DISCUSSION OF METHODS ON DETERMINING THE MEAN MATTER DENSITY OF THE UNIVERSE

Tammann: The question of the mean mass density in the Universe has been mentioned many times and the organisers thought it would be useful to look at future prospects for obtaining improved estimates of Ω. The methods may be split into two types. First, the conventional methods involve determining the luminosity density in the Universe and multiplying by an appropriate mass-to-luminosity ratio. It must be emphasised that the mass determinations are dynamical and that most of the mass is not visible. There is good agreement among independent workers about the luminosity density and this figure seems to be known within a factor of 2. The appropriate mean value of M/L is more controversial, values between 10 and 200 having been discussed in the preceding lectures. It is agreed, however, that if the mean value of M/L lies in this range, one cannot close the Universe. Perhaps one should be more cautious and say that even granted the uncertainties in the quantities involved, it is unlikely that the Universe is closed.

Second, there are the new methods which have been mentioned in previous discussions. These may be called large scale dynamical methods and we want to concentrate upon these in the discussion in the hope of encouraging future observations to make them work in practice. Three such methods will be described by Drs Silk, Peebles and Falls.

Silk: Some day we shall see Ω (or at least a solid lower limit thereon) written on the sky! By studying the velocