EVIDENCE FOR DARK MATTER IN GALACTIC SYSTEMS

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ABSTRACT

The evidence for dark matter in binaries and groups of galaxies is very strong, and is seen in all recent observational studies. Measurements of mass in galactic systems is possible on scales ranging from 50 kpc using virial analysis of binary galaxies to 15 Mpc using Virgocentric infall analysis. The Ω estimates derived from these studies are generally consistent with $\Omega < 0.2$, with a fairly weak trend toward larger Ω estimates on larger scales. However, measurements of the galaxy distribution in the IRAS catalog yields a dipole anisotropy consistent in direction with the microwave dipole anisotropy, suggesting that the local galaxy distribution is responsible for the microwave velocity. This will eventually provide the most reliable estimate of Ω, and is likely to result in a value somewhat larger than previous estimates on smaller scales. Study of the velocity field around large clusters in cosmological n–body experiments provides a useful guide for understanding the limitations of the spherically symmetric models of Virgocentric infall. We point out a number of biases that could affect the existing Virgocentric flow studies.

1. INTRODUCTION

Discussions of dark matter in groups and clusters of galaxies is an old and venerable subject that dates back at least to Zwicky's (1933) comments on the missing mass problem in the Coma cluster. One way to discuss the dark matter problem is in terms of M/L ratios. The observed B_o luminosity density of galaxies is known within approximately 20% uncertainty to be $L_B \approx 1.1 \times 10^8\ h^2\ L_\odot/\mathrm{Mpc}^3$ ($H_0 = 100$ h km s^{-1} Mpc^{-1}) (Davis and Huchra, 1982). The cosmological density parameter Ω can then be expressed as

$$M/L_B \approx 2300 h\Omega\ M_\odot/L_\odot$$

Since M/L ratios of stellar populations range from 1-10, "dark matter" must be supplied to explain any measurements that imply $\Omega > 0.005$.

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In this paper I shall briefly review evidence for dark matter in groups of galaxies and in Virgocentric flow studies. I shall focus on results postdating the detailed review of Faber and Gallagher (1979). Recent binary galaxy results were presented in the oral version of this presentation but have been transferred to J. Ostriker's report (this volume). In section 2 I shall discuss the measurement of relative peculiar velocity of pairs of galaxies and the continuity of its behavior on scales from binary orbits to clusters of galaxies. The status of the virial analysis of groups of galaxies has not greatly changed in the last few years, and was reviewed last year by Geller (1984); I shall limit the discussion of section 3 to one new study by Nolthenius and White. Much recent activity has focused on the measurement of the anisotropy of the Hubble flow around the Virgo supercluster, which gives a mass estimate on a scale of 15 Mpc and so is sensitive to matter that perhaps is not clustered on smaller scales. The subject has been reviewed by Davis and Peebles (1983a) and new results are reviewed in section 4. Section 5 discusses a new sample of galaxies; the IRAS galaxy list, which can be used in an improved version of large scale mass determination. Finally, section 6 describes recent n–body studies designed to test the reliability of Virgocentric mass determinations.

2. THE RELATIVE VELOCITY OF PAIRS OF GALAXIES

The median velocity difference of well isolated late-type binary galaxies is about 100 km s^{-1} (White *et al.*, 1982; Schweizer, 1985). Binary galaxies that are less isolated have an RMS velocity difference of 200 km s^{-1}. These "binary" galaxies are presumably influenced by the gravitational field of additional neighbors, and the distribution function of their velocity differences is in fact indistinguishable from that of all close galaxy pairs ($r_p < 100\ h^{-1}$ kpc) in the CfA Survey (Davis and Peebles, 1983b).

The measured rms peculiar velocity of all pairs is a smooth function of the projected separation from the scale of 20 h^{-1} kpc to 5 h^{-1} Mpc (Davis and Peebles, 1983a; Bean *et. al.*, 1983); over the measured range the RMS velocity difference of all pairs is 200-350 km s^{-1}. On larger scales it is very difficult to separate the effects of Hubble expansion from peculiar velocity and the dispersions become model dependent.

The smooth behavior of the relative velocities must be a significant clue to the nature of the dark matter on these scales, although we do not yet understand its implications. If galaxies trace the mass and if the two point correlation function $\xi(r) \propto r^{-\gamma}$ then relative velocities should scale as $\langle v_{21}^2(r)\rangle \propto \Omega r^{2-\gamma}$ (Peebles, 1980). Since γ is observed to be 1.8 we expect a slowly rising behavior for $v_{21}^2(r)$, as observed in the largest sample studied to date. With the proportionality constants in place, the derived density estimate is (Davis and Peebles, 1983b) $\Omega \approx 0.2e^{\pm 0.4}$.

