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This report covers astronomical research carried out during the period July 1, 1997 – June 30, 1998. Astronomical studies at the Department of Terrestrial Magnetism (DTM) of the Carnegie Institution of Washington include observational and theoretical fields of planet structure 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, John A. Graham, Vera C. Rubin, François Schweizer, George W. Wetherill

Postdoctoral Fellows: Kenneth M. Chick, Andrew M. Freed, Daniel D. Kelson, Stephen J. Kortenkamp, Stacy S. McGaugh, Patrick J. McGovern, Bryan Miller, Larry Nittler, Michael Regan, Harri A. T. Vanhala

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2. RESEARCH PROGRAMS

2.1 The Solar System

The Mars Orbiter Laser Altimeter (MOLA) on the Mars Global Surveyor (MGS) spacecraft has to date yielded more than 200 high-resolution altimetry profiles over the northern hemisphere of Mars. The sampled regions include the flanks of the large shield volcanoes Olympus Mons, Arsia Mons, and Alba Patera, located in the relatively young and volcanically active Tharsis region. Because the along-track resolution of these altimetry profiles is far superior to that of prior topography data for Mars, these new data permit a fresh examination of models for the growth and evolution of large volcanoes on that planet as well as for loading and flexure of the Martian lithosphere. Patrick McGovern and Sean Solomon have been engaged in several studies addressing these issues.

Olympus Mons is the tallest volcano on Mars, with an edifice 600–800 km in diameter and a height about 27 km above its base. MOLA altimetry profiles indicate that the edifice flanks have shallow slopes (several degrees) and are encircled by steep escarpments that define the base of the edifice. There are relative topographic lows outward of the edifice, and a reasonable working hypothesis is that these lows reflect subsidence arising from the loading and flexure of the Martian lithosphere by the volcano. Outward of the basal scarp are relative topographic highs resembling arches in terrestrial bathymetric profiles attributed to lithospheric flexure. Under this interpretation McGovern and Solomon obtain best-fitting lithosphere thickness estimates that vary both spatially (thickness increasing from east to west) and with age of the arched terrain (thickness increasing with decreasing age). The former result is consistent with a spatially

variable lithosphere thickness, possibly related to the thermal structure of the Tharsis Rise centered southeast of Olympus Mons, while the latter result is consistent with cooling of the Martian interior with time. The presently limited altimetric coverage of the terrain surrounding Olympus Mons does not allow these hypotheses to be distinguished.

McGovern and Solomon also applied MOLA data to a study of the loading history of Alba Patera, a large volcano on the northern slope of the Tharsis Rise. An extensive system of extensional faults (graben) cuts across Alba Patera, extending from Ceraunius Fossae to the south to Tantalus Fossae to the northeast. In the vicinity of the Alba Patera edifice, the otherwise locally linear graben are deflected to orientations approximately concentric to the summit, a result previously attributed to the influence of stresses induced by the loading of the lithosphere by the volcano. MOLA altimetry profiles, however, indicate that these extensional faults lie on the flanks of the volcanic edifice rather than in the surrounding lithosphere. Because flexure models that include the edifice stress state predict horizontal principal compression at the edifice surface, the interpretation of Alba Patera graben as extensional features resulting from surface loading is untenable. McGovern and Solomon demonstrated instead that deep-seated uplift from a sublithospheric load (e.g., by underplating of magma, development of a low density residuum, or dynamic support from mantle convection), probably relatively late in the volcano's history, can yield a state of horizontal principal extension at the edifice surface consistent with observed deformation.

No long-wavelength topographic depressions are evident around either Alba Patera or Arsia Mons, a 400-km-diameter volcano located near the crest of the Tharsis Rise. Instead edifice flanks merge smoothly into the surrounding long-wavelength topographic gradients. Because lithospheric loads of such magnitude should generate a flexural subsidence, McGovern and Solomon proposed that any moats must be completely filled or overfilled by volcanic material, either emplaced as flows (as with most large volcanoes on Venus) or from failure of the flanks (as seen at ocean island volcanoes on Earth). Lobate deposits on the northwestern flanks of Arsia Mons and other large Tharsis volcanoes may be products of the latter process. Further, deep-seated uplift of the volcanoes (by the mechanisms described above) may substantially diminish the topographic depression expected from a purely surface-loading flexural model.

The Mars Global Surveyor spacecraft is scheduled to complete aerobraking maneuvers in March 1999. The subsequent "mapping" phase of the MGS mission will obtain global high-resolution altimetry and gravity field coverage, allowing more rigorous testing of the above ideas.

