties which in general make it ideal for accurately computing fluid flow over long time scales. However, the standard application of the scheme to the accretion disk problem suggests that the computation becomes inaccurate rather quickly, after about one orbit of the star-planet system. The inaccuracy appears to be associated with the interior boundary of the disk. Chick is currently exploring whether a slight generalization of Beam-Warming scheme yields a refinement in accuracy.

The flow is particularly complicated at the inner boundary, due to the convergence of a spiral shock pattern toward the center of the disk, and also due to the periodic reversal of flow-direction across the interior boundary. Some boundary conditions may lead to flow which is inherently unstable. Various boundary conditions have been applied in previous numerical research, and Chick is attempting to resolve exactly which conditions lead to a physically realistic, and well-posed problem.

2.3 Stars and Star Formation

Studies of meteoritic material have revealed the presence of short-lived radioactivities in the early solar system. J. N. Goswami (Physical Research Laboratory, Ahmedabad, India) and Vanhala reviewed the latest meteoritic data for *Protostars & Planets IV* and discussed the possible scenarios for production of the radioactivities. They concluded that the most likely explanation for the radionuclides is their production in a nearby explosive stellar event and transportation to the molecular cloud core from which the solar system formed by an interstellar shock wave, which also initiated the collapse of the core. The hypothesis of the triggered origin of the solar system can be further tested through numerical simulations, and these simulations generally confirm its viability.

A. G. W. Cameron (Harvard-Smithsonian Center for Astrophysics) and Vanhala examined the processes involved in assisted star formation by using a three-dimensional smoothed particle hydrodynamics code to study the impact of interstellar shock waves on molecular cloud cores. The calculations show that cores can be triggered into collapse if the velocity of the shock wave is $20\text{--}45 \text{ km s}^{-1}$. The evolutionary state of the preimpact core influences the results: highly evolved cores can be triggered to collapse at lower shock velocities than less evolved cores, while the latter may fragment during compression and form a multiple star system. Since the calculations did not make any specific assumptions about the origin of the shock wave, the results apply to any shock wave traveling at the desired velocity, whether the source be an explosive stellar event, protostellar outflow, or a molecular cloud collision.

Another test for the viability of the triggered origin scenario is to determine whether radioactivities carried by the shock wave can be injected into the collapsing system. Vanhala and Boss used two-dimensional piecewise-parabolic method simulations to study the behavior of shock wave material during its interaction with the molecular cloud core. They extended previous studies of the process to higher spatial resolutions and showed that the results are robust: in isothermal shock waves, material can be injected into the collapsing system through Rayleigh-Taylor fingers developing at the surface of the compressed core. Injection proceeds steadily for $\sim 400,000$ years with an efficiency of 10-20%. The amount of injected material in the central parts of the collapsing system is typically $\sim 0.7\%$ of the total mass contained in that region.

Boss is continuing to study the 3D collapse of magnetically-supported, dense cloud cores undergoing ambipolar diffusion, in order to learn whether or not binary fragmentation can still take place in the presence of magnetic effects. The results of a lengthy series of models were published, where the initial cloud rotation rates were decreased until the clouds no longer fragmented during their collapse phase. The resulting critical value of the initial cloud rotation rate fell roughly in the middle of the range observed for pre-collapse cloud cores, implying that collapsing clouds should form single and binary stars about half the time each, an outcome that is in rough agreement with observations of binary star frequencies. These models included magnetic

field effects in the magnetic pressure approximation, which should be adequate for the initial phases of collapse. A new set of models is in progress, where magnetic tension forces are approximated late in the collapse, once a dense protostellar disk has formed and magnetic tension begins to dilute the gravitational force.

Working with Robert Fisher, Richard Klein, and Christopher McKee of U.C. Berkeley, Boss further investigated the importance of the Jeans condition advanced by the Berkeley group as an important indicator of the reliability of 3D collapse and fragmentation calculations. Using his hydrodynamics code, Boss was able to reproduce the filamentary solution first obtained by the Berkeley group for the collapse of an isothermal cloud with an initial Gaussian radial density profile. Reproducing this filamentary collapse solution appears to be an excellent means for testing the reliability of any self-gravitational hydrodynamics code.