However, this cosmic virial theorem result actually depends on the ratio of a nearly divergent moment of the three point correlation function ς and on the assumption that the three point function can be accurately written as a product function of the two point correlations, $\varsigma_{123} = Q(\xi_1\xi_2 + \xi_2\xi_3 + \xi_1\xi_3)$, which is consistent with observations for $Q \approx 0.8$. Furthermore one wonders how well galaxies can be expected to trace the mass, particularly on small scales. The smoothness of $\langle v_{21}^2(r_p)\rangle$ and the derived Ω estimate suggests dark halos around galaxies extend a considerable distance, of order 300 h^{-1} kpc, or that most of the measured mass is associated with numerous lower luminosity objects clustered with the larger, brighter galaxies which dominate the observed samples.

3. GROUPS OF GALAXIES

A complementary type of analysis to the above statistical approach is virial analysis of individual groups of galaxies. At least two separate group analyses have been performed on the CfA catalog. Press and Davis (1982) selected groups on the basis of crossing time and reported a linear trend of M/L on group size, in the range 50 kpc $< hr_G <$ 2 Mpc. Unfortunately the larger size groups were frequently contaminated by bogus outliers and the strong trend must be discounted for hr_G $>$ 300 kpc. This contamination did not occur in the fake catalogs drawn from n–body models which were used to calibrate the method.

Huchra and Geller have selected groups on the basis of overdensity, using a neighbor sphere that varies with distance to account for the selection effect. They find an enormous scatter in M/L estimates (a factor of 10^4!) and argue the data is too noisy to discern any trends of M/L versus anything. This work has been recently reviewed by Geller (1984). More recently Nolthenius and White (1986) have extended this analysis and have made a detailed comparison to n–body models of cold dark matter dominated universes (Davis *et al.*, 1985). They compared groups drawn from the CfA catalog to groups taken from model universes with $\Omega = 0.2$ and $\Omega = 0.3$ in which galaxies trace the mass, and to a model with $\Omega = 1.0$ in which galaxies are a biased mass tracer. In the unbiased models, one expects no trend of M/L with scale size and none is observed. The biased models are expected to show a trend of M/L with size, but it is very weak and is completely consistent with the CfA data. Nolthenius and White argue that the $\Omega = 1$ biased model gives the overall best fit to the data; if one insists that galaxies must trace the mass, then $\Omega = .1$ or $.2$ is indicated, in complete agreement with the statistical approach.

4. VIRGOCENTRIC FLOW

The Virgo supercluster presents a unique opportunity to measure mass on a really extended scale, our distance to the center of Virgo, $r \approx 15$ Mpc. These studies combine some measure of density fluctuations, such as the mean overdensity $\bar{\delta}$ within our radius to Virgo, with a peculiar velocity derived from the anisotropy of the microwave background radiation or from anisotropy of the local Hubble flow. The mean galaxy overdensity has been measured to be $\bar{\delta} \simeq 2.0 \pm$

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0.2 (Davis and Huchra, 1982). This value supercedes previous higher estimates of $\bar{\delta}$ which were based on smaller, shallower redshift catalogs.

One can derive an estimate of Ω with the additional assumption of spherical symmetry for Virgo, which in linear theory gives the mean infall velocity V_v averaged on a sphere at radius r from the cluster center as

$$V_v/Hr = \frac{1}{3}\bar{\delta}\Omega^{0.6}. \tag{1}$$

Alternatively one can relax the assumption of spherical symmetry and use the linear perturbation theory result (Peebles, 1980).

$$\vec{v}_p = \frac{2}{3}\left(\frac{\vec{g}}{H\Omega}\Omega^{0.6}\right), \tag{2}$$

where $\vec{g}$ is the net peculiar gravitational acceleration measured by an observer with velocity $\vec{v}_p$. Unfortunately the real Virgo cluster is both non–linear and non–spherical, and there may be systematic errors that bias Ω estimates from these analyses, a topic to be discussed below in section 6.

The observation of primary relevance for Virgo flow analysis is the velocity inferred from the microwave dipole anisotropy, V_μ. In the local group center of mass the measured velocity is $V_\mu = 600 \pm 50$ km s^{-1}, directed toward $\ell = 270°$, b $= 30°$, some 45° from the direction of the Virgo cluster (Fixsen *et al.*, 1983; Lubin *et al.*, 1983). The fundamental question here is to understand what fraction of the microwave anisotropy is induced by the local supercluster, and what is responsible for the balance.

A number of recent studies strongly suggest that the entire microwave anisotropy is likely to be induced by matter distributed within 50 h^{-1} Mpc of us, a region largely dominated by the local supercluster. In particular, Aaronson *et al.* (1985) measure a dipole Hubble flow anisotropy of 800±200 km s^{-1} in a set of 10 clusters arranged around the sky, and at distances of 40–100 h^{-1} Mpc. The direction and amplitude is consistent with the microwave results and implies that we are moving relative to the clusters which themselves appear to be at rest in the comoving frame. This result confirms previous, less secure Hubble anisotropy studies of Hart and Davies (1982) and de Vaucouleurs and Peters (1984). It furthermore is consistent with theoretical prejudices that the primordial power spectrum of density perturbations is the Zel'dovich constant curvature spectrum in which case the peculiar velocity field will be dominated by perturbations of wavelength short compared to 100 h^{-1} Mpc (Peebles, 1980; Davis, 1985).