2.2 Planetary System Formation

George Wetherill continued theoretical studies relevant to the formation of the terrestrial planets, the asteroids, and their relationship to the giant planets.

The conventional core-mantle model for the formation of the planets assumes that the formation of the giant planets required five to ten million years. If so, it would be expected that Mars-size or larger solid planet “embryos” would form both in the terrestrial planet region and the asteroid belt. During the past year, both Monte Carlo studies and numerical integration have shown that these large asteroidal planets would be self-cleared by perturbation of one another into giant planet resonances, and as a consequence ejected into the Sun, beyond Jupiter, or collide with a terrestrial planet.

These calculations, as well as those of the first 3D simulations of inner planet formation, to be published in *Icarus* in collaboration with John Chambers of the Armagh Observatory, lead to some probably significant differences between the calculations and the observed planets, such as excessively high eccentricities and inclinations of the final terrestrial planets. Further work, using an improved version of the kinetic theory model of planet formation of Stewart and Wetherill showed that damping of these orbital elements by gravitational friction imposed by a large mass of small planetesimals probably will not resolve this problem.

For this reason, Steve Kortenkamp and Wetherill have begun an investigation of the consequences of the proposal of Alan Boss that Jupiter and Saturn formed very rapidly by gravitational instability, possibly precluding the formation of large bodies in the asteroid region. However, this possibility nevertheless opens a range of new possibilities relevant to terrestrial planet and asteroid evolution.

Kortenkamp and Wetherill are attempting to determine what effect these giant planets would have on the subsequent formation of terrestrial planets and asteroids. The distribution of encounter velocities is one of the key factors which controls the growth of planetesimals into planetary embryos. In this regard the influence of giant planets is important because of secular perturbations which act at all heliocentric distances. The perturbations of Jupiter and Saturn are quite sensitive to their semi-major axes and decrease when the planets’ heliocentric distances are increased to allow for protoplanet migration. It is possible that this could produce a depleted asteroid belt but permit formation of a system of terrestrial planets.

Alan Boss investigated a long-discarded mechanism for giant planet formation: gravitational instability of a protoplanetary disk. Starting with axisymmetric models of a quasi-equilibrium disk obtained with his radiative hydrodynamics code, Boss used his three dimensional gravitational hydrodynamics code to study the growth of nonaxisymmetry in low mass ($0.14 M_{\odot}$ inside 10 AU) disks in orbit around a $1 M_{\odot}$ star. Boss found that with reasonable outer disk temperature profiles, such disks have a Toomre Q stability parameter of order 1. These disks form giant gaseous protoplanets within a few thousand years. Dust grains within these protoplanets will sediment to form solid cores on a similar time scale, while the protoplanet as a whole will contract in $\sim 10^5$ yrs. The models suggest that giant planets with

masses on the order of a Jupiter mass or more can form quickly in relatively low mass protoplanetary disks.

Boss also proposed an observational test for determining the dominant mechanism of giant planet formation. The conventional method of forming giant planets involves the accretion of gas from the protoplanetary disk by a $\sim 15M_{\oplus}$ solid core, formed by collisional accumulation. The entire process requires on the order of 10^7 yrs to form a Jupiter-mass planet. In this case, young stars would not begin to wobble because of their planetary companions until ages of at least 10 Myr were reached. The disk instability process, however, occurs nearly instantaneously, and can form giant planets around even the youngest (0.1 Myr) stars. Boss therefore proposed that by searching an ensemble of young stars for the telltale wobbles caused by Jupiter-mass companions, the epoch of giant planet formation could be determined, providing a fairly definitive determination of which mechanism is responsible for forming most giant planets.

C. Alexander and J. 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 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 $p(\text{H}_2) \geq 10^{-5}$ atm.

2.3 Stars and Star Formation

Prudence Foster (University of Tokyo and Okayama University) and Boss continued their study of the interaction of interstellar shock waves with dense molecular cloud cores. Their previous work had shown that suitable shock waves could both trigger the self-gravitational collapse of target cloud cores and inject shock-wave material (gas and dust grains) into the collapsing cloud through Rayleigh-Taylor instabilities. In new work, Foster and Boss showed that even material lagging far behind the leading edge of the shock front can be injected into the cloud, provided that it is on a trajectory that leads to one of the penetrating Rayleigh-Taylor fingers. This implies that short-lived isotopes synthesized even deep within massive stars, such as ^{26}Al , can still be injected into a collapsing cloud, as has been inferred to have been the case for the presolar cloud.

The hypothesis of triggered, or assisted, star formation suggests that star formation may in some cases be induced by outside agents such as explosive stellar events, protostellar outflows and molecular cloud collisions. A. G. W. Cameron (Harvard-Smithsonian Center for Astrophysics), Harri Vanhala (DTM) and Peter Höflich (University of Texas)

used a three-dimensional Smoothed Particle Hydrodynamics code to study the impact of interstellar shock waves on molecular cloud cores. The calculations revealed that cores can be triggered into collapse if the velocity of the impacting shock wave is 20-45 km s⁻¹. The results are found to depend on the evolutionary state of the preimpact core. 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.

One application of the hypothesis is the proposal of the triggered origin of the solar system. The presence of short-lived radioactivities in the early solar system, evidence for which has been detected in primitive meteoritic material, suggests that the formation of the solar system was initiated by the impact of a shock wave created by a nearby explosive stellar event. J. N. Goswami (Physical Research Laboratory, Ahmedabad, India) and Harri Vanhala (DTM) reviewed the latest meteoritic data, discussed the possible scenarios for the production of the radioactivities, and concluded that the stellar source of the radioactivities remains the most plausible explanation. Numerical simulations confirm the viability of the triggered origin scenario by showing that the collapse of molecular cloud cores can be triggered by the impact of a shock wave, that material carried by the shock wave can be injected into the collapsing system, and that the time scale of the process is sufficiently short for the survival of the radioactivities.

Boss continued to study the collapse of magnetically-supported, three dimensional, dense cloud cores undergoing ambipolar diffusion. In a new series of models, 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 falls roughly in the middle of the range observed for pre-collapse cloud cores, implying that, if these models are appropriate, collapsing clouds should form single stars about half the time, and fragment into binary stars the rest of the time, an outcome that seems to be in agreement with observations of the frequency of binary stars.

Calculations of molecular cloud core collapse and fragmentation span many orders of magnitude of increase in density and decrease in linear scale. Numerical codes must be able to resolve properly the collapsing cloud if physically accurate results are to be obtained. Recently Richard Klein and his colleagues at UC Berkeley have advanced the Jeans condition as a necessary condition for resolving collapsing clouds. Boss extended their concept to the case of a nonuniform spherical coordinate grid, and applied the condition to several collapse calculations. In collaboration with Klein, Andi Burkert (MPI for Astronomy, Heidelberg) and Peter Bodenheimer (UC Santa Cruz), Boss prepared a review chapter for *Protostars and Planets IV* on the topic of calculations of collapse and fragmentation.

Kenneth Chick has begun development of a computer code to simulate the hydrodynamic behavior of gas accretion disks surrounding protostars. Past numerical work in this field has employed explicitly time-differenced schemes. Due to excessive CPU costs, such schemes are restricted to simulating disks over short time scales (on the order of tens of

years). The actual disk lifetime is many orders of magnitude longer (10⁶ yr).

The code under development is specialized to model the evolution of a disk over realistic time scales. This is accomplished using the Beam-Warming implicit time-differencing scheme. A program for the two-dimensional inviscid hydrodynamic equations has been written. Testing against reference solutions with short time scales has been successful, and tests for progressively longer scales are under way. The first astrophysical application will be to study the long-term fate of concentrations in density which have been shown to form rapidly in disks due to gravitational instabilities, and which may represent protoplanets.

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. C. Alexander, L. Nittler and J. 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 and a detailed analysis of the GCE of Si, Ti and O as recorded in presolar grains.

2.4 Dynamics and Evolution of Galaxies

John Graham published a paper describing the shocked gas and consequent star formation which is observed in the NE lobe of the bright radio galaxy Centaurus A (NGC 5128). This star forming event was apparently precipitated by the impact of the radio jet on an adjacent H I gas cloud. During the past year, Graham carried out *UBV* photometry of the individual blue supergiant stars which were created in this way. Through careful positioning of the large format CCD chip, it was possible to include several stars from a previously published faint photometric sequence in the same field, thus providing a firm photometric calibration. Three concentrations of blue stars were identified. They extend over an arc 5 min (5 Kpc) long, aligned approximately NS. The brightest stars are close to magnitude 20 and are similar in many ways to the brightest blue stars in the Large Magellanic Cloud. The brightest and bluest stars are observed in the southernmost concentration which is evidently the youngest of the three. It is also the most compact. The northernmost concentration is very loose and is on the verge of blending into the extended halo population of NGC 5128 itself. Few of the stars in the northern group are brighter than 24 mag and they are significantly redder than those in the concentrations to the south. The reddening appears to be produced by dust absorption within the H I cloud from which the stars were formed. A paper discussing the color-magnitude and color-color diagrams and identifying the brightest stars for spectroscopic observation is almost ready for submission.

Michael Regan, Kartik Sheth (UMD), and Stuart Vogel (UMD) analyzed the kinematics of the molecular gas in a sample of seven barred galaxies. They were able to show that the dense gas kinematics are a good match to the expectations of hydrodynamic models. These models had predicted that the gas upon encountering the dust lanes along the leading edge of the bar would flow directly down the dust lanes. As the gas flows down the dust lane it encounters a ring at the terminus of the dust lanes. The models predicted that the majority of the gas would flow past the ring to encounter the dust lane on the other side of the bar. This gas that is spraying back into the bar region was clearly detected in the two galaxies whose orientations were favorable. Their kinematic observations were also not consistent with the molecular gas in the bar region consisting of ballistic clouds with long mean-free-paths.

Michael Regan and John Mulchaey (OCIW) are continuing their studies of the fueling methods of active galactic nuclei. Using color maps obtained by combining HST NICMOS and WFPC2 images they were able to map out the nuclear dust morphology in a sample of 12 Seyfert galaxies. By comparing these dust morphologies to that produced by a barred potential, they were able to rule out strong bars as the primary method of fueling active nuclei. An interesting discovery in their color maps was the frequency of spiral dust features. These were the most common morphology and could be another method of fueling active nuclei.

Michael Regan, Tamara Helfer (NRAO), Michele Thornley (NRAO), Kartik Sheth, Stuart Vogel, Andy Harris (UMD), Tony Wong (UCB), Leo Blitz (UCB), and Douglas Bock (UCB) began 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. Observations for the survey started last spring and they plan to finish the observing in the spring of 1999.

Stacy McGaugh (UMD, formerly DTM) completed and published an extensive study of the implications of the rotation curves of low surface brightness galaxies. Collaborator Erwin de Blok (University of Melbourne) made detailed fits to these data while he was a visitor at DTM. The data provide surprising and strong support for the hypothesis of modified Newtonian dynamics proposed by Milgrom as an alternative to dark matter.

Together with Povilas Palunas (NASA GSFC) and Jerry Sellwood (Rutgers), McGaugh began analysis of a large number of high spatial resolution Fabry-Perot rotation curves. They hope to be able to shed further light on the disk-halo conspiracy and the efficacy of maximum disk fits. In particular, they are interested in the transition between disk and halo domination from high to low surface brightness galaxies.

McGaugh also spent a good deal of time investigating the implications of the modified dynamics for cosmology, which are both profound and disturbing.

Galaxy collisions and mergers are dramatic forms of galaxy evolution. Mergers of spiral galaxies of near-equal mass are especially vehement, producing not only remnants that resemble elliptical galaxies but apparently also new sub-systems of globular clusters in them. François Schweizer continued his observational studies aimed at using globular clusters to age-date past mergers and at understanding the cluster formation process itself.

Schweizer and Patrick Seitzer (U. Michigan) refined their spectroscopic analysis of eight young globular clusters in the merger remnant NGC 7252, deriving improved ages for all eight clusters and mean metallicities for three of them. Six of the eight clusters have ages in the narrow range of 400–600 Myr, implying that they formed during a relatively short period beginning about 100–200 Myr after the first close encounter of the two progenitor galaxies. According to the best available N -body simulations of NGC 7252 by Hibbard, Mihos, and Hernquist, that close encounter occurred about $770 h_{75}^{-1}$ Myr ago, and it should have taken the induced star formation ~ 170 Myr to peak. The near agreement between the model predictions and the spectroscopically determined cluster ages seems remarkable. The mean metallicities measured for three clusters are $[Z] \equiv \log(Z/Z_{\odot}) = 0.00 \pm 0.08$, $+ 0.10_{-0.19}^{+0.16}$, and $- 0.12 \pm 0.04$, respectively, and thus essentially solar. Since NGC 7252 itself shows the characteristics of a 0.5 – 1 Gyr old protoelliptical, its second-generation globular clusters of solar metallicity provide direct evidence that elliptical galaxies with not only metal-poor, but also metal-rich globulars can form through major disk mergers.

