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Department of Terrestrial Magnetism

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The following report covers astronomical research carried out during the period July 1, 1995 - June 30, 1996. Astronomical activites 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 Chambers, Prudence N. Foster, Munir Humayan, Catherine Johnson, Stacy S. McGaugh, Patrick McGovern, Bryan W. Miller, Elizabeth Myhill, David L. Rabinowitz

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, Merri Wolf

2. RESEARCH PROGRAMS

2.1 Planetary System Formation and Evolution

Alan Boss calculated the thermal structure of a variety of likely protoplanetary disk models with different assumptions about the stellar mass, disk mass, mass accretion rate, dust grain opacity, degree of dust grain growth, and other model assumptions. The general result was that with reasonable choices of disk parameters, protoplanetary disk midplanes are likely to be considerably hotter ($\sim$1000 K or more) inside $\sim$3 AU than had previously been thought likely. At the same time, the disks cool to temperatures of the order of 150 K outside about 4 AU, permitting the condensation of ice grains and the growth of the ice/rocks cores thought to be necessary for the formation of the giant planets. The models seem to rule out forming giant planets closer than a few AU from their parent stars, so that the recent discovery of several 'hot Jupiters' (e.g., 51 Peg B) orbiting at 0.05 AU from their stars apparently requires a phase of orbital decay after giant planet formation. The hot inner disks, while inhospitable to giant planet formation, are hot enough to explain the depletion of volatile elements in the terrestrial planets and chondritic meteorites. They are also hot enough to provide the thermal ionization needed for magnetic field maintenance in the inner disk.

Boss and Harold Yorke (U. Würzburg) calculated the spectral appearance of the new protoplanetary disk models. They found that these disks could exhibit either mid-infrared *dips* in their spectral energy distributions, or even mid-infrared *humps*, depending on parameters such as the mass of the disk and the viscous energy dissipation rate. The results should be useful in interpreting the data returned by the *Infrared Space Observatory*.

The survey of protoplanetary disk thermal profiles led to the interesting possibility that a 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 gravitational instability, even for a relatively low mass disk (about 0.14 $M_\odot$). This hypothesis was checked by using the results of the previous study as input for fully three dimensional models of protoplanetary disk evolution. As expected, these intermediate mass disks were gravitationally unstable and formed strong trailing spiral arms. What was not expected was that these arms went on to fragment into one or two Jupiter-mass clumps orbiting around 8 AU. 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.

The Magellan mission to Venus has provided us with almost complete global coverage of the planet's topography, gravity field and radar backscatter characteristics. In the absence of seismic measurements, we rely on gravity and topography data to provide constraints for models for the thermal and tectonic evolution of Venus. Although very similar to Earth in many respects (size, mass, proximity in the solar system), Venus does not appear to exhibit present-day plate tectonics, an observation which has important implications for both current and previous heat loss from the planet. Indirect information on spatial variations in heat flow can be obtained from inferences of the thickness of the thermal boundary layer (lithosphere) using gravity and topography data. Constraints on temporal variations in heat flow come from impact crater densities and local stratigraphic relations observed in radar images. Catherine Johnson has been pursuing several global and regional studies in collaboration with Sean Solomon, all ultimately aimed at addressing these broad questions.

Estimates of lithospheric thickness have been obtained from topographic flexural signatures at several features on Venus and suggest Earth-like values for the thermal boundary layer thickness. These results were obtained in an earlier study and have been incorporated into a chapter in a new book on Venus. This study is currently being augmented by combining information from impact crater densities with the estimates of lithospheric thickness to attempt to distinguish between temporal and spatial variations in venusian heat flow. Inferences of lithospheric thickness from gravity data returned by Magellan are complicated by the varying spatial resolution of the gravity dataset. Catherine Johnson is performing a global study of the resolution of the gravity data using multi-taper spectral techniques. The results of this study are critical to inferences of thermal boundary layer thickness based on joint analyses of gravity and topography data. Stresses in the present-day venusian lithosphere inferred from the gravity field provide an estimate of the overall strength of the lithosphere, and can be compared with the locations of rifting to provide a lower bound on present day heat flow in these regions.

