ESTIMATES OF Ω BASED ON MOTIONS WITHIN THE LOCAL SUPERCLUSTER

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ABSTRACT. Three ways to estimate Ω from the motions of nearby galaxies are reviewed: (i) comparisons can be made between observed local streaming motions and observed density fluctuations, (ii) a timing argument can give a value of $f(\Omega) = t_o H_o$, and (iii) the motions in groups provide solid evidence regarding the amount of matter that is distributed like galaxies on a scale of 0.5 Mpc. In each case, the evidence suggests the Universe is open, but only by a factor of 3-5 and, given the uncertainties, a closed Universe definitely is not precluded.

1. LOCAL DENSITY FLUCTUATIONS AND STREAMING MOTIONS

Silk (1974) made the first serious attempt to measure Ω, the ratio of the density of the Universe ρ to the critical density for closure ρ_c, from the kinematic effects of density fluctuations on the scale of the Local Supercluster. Peebles' (1980) description in the linear regime can be approximated by:

$$u \propto H_o \, r \, \Omega^{0.6} \, \delta \quad . \tag{1}$$

It might be possible to estimate Ω by making measurements of streaming velocities u on a scale r, if it is possible to estimate the local overdensity of matter $\delta = \Delta\rho/\rho$.

Yahil, Sandage, and Tammann (1980), Davis and Huchra (1982), and Lahar (1986) have compared the distribution of nearby galaxies with evidence for infall toward the Virgo Cluster of ~300 km s^{-1} and a motion of a similar amplitude toward the apex defined by the cosmic microwave background dipole anisotropy and concluded $\Omega \sim 0.15$, 0.4, and 0.3, respectively. Higher values were deduced from the observed coincidence in the anisotropy of IRAS sources and the cosmic microwave background (Meiksin and Davis 1986: $\Omega \sim 0.5$; Yahil, Walker, and Rowan-Robinson 1986: $\Omega \sim 1.0$).

These calculations require an extremely important assumption: that blue or far-infrared light accurately traces the distribution of

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matter on supercluster scales. This assumption is always identified, but it is routinely ignored that the assumption must be invalid if $\Omega \sim 1$, at least, in the case of blue light. The mass-to-light ratio for the Universe at large is (Davis and Huchra 1982 but adjusted to include internal and galactic absorption):

$$M/L \sim 1600\ \Omega\ h_{100}\ M_\odot/L_\odot\ . \qquad (2)$$

The value $\Omega \sim 1$ is larger than values associated with galaxies on scales <1 Mpc. Hence, if the Universe is closed then dark matter is more widely spread than galaxies or distributed differently.

Hoffman, Olson, and Salpeter (1980) and Hoffman and Salpeter (1982) have pointed out that there is another constraint in the environment of the Local Supercluster, namely, the central density of the mass concentration in the Virgo Cluster. If the assumption that mass follows light is dropped, then the consequence of an established central density is lower peculiar velocities in a higher Ω universe, since the overdensity is lower.

In summary, the tenet of this approach has been that larger peculiar velocities imply greater Ω. Yet, if peculiar velocities were observed large enough to imply $\Omega \sim 1$, then there would have to be mass concentrations in excess of what is seen in clusters. The assumption that mass follows blue light is so dubious that the present formulation of the method probably only has value as a lower limit on Ω. Far-infrared emission might be a fairer tracer of the mass since it is less concentrated, as it is preferentially associated with spiral galaxies, but the very difference between the blue and infrared results cautions us to mistrust either result.

If these criticisms are not enough, the conventional interpretation is thrown in extreme doubt by recent supercluster collapse simulations that reveal biases in "observed" Ω in models with closure density (Villumsen and Davis 1986; Melott 1986). In the mean, an observer in a region with $\delta \sim 2\text{-}3$ would estimate $\Omega \sim 0.8\text{-}0.9$, with systematically lower values of Ω estimated in regions of higher δ. Worse, the range of "observed" Ω values is very large: $\Omega \sim 0.3$ is a typical measurement of an observer situated on the major axis of a quadrupole feature. There is evidence in the Local Supercluster for the sorts of motions seen in the n-body simulations: rotation or shear (Aaronson et al. 1982), bulk transverse motion (Aaronson et al. 1986), and quadrupole distortion (Lilje, Yahil, and Jones 1986). The evidence, though, is that we are orthogonal to the major axis of the quadrupole distortion of the Local Supercluster.

