Carnegie Institution of Washington
Department of Terrestrial Magnetism

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This report covers astronomical research carried out during the period July 1, 1996 – June 30, 1997. 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 extragalactic distance scale, and the structure, dynamics, and evolution of galaxies.

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: Harold Butner, John E. Chambers, Kenneth M. Chick, Prudence N. Foster, Stacy S. McGaugh, Catherine L. Johnson, Stephen J. Kortenkamp, Patrick J. McGovern, Bryan W. Miller, Elizabeth A. Myhill, Larry Nittler, Harri A. T. Vanhala

Predoctoral Fellow: Lori K. Herold

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 The Solar System

The Magellan mission to Venus produced nearly complete global coverage of the planet's topography, gravity field, and radar backscatter characteristics. In the absence of seismic measurements, gravity and topography data provide the strongest constraints on models for the thermal and tectonic evolution of the planet. Although similar to Earth in many respects (radius, mass, solar distance), Venus does not display evidence for present or past Earth-like plate tectonics, an observation that has important implications for current and past heat loss from the planetary interior. Indirect information on spatial variations in heat flow can be obtained from estimates of the thickness of the thermal boundary layer (or lithosphere) from gravity and topography data. Constraints on temporal variations in heat flow come from combining lithospheric thickness estimates with information from impact crater densities and local stratigraphic relations seen in radar images. Catherine Johnson, Patrick McGovern, and Sean Solomon have been pursuing several global and regional studies aimed at these broad questions.

Estimates of lithospheric thickness have been obtained from topographic flexural signatures at a number of features on Venus. These estimates are being combined with information from impact crater densities and geological mapping in an effort to distinguish between temporal and spatial variations in heat flow. The lithospheric thickness may also be estimated from the harmonic analysis of gravity and topography, but such analyses are complicated by the varying spatial resolution of the gravity field. Johnson is performing a global study of the laterally varying resolution of the Venus gravity field using multi-taper spectral techniques. Her resolution analysis provides information critical to regional estimates of lithosphere thickness inferred from joint spectral analysis of gravity and topography, in work being carried out collaboratively by Mark Simons (Caltech), Brad Hager (MIT), and Solomon.

An important class of landform on Venus, as well as on other terrestrial planets, is the large volcano (greater than 100 km in diameter). Such structures not only deform the lithosphere in a manner diagnostic of lithospheric thickness, but their magmatic and tectonic histories provide important clues to the processes of melt generation and magma transport inside the planet. McGovern and Solomon constructed finite element models of the stress and displacement fields inside growing volcanoes subject to lithospheric flexure for comparison to information on volcano evolution from radar images, topography, and gravity. Because of the lack of water and sediments on Venus, large volcanoes are firmly attached (welded) to the underlying lithosphere. The stress state in a growing, basally welded volcano is characterized by horizontal principal compression, with a differential stress magnitude that decreases with height in the edifice. To reorient the near-summit stress field to a state favorable to continued magma ascent and volcano growth, either magma overpressure or basal loading by a broad source of buoyancy (underplating or dynamic support), of a magnitude larger for thinner underlying lithosphere, is required. Large volcanoes are therefore more likely to form on thick lithosphere.

Even on thick lithosphere, flexure due to the load of a large volcano should produce a topographic depression or moat, as is seen around large volcanoes on Earth and Mars. Such moats are not generally seen, however, around large volcanoes on Venus. Instead, conical volcanic edifices are surrounded by a relatively flatter apron of lavas that have flowed radially away from the volcano center. McGovern and Solomon have suggested that flexural moats on Venus filled as they formed by radial lava flows. Under such a hypothesis, the total volume of erupted and intruded material in the volcano-moat system is about an order or magnitude greater than the volume of the edifice alone. With this correction, the magmatic flux at large volcanoes on Venus over the last 500 My is comparable to the intraplate magmatic flux on Earth.

Observations of the topography and gravity field of the planet Mars comparable in resolution and coverage to the information obtained at Venus by Magellan is due to be produced by the Mars Global Surveyor spacecraft, inserted into Mars orbit in September 1997. Once the spacecraft has completed a series of aerobraking maneuvers to circularize its initially highly elliptical orbit, a laser altimeter will determine along-track elevations and X-band tracking will yield significant improvements to the global gravity field. Solomon, Johnson, and McGovern will combine the topographic and gravity information with procedures similar to those used at Venus to infer lithospheric thickness, heat flow, and their spatial and temporal variations on Mars.

George Wetherill studied the orbital evolution of asteroidal material originating in the 3:1 Jovian commensurability resonance at 2.5 AU, using a hybrid symplectic-Bulirsch-Stoer integrator prepared by John Chambers, based on codes provided by H. Levison. All the planets except Pluto, and 258 test bodies were included for integration times up to 20 m.y. Three actual Earth impacts were found, and the orbits of 223 ''surrogate'' impacts, based on close encounters within < 20 Earth radii. It was found that the orbital distribution of eccentricities covered almost all the allowed semimajor axis-eccentricity space for bodies grazing the Earth. When the effects of atmospheric ablation were considered, the distribution of *a, e,* and *i* were similar to those inferred from meteoritic fireball observations.

The four terrestrial planets of our Solar System orbit the Sun enveloped in a tenuous cloud of dust known as the zodiacal cloud. Poynting-Robertson light drag and solar wind drag acting on small dust particles in the zodiacal cloud cause their orbits to decay towards the Sun, removing them on time scales of 10^4 to 10^6 years. Continuous replenishment of the zodiacal cloud against the depleting action of drag is a task once thought to be performed almost exclusively by comets. However, in 1983 the Infrared Astronomical Satellite revealed circumsolar near-ecliptic bands of dust that originate in the asteroid belt and extend to inside the orbit of the Earth. These dust bands are now known to be related to the prominent asteroid families Eos, Themis and Koronis, that is, to known collision products in the asteroid belt. In fact, these three asteroid families remain the only *abundant* sources to be unambiguously linked to dust in the zodiacal cloud. Each year the Earth accretes about 3×10^7 kg of interplanetary dust particles (IDPs) from the zodiacal cloud. Some of these IDPs are retrieved from the stratosphere and form an important collection of extraterrestrial material. However, the origin of these collected IDPs, whether asteroidal or cometary, is a matter of debate. Stephen Kortenkamp has been working in collaboration with his former Ph.D. advisor Stanley Dermott (U. of Florida) to model the way in which the Earth accretes dust particles from the zodiacal cloud.

Using direct numerical integration of the full equations of motion, Kortenkamp and Dermott modeled the orbital evolution of dust particles from the Eos, Themis and Koronis asteroid families as well as from all other non-family asteroids and from the population of all known short period comets. These simulations include gravitational perturbations from the planets, radiation pressure, Poynting-Robertson light drag and solar wind drag. They found that a large and perhaps dominant fraction of the accreted IDPs come from the asteroid families Eos, Themis and Koronis, and that probably fewer than 25% of all accreted IDPs come from comets. They also found a seasonal variation in the distribution of ascending nodes of the Themis and Koronis dust particle orbits near the Earth. They suggest that Earth-orbiting instruments utilizing aero-gels could exploit these seasonal variations to collect and return intact samples of these two asteroid families. Kortenkamp and Dermott also modeled the historic accretion rate of IDPs dating back 1.2 million years and found variations of a factor of 2–3 in the accretion rate of asteroidal dust from all sources. These variations display a 100,000 year periodicity and are anti-correlated with the changing orbital eccentricity of the Earth. They suggest that these variations may be used for independent absolute chronology of ice cores and deep-sea sediment cores.