More localized information on tectonic processes comes from detailed mapping of stratigraphic relations using the radar image data. Eric Hargrave, a summer intern (NASA's Planetary Geology and Geophysics Undergraduate Research Program) worked with Johnson and Solomon, mapping volcanic and tectonic relations in E. Eistla Regio, a region possibly related to hotspot activity in the recent past.

Sean Solomon and Patrick McGovern of M.I.T. (now at DTM), as part of the latter's Ph.D. thesis, studied the growth and structural evolution of large volcanoes on Venus. They constructed finite element models of the stresses and displacements in growing volcanoes subject to lithospheric flexure. Due to the lack of water and sediments on Venus, large volcanoes are likely solidly attached (welded) to the underlying lithosphere. McGovern and Solomon demonstrated that the stress state in a growing, basally welded volcano is characterized by horizontal principal compression which decreases in magnitude with height in the edifice. Stresses induced by pressurization of a magma chamber are required to reorient principal stresses in the central edifice: this allows continued magma ascent to the summit and formation of radial dikes in the uppermost (youngest) layers. The magnitude of pressurization required increases with volcano size and is inversely proportional to the elastic lithosphere thickness T_e. Larger volcanoes are therefore more likely to form on thicker lithosphere. This mode of growth is similar to that of volcanoes in the western Galápagos Islands on Earth.

McGovern and Solomon also investigated the structure of flexural depressions (moats) around large volcanoes on Venus. Such moats are not observed in the Magellan topography data. Instead, conical edifices are surrounded by relatively flat terrain which is covered by flows oriented radially to the edifice peak. Assuming that the lithosphere is deflected by the volcano load (consistent with analysis of the gravity field), McGovern and Solomon suggest that the resulting moats are filled as they form by radial flows. Using analytic models of plate flexure that account for moat-filling material, they determined that the total volume of erupted and intruded material in the entire volcano-moat system is 7–13 times the volume of the topographically prominent edifice alone. Applying such a correction to the volumes of 145 large volcano edifices yields Venus global magma flux estimates comparable to the current terrestrial hotspot flux.

2.2 Star Formation and Evolution

Alan Boss studied the collapse and fragmentation of initially oblate dense cloud cores. Observations of dense cloud cores by Philip Myers (CfA) and his colleagues had shown that while most dense cloud cores are prolate in shape, some fraction is likely to be oblate. Boss calculated the three dimensional, gravitational collapse of a suite of oblate cloud cores, in order to determine the outcome with respect to fragmentation. Both initially uniform density and centrally condensed (Gaussian radial density profiles) clouds were found to fragment following the formation of a very thin disk. The number of fragments obtained was on the order of 4 to 10, compared to the typical result of 2 to 4 fragments for initially prolate clouds. Oblate cloud cores appear to be capable of forming small clusters of protostars.

In a second survey, Boss studied the effects of magnetic fields on three dimensional protostellar collapse. 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. When the timescale for ambipolar diffusion was short enough (less than about 10 free fall times), fragmentation occurred. However, for slower ambipolar diffusion, fragmentation was inhibited and a single protostar resulted.

Elizabeth Myhill and Boss began preliminary work for developing a powerful new protostellar hydrodynamics code based on implicit time differencing rather than the commonly used explicit time differences. Myhill computed the performance of various explicit hydrodynamics schemes on the Sod shock tube problem, a standard for hydrodynamical code tests. The Sod problem will be one of a number of benchmark problems for comparing the performance of the new implicit code with that of explicit schemes.

Lee Hartmann and Nuria Calvet (both of the CfA) and Boss published a detailed analysis of the expected observational appearance of dusty protostellar or protoplanetary disks. The disks are envisioned to form even from the collapse of non-rotating, non-magnetic clouds, provided that the collapse begins from a sheet-like configuration, for which there is observational support. Compared to spherical collapse, sheet collapse quickly produces evacuated cavities along the symmetry axis that better represent observed dust emission from young stellar objects.