Recently, Burstein et al. (1986) and Collins, Joseph, and Robertson (1986) have claimed to detect streaming motions on scales larger than the Local Supercluster. What these motions imply with regard to the density of the Universe remains to be seen. It need not be exceptional if it should prove that there is a substantial density enhancement within the Hydra-Centaurus complex (which we are part of) that lies in the zone of obscuration.

2. A TIMING ARGUMENT

Tully and Shaya (1984) did some preliminary work on the idea that will be presented, but Shaya (1986a,b) has developed the concept more fully. The aim is to measure the quantity

$$f(\Omega) = t_o H_o , \tag{3}$$

where

$$f(\Omega) = (1 - \Omega)^{-1} - 1/2\Omega(1 - \Omega)^{-3/2} \cosh(2\Omega^{-1} - 1), \tag{4}$$

so that $f(0) = 1$ and $f(1) = 2/3$.

It will obviously be difficult to constrain Ω in a situation where the difference in the product $t_o H_o$ between empty and closed models is only 33%. However, to our distinct advantage, the product does not require a knowledge of the distance scale. The product is a function of accurately measurable quantities only.

We must deal with the nonlinear collapse regime, which requires numeric integration of the equations that describe a Freidmann universe. This situation is sufficiently difficult to describe that it is worthwhile to start by presenting essentially a dimensionality argument.

A galaxy that is being pulled into a cluster will have a streaming velocity toward the cluster that is dependent on the accelerating force and the age of the Universe. At the present epoch, the infall velocity of a galaxy falling toward a mass $M(<r)$ at a distance r will have the approximate dependencies

$$v_r \propto \frac{M(<r)}{r^2} t_o . \tag{5}$$

Suppose that the only mass interior to r is the cluster mass which can be estimated by an application of the virial theorem. Then equation (5) can be rewritten:

$$v_r \propto \frac{\sigma_v^2 \Theta_v D}{\Theta_r^2 D^2} t_o , \tag{6}$$

where σ_v is the rms velocity dispersion of the cluster, Θ_v is the angular virial radius (related to a harmonic radius), Θ_r is the angular distance of the infalling galaxy from the center of the cluster, and D is the distance of the cluster. If the cluster would have a systemic velocity if it were freely expanding of $V_c = H_o D$, then

$$t_o H_o \propto \frac{V_r \Theta_r^2 V_c}{\sigma_v^2 \Theta_v} . \tag{7}$$

Hence, if galaxies can be identified that are just falling into clusters, it is possible to derive an estimate of Ω that only depends on measurements of velocities and positions on the sky.

Shaya has developed this concept more formally with application to a substantial group of galaxies that Tully and Shaya identified to be falling into the Virgo Cluster today. There is a large group of spiral and irregular galaxies, well contained both spatially and in redshift, that distance estimates place at, or just beyond, the cluster distance but that are substantially blueshifted with respect to the cluster. It is argued that this group is just at the edge of the Virgo Cluster and will soon be merged into it.

Shaya uses the formalism developed by Schechter (1980) to describe the collapse of spherical shells in terms of dimensionless expansion and density parameters that depend only on the familiar arc-parameter, η. He calculates the value of the arc-parameter, η_6, for the shell at 6° radius that we surmised is just entering the Virgo Cluster, where the mass interior to this shell is the virial estimate of the mass of the cluster. The arc-parameter at infinity, η_∞, is given by Schechter's expansion formula and an estimate of the free-expansion velocity of the Virgo Cluster, V_c (the observed redshift of the cluster adjusted for the infall and peculiar velocities of the Galaxy). Then Ω is found from Schechter's density formula:

$$\Omega = \frac{2}{1 + \cos \eta_\infty} . \qquad (8)$$

In his initial development of the idea, Shaya (1986a) concluded $\Omega \sim 0.1$, but this result is quite uncertain. In particular, there is a gap between most of the galaxies that are claimed to be falling into Virgo (they are at a typical radius of 10°) and the 6° core that contains the mass estimated by the virial analysis. Then, there are uncertainties in the virial mass estimate, in the deprojected infall velocities, and the free-expansion Virgo redshift.

In the subsequent work, Shaya (1986b) is placing further constraints, such as knowledge regarding the position of the turn-around radius, and allowing himself the assumption that the mass falloff in the region of the supercluster outside the central cluster but within our radius is the same as the distribution of light. He has developed an overconstrained set of equations that should only be satisfied by a restricted range of Ω.

This work is still in progress. Ultimately, more sophisticated models that do not necessarily assume spherical symmetry can be used. In spite of the complexity of the problem, and the need for great accuracy, there is some hope because, with time, the method can be applied to a large number of clusters and circumstances.

3. NEARBY GROUPS

This topic deviates from the spirit of the title of the talk because it does not lead to a global Ω estimate. However, it is relevant to

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application of the "cosmic virial theorem" which could be construed as doing so. Also, on the scale of groups, ~1 Mpc, we now have very good estimates of the density and these estimates are remarkably high. Large M/L values for groups have been claimed before, but the new data is especially convincing.

The present analysis is based on a soon-to-be-published group survey (Tully 1987). It has the following features: (i) there is uniform, all-sky coverage, (ii) low-luminosity galaxies are well represented, (iii) velocity measurement errors are insignificant, (iv) galaxies are linked into groups by an algorithm that mimics gravity and includes the tidal effects of adjacent groups, (v) galaxies were accepted as group members if they satisfied a specific local density (not overdensity) requirement.

Within a distance of reasonable completion of 25 h_{75}^{-1} Mpc (corresponding to velocities <1900 km s^{-1} but with a Virgocentric retardation model incorporated) 178 groups of two or more galaxies were defined, and there are 50 groups with five or more members. There is no evidence of an interloper problem in that faint candidate members do not tend to have larger redshifts than bright candidate members. The median virial radius for the 50 largest groups is $\langle r_V \rangle = 340\ h_{75}^{-1}$ kpc and $r_V < 500\ h_{75}^{-1}$ kpc for 80% of these groups. There is evidence that the groups are bound in that (i) crossing times are substantially less than the age of the Universe (the median for the 50 large groups is $t_x H_o = 0.2$), and (ii) collapse times, defined as $t_c = 8.5 \times 10^6 (r_V^3/M_V)^{1/2}$ years (r_V is the virial radius in Mpc and M_V is the virial mass in $M_\odot$), are typically less than a Hubble time (the median for the 50 large groups is $t_c H_o = 0.6$ and 94% satisfy $t_c < 2\ H_o^{-1}$). This evidence strongly suggests the groups are bound, though not necessarily well virialized.

Figure 1 presents data that some might find contentious. It is a histogram of unweighted group velocity dispersions, corrected for measurement errors in velocities. The corrections are usually small but 29 pairs to quadruples have velocity dispersions less than the uncertainties in the measurements. The median one-dimensional dispersion for the 50 largest groups is 100 km s^{-1}. Eighty-eight percent of the groups have velocity dispersions below 130 km s^{-1}, although there is a long tail that extends out to 715 km s^{-1} (the Virgo Cluster).

Rivolo and Yahil (1981) found the similarly small characteristic velocity dispersion of 100 km s^{-1} for pairs of galaxies, but Huchra and Geller (1982) derived a median value of 180 km s^{-1} for groups with more than 5 members identified in the Shapley-Ames sample and Davis and Peebles (1983) found a characteristic one-dimensional velocity dispersion of 300 km s^{-1} at a radius of 300 h_{75}^{-1} kpc between correlated pairs in their application of the cosmic virial theorem. The studies that get larger velocity dispersions (i) tend to include a larger percentage of rich groups than my very local sample, and (ii) may suffer a greater interloper problem because insufficient account might be taken of the filamentary nature of large-scale structure and the consequence that the background density is high in the vicinity of groups.

Given the distribution of velocity dispersions in Figure 1 (most below 130 km s^{-1} and a long tail to high velocities), the cosmic virial

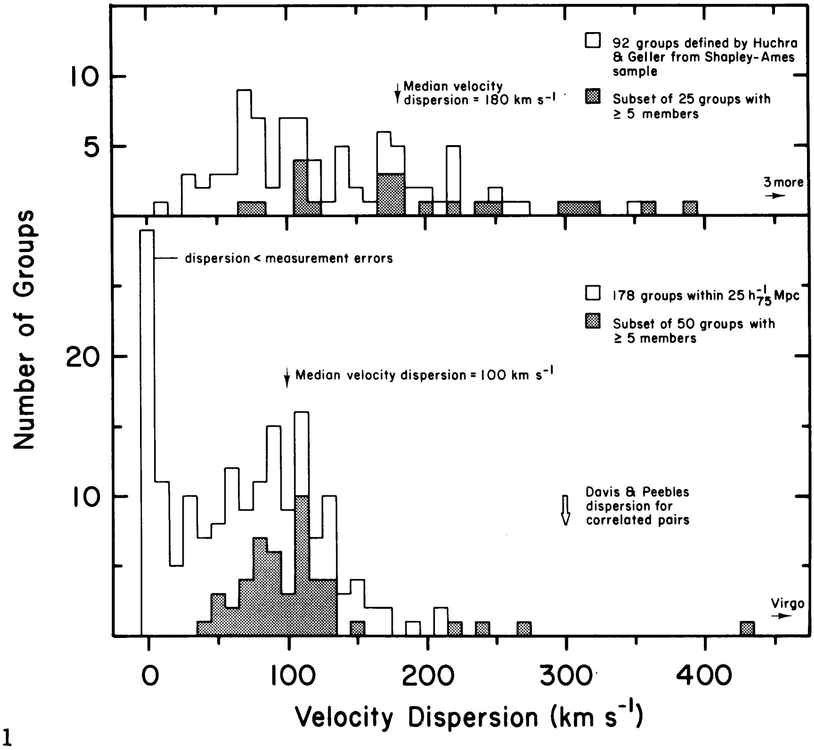

Figure 1

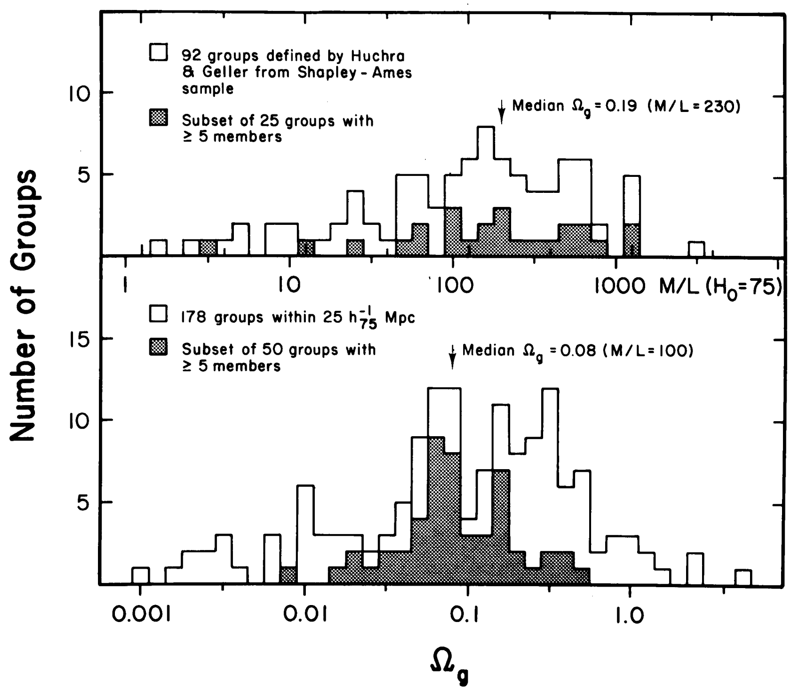

Figure 2

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dispersion of 300 km s^{-1} is not easily interpreted. It is not representative of the "field" outside of the principal clusters. Davis and Peebles estimated $\Omega \sim 0.2$ from the cosmic virial theorem, but Rivolo and Yahil concluded that this estimate should be reduced.