In order to facilitate future multi-object spectroscopy of globular clusters in merger remnants and early-type galaxies, Schweizer and Seitzer began a program of imaging such galaxies in the B and I passbands. Deep images of six systems were obtained with the du Pont 2.5-m telescope at Las Campanas and the Hiltner 2.4-m telescope at MDM Observatory. The large-field images ($8'8 \times 8'8$) will be compared with smaller-field-of-view WFPC2 images from the *HST* Archive to produce samples of candidate globular clusters for follow-up spectroscopy. The goal is to derive more accurate cluster ages and metallicities and to use globulars for age-dating past merger events.

Bradley Whitmore (STScI), Schweizer, Bryan Miller (DTM, now Leiden), Claus Leitherer (STScI), and Michael Fall (STScI) continued their studies of young star clusters in galaxies imaged with the *Hubble Space Telescope*. These studies aim at understanding the merger-induced formation of clusters (especially globulars) and their subsequent evolution. Whereas the observations support the hypothesis that young globulars are born from giant molecular clouds squeezed by overpressure in the surrounding gas, the detailed evolution of the cluster luminosity function from an initial power-law shape to the lognormal shape characteristic of old cluster systems remains unclear. So far, five galaxies forming a sequence of different merger stages have been observed (NGC 4038/39, 3921, 7252, 1700, and 3610), with results mostly published. A paper describing the properties of clusters in NGC 4038/39 (“The Antennae”) based on a new set of *HST* observations during Cycle 5 is in preparation. In an

effort to track cluster evolution longer in time, five galaxies thought to represent late-stage merger remnants have been added to the program and are awaiting Cycle-7 observations.

Clusters of galaxies offer a valuable venue for studying the kinematics of galaxies. We can examine the effects of the high matter density in the cluster on the range of physical and dynamical parameters of galaxies, for a sample of galaxies all located at the same distance from us. The Virgo cluster of galaxies, the nearest cluster, is especially attractive for study, for it is possible to observe galaxies at high spatial resolution, and to detect morphological and kinematical details that are invisible in galaxies more distant. Some years ago, Vera Rubin, in collaboration with Jeffrey Kenney (Yale University), completed an observing program to obtain spectra and measure rotation curves for about 100 galaxies in the Virgo cluster.

Rubin, along with student Andrew H. Waterman, Montgomery Blair High School, and Kenney have now completed an analysis of the data for all of these Virgo galaxies. For 79 galaxies, rotation curves are sufficiently extended so that their forms can be classified as regular (38) or disturbed (41); disturbances range from mild to major. Velocity complexities are generally consistent with tidal encounters within the last 10^9 years. Hence many Virgo spirals have experienced a significant kinematical disturbance during their lifetimes. There is no correlation of rotation curve complexity with proximity to M87, with local galaxy density, with Hubble type, or with galaxy luminosity.

However, there is a very different distribution of galaxy central velocity for galaxies with regular rotation curves and galaxies with disturbed rotation curves. Galaxies with regular rotation show a flat distribution with central velocities ranging from $V_0 = -300$ km/sec to $V_0 = +2500$ km/sec; galaxies with disturbed rotation have a Gaussian distribution which peaks at $V_0 = +1183 \pm 103$ km/sec, close to the cluster mean velocity, and with dispersion $\sigma(v) = 659 \pm 73$ km/sec. This suggests that the population of galaxies with disturbed rotation is a relaxed spiral population, and that gravitational interactions have driven the relaxation process. It has long been known that the Virgo spheroidal galaxies show a velocity distribution peaked at the mean cluster velocity, but that spirals exhibit an essentially flat velocity distribution. The new results imply that there are two populations of spirals, which have now been separated by characteristics of their rotation patterns.

Rubin, Bryan Miller (formerly DTM, now Leiden), Kenney, Bradley Whitmore (STScI), and Hubble Fellow Laura Ferrarese (Caltech) are completing analysis of HST V and I images of 8 Virgo galaxies, most of them chosen from the 14 galaxies with circumnuclear gas disks. A major surprise has been the high degree of dust and gas very close to the center of each galaxy. They are attempting to characterize the morphology of this generally chaotic material. Now that the photometry is completed, they are comparing the dust features with the rotation curves from ground-based spectra. They are also attempting to develop a method for distinguishing clusters from stars, and to make evolutionary models of the cluster systems.