Prudence Foster and Boss have expanded their models of shock triggered-collapse of the solar nebula to include tracking of the shock material. Their work is motivated by observations of the decay products of short-lived radioactive isotopes in meteoritical inclusions, suggesting the presence of the live isotopes at the time of the inclusions' formation. Accumulating meteoritical evidence suggests these isotopes come from stellar sources. To avoid the unlikely coincidence of stellar material arriving just as the solar system is forming, triggering is hypothesized. Last year, Foster and Boss studied the collapse properties of shock triggered-star formation.

This year, Foster and Boss developed two techniques to track the shock material and thus to study the injection of radioactive isotopes from a star formation-triggering shock wave. The first of the two tracking techniques is a highly accurate advection scheme which introduces a new fluid element - the ''color.'' The color is initiated with a value of 1 inside the shock front and 0 elsewhere, and it is then updated in the same manner as the density field. While this technique yields accurate capture efficiencies, it can give little temporal and no spatial information about the trajectories of the arriving material. Therefore, Foster and Boss have developed a second technique to track the shock material. This method follows the trajectories of 3000 test particles initially in the shock front. During each timestep, the velocities at the tracers' positions are determined via interpolation of the hydrodynamical velocity field. Using the interpolated velocity, the tracer positions are updated. The two techniques have been successfully tested against analytical problems and against each other.

Both the tracers and the color show that $\approx$ 17% of the impacting shock material is captured in the collapsing region. This low of a capture efficiency could present problems for the AGB star-triggering scenario as it would require the AGB star to be very close to the precollapse cloud in order to pollute the entire solar nebula to the level observed in meteorites. However, the tracers show that much of the shock material arrives as the parent molecular cloud is just finishing its collapse. So instead of having to populate an entire 1 $M_\odot$ cloud, the radioactive stellar ejecta may have to populate only the late-arriving material. Foster and Boss are examining this possibility in more detail, as well as possible spatial heterogeneity introduced by the trajectories of injected material.

John Graham concluded his spectroscopic study of the 3 micron ice band as a potential probe of the changing conditions in the dust around a recently formed star. Using the refurbished IR spectrometer on the CTIO 4m spectrograph, new observations were made of the FU Orionis star V346 Nor and of HH100-IR and TS2.4, two deeply embedded pre-main sequence stars in the Corona Australis cloud. These showed that the 2.97μm feature reported in 1991 by Graham and Chen and attributed to ammonia ice was spurious. It was apparently a consequence of incorrect subtraction of terrestrial bands due to flexure in the spectrometer. Compared to HH100-IR, the long wavelength wing of the ice band is relatively weak in V346 Nor and suggests that some processing of the circumstellar dust is already taking place there. The spectrum of HH100-IR shows a broad feature at 3.47μm which probably arises from C$-$H stretch absorption and a second smaller feature at 3.55μm which may be linked to solid CH_3OH. A summarising paper is in preparation.

Together with Garik Israelian (Vrije Universiteit Brussel), Graham analysed optical spectra of the peculiar emission-line B star, HD 45677 (FS Canis Majoris). The spectra display characteristics in common with the Herbig Ae/Be star R Coronae Australis such as He I and Si II absorption features which change on a night-to-night time scale and are indicative of a clumpy distribution of circumstellar material.

In May, 1996, Harold Butner and Steve Charnley (NASA Ames) studied the deuterium chemistry of the Orion Complex. Looking at several different regions in the cloud, each with a known temperature, they hope to determine the likely pathways of the deuterium chemistry for various molecules. Since deuterated species tend to be destroyed in warm environments, the deuterium fractionation assesses the current physical conditions of the molecular gas. They measured the deuterium fractionation of a number of species using the NRAO 12 meter telescope in Tucson.

In February 1996, Harold Butner, Diane Wooden (NASA Ames), and collaborators measured the silicate emission feature for a number of T Tauri, Herbig Ae/Be stars and other young stellar objects. The purpose was two-fold, to expand their sample of known mid-infrared spectra (useful to study the dust properties of the source), and to also look for variability in the mid-infrared features they observed. The latter was done by focusing on a group of stars that they have been monitoring over the last 3 years. The objects are known to be variable at shorter wavelengths. Evidence for variability (or lack of it) would set limits on the physical properties of disk regions where the mid-infrared emission is thought to arise.