Boss and his colleagues then showed that in the more physically realistic case of an identical initial cloud with nonisothermal heating in the 3D Eddington approximation, thermal retardation of the collapse permits the Gaussian cloud to fragment into a binary protostar system at the same maximum density where the isothermal collapse yields a thin filament. However, the binary clumps soon thereafter evolve into a central clump surrounded by spiral arms containing two more clumps. A roughly similar evolution is obtained using the Berkeley code with a barotropic equation of state – formation of a transient binary, followed by decay of the binary to form a central object surrounded by spiral arms, though in this case the spiral arms do not form clumps. When the same barotropic equation of state is used with the Boss code, the agreement with the initial phases of the Berkeley calculation is quite good, showing that these two codes yield mutually consistent results. However, the Boss code barotropic result differs significantly from the Boss code Eddington result at the same maximum density, demonstrating the importance of detailed radiative transfer effects. The sensitivity of these calculations to the thermodynamical treatment demonstrates the need for careful handling of nonisothermal thermodynamics in 3D fragmentation calculations.

With summer intern Kaisa E. Mueller (U. Missouri), Graham conducted a search for $H\alpha$ emission-line stars within a field containing the reflection nebula NGC 2626 in Vela. Thirty-two such stars, most of them new, have been detected on CCD frames taken between 1991 and 1999 with the Swope 1m telescope at Las Campanas Observatory. Some are variable in light. The reflection nebula is illuminated by a 10th magnitude B1V star, CoD -40°4432. In an associated dark globule-like cloud, a smaller reflection nebula shows changes in appearance and brightness which are caused by a variably obscured young stellar object embedded within. The young stellar object is the probable source of IRAS 08337 – 4028 and the Herbig-Haro object HH 132. It is located at a transverse distance of only 0.5 pc from the B1 star. The overall morphology of the small nebula is strikingly similar to that of the well studied HH 46-47 configuration but the NGC 2626 region is at about twice the distance.

2.4 Dynamics and Evolution of Galaxies

Following on the work reported last year, Graham has been working with summer intern Caleb I. Fassett (Williams College) in carrying out photometry of the blue stars associated with the shock-excited gas in the NE radio lobe of Centaurus A. It is likely that the formation of these stars was triggered from shocks generated by the adjacent radio jet. Additional observational material was obtained with the 2.5m du Pont telescope at Las Campanas Observatory in February 1999. Three concentrations of blue stars have been identified. The brightest are close to magnitude 20 and are similar to the brightest stars in the Large Magellanic Cloud. Isochrones based on the Geneva evolutionary tracks have been fitted to color-magnitude diagrams and indicate a significant age range for the stars extending from less than a million to more than 15 million years.

Schweizer continued observational studies aimed at improving our understanding of galactic mergers, the young star clusters formed in them, and possible connections between such clusters and the old cluster systems of elliptical galaxies. With clusters in several 0.5–1 Gyr old merger remnants now reasonably well observed and age dated, the main effort was to extend the dating methods to both younger clusters in ongoing mergers and older clusters in galaxies suspected to be remnants of ancient mergers.

Bradley Whitmore, Qing Zhang, Claus Leitherer, Michael Fall (STScI), Schweizer, and Bryan Miller (Leiden) completed their analysis of *Hubble Space Telescope* images of NGC 4038/4039 (“The Antennae”), a prototypical pair of colliding spiral galaxies. These images reveal $\sim 14,000$ point-like sources, of which the majority are individual stars and over 1000 are likely star clusters. Age dating these clusters from their *UBVI* colors, $H\alpha$ emission, and—in some cases—ultraviolet spectra yields three distinct populations that seem to trace peaks in the star-formation history of the galaxies: 0–100 Myr old clusters clearly formed during the present collision, ~ 500 Myr old globular clusters apparently formed during the previous collision that lead to the ejection of tidal tails, and over a dozen truly old (≥ 10 Gyr) globulars that must have formed very early in the two component spirals. Most candidate clusters appear slightly resolved, with a median effective radius of 4 ± 1 pc similar to that of Milky-Way globulars. Some of the youngest and most luminous clusters feature huge power-law envelopes (e.g., $R \geq 450$ pc for “Knot S”) not seen in Milky-Way globulars. These envelopes may be a natural product of globular-cluster formation, but visible only in clusters so young that tidal forces have not yet had time to erode them.