For one of these galaxies, NGC 4526 (S0), three spectra

were obtained on November 16, 1996, using the HST Faint Object Spectrograph. The analysis of the FOS spectra is now well underway. The spectra were calibrated by the standard HST pipeline, including paired-pulse correction, background and scattered light subtractions, flat fielding, generation of a wavelength scale from dispersion coefficients derived from archival spectra, and flux calibration. From arc lamp spectra, observed either immediately before or after each science spectrum, dispersion coefficients are computed. The dispersion coefficients assigned to each science spectrum are the mean of the coefficients of the two arc spectra immediately preceding and following it, weighted by the time lapsed between the science and the arc lamp exposures.

Wavelengths and intensities for $H\alpha$, [NII] and [SII] doublets have been calculated. Using the peak-up data, they have established that the positioning of the two off-nuclear spectra differ only by +5% and -10% (in declination) from the optimal position, an excellent result. Rubin and collaborators are presently studying the kinematics and dynamics implied by the velocities.

It has recently become possible to measure the internal kinematics of early-type galaxies in intermediate redshift galaxies. Dan Kelson, Garth D. Illingworth (UCSC), Marijn Franx, Pieter G. van Dokkum, and D. Fisher (Groningen) and D. Fabricant (CfA) have measured internal velocity dispersions all the way out to redshifts of $z = 0.83$. They have constructed the ‘‘Fundamental Plane’’ of early-type galaxies in these clusters. The Fundamental Plane is an empirical locus of galaxies in a three-dimensional space of observable parameters: half-light radius, surface brightness, and central velocity dispersion. The existence of this plane implies that galaxy Mass-to-Light ratios are strongly correlated with their structural parameters. Indeed, by measuring the Fundamental Plane at high redshift, we directly observe galaxy Mass-to-Light ratios at a time when the galaxies were much younger than they are today. If we look at the mean Mass-to-Light ratios of early-type galaxies as a function of redshift, we can directly trace their histories back to their epoch(s) of formation. Furthermore, we can use the evolution of the Color-Magnitude relation to place independent constraints on their formation histories.

Kelson, along with Carnegie Fellow Scott Trager (OCIW), is initiating an ambitious project to measure the Color-Magnitude and Fundamental Plane relations of early-type galaxies in nearby poor groups. There is presently a poor understanding of the formation of early-type galaxies. One of the outstanding questions is where the formation of these galaxies primarily takes place. While most elliptical galaxies are located in clusters, theory tells us that they did not form in these dense environments. Do ellipticals form in less rich regions such as groups, which may disrupt and merge while being accreted by massive clusters? By looking at the colors and M/L ratios of early-type galaxies in groups, and comparing them to equivalent data taken in clusters, it will be possible to tell immediately whether group galaxies are systematically younger than their cousins in rich clusters. If so, then we will learn where cluster galaxies undergo their last epochs of star-formation, and where field galaxies un-

dergo their morphological transformations to the morphologies more typical of cluster members.

Graham continues to participate in the HST Key Project concerning the determination of the extragalactic distance scale. Just submitted is a paper on the Cepheid variable stars in the Virgo spiral galaxy NGC 4548 in which 24 stars of this type were identified. The period-luminosity relation points to a distance of 16 Mpc which agrees well with the Cepheid distances to other spiral galaxies in Virgo. No correction has been made for metallicity which appears to be especially high for NGC 4548. Other galaxies in the Virgo core have been found metal rich and if such a correction is applied, it is clear that all Cepheid distances here will be changed in the same sense. In an effort to specify the metallicity correction explicitly and empirically, Graham is working with Wendy Freedman (OCIW) and a small group of collaborators to reobserve in the infrared $H(1.6\mu\text{m})$ band a selected sample of Cepheids from the Key Project data base. They are making use of the near infrared camera (NICMOS) on the HST for this purpose. In the infrared, chemical abundance differences are expected to have a much smaller effect on the Cepheid period-luminosity relation than at visual wavelengths. The observational program is now effectively completed and they are now engaged in the analysis of the NICMOS frames.

Kelson, also a member of the HST Key Project, has been actively involved in measuring Cepheid distances to nearby galaxies. The team has now begun to move into its final phase of turning its many distances into a single value of the Hubble Constant. At this time, they are using the Cepheid distances to groups and clusters like Leo I, Virgo and Fornax, along with the Fundamental Plane of early-type galaxies, to determine a value for the Hubble Constant. The Fundamental Plane is an empirical relation which uses the half-light radii of early-type galaxies as a standard rod (for fixed surface brightness and velocity dispersion). Using Cepheid distances, they can refer these standard rods to physical units of distance, and thus use the angular-size-redshift diagram to infer a value of the Hubble Constant.

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