In October 1995, Lynne Deutsch (FCAD/U. Mass) and Harold Butner obtained images of the Trapezium complex over a large region centered on the HST images. These images were taken at the NASA IRTF telescope with the MIRAC2 camera. Other members of the group include the MIRAC team (W. Hoffmann and A. Dayal (Steward), G. Fazio (CfA), J. Hora (IfA)). They obtained deep 10 and 20 μm images over a field of view roughly 2$'$ in diameter.

In September 1995, Harold Butner, Gerald Moriarty-Schieven (JAC), Mike Ressler and Mike Werner (JPL) used the Kuiper Airborne Observatory to obtain far-infrared images at 100 and 200μm for several sources in Taurus, bringing their total sample up to 10 objects. The maps reveal a range of density gradients around the embedded young stellar objects of the sample. They are currently modeling the data. Overall, these images should allow them to assess the role of inside-out collapse versus other star formation models for the Taurus embedded objects.

3. THE EXTRAGALACTIC DISTANCE SCALE

John Graham is actively participating in the Hubble Space Telescope Key Project Team which is involved in determining 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 which is a member of the Leo I group of galaxies. 49 probable Cepheids were found with periods in the range 10$-$43 days. Using apparent period-luminosity functions in the V and I photometric systems, a true distance modulus of 30.01 $\pm$ 0.19 mag was derived corresponding to a distance of 10.05 $\pm$ 0.88 Mpc. A good distance to the Leo I group is particularly important as its wide range of galaxy types makes the group especially useful for the calibration of secondary distance indicators. A paper is in press. Together with summer intern Erik Schoenfeld (Saint Albans School), Graham used images obtained by HST on a later revisit to NGC 3351 to refine the periods of the Cepheids. There were no major changes to the periods but the new values are more accurate by about a factor 4 because of the longer time base. Graham has now begun work (with Laura Ferrarese (Caltech) as principal collaborator) on studying the Cepheids in the Virgo cluster galaxy NGC 4548. 28 probable Cepheids have been discovered to date in this galaxy.

4. DYNAMICS AND EVOLUTION OF GALAXIES

Vera Rubin, in collaboration with Jeffrey Kenney (Yale U.), has completed an observing program to obtain spectra and measure rotation curves for about 100 galaxies in the Virgo cluster. In in the last few years, they, along with colleagues Pere Planesas (Yebes, Spain), and Judith Young (U. Mass), have combined imaging, long slit spectroscopy, and CO interferometry to study the highly disturbed Virgo pair, NGC 4438 (Sb) and NGC 4435 (SB0). Kenney, Rebecca Koopmann, a Yale graduate student, Rubin, and Young have also completed a study of NGC 4424 (Sa), whose morphology and complex inner gas kinematics indicate a recent merger.

Rubin, Kenney, and Young have identified fourteen of these Virgo galaxies, types E/S0 to Sc, whose spectra reveal small, rapidly rotating circumnuclear (CN) gas disks, kinematically distinct from the outer disk. Disk radii are typically ≈500pc; masses interior to the disk radius are ≈3 x 10^9M ⊙ (ranging up to 10^{10}M⊙). There is a good correlation of radius, mass, and peak rotation of the CN disk with radius, mass, and peak rotation within the corresponding optical disk. Inner 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 and Bryan Miller obtained relatively deep high dispersion spectra of NGC 3626, a galaxy they chose to observe because of its morphological resemblance to NGC 4826, the Sleeping Beauty galaxy, as well as more spectra of NGC 4826. In the inner portion of NGC 4826, the stars and gas rotate prograde; beyond the deep dust lane, the stars continue prograde while the gas velocities fall through zero (with respect to the center) and end up orbiting retrograde. The new spectra detail some of the kinematic complexities in the region where the gas reverses direction. An infall is also observed in the gas motions in the region of the deep dust lane.

In contrast to NGC 4826, the orbital velocity of the gas in NGC 3626 is retrograde with respect to the orbital sense of the stars in the region interior to the dust lane. Beyond, however, the gas velocities fall rapidly to almost zero, but do not appear to become prograde. We are presently attempting to disentangle the complex gas motions in NGC 3626.