Schweizer, in collaboration with Jean Brodie (Lick Observatory), Linda Schroder (UCSC), and Patrick Seitzer (U. Michigan), used the Keck II telescope to obtain low-resolution spectra of seven globular clusters in NGC 3610. This field elliptical shows fine structure, *UBV* colors, and spectral indices suggestive of a major merger event a few Gyr ago. The goal of the new observations is to derive globular-cluster ages and metallicities in order to test whether two distinct cluster populations exist and whether the more metal-rich clusters are of intermediate age. Although the data reduction is still in progress, the spectra of

two of the clusters already seem to show enhanced $H\beta$ absorption, which would make these clusters only about 1.5–3 Gyr old. Follow-up Keck observations of these and additional globular clusters in NGC 3610 are planned for next spring.

Schweizer, Whitmore, Fall, and Miller continued their *Hubble Space Telescope* program to study globular-cluster populations in a sequence of galaxies thought to extend from recent to ancient merger remnants. During Cycle 7 moderately deep V and I images were obtained for five new systems, bringing the number of objects along the sequence to a total of 10. Whereas globular clusters are visible in all five newly-observed galaxies, none of the clusters are obviously young, i.e., blue and overluminous. A refined analysis has been initiated to test whether any of these globular-cluster systems show clearly bimodal color distributions and whether the expected crossover in color between first- and second-generation clusters can be detected along the sequence.

Regan, Tamara Helfer (U. Arizona), Michele Thornley (NRAO), Kartik Sheth (U. Maryland), Stuart Vogel (U. Maryland), Andy Harris (U. Maryland), Tony Wong (U.C. Berkeley), Leo Blitz (U.C. Berkeley), and Douglas Bock (U.C. Berkeley) finished the observing for the first imaging survey of nearby spiral galaxies in the millimeter wave transition of CO. This survey will attempt to understand the distribution and physical conditions of the molecular component of the ISM in nearby galaxies. They plan to address several scientific areas: the relationship between giant molecular cloud distributions and star formation, bar dynamics and their contributions to nuclear activity, and molecular gas in active and quiescent galaxies.

Clusters of galaxies offer unique opportunities to study the processes of galaxy evolution and formation. By comparing galaxies in nearby clusters with those in clusters which are 3–7 Gyr away, we can directly observe how galaxies evolved from a time when the Universe was half its present age to the present epoch. To date, Kelson, Pieter van Dokkum (CalTech), Marijn Franx (Leiden), and Garth Illingworth (UCSC) have observed four clusters between redshifts of $z = 0.33$ and $z = 0.93$, each with large mosaics of WFPC2 imaging already obtained or to be taken during the next cycle. Using high-resolution Keck spectra and HST imaging for more than 50 galaxies in CL1358+62 ($z = 0.33$), Kelson measured internal kinematics and half-light radii in order to construct the “fundamental plane” of early-type galaxies. Kelson found that the slope of the fundamental plane of early-type galaxies is constant with redshift, indicating that the ages of the stellar population do not depend on galaxy mass. Furthermore, the scatter in M/L ratios for E/S0 galaxies remains very low at $z = 0.33$. The spirals follow a different plane, but in a manner consistent with the low-mass spirals having a young stellar component. Correcting the spirals for their bluer colors produces a fundamental plane of the spirals which is then consistent with the early-types of the cluster, suggesting that the spirals may passively evolve into present-day early-type galaxies. Analysis of the absorption line strengths in the E/S0s indicate a very tight sequence of chemical abundances along the early-type galaxy scaling

relations, with a very low spread in ages. The spirals are clearly “younger,” but also show a spread in mean chemical abundances as well.