2.2 Planetary System Formation

Alan Boss pursued the possibility that a protoplanetary disk might be hot enough in its inner regions (inside 4 AU) to remain gravitationally stable, but cold enough (100 K) in its outer regions (outside 4 AU) to undergo a sustained gravitational instability, even for a relatively low mass disk (about 0.14 $M_\odot$). Fully three dimensional models were used to show that such intermediate mass disks could be gravitationally unstable, leading to the formation of strong trailing spiral arms and eventually one or two Jupiter-mass clumps between 5 AU and 10 AU. The instability appears to be robust enough to occur when either locally isothermal or locally adiabatic thermodynamics is assumed. The formation of giant gaseous protoplanets in these models represents an alternative to the leading mechanism for forming giant planets, which requires the prior formation of a $\sim 10 M_\oplus$ ice and rock core capable of accreting gas from the disk. Recent models of giant planet interiors suggest that their ice and rock cores may be considerably smaller than had previously been thought to be the case, strengthening the possibility that giant planets form by the gravitational instability mechanism.

Boss summarized cosmochemical constraints, astronomical observations, and theoretical models of the temperature distribution in protoplanetary disks like the solar nebula for the Annual Reviews of Earth and Planetary Science. Boss also wrote a popular-level book on the search for extrasolar planets and brown dwarf stars, to be published in 1998 by John Wiley & Sons.

John Chambers modeled the late stages of terrestrial planet formation by 3D n-body integration for up to 100 m.y. of $\sim$ 40 initially isolated, nearly coplanar planetary ''embryos,'' ranging from 0.02 Earth masses to 0.2 Earth masses. Altogether, 27 simulations were made and included calculations with and without giant planets, and for systems initially confined to the terrestrial planet region, as well as those including the asteroid belt as well. The orbital evolution is characterized by large amplitude secular oscillations resulting from perturbations between embryos. Larger objects tend to have smaller e and i consistently larger than those observed on Earth and Venus. Further from the Sun, the accumulation rate falls off rapidly, and objects in the ''Mars'' region ($1.5 < a < 2$ AU) are usually scattered and accumulated by ''Earth'' or ''Venus'' or scattered outwards and ejected by resonances, before they can merge with one another. As found earlier by Monte Carlo calculations, the asteroid belt is efficiently cleared as objects are scattered by resonances, resulting in ejection from the Solar System or collision with the Sun, leaving at most one surviving object.

In 2/3 of the simulations that include giant planets, the accumulation is complete by 10^8 years.

Wetherill has proposed an alternative model for the evolution of the asteroid belt, in which originally this region was populated by about 20 bodies the size of the smaller planets, i.e., Mercury or Mars. These bodies were removed as mutual gravitational interactions perturbed them into giant planet resonances, resulting in their loss from the system. Using the same *n*-body code used in the above investigations, Wetherill made a further extensive study of the self-clearing of the asteroid belt. The purpose of this was to determine how robust this process is, and the extent to which it is affected by conditions outside the range of outcomes found by present *n*-body simulations of terrestrial planet formation. It was found that complete asteroid belt clearing is found for about half the evolutionary histories studied. These include cases in which Earth and Venus are absent, Saturn is absent, different degrees of initial, or the initial asteroidal bodies, were as small as 1.4 lunar mass. The only systems studied in which the asteroid belt had failed to clear were those in which the giant planets were absent.

The conventional ''core-mantle'' accretion model for the formation of Jupiter and Saturn requires between $10^6 - 10^7$ years for the gas giants to acquire their present masses. George Wetherill has shown that by this time accretion in the inner Solar System is well under way, with perhaps a few dozen lunar to martian sized bodies distributed between 0.5 and 3.0 AU. Models pertaining to the evolution of the inner Solar System typically evolve these planetesimals for 5–10 million years before introducing Jupiter and Saturn. However, Alan Boss has investigated an alternative model for the formation of Jupiter and Saturn involving gravitational instability of the gaseous solar nebula. Boss proposes that by this method the two gas giants may have formed in as little as $\sim 10^2$ years. If this was the case then the evolution of small planetesimals in the inner Solar System may have proceeded while enveloped in the solar nebula and under the gravitational influence of Jupiter and Saturn. Stephen Kortenkamp has been working with Wetherill to investigate just such a scenario in order to determine whether the early presence of Jupiter and Saturn helps or hinders terrestrial planet formation. He has modified the SWIFT N-body symplectic integrator to account for nebular gas drag acting on small planetesimals. (SWIFT was developed by Hal Levison of Southwest Research Inst. and Martin Duncan of Queen's U., Kingston, Ontario.) Kortenkamp is using SWIFT to model the orbital evolution of planetesimals ranging in size from 0.5 km to 2000 km radius. In these simulations the tendency for gas drag to keep these planetesimals on concentric coplanar orbits is overcome by the strong gravitational perturbations of Jupiter and Saturn. Early results show that relative encounter velocities among the planetesimals are in the range from 100 m/s to 1 km/s. These encounter velocities are above the surface escape velocities of all but the largest planetesimals used in the simulations. Impacts at such high velocities would inhibit the growth of Earth-like bodies in the inner Solar System. These preliminary findings suggest that it may be difficult to grow the terrestrial planets and the largest asteroids unless 100 km to 1000 km bodies exist in the inner Solar System before the formation of Jupiter and Saturn.

C. Alexander and J. Wang are also 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 epoc in the evolution of the Solar Nebula just prior to or during the formation of the terrestrial planets.

2.3 Stars and Star Formation

Prudence Foster and Boss continued their studies of shock wave triggering of protostellar collapse, turning their focus to the question of the injection of shock wave matter into the collapsing protostar. This process is critical for explaining the presence of short-lived isotopes in solar system meteorites by the injection of freshly synthesized radioactivities carried by, e.g., a supernova shock front. Foster and Boss developed two complementary techniques for following the locations of shock wave matter, a Lagrangian tracers technique, and a color equation, identical to the continuity equation. With these tools, Foster and Boss were able to show that between 10% and 20% of the shock wave matter incident upon a target dense cloud core is injected into the collapsing protostar. The models show that injection proceeds as a result of Rayleigh-Taylor instabilities in the shock-compressed cloud boundary.

A.G.W. Cameron (Harvard-Smithsonian Center for Astrophysics), Harri Vanhala (DTM) and Peter Höflich (University of Texas) studied the proposed triggered origin of the Solar system. The idea of an interstellar shock wave triggering the formation of the Solar system has been suggested to explain the anomalous abundances of short-lived radioactivities detected in primitive meteoritic material. As part of his Ph.D. thesis from the University of Oulu, Finland, Harri Vanhala used a three-dimensional Smoothed Particle Hydrodynamics code to study the interaction of an interstellar shock wave with a molecular cloud core. The calculations show that a molecular cloud core can be triggered to collapse by an interstellar shock wave with a velocity of 20–45 km/s. The result also depends on the evolutionary state of the pre-impact core. Highly evolved cores can be triggered at lower velocities than less evolved systems, and they can also withstand higher velocities without being torn apart, while less evolved cores may fragment during impact and create binaries and multiple star systems.

Boss studied the collapse and fragmentation of magnetically-supported, three dimensional, dense cloud cores undergoing ambipolar diffusion. Initially prolate clouds that would collapse and fragment in the absence of magnetic effects were given additional support through the inclusion of the magnetic pressure term ($B^2/8\pi$). Central field strengths on the order of 150 μG were found to be sufficient to lead to a quasi-stable cloud. These magnetically-supported clouds were then allowed to contract through the simulated effects of ambipolar diffusion, leading to rapid collapse. Even with timescales for ambipolar diffusion as long as 10 to 20 free fall times, fragmentation still occurred. The main effect of the magnetic support was merely to delay the onset of cloud collapse and fragmentation.