Bryan Miller, and Michael Fall (STScI), continued the reduction and analysis of *HST* observations of globular clusters in merger remnants and elliptical galaxies. Two goals of this program are the study of merger-induced cluster formation and the use of globular clusters for dating past merger events. Miller and François Schweizer paid special attention to NGC 3921, a ~700 Myr old merger remnant that is a key transition object between ongoing disk–disk mergers like NGC 4038/4039 and elliptical galaxies thought to be ancient merger remnants. A search of *HST* images obtained during Cycle 4 yielded 102 candidate globular clusters and 49 more extended stellar associations brighter than $V=26$. Most of the globulars have remarkably uniform, blue colors ($V-I\approx0.65$) indicative of a median age of about 300 Myr. The color distribution of the clusters suggests a prolonged formation period of several hundred Myr, roughly in agreement with the estimated duration of the merger. The most luminous candidate globulars have absolute visual magnitudes of -12 to -13 and are predicted to fade by 3–4 mag over the next 15 Gyr, whence they will then have luminosities typical of old globular clusters. The projected radial distribution of these young globulars is centrally concentrated and follows closely the light profile (~ $r^{1/4}$-law) of the galaxy. This suggests that the cluster progenitors experienced the same violent relaxation as did the average luminous matter of the two merging galaxies. This fact and the cluster luminosity function both favor the notion that the cluster progenitors were giant molecular clouds in the merging spirals. A comparison with the estimated number of old globular clusters in the remnant suggests that the merger led to an increase of at least 40% in the total number of globulars. Thus, NGC 3921 is the third case of a merger remnant known to have significantly increased its globular-cluster population while also apparently evolving into a future E or S0 galaxy.

François Schweizer, in collaboration with Patrick Seitzer (U. Michigan) continued their analysis of spectra of 9 candidate young globular clusters in NGC 7252. These spectra were obtained with the CTIO 4-m telescope and cover the spectral range of λλ3600–5500 Å. One of the objects turned out to be a background galaxy. Of the other 8 candidate globular clusters, seven show strong Balmer absorption lines indicative of ages less than 1 Gyr and one features strong emission lines, as expected from its location in a known H II region. This latter cluster is probably less than 10 Myr old. For the 7 other globulars, comparison with new models of star clusters by Bruzual and Charlot shows that the measured equivalent widths of the Balmer absorption lines Hβ–Hδ now agree well with the maximum equivalent widths predicted by the models for ages of about 200–600 Myr. Hence, the problem with older, pre-1996 models, which failed to reproduce the observed strengths of the Balmer lines, seems to have been solved. The spectroscopically determined ages of these young globulars support previous, less accurate age estimates based on broad-band colors measured with *HST*. Thus NGC 7252, too, seems to have formed globular clusters over a period of several 100 Myr coincident with the duration of the merger.

Guiseppina Fabbiano (CfA), Schweizer, and Glen Mackie (CfA) completed their analysis of X-ray observations of the ''Antennae'' galaxies (NGC 4038/39) obtained with the High-Resolution Imager of the *ROSAT* satellite. The X-ray image of this merging pair of galaxies covers a field of about 38′ diameter with a resolution of ~5″ and a bandpass of 0.1–2.5 keV. Over the region of the two optical main bodies, this image reveals complex and intricate X-ray emission, including regions of almost filamentary emission closely following the Hα emission from star-formation regions and prominent nuclear emission peaks with X-ray luminosities of ~10^{40} erg s^{-1}. Estimates suggest that most of the observed X-ray emission is probably a combination of emission from discrete evolved X-ray sources (binaries and supernova remnants) and from a diffuse hot interstellar medium, while early-type stars contribute only in a minor manner. The morphology of the image suggests that the hot interstellar medium may occur in one or two superbubbles and in two nuclear outflows analogous to those observed in other starburst galaxies.

John Graham continues his study of an unusual burst of star formation associated with the NE radio lobe of the bright radio galaxy NGC 5128 (Cen A). This appears to be a consequence of the interaction of the radio jet with an H I cloud which is most probably a surviving remnant of an earlier merger. The brightest blue stars are at $V = 20.0$ mag and have colors close to $B-V = 0.0$ and $U-B = -0.9$ mags and are similar to the brightest blue stars in the Large Magellanic Cloud. A minority of red supergiant stars is also clearly present. Stars so massive are destined to become supernovae which will contribute to the disruption of the H I cloud. Lower mass stars will disperse into the extended ellipsoidal stellar component of the galaxy.

Bryan Miller used Hα imaging and nebular spectroscopy to investigate the recent star formation histories of eight dwarf galaxies in the Sculptor Group. Only two of the eight galaxies have current star formation, and the oxygen abundances in their HII regions are 10-15% of solar. The general star formation activity of the Sculptor Group dwarfs is less than in dwarf galaxies in the Local Group or M81 Group. Since the mass density in the Sculptor Group is less than in either the Local or M81 Groups, large-range gravitational interactions may play a role in regulating star formation in dwarf galaxies. However, the O/H, M_B relation seems to hold for all environments so galaxy mass appears to be the primary factor governing a galaxy's chemical evolution.

Miller, Whitmore (STScI), Ferguson (STScI), and Stiavelli (STScI) are working on preliminary analysis of a Hubble Space Telescope snapshot survey of dwarf elliptical (dE) galaxies. The goals are to compare the globular cluster populations of nucleated and non-nucleated dE's and to study the properties of the nuclei. With twelve galaxies observed to date their preliminary finding is that nucleated dE's have higher globular cluster specific frequencies, S_N, than non-nucleated dE's. Also, both types seem to have values of S_N more like giant ellipticals than spirals or irregulars. Finally, many of the nuclei are offset from the geometrical centers of the galaxies.

Miller and Rubin continue to obtain Hα spectroscopy of Virgo ellipticals and early-type spirals with kinematically distinct cores. The kinematical information from the specta will be compared with HST images of the cores of these galaxies in order to see the relationships between the stars, dust, and gas.

Together with Greg Aldering (U. Minn) and Mario Mateo (U. Mich), Stacy McGaugh made good progress in a large survey for very low surface brightness galaxies. The project aims to cover 100 square degrees to an isophotal limit of 27 R mag per square arcsecond. Slightly over half the target area has been surveyed to date. They expect to identify approximately 1000 galaxies with central surface brightnesses fainter than 24 R magnitudes per square arcsecond, a regime which is virtually unexplored. They will also construct a rigorously complete sample of galaxies of all surface brightnesses in order to obtain the bivariate distribution of size and surface brightness.

In addition to searches for new low surface brightness galaxies, McGaugh has also worked on the physical characteristics of these galaxies. Such studies have been very illuminating, shedding light on general issues of galaxy dynamics, evolution, and formation.

With collaborators de Blok and van der Hulst (Groningen), McGaugh has conducted an exhaustive HI study of two dozen low surface brightness disks. Like the star light, the HI is also low surface density, though not by as large a factor. Roughly speaking, a factor of 5 in luminous surface density corresponds to a factor of 2 in HI. This is the expected signature of star formation regulated by a critical density criterion.

One interesting result with important implications for galaxy evolution is that the gas mass fraction of spiral galaxies is well correlated with the central surface brightness of the disk, in the sense that lower surface brightness galaxies are more gas rich. This confirms that low surface brightness galaxies are slowly evolving systems, having converted relatively little of their original gas into stars. This slow evolution appears to be caused by the low surface densities, again as expected in critical density regulated star formation.

The kinematics revealed by the HI rotation curves are most interesting. The rotation curves confirm earlier line-width results that low surface brightness galaxies obey the same Tully-Fisher relation, with the same normalization, as high surface brightness spirals. This is contrary to the predictions of some scenarios for the formation of these galaxies. The rotation curves rise slowly, in perfect accord with these same scenarios. This paradoxical situation places strong constraints on theories of galaxy formation.

McGaugh and Rachel Pildis (CfA) also examined whether a Local Group X-ray halo could contribute to the microwave background anisotropy observed by COBE through the Sunyaev-Zeldovich effect. Comparison to similar and richer groups observed with ROSAT show that such an effect would be completely negligible unless the Local Group was very atypical with many orders of magnitudes more hot gas than other groups. The Sunyaev-Zeldovich mechanism can therefore not be the cause of the peculiar normalization of the COBE-derived power spectrum.

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