This study is being continued in more distant clusters by observing more than 200 galaxies in the field of MS2053–04 ($z=0.58$), confirming membership for 100 of them. Using high-resolution Keck spectra, Kelson now has velocity dispersions and absorption line strengths for more than 40 of them. In their study of MS1054–03, Kelson and his colleagues used 30 spectroscopically confirmed members to derive a velocity dispersion for the cluster of 1170 km/s. Using this value, one infers a mass of the cluster which is consistent with that derived from weak-lensing analysis and the temperature of the cluster’s X-ray gas. After measuring a total of 400 redshifts, derived from 600 spectra, they now have a total of 120 spectroscopically confirmed cluster members, 30 of which now have measured velocity dispersions and line strengths. Using the HST imaging, and membership alone, they found that 17% of the galaxies brighter than L^* appear to be undergoing mergers. The implication is that 50% of present-day E/S0 galaxies underwent a merger around redshifts of unity. The mergers do not appear to be particularly dissipative, and have colors which are slightly bluer than the color-magnitude relation. They also measured the evolution of the mean M/L ratio to $z = 0.83$ and showed that the evolution is inconsistent with cosmologies which have high values of q_0 . Using the line strengths and M/L ratios, plus the addition of the higher redshift clusters around 3C336 ($z = 0.93$) and CIG0848+44 ($z = 1.27$), they plan to further constrain the cosmological parameters as well as the earliest epochs of star-formation for cluster galaxies.

In a complementary study, summer intern Patrick Kelly, a high school student at Sidwell Friends, has been analyzing U and V imaging of galaxies in nearby poor groups with Kelson. By studying the colors of galaxies in environments which are less dense than clusters, Kelly and Kelson can uncover differences in the star-formation histories of group and cluster galaxies. Poor groups are likely to be the most common environments in the field, and by studying the histories of galaxies in these groups, they can finally understand the histories of typical galaxies in the Universe, compared to the cluster galaxies which have dominated studies for so long.

Clusters of galaxies are also valuable venues for studying the kinematics of galaxies located in regions of high matter density. During the past year, Rubin and collaborators Andrew H. Waterman (Montgomery Blair High School; now Stanford University) and Jeffrey Kenney (Yale University) completed an analysis of the kinematic properties of 87 galaxies in the Virgo cluster based on long-slit optical spectra. The results indicate that spirals with disturbed rotation properties define a population of spirals whose distributions in the cluster and in velocity space are different from the Virgo spirals with normal rotation properties. Spirals with disturbed rotation exhibit a velocity distribution which matches the velocity distribution of cluster ellipticals. Because the disturbed population does not exhibit an HI deficiency, the cause of the gas truncation is different from the cause of the kinematic disturbance. It is likely that galaxy-galaxy interac-

tions are altering the morphology of the kinematically disturbed galaxies, and are also driving the cluster toward equilibrium.

Although the Virgo cluster is unique in its proximity, the study of more distant clusters also reveals the evolution of clusters and of the spirals within. Rubin, along with former postdoctoral fellow Andy Fruchter (STScI), and graduate student Leslie Hebb (Johns Hopkins University) are presently analyzing their observations of more distant clusters. For Abell clusters A194, A400, A496, A754, A1185, A1228, A1367, A1656, A1983, A2151, A2870, A3381, A3389, A4038, Cancer, and Z74-23, Rubin and Fruchter have obtained spectra and photometry for about 70 spirals. The cluster redshifts range up to 15000 km/sec, although background galaxies with velocities up to 30000 km/sec have been observed. All velocities are measured; photometric reductions are now being completed. These data will be used to examine the the Tully-Fisher relation for clusters at increasing distances, and also to study the kinematic properties of the spirals as a function of cluster properties.

Rubin, in collaboration with former postdoctoral fellow Stacy McGaugh (University of Maryland), is observing low surface brightness (LSB) galaxies to determine their $H\alpha$ rotation curves. Previous studies of LSB kinematics have been carried out at 21-cm, where the low spatial resolution degrades the velocity resolution near the nucleus; the resulting mass deconvolutions are imprecise. Because the spatial resolution in the optical is an order of magnitude higher than that in the radio region, the combination of inner optical velocities and outer extended 21-cm observations will better constrain masses of disk, bulge, and halo. The analysis can determine if the ratio of dark matter to luminous matter is excessively high in LSB galaxies, as 21-cm studies suggest. A preliminary comparison of the optical and 21-cm velocities shows a wide range of differences. For some, the optical and 21-cm velocities agree well; for others, there is very little agreement, with the optical velocities rising more steeply than the 21-cm. The halo mass distributions will be used to test cosmological structure formation models, leading to limits on cosmological parameters.

2.5 The Extragalactic Distance Scale

Graham and Kelson continued their participation in the HST Key Project for the determination of the extragalactic distance scale. A paper on Cepheid variable stars in NGC 4548 with Graham as the lead author was published. The metallicity correction for the Cepheid distances remains uncertain and in an effort to specify this explicitly, Graham is working with Wendy Freedman (OCIW) and a small group of collaborators to photometer in the infrared $H(1.6\mu\text{m})$ band a selected sample of Cepheids from the Key Project data base. The NICMOS observations from HST are now being analysed.

Using nearby clusters, and accurate Cepheid distances to them, Kelson and Graham have used the "fundamental plane" of early-type galaxies to derive a value for the Hubble constant. The fundamental plane is an empirical relation which uses the half-light radii of E/S0 galaxies as a standard rod (for fixed surface brightness and velocity dis-

persion). By comparing the observed fundamental plane relations in different clusters, one can infer the relative distance between them. Thus, one can combine the published Cepheid distances to, *e.g.*, Virgo, compare the Virgo fundamental plane to that in, *e.g.*, Coma, and derive a value for the local expansion rate of the Universe. In this work, Kelson and Graham found $H_0 = 79 \pm 5 \pm 9$ km/s/Mpc, and, when combined with the other secondary distance indicators used in the project, the Team derived a final value of $H_0 = 71 \pm 6$ km/s/Mpc.

PUBLICATIONS

- Alexander, C. M. O'D.** 1999, A quantitative kinetic model for the evaporation of silicate melts in vacuum and hydrogen, *Meteoritics Planet. Sci.*, submitted.
- Alexander, C. M. O'D.**, Grossman, J. N., **Wang, J.**, Zanda, B., Bourot-Denise, M. & Hewins, R. H. 1999, The lack of potassium isotopic fractionation in Bishunpur chondrules, *Meteoritics Planet. Sci.*, submitted.
- Alexander, C. M. O'D. & Nittler L. R.** 1999, The Galactic chemical evolution of Si, Ti and O isotopes, *ApJ*, 519, 222.
- Alexander, C. M. O'D. & Wang, J.** 1999, Iron isotopes in chondrules: Implications for the role of evaporation during chondrule formation, *Meteoritics Planet. Sci.*, submitted.
- Boss, A. P.** 1999, Planets Elsewhere: More Surprises, *Modern Astronomer*, 3, 59.
- Boss, A. P.** 1999, The Birth of Binary Stars, *Sky & Telescope*, June, 32.
- Boss, A. P.** 1999, Collapse and Fragmentation of Molecular Cloud Cores. VI. Slowly-Rotating Magnetic Clouds, *ApJ*, 520, 744.
- Boss, A. P.** 1999, Formation of Extrasolar Giant Planets: Core Accretion or Disk Instability?, *Earth, Moon, Planets*, in press.
- Boss, A. P.** 1999, Collapse and Fragmentation of Magnetic Molecular Cloud Cores, in *Star Formation 1999*, T. Nakamoto, ed. (Nobeyama: Nobeyama Radio Observatory), in press.
- Boss, A. P.**, Beichman, C. A. & Thronson, H. A. 1999, NASA and the Search for Extrasolar Planets, *Earth, Moon, Planets*, in press.
- Boss, A. P.**, Fisher, R., Klein, R. I. & McKee, C. F. 1999, The Jeans Condition and Collapsing Cloud Cores: Filaments or Binaries?, *ApJ*, in press.
- Boss, A. P. & Vanhala, H. A. T.** 1999, Triggering Protostellar Collapse, Injection, and Disk Formation, *Space Sci. Rev.*, in press.
- Bresolin, F., . . . , **Graham, J. A. et al.** 1998, An HST Study of Extragalactic OB Associations, *AJ*, 116, 119.
- Burkert, A., Bodenheimer, P., Klein, R. I. & **Boss, A. P.** 2000, Multiple Fragmentation of Protostars, in *Protostars & Planets IV*, V. G. Mannings, A. P. Boss, & S. S. Russell, eds. (Tucson: Univ. Arizona Press), in press.
- Butler, R. P.** 1998, Other Planetary Systems, in *The New Solar System*, J. K. Beatty, C. C. Petersen, A. Chaikin, eds. (Cambridge: Sky Pub. Corp.).

- Butler, R. P.** 2000, Identifying Planetary Systems, *Natural History*, in press.
- Butler, R. P.**, Marcy, G. W., Fischer, D. A., Brown, T. M., Contos, A. R., Korzennik, S. G., Nisenson, P. & Noyes R. W. 1999, Evidence for Multiple Companions to Upsilon Andromedae, *ApJ*, in press.
- Butler, R. P.**, Marcy, G. W., Vogt, S. S. & Apps, K. 1998, A Planet with a 3.1 Day Period Around a Solar Twin, *PASP*, 110, 1389.
- Chambers, J. E. & **Wetherill, G. W.** 1999, Planets in the asteroid belt, *Nature*, submitted.
- Cumming, A., Marcy, G. W. & **Butler, R. P.** 1999, The Lick Planet Search: Detectability and Mass Thresholds, *ApJ*, in press.
- Ferrarese, L., . . . , **Graham, J. A.** *et al.* 1998, The HST Key Project on the Extragalactic Distance Scale; The Cepheids in NGC 2541, *ApJ*, 507, 655.
- Fischer, D. A., Marcy, G. W., **Butler, R. P.**, Vogt, S. S. & Apps, K. 1999, Planetary Companions Around Two Solar Type Stars: HD 195019 and HD 217107, *PASP*, 111, 50.
- Goswami, J. N. & **Vanhala, H. A. T.** 2000, Extinct Radio-nuclides and the Origin of the Solar System, in *Protostars & Planets IV*, V. G. Mannings, A. P. Boss, & S. S. Russell, eds. (Tucson: Univ. Arizona Press), in press.
- Graham, J. A.** 1998, Shocked Gas and Star Formation in the Centaurus A Radio Galaxy, *ApJ* 502, 245.
- Graham, J. A.**, *et al.* 1999, The HST Key Project on the Extragalactic Distance Scale; The Discovery of Cepheids in the Virgo Cluster Galaxy NGC 4548, *ApJ*, 516, 626.
- Grossman, J. N., **Alexander, C. M. O'D.**, **Wang, J.** & Brearley, A. J. 1999, Bleached chondrules: Evidence for widespread aqueous alteration processes on the parent asteroids of ordinary chondrites, *Meteoritics Planet. Sci.*, in press.
- Inaba, S.**, Tanaka, H., Ohtsuki, K. & Nakazawa, K. 1999, High-accuracy statistical simulation of planetary accretion: I. Test of the accuracy by comparison with the solution to the stochastic coagulation equation, *Earth, Planets and Space*, 51, 205.
- Kelson, D. D.**, . . . , **Graham, J. A.** *et al.* 1999, The HST Key Project on the Extragalactic Distance Scale; The Cepheids in NGC 3198, *ApJ*, 514, 644.
- Kelson, D. D.**, . . . , **Graham, J. A.**, *et al.*, 2000, The Extragalactic Distance Scale Key Project XXVII. A Derivation of the Hubble Constant Using the Fundamental Plane and $D_n - \sigma$ Relations in Leo I, Virgo, and Fornax, *ApJ*, in press.
- Kelson, D. D.**, Illingworth, G. D., van Dokkum, P. G., & Franx, M. 2000, The Evolution of Early-Type Galaxies in Distant Clusters I. Surface Photometry and Structural Parameters for 53 Galaxies in the $z = 0.33$ Cluster CL1358+62, *ApJ*, submitted.
- Kelson, D. D.**, Illingworth, G. D., van Dokkum, P. G., & Franx, M. 2000, The Evolution of Early-Type Galaxies in Distant Clusters II. Internal Kinematics of 55 Galaxies in the $z = 0.33$ Cluster CL1358+62, *ApJ*, in press.
- Kelson, D. D.**, Illingworth, G. D., van Dokkum, P. G., & Franx, M. 2000, The Evolution of Early-Type Galaxies in Distant Clusters III. M/L_V Ratios in the $z = 0.33$ Cluster CL1358+62, *ApJ*, in press.
- Kortenkamp, S. J.** 1998, Amid the swirl of interplanetary dust, *Mercury*, 27(6), 7.
- Kortenkamp, S. J.** & Dermott, S. F. 1998, Accretion of interplanetary dust particles by the Earth, *Icarus*, 135, 469.
- Kortenkamp, S. J.**, Kokubo, E. & Weidenschilling, S. 1999, Formation of planetary embryos, in *Origin of the Earth and Moon*, R. Canup & K. Righter, eds. (Tucson: Univ. Arizona Press), in press.
- Kortenkamp, S. J.** & **Wetherill, G. W.** 1999, Terrestrial planet and asteroid formation in the presence of giant planets I. Relative velocities of planetesimals subject to Jupiter and Saturn perturbations, *Icarus*, in press.
- Macri, L.M., . . . , **Graham, J. A.** *et al.* 1999, The HST Key Project on the Extragalactic Distance Scale; The Discovery of Cepheids and a New Distance to NGC 4535, *ApJ*, 521, 155.
- Madore, B.F., . . . , **Graham, J. A.** *et al.* 1999, The HST Key Project on the Extragalactic Distance Scale; Implications of a Cepheid Distance to the Fornax Cluster, *ApJ*, 515, 29.
- Mannings, V. G., **Boss, A. P.** & Russell, S. S. (eds.) 2000, *Protostars and Planets IV*, (Tucson: Univ. Arizona Press), in press.
- Marcy, G. W. & **Butler, R. P.** 1998, Detection of Extrasolar Giant Planets, *ARAA*, 36, 57.
- Marcy, G. W. & **Butler, R. P.** 1998, Extrasolar Planets: Techniques, Results, and the Future, in *Physics of Star Formation and Early Stellar Evolution*, C. Lada & N. D. Kylafis, eds. (Dordrecht: Kluwer).
- Marcy, G. W. & **Butler, R. P.** 2000, Extrasolar Planets, *Astronomy*, in press.
- Marcy, G. W., **Butler, R. P.** & Fischer, D. A. 1998, Doppler Detection of Extrasolar Planets, in *Precise Stellar Radial Velocities*, J. B. Hearnshaw & C. D. Scarfe, eds. (San Francisco: ASP Conf. Ser.).
- Marcy, G. W., **Butler, R. P.**, Vogt, S. S., Fischer, D. A. & Lissauer, J. J. 1998, A Planetary Companion to the M4 Dwarf, GL 876, *ApJ*, 505, L147.
- Marcy, G. W., **Butler, R. P.**, Vogt, S. S., Fischer, D. & Liu, M. 1999, Two New Planets in Eccentric Orbits, *ApJ*, 520, 239.
- Nittler, L. R.** & **Alexander, C. M. O'D.** 1999, Can stellar dynamics explain the metallicity distributions of presolar grains?, *ApJ*, in press.
- Regan, M. W.** & Mulchaey, J. S. 1999, Using Hubble Space Telescope Imaging of Nuclear Dust Morphology to Rule Out Bars Fueling Seyfert Nuclei, *AJ*, 117, 2676.
- Regan, M. W.**, Sheth, K. & Vogel, S. N. 1998, Molecular Gas Kinematics in Barred Spiral Galaxies, *ApJ*, in press.
- Rubin, V. C.** 1999, Recollections after Fifty Years: Haverford AAS Meeting, December 1950, in *The American Astronomical Society's First Century*, D. DeVorkin, ed. (New York: AIP Press), 90.
- Rubin, V. C.**, Waterman, A. W., & Kenney, J. P. D. 1999, Kinematic Disturbances in Optical Rotation Curves among 89 Virgo Disk Galaxies, *AJ*, 118, 239.