Another set of observations is limited to determination of the component of our infall velocity directed toward Virgo. Tonry and Davis (1981) argued that the Faber–Jackson luminosity–velocity dispersion correlation for E and S0 galaxies distributed within cz < 8000 km s^{-1} leads to an infall estimate consistent with this component of microwave anisotropy (420 km s^{-1}). Dressler (1984) also used

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the Faber–Jackson relation to measure the relative distance modulus of elliptical galaxies in Coma and Virgo and took special precaution to maintain apertures of constant projected metric size for the velocity dispersion measurements. His derived infall velocity was 230±80 km s^{-1}. The source of this discrepancy with the Tonry–Davis result is presently unresolved.

The best local studies of Virgo flow use distances derived independently of redshift to attempt to fit the observed Hubble anisotropy to a non-linear spherical flow model centered on the Virgo cluster (e.g. Aaronson *et al.*, 1982). These studies are usually confined to galaxies with cz < 3000 km s^{-1}, and typically yield infall estimates of 200–300 km s^{-1}, substantially less than the Virgo component of microwave anisotropy.

If Virgo itself induces this relatively small infall velocity then the entire Virgo supercluster must be moving at some 400 km s^{-1}, roughly in the direction of the Hydra–Centaurus cluster ($\ell \sim 285°$, $b \sim 25°$). Hydra–Centaurus has a redshift cz $\approx$ 3000 km s^{-1}, so by equation (1) with fixed Ω the mean overdensity toward Hydra–Centaurus should be $\bar{\delta}_{HC} > 1$, compared to the $\bar{\delta}_{Virgo} \approx 2$, in order to induce this velocity. If this were the case, we should expect to readily observe a hemispheric anisotropy of the galaxy counts extending beyond 15^{th} magnitude toward this direction that should rival the anisotropy of the Shapley Ames catalog induced by the Virgo supercluster. No such anisotropy exists.

It is important to keep in mind that the Virgo flow test is not a measure of the mass of the central region of the Virgo or Hydra-Centaurus clusters, but of **all** the matter overdensity within a radius of our distance to the cluster center. It is unrealistic to imagine that Hydra–Centaurus, clusters virtually unrecognizable in full–sky maps of the galaxy distribution, would have more influence on our peculiar velocity than the net effect of the Virgo supercluster. Although most studies point toward a low infall velocity toward Virgo, and a corresponding low estimate of density Ω (< 0.25), these conclusions are unsettling because they do not readily explain the bulk of the microwave anisotropy, which would appear to have been generated by matter within 50 h^{-1} Mpc of us, yet neither by Virgo nor by Hydra–Centaurus, the only known superclusters within this distance and in this general direction.

5. THE IRAS GALAXY CATALOG

The above confusion is likely to be resolved soon by a dramatic result that has emerged from the IRAS point source catalog. In this catalog it is a straightforward procedure to separate stars from galaxies on the basis of IR color. Meiksin and Davis (1985) (see also Yahil, this conference) have generated a galaxy catalog from the IRAS database, which is ideal for measurement of the anisotropy of the local galaxy distribution. Given a catalog of galaxies complete over the entire sky, the net measured dipole of the surface density distribution, weighting galaxies either by number or by flux, is proportional to the net peculiar gravitational acceleration acting on us. In linear perturbation theory, one would expect this dipole direction to agree with the direction of the microwave dipole anisotropy. The proportionality constant between the surface density dipole of IRAS sources and the gravitational acceleration $\vec{g}$ can be readily inferred once redshifts are available for the sample. Of course the method assumes these objects trace the underlying mass distribution on these large scales.

The IRAS galaxy catalog is uniquely suited for this type of whole sky analysis. The catalog generated by Meiksin and Davis contains 6730 sources, selected to have flux $f_{60\mu} > .6$ Jy and to have $f_{60\mu}/f_{12\mu} > 3$. We estimate the catalog is contaminated by less than 10 stars, although some galactic cirrus may be masquerading as external galaxies. These contaminating sources will be readily weeded out in followup optical studies. The resulting catalog is displayed in figure 1. We have eliminated all sources with $|b| < 10°$, and have excised additional sections of the sky around prominant HII regions, which are associated with excessive quantities of cirrus. The empty slices through the middle of each hemisphere are the two small regions not surveyed by IRAS. Our catalog has been generated from 9.55 steradians in a uniform fashion, which would be an impossible task for an optically selected catalog because of galactic extinction.

The most conspicuous clusters apparent in figure 1 are the Virgo and Perseus superclusters. None of the clusters are especially prominent because of the dilution in projection by background galaxies. We estimate this catalog samples to a depth of order 50–100 h^{-1} Mpc, well beyond the local supercluster. The IRAS galaxies are preferentially late type spirals undergoing active star formation, and we believe these should be a fair, nearly random sample of all late type spirals. Certainly the IRAS galaxies will underrepresent regions dominated by E and S0 galaxies in the centers of clusters, but most galaxies, and we suspect most mass, are not associated with the high density regions underrepresented by spirals. In any event, if galaxies are a biased mass tracer, it is likely that spirals more closely trace the mass distribution than do the early type galaxies. The large scatter in infrared to optical flux or in infrared flux to mass can dilute, but will not erase the anisotropy. For the purposes of the anisotropy study, we are indifferent to all details of the IR properties of the selected galaxies. We are interested only that the flux limit and other sampling considerations be uniform across a large region of the sky, and that the IR properties of bright galaxies are a random and fair sample of all galaxies of their morphological type.

Given the above prelude, we measured the dipole anisotropy of the sample as a whole, and after subdividing it into 4 independent subsamples based on quartiles of 60μ flux. Details are provided by Meiksin and Davis (1985). The overall dipole anisotropy is only 4.1% of the mean surface density, but the top quartile subsample, comprised of the brightest sources which should be statistically the closest to us, has an anisotropy of 7%. The anisotropy directions of the 4 independent samples are shown in figure 1, along with the microwave anisotropy direction and the direction of anisotropy seen in the CfA analysis (Davis and Huchra, 1982) which was generated from an optically selected catalog with $|b| \geq 40°$. The center of the Virgo cluster is also indicated. The major result to note is that the IRAS anisotropies for the top 3 quartiles all point very close to the microwave anisotropy, $\theta \sim 22$–$29°$, and about 35 degrees from Virgo. The faintest quartile deviates in direction, but this subsample is the most affected by galactic cirrus and other problems. Our anisotropy results agree very well with those of Yahil *et al.* (1985), whose analysis of the IRAS data is quite independent and different from ours.

Examination of figure 1 shows no prominent density peak in the direction of the anisotropy. The dipole is truly the vector sum of all the clusters and voids seen in the catalog, and the low density regions in figure 1 play as significant a role in repelling us as the clusters do in attracting us. The robustness of the anisotropy implies it is dominated by the local galaxy distribution well sampled in all flux quartiles. The fact that the IRAS anisotropy is relatively close in direction ($\theta \sim 30°$) to the CfA anisotropy, which necessarily presumed no anisotropy was generated from matter in the region $|b| < 40$, suggests that the same clustering dominates both samples. Complete redshift information is available for the CfA analysis, and as shown by Davis and Huchra (1982), the peculiar gravity $\vec{g}$ of that sample is completely dominated by the Virgo supercluster. Quantitatively the gravity anomaly measured in the CfA catalog should generate a peculiar velocity $|v_p| \simeq 670\Omega^{.6}$ km s^{-1}. The additional anisotropy detected by the IRAS sample will probably raise the expected peculiar velocity to $\approx 900\ \Omega^{.6}$ km s^{-1}. This expected velocity should be compared directly with the microwave velocity and in turn implies a high value of density, $\Omega \approx 0.5$. When redshifts are available for a subset of the IRAS galaxies (e.g. the brightest quartile) this density estimate will be better quantified. Since it is the largest scale mass estimate conceivable and is the least model dependent it should become the most reliable measure of the true cosmological density.

6. CLUSTER FLOW IN N–BODY SIMULATIONS

There remains an explanation for the serious discrepancy of the low infall velocity measured in the local Hubble flow studies with the larger peculiar velocity indicated by the microwave and IRAS anisotropies. As indicated above, I seriously doubt if the center of the Virgo cluster is moving anywhere at a speed approaching 400 km s^{-1}. A possible explanation for the discrepancy could be some inadequacy of the spherical models used to measure the local Hubble anisotropy.

To study the accuracy of the spherical models, Villumsen and Davis (1985) have examined cluster formation in cosmological n–body simulations. Since the clusters are sliced out of large models, their exterior boundary conditions are much more realistic than the usual assumption of spherical symmetry. The initial conditions of the models studied by Villumsen and Davis were either power law models, $\delta_K^2 \propto k^n$, n $= -1, -2$, or of the cold dark matter type (Blumenthal and