In the process of testing numerical hydrodynamics schemes against the analytical solution for the Sod shock tube problem, Elizabeth Myhill uncovered a finite-differencing variation that considerably improved numerical stability in the presence of shocks. Boss then tested this variation in his 3D hydrodynamics codes, and found that the seemingly minor variation significantly improved the numerical stability, allowing larger time steps to be taken. Boss thereupon recomputed all of the magnetic cloud collapse models with the improved version of the code, and was able to compute the models to later times.

Kenneth Chick and Boss began research on the development of a powerful new protostellar hydrodynamics code based on implicit time differencing rather than the commonly used explicit time differences. The new code should allow the evolution of, e.g., protostellar disks to be calculated for unprecedented periods of time.

John Graham has concluded his spectroscopic study of the 3 micron ice band absorption which is produced by ice-covered dust grains around young, recently formed stars. A paper is in press. A comparison is made between the profiles produced around embedded young stellar objects like HH 100 IR and the now visible FU Orionis star V346 Normae. The ice band in V346 Nor has a weaker long wavelength wing than in HH 100 IR. It matches well a profile observed in Elias 13 that lies behind the Taurus dark cloud and leads to the conclusion that the line of sight to V346 Nor passes through quiescent intracloud material rather than through the dense dust observed in cloud cores. Fine structure in the ice-band wing, due to C$-$H stretch absorption to CH_3OH absorption is observed in HH 100 IR.

Graham has found evidence for shock-induced star formation in the NE radio lobe of the nearby radio galaxy Centaurus A (NGC 5128). A gas cloud, recently detected in H I, is impacted by the adjacent radio jet to the extent that cloud collapse is triggered and loose chains of blue supergiant stars are formed. Diffuse clouds and filaments of ionized gas have been observed near the interface of the H I cloud and the radio jet. These show velocities which cover a range more than 550 km s^{-1}. Line intensities in their spectra are characteristic of a shock-related origin with strong [N II] and [S II] relative to Hα. The [O III]/Hα line ratio indicates a large range in excitation which is not correlated with velocity. Distinct from this component is a group of 4 apparently normal H II regions which are excited by embedded young stars and whose velocities are very close to that of the H I cloud. Star formation will continue for as long as the gas cloud remains close to the radio jet. The loose chains of blue stars in the area are resolved only because NGC 5128 is so close. The reported faint blue extensions and plumes in more distant analogs probably have a similar origin. A paper has been submitted to the Astrophysical Journal.

The relatively recent 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 are developing 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 of some elements.

2.4 Dynamics and Evolution of Galaxies

Bryan Miller, François Schweizer, Bradley Whitmore (STScI), and Michael Fall (STScI) continued their efforts to study young star clusters in galaxy merger remnants. They identified 499 cluster candidates in *HST* WFPC2 images of the young merger remnant NGC 7252. Based on $UBVI$ colors, these cluster candidates can be divided into three groups: (1) very young objects with ages less than 10 Myr associated with the central gas disk; (2) approximately 700 Myr old clusters that were probably formed during the merger; and (3) the brightest of the old ($\sim$15 Gyr) clusters from the two progenitor galaxies. These objects have effective radii similar to those of typical globular clusters, yet the cluster luminosity function is a power law of slope $\alpha \approx -1.8$ down to the completeness limit at $V=26$. The specific cluster frequency for clusters with masses greater than $10^6\ M_\odot$ is currently $S_N = 0.5 \pm 0.1$, but will — after the remnant has faded for $\sim$15 Gyr — increase to about 2.5. This value lies in the range of S_N for field ellipticals. Therefore, after several Gyr NGC 7252 may begin to resemble field ellipticals even in its globular-cluster population.