- Rubin, V. C.** 1999, The Trials and Triumphs of American Women in Science, AWIS Magazine (Association for Women in Science), 28, 34.
- Rubin, V. C.** 1999, Commentary on ‘‘A Correlation Between the Spectroscopic and Dynamical Characteristics of the Late F- and Early G-Type Stars’’ by Nancy G. Roman, ApJ 112, 554, 1950, ApJ, in press.
- Rubin, V. C.** 2000, Cecilia Payne-Gaposchkin, in *Contributions of Women to Twentieth Century Physics*, Nina Byers, ed. (London: Institute of Physics), in press.
- Saar, S. H., **Butler, R. P.** & Marcy, G. W. 1998, Magnetic Activity-Related Radial Velocity Variations in Cool Stars: A First Look at Their Effects in the Lick Extrasolar Planet Survey, ApJ, 498, L153.
- Sakai, S., . . . , **Graham, J. A.** *et al.* 1999, The HST Key Project on the Extragalactic Distance Scale; The Discovery of Cepheids in NGC 3319, ApJ, 523, 540.
- Schweizer, F.** 1999, Overview: Low- z Observations of Interacting and Merging Galaxies, in *Galaxy Interactions at Low and High Redshift*, J. E. Barnes & D. B. Sanders, eds. (Dordrecht: Kluwer), pp. 1.
- Schweizer, F.** 1999, Young Globular Clusters, in *Spectrophotometric Dating of Stars and Galaxies*, I. Hubeny, S. Heap, & R. Cornett, eds. (San Francisco: ASP), in press.
- Schweizer, F.** 1999, Effects of Late Mergers on Stellar Populations in E and S0 Galaxies, Ap&SS, in press.
- Schweizer, F.**, & Seitzer, P. 1998, Ages and Metallicities of Young Globular Clusters in the Merger Remnant NGC 7252, AJ, 116, 2206.
- Silbermann, N.A., . . . , **Graham, J. A.** *et al.* 1999, The HST Key Project on the Extragalactic Distance Scale; The Cepheids in NGC 1365, ApJ, 515, 1.
- Smith, D. E., . . . **Solomon, S. C.**, . . . **McGovern, P. J.** *et al.* 1999, The global topography of Mars and implications for surface evolution, Science, 284, 1495.
- Solomon, S. C.**, Bullock, M. A. & Grinspoon, D. H., 1999, Climate change as a regulator of tectonics on Venus, Science, 286, 87.
- Stetson, P.B., . . . , **Graham, J. A.** *et al.* 1998, The HST Key Project on the Extragalactic Distance Scale; Cepheid Variables in an Inner Field of M101, ApJ, 508, 491.
- Tran, K.-V., **Kelson, D. D.**, van Dokkum, P. G., Franx, M., Illingworth, G. D. & Magee, D. 1999, A Dynamical Study of the High Redshift, X-Ray Luminous, Massive Galaxy Cluster MS1054.4 – 03, ApJ, 522, 39.
- van Dokkum, P. G., Franx, M., Fabricant, D., **Kelson, D. D.** & Illingworth, G. D. 1999, A High Merger Fraction in the Rich Cluster MS1054–03 at $z = 0.83$: Direct Evidence for Hierarchical Formation of Massive Galaxies, ApJ, 520, L95.
- van Dokkum, P. G. Franx, M., **Kelson, D. D.**, & Illingworth, G. D. 1998, Luminosity Evolution of Early-Type Galaxies to $z = 0.83$: Constraints on Formation Epoch, ApJ, 504, L17
- van Dokkum, P. G., Franx, M., **Kelson, D. D.**, Illingworth, G. D., Fisher, D. & Fabricant, D. 1998, The Color-Magnitude Relation in CL 1358+62 at $z = 0.33$: Evidence for Significant Evolution in the S0 Population, ApJ, 500, 714.
- Vanhala, H. A. T.** 1998, The Triggered Origin of the Solar System. Proc. Indian Acad. Sci. (Earth Planet. Sci.), 107, 391.
- Vanhala, H. A. T. & Boss, A. P.** 1999, Injection of Radioactivities into the Protosolar Cloud: Convergence Testing, ApJ, submitted.
- Vanhala, H. A. T.** & Cameron, A. G. W. 1998, Numerical simulations of triggered star formation. I. Collapse of dense molecular cloud cores, ApJ, 508, 291.
- Wetherill, G. W.** 1999, Planetary accumulation with a continuous supply of planetesimals, Space Sci. Rev., in press.
- Whitmore, B. C., Zhang, Q., Leitherer, C., Fall, S. M., **Schweizer, F.**, & Miller, B. W. 1999, The Luminosity Function of Young Star Clusters in ‘The Antennae’ Galaxies (NGC 4038/4039), AJ, in press.
- Zuber, M. T., . . . **Solomon, S. C.** *et al.* 1998, Observations of the north polar region of Mars from the Mars Orbiter Laser Altimeter, Science, 282, 2053.
- Zuber, M. T., . . . **Solomon, S. C.** *et al.* 1998, Shape of the northern hemisphere of Mars from the Mars Orbiter Laser Altimeter (MOLA), Geophys. Res. Lett., 25, 4393.