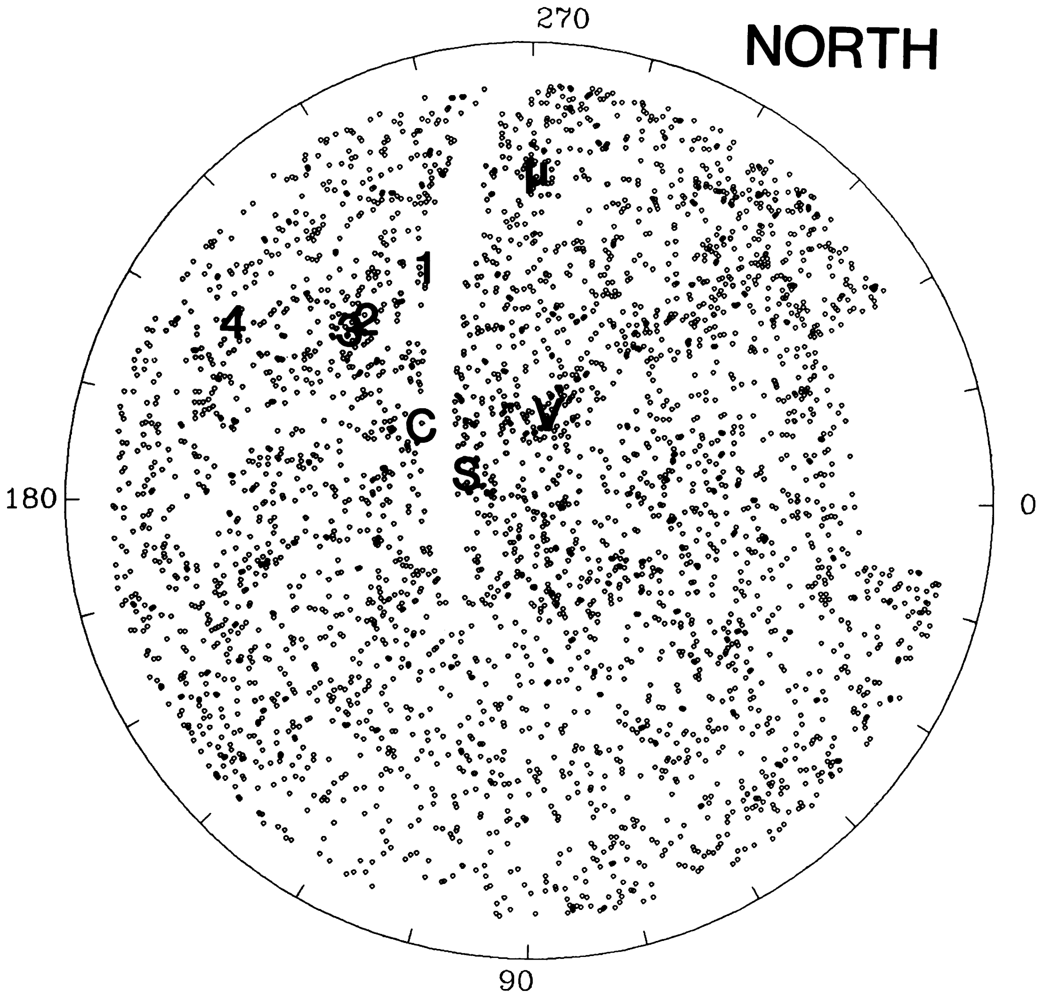

Figure 1a: Equal area projection of the north galactic hemisphere of the IRAS Galaxy catalog of Meiksin and Davis (1985). 3476 galaxies are plotted. The microwave anisotropy direction is indicated by the μ, the Virgo cluster center by V, the Shapley-Ames luminosity anisotropy by S, the CfA dipole anisotropy direction by C, and the dipole directions of the four independent flux quartiles of the IRAS sample by 1–4.

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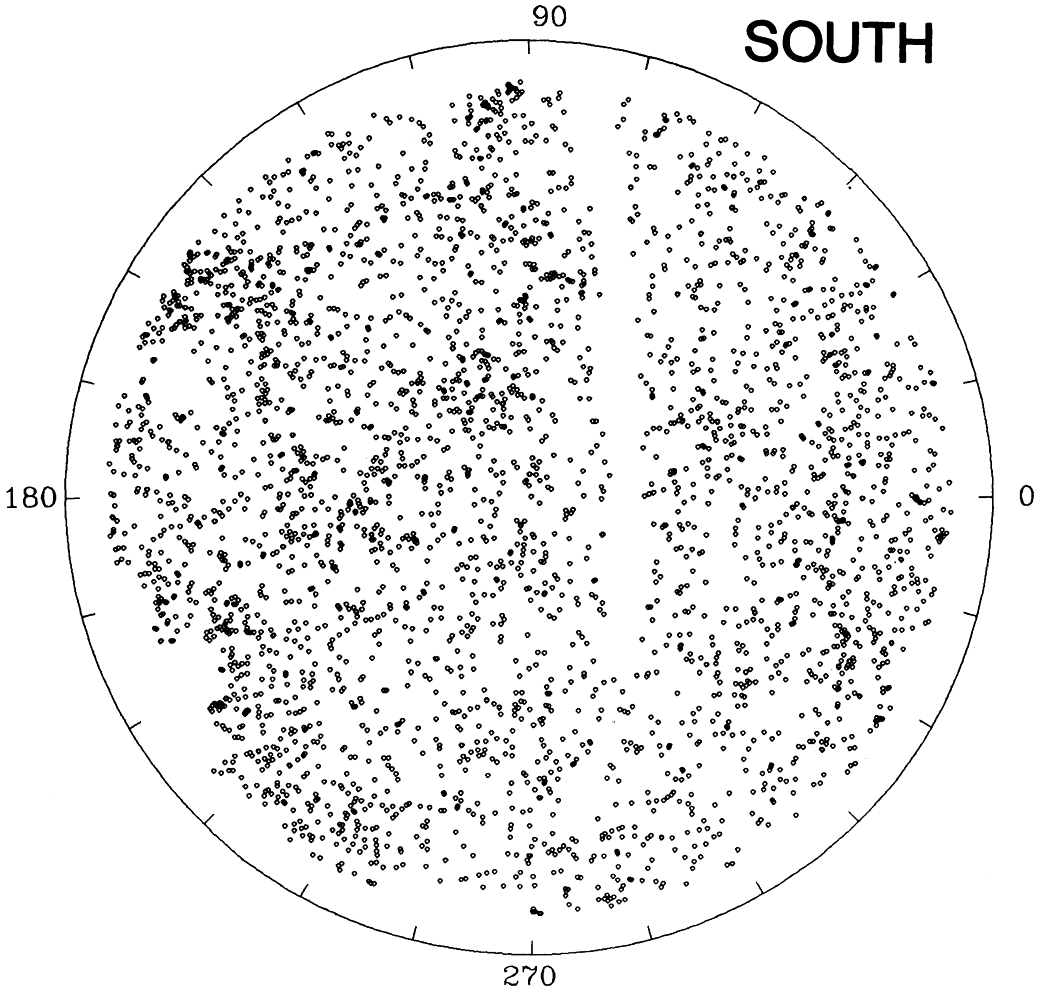