Whitmore, Miller, Schweizer, and Fall analyzed *HST* observations of the globular-cluster systems in the two dynamically young elliptical galaxies NGC 3610 and NGC 1700. A search for intermediate-age globulars formed during merger or accretion events yielded a population of about 70 candidates in NGC 3610, but few or none in NGC 1700. In the former galaxy, the clusters are 0.2 mag redder in $V-I$ and 0.7 mag brighter in V than typical old, metal-poor globulars. Both the color and magnitude differences are consistent with an age of 4 ± 2.5 Gyr for these clusters, in good agreement with age estimates of $\sim$4 Gyr for a past merger in NGC 3610 based on the galaxy's UBV colors. Therefore, NGC 3610 may represent a crucial ''missing link'' between young merger remnants and old ellipticals. Further observations of this interesting elliptical are planned for *HST* Cycle 7.

Miller and Fall used the luminosity functions and colors of the cluster candidates in NGC 7252 and NGC 3921 to investigate the shape of the cluster mass function. All old globular cluster systems have a Gaussian-shaped luminosity function while young cluster systems have power-law luminosity functions. Yet, for any spread in ages that reproduces the observed color distributions, simulated clusters drawn from a lognormal mass function do not match the observed power-law luminosity functions. On the other hand, simulations using a power-law cluster mass function reproduce the observations extremely well. This implies that the physical processes that form young star clusters are scale-free.

Miller, along with Whitmore, Harry Ferguson, Massimo Stiavelli and Jennifer Mack from STScI, and Jennifer Lotz (JHU) are continuing analysis of data from a Hubble Space Telescope snapshot survey of dwarf elliptical (dE) galaxies. In a sample of 25 galaxies we find that nucleated dE's have higher globular cluster specific frequencies S_N than non-nucleated dE's. Also, the value of S_N in the nucleated galaxies is more like giant ellipticals than spirals or irregulars. Finally, many of the ''nuclei'' are offset from the geometrical centers of the galaxies. These may be the most massive globular clusters that are still being dragged into the centers. Therefore, we may be witnessing some process associated with nucleus or bulge formation.

Schweizer and Patrick Seitzer (U. Michigan) continued their spectroscopic studies of merging galaxies and globular clusters in them. The analysis of spectra of 8 candidate young globular clusters in NGC 7252, reported on last year, was completed. Seven of these clusters show strong Balmer absorption lines indicative of ages of about 200–600 Myr, while the eighth — lying in a known H II region — features emission lines and is likely $\lesssim 10$ Myr old. The metallicities of the two bright clusters NGC 7252:W3 and W6 can be measured from spectra covering rest wavelengths $\lambda\lambda 3515$–5480 Å and are approximately solar ($Z = 1.0^{+1.0}_{-0.5}\ Z_\odot$). The line-of-sight velocity dispersion of the 8 clusters is 147 km s^{-1}, similar to that of the globular clusters in NGC 5128 and indicative of a moderately massive host galaxy. These spectroscopic results further support the notion that the merger of two spirals in NGC 7252 triggered the formation of a new subsystem of globular clusters of roughly solar metallicity. Spectra were also obtained with the Hiltner 2.4-m telescope of candidate globular clusters in the merger remnant NGC 3921 and the elliptical galaxy NGC 1700. In the latter, the bright point source 20.4″ north of the nucleus is a galactic foreground star, as already suspected from *HST* observations by Whitmore *et al.* (1997).

Several 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. In the last few years, Rubin and Kenney, along with colleagues Pere Planesas (Yebes, Spain), Judith Young (Univ. Mass. Amherst), and Rebecca Koopmann, (Yale Ph.D. 1997), have combined imaging, long slit spectroscopy, and CO interferometry to study the highly disturbed Virgo galaxies, NGC 4438 (Sb), NGC 4435 (SB0), and NGC 4424 (Sa).

Rubin and student Andrew H. Waterman, Montgomery Blair High School, have now prepared for publication a compilation of the data for these Virgo galaxies. Major axis velocity data exist for 90 galaxies; 14 other galaxies have only nuclear or no emission. Rotation curves are formed for 77 galaxies, and minor axis (or other off-nuclear velocities) are available for 46.