If velocity dispersions are modest, M/L values are nonetheless substantial. Figure 2 is a histogram of mass-to-light values for the individual groups, ratioed to the value required for a closed universe (to eliminate the dependency on the distance scale). The median value for the 50 largest groups corresponds to $\Omega = 0.08$ ($M/L_B{}^{b,i} = 100\ h_{75}\ M_{\odot}/L_{\odot}$). My typical groups have large mass-to-light ratios in spite of low velocity dispersions because they also have low integrated luminosities.

4. FINAL COMMENTS

Comparison of velocity streaming motions with fluctuations in the distribution of light leads to estimates of $\Omega \sim 0.4$. However, standard methodology requires the assumption that mass is distributed like light, which is obviously dangerous. A result of the group analysis is that <1% of galaxies lie outside of the filamentary clouds that dominate large-scale structure, a circumstance that strongly implies biased galaxy formation. The present velocity streaming studies do not preclude $\Omega = 1$ and, hence, do not yet strongly constrain the density parameter.

In principle, the timing argument could give us a value of Ω relatively free of assumptions (of course, the entire discussion is pointless if $\Lambda = 0$ is not assumed). It is premature to make much of present results, but the method should not be written off because it eventually could be applied to a large number of situations.

The group analysis provides the firmest results, though the implications are restricted. There is strong evidence that $\Omega_g \sim 0.1$ on a scale of 0.5 Mpc about galaxies. It is to be noted that the 178 groups of pairs and larger include 69% of the galaxies within 25 $h_{75}{}^{-1}$ Mpc and 77% of the light (single galaxies tend to be low-luminosity systems). Hence, I argue that the value $\Omega_g \sim 0.1$ ($M/L_B{}^{b,i} \sim 100\ h_{75}\ M_{\odot}/L_{\odot}$) characterizes the distribution of mass on a scale of ~0.5 Mpc around the average galaxy and, hence, represents a rather firm lower limit to the universal value of Ω.

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DISCUSSION

GELLER: (1) Could you clarify your procedure for selecting groups? (2) How do you choose the cutoff in your selection parameter?

TULLY: I use a dendogram method. Galaxies are merged into units on the basis of the "force" measure and groups are defined as those units that exceed a certain threshold in density. The threshold was chosen after considerable experimentation and taking into account the core-halo nature of observed groups. If the cutoff is increased or decreased a factor of 2 or 3, either the crossing times of outlying objects become long compared with a Hubble time or qualitatively evident groups are frequently broken up.

FALL: When discussing estimates of Ω from the Virgocentric infall, you emphasized the uncertainty caused by the possible segregation of mass and light. It seems to me that the same considerations apply to your virial analysis of small groups, which is based on the assumption that mass and light are distributed in the same way. One might even suspect that the segregation of mass and light is greater on small scales although the sign of the effect is far from clear.

TULLY: While it is possible that dark matter might be more centrally concentrated than the galaxies and, hence, virial masses might be over-estimated, it would seem considerably more likely that, if dark matter deviates from the light, it would be less centrally concentrated and then my mass estimates represent lower limits.

KIANG: I suppose your results do not exclude the possibility of a much larger mean density of the universe. If dark matter is distributed more uniformly than luminous matter, then both the results from Virgo cluster infall analyses and your application of the cosmic virial theorem will be consistent with a much larger value of Ω.

TULLY: Definitely, yes.

PECKER: Does the hierarchical structure of the universe, as postulated years ago by de Vaucouleurs (after others!) affect your results? In a sense, the ρ_o value has (if such a "fractal" structure applies to the whole universe) no real meaning; and when the extrapolation of the observed data is done, one can go as well to $\rho_o \sim 2 \times 10^{-31}$ g cm^{-3} or much lower values of ρ_o at the large scale, the latter giving rise to a definitely open universe, - if I am not mistaken! How do you react to this difficulty? Does not your methodology imply a well-defined ρ_o?

TULLY: Yes, it assumes both a well-defined closure density and that a reasonable estimate has been made of the mean luminosity density. Given the apparent existence of extremely large scale structures, even the simpler second assumption involves considerable uncertainty.

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