Figure 1b: The same as figure 1a, for the south galactic hemisphere. 3254 galaxies are plotted. Perseus is centered at $l = 150°$, $b = -13°$.

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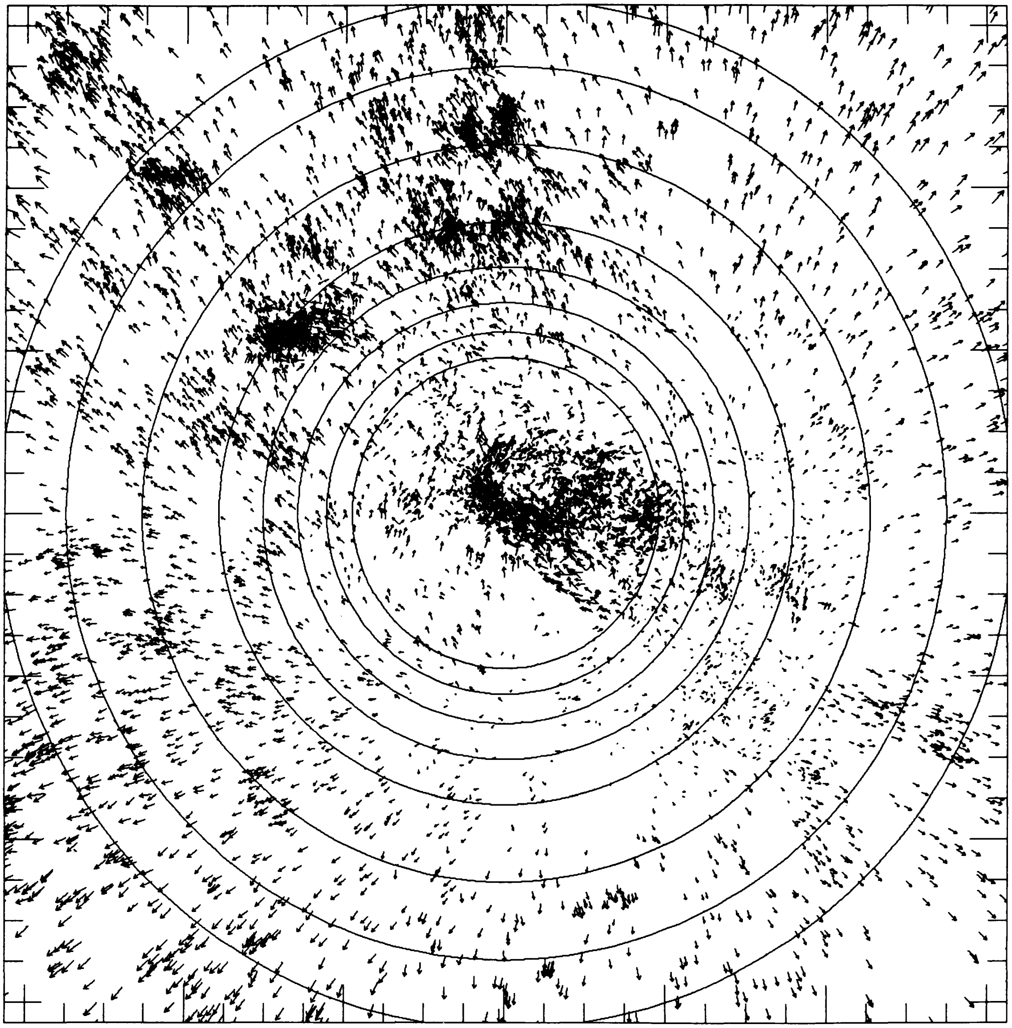