For 14 of these Virgo galaxies, types E/S0 to Sc, Rubin, Kenney, and Young (1997) have detected small, rapidly rotating circumnuclear gas disks, kinematically distinct from the outer disk. These disks extend about 3 or 4% of the outer disk isophotal (R_{25}) radius, with a mass of about 4% of the mass interior to R_{25}, and a rotation velocity approximately equal that of the outer disk. We estimate that up to 50% of bright disk galaxies in Virgo may contain such structures.

Rubin, postdoctoral fellow Bryan Miller, Kenney, Bradley Whitmore, STScI, and Hubble Fellow Laura Ferrarese (Caltech) are completing analysis of HST V and I images of 7 Virgo galaxies, 5 of them chosen from the 14 galaxies with circumnuclear gas disks. For one of these, NGC 4526 (S0), HST nuclear spectra from the Faint Object Spectrograph were obtained and are being analyzed.

Stacy McGaugh devoted most of his effort to the interpretation of the rotation curves of low surface brightness galaxies. These data, obtained collaboratively with Erwin de Blok and Thijs van der Hulst of the Kapteyn Astronomical Institute at the University of Groningen, show that low surface brightness galaxies have severe mass discrepancies. Unlike the case of high surface brightness galaxies where much of the inner rotation can at least in principle be attributed to the luminous disk (the ''maximum disk'' hypothesis), low surface brightness galaxies show large mass discrepancies right from the center.

This situation makes low surface brightness galaxies an ideal laboratory for testing theories of galaxy formation. Since their disks are dynamically insignificant, the data directly trace the potential of the putative dark matter halo. This fact is now widely recognized and is being exploited by numerous groups working on the theory of galaxy formation. One important result is that the density distribution of halos predicted by the popular cold dark matter model (the ''NFW halo'') is clearly not consistent with the data.

McGaugh has examined a wide variety of possible galaxy formation scenarios. No dark matter based theory correctly anticipates the observations. Indeed, severe fine-tuning problems arise in any dark matter dominated scenario. Rather surprisingly, there is one theory which is not only consistent with the data, but which accurately predicted all of its essential aspects: the modified force law ''MOND'' hypothesized by M. Milgrom as an alternative to dark matter. Exhaustive review of the literature has uncovered no clear empirical evidence which contradicts the possibility that in fact MOND, rather than dark matter, is the solution to the mass discrepancy problem.

2.5 The Extragalactic Distance Scale

John Graham continues his active participation in the Hubble Space Telescope Key Project Team which is involved in the determination of the extragalactic distance scale. W. Freedman (OCIW), R. Kennicutt (U.Ariz) and J. Mould (MSSO) are the PIs in this effort. Graham was the lead investigator in the study of the Cepheid variable stars in the barred spiral galaxy NGC 3351 (Messier 95) which is a member of the Leo I group of galaxies. A true distance modulus of 30.01 ± 0.19 mag was derived corresponding to a distance of 10.05 ± 0.88 Mpc. This work is now published.

Caleb Fassett (summer intern, Montgomery Blair High School) and Graham obtained from the HST public archive the available images for the adjacent Leo I galaxy NGC 3368 (Messier 96) and searched for variable stars. 14 likely Cepheid variables were discovered. 6 could be identified among the 8 discovered in an earlier study of the same material by Tanvir *et al.* The new photometry agrees quite well with their published data, but our new preliminary distance of 10.3 ± 1.0 Mpc is somewhat smaller than their value and is in closer agreement with the distance to NGC 3351 mentioned earlier.

An investigation of the Cepheid variables in the Virgo cluster galaxy NGC 4548 is now in an advanced stage. 30 Cepheids have been identified. New HST observations obtained in May 1997 are making possible improvements to the preliminary periods derived from the 1996 data set and the material is now being prepared for publication.

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