Figure 2: The flowfield around a cluster in a cosmological n–body simulation with cold dark matter, random phase, initial conditions. The arrows denote proper velocity. The circles are draw at $\overline{\delta} = 2^{\frac{n-1}{2}}$, n = 1,...,8. Both small scale and large scale deviations from a spherically symmetric radial flowfield are apparent. The degree of subclustering and asphericity is typical of these models.

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Primack, 1983). All models were for $\Omega = 1$ and assumed random phase initial conditions, although some had enhanced power in the fundamental wave. The qualitative nature of the departures from spherical symmetry are independent of initial conditions in the models, although the exterior tidal fields are larger for the models with more power on large scales, as expected.

Clusters were selected from the models if their surface of $\bar{\delta} \simeq 2$ occurred at a distance from cluster center $r \sim 2$–$3\, r_o$, where r_o is the correlation length $\xi(r_o) = 1$. This approximates the situation for Virgo, presuming galaxies trace mass. We also attempted to select clusters reasonably isolated from their neighbors. An example of a flowfield around a cluster is shown in figure 2. There are a number of features in common among all these clusters which I mention here. Details are provided in Villumsen and Davis (1985).

1. The clusters are never spherical or isolated; they are usually triaxial. They are always subclustered and perturbed by adjacent clusters.

2. The velocity field, when averaged over spherical surfaces, fits the non–linear flow model quite well for $\bar{\delta} < 3$ but the mean infall is systematically low for increasing $\bar{\delta}$ and is 25% below the spherical model prediction at the $\bar{\delta} = 6$ surface.

3. Substantial (50%) quadrupole and higher order distortions to the velocity field are frequently present in the clusters which can seriously affect infall and mass estimates based on spherical models. The asphericity of the flow field can bias the estimation of mass by a factor of 2-3.

4. These distortions in the velocity field correlate very poorly with the inertia tensor of the interior mass distribution, indicating they are largely influenced by the exterior mass distribution.

5. In spite of the serious local deviations from the spherical models, even on the $\bar{\delta} < 3$ surfaces, the local peculiar velocity field is extremely well aligned with the local force field. On the $\bar{\delta} = 2$ surface, the mean cosine of the angle between the local force and velocity is 0.9, an average deviation of 25°. The constant of proportionality is close to that expected by equation (2). This result applies only for those points not imbedded in dense subclumps.

Several important lessons for application to the Virgocentric flow problem can be drawn from this study:

1. The aspherical flow fields observed in the models can seriously bias the measured mean infall even on the $\bar{\delta} = 2$ surface unless data is drawn from the full 4π steradians of the sphere surrounding Virgo. In practice this is rather difficult to arrange. Not only are the galaxies preferentially distributed on the supercluster plane, but the galaxies near us on the front side of the cluster have more weight than those on the backside of the cluster. Whether the bias increases or decreases the mean infall velocity depends on the exterior mass distribution; perhaps it can be calculated from the IRAS catalog.

2. What is actually measured in the Hubble anisotropy studies is the gradient of the peculiar flow field; solid body rotation would of course be undetectable. A good deal of weight to the measured infall comes from galaxies within our Virgocentric radius (but outside the triple value zone). However the n–body models show that the mean infall drops below the spherical prediction for higher δ, diminishing the spatial gradients in the peculiar velocity field. This is a clear bias that will result in an underestimate of the true infall velocity. It could be dealt with by deleting all galaxies located within the $\bar{\delta} = 3$ surface, but this will likely result in larger statistical errors for the infall.

3. Fortunately the deviations from spherical symmetry seem to obey linear perturbation theory (equation (2)), which provides the best possible measure of Ω. The 25° deviation of the local "gravity" direction seen by IRAS from the microwave anisotropy direction is fully consistent with the behavior of the n–body models.

7. SUMMARY

Observations of binary galaxies suggest they have an extended mass distribution but are consistent with $\Omega = 0.05$ on scales of $\sim 50\ h^{-1}$ kpc. Groups and clusters of galaxies are consistent with $0.1 < \Omega < 0.2$ on scales of less than a few Mpc, whether analysed by the cosmic virial theorem or by use of the virial theorem on individual groups. This is consistent with calibrations against fake catalogs drawn from n–body models. However the data is also consistent with $\Omega = 1$ if galaxies are a biased mass tracer.

The general consensus seems to be that the infall velocity to Virgo is small, again consistent with $\Omega < 0.2$. However this result cannot readily explain the bulk of the microwave dipole anisotropy and it is very unlikely that Hydra–Centaurus is the accelerator. It is more probable in my opinion that the bulk of the microwave anisotropy has been induced by material loosely connected to the local supercluster ($cz < 3000$ km s^{-1}). The comparison to n–body results suggest that the spherical infall models used to measure mass in the Virgo cluster are not terribly accurate and may be biased. However, the models do indicate that an excellent cosmological test is possible by comparing local forces to local velocities. The close agreement in direction of the IRAS and microwave dipole anisotropies is very encouraging and suggests that an accurate Ω estimate at large scales is close at hand. The resulting estimate is likely to be larger than measured on smaller scales.

In brief, estimates of Ω are probably not consistent on different scales, and there is no existing data that contradicts the notion that galaxies are a biased mass tracer and that we live in an $\Omega = 1$ universe.

REFERENCES

Aaronson, M., Huchra, J., Mould, J. *et al.* 1985, *Ap.J.*, submitted.

Bean,A.J., Efstathiou,G., Ellis,R.S., Peterson,B.A., and Shanks,T.,1983, *M.N.R.A.S.*,,2

Blumenthal, G. P. and Primack, J. P. 1983, in *Fourth Workshop on Grand Unification*, ed. H. A. Weldon, P. Langacker, and P. J. Steinhardt, (Boston:Birkhausen), p. 256.

Davis, M. 1985, in *Proceeding of the Inner Space–Outer Space Workshop*, Fermilab, 1984, (ed. by M. Turner and R. Kolb, Univ. of Chicago Press).

Davis, M. and Huchra, J. 1982, *Ap.J.* **254**, 425.

Davis, M. and Peebles, P. J. E. 1983a, *Ann. Rev. of Astron. & Astrophys.* **21**, 109.

Davis, M. and Peebles, P. J. E. 1983b, *Ap.J.* **267**, 465.

Davis,M., Frenk,C.S., Efstathiou, G., and White,S.D.M.,1985,*Ap.J.*, **292**,371.

de Vaucouleurs, G. and Peters, W. L. 1984, *Ap.J.* **287**, 1.

Dressler, A. 1984, *Ap.J.* **281**, 512.

Faber, S. M. and Gallagher, J. S. 1979, *Ann. Rev. Astron. & Astrophys.* **17**, 135.

Fixsen, D. J., Cheng, E. S. and Wilkinson, D. T. 1983, *Phys. Rev. Lett.* **50**, 620.

Geller, M. J., in *Clusters and Groups of Galaxies*, IAU Trieste meeting.

Hart, L. and Davies, R. D. 1982, *Nature* **297**, 191.

Lubin, P. M., Epstein, G. L. and Smoot, G. F. 1983, *Phys. Rev. Lett.* **50**, 616.

Meiksin, A. and Davis, M. 1985, *A.J.*, submitted.

Nolthenius, R. and White, S. 1986, (abstract in this volume).

Peebles, P. J. E. 1980, *The Large Scale Structure of the Universe*, Princeton Press.

Press, W. H. and Davis, M. 1982, *Ap.J.* **259**, 449.

Schweizer, L. 1985, Ph.D. thesis, UC Berkeley.

Tonry, J. and Davis, M. 1981, *Ap.J.* **246**, 680.

Villumsen, J. and Davis, M. 1985, in preparation.

White, S., Huchra, J., Latham, D. and Davis, M. 1983, *M.N.R.A.S.* **203**, 701.

Yahil, A., Walker, D. and Rowan–Robinson, M. 1985, preprint.

Zwicky, F. 1933, *Helv. Phys. Acta* **6**, 110.

DISCUSSION

TULLY: I would like to make two points. First, with respect to the Hydra-Centaurus structure: I have a poster paper which shows the distribution of large-scale structure around us. On that diagram is something called Virgo-Hydra-Centaurus. This is a unit of five Abell-class clusters (since it is in the southern hemisphere, only one of them actually appears in Abell's catalogue). One of these clusters, the Centaurus Cluster, is almost certainly about twice the size of Virgo. So I don't at all discount that it has the overdensity you were talking about. It is a major feature which extends about 50 - 60 Mpc, although unfortunately it is badly cut up by the galactic plane.

Second, with regard to your statement about transverse peculiar velocities: That is something I definitely <u>do</u> see. I describe the Local Supercluster as an environment made of clouds of galaxies, and I have gotten distances, independent of redshift, for many of these clouds. The picture is quite complex, with significant transverse, non-Virgocentric velocities.

OSTRIKER: In the latter part of your talk, when you were discussing recent results, you convinced us that galaxies don't fairly represent the mass distribution. But in your earlier discussion, you described the virial method for getting the mass distribution, which seemed to indicate that galaxies <u>are</u> good tracers of the mass.

DAVIS: Well, the first part of the discussion was based on an argument which depends not on the two-point correlation function but on a very difficult integral of the three-point correlation over the two point correlation which may not have the simple scaling that I put down. In fact, we've never been able to get that behavior in the numerical simulations, try as we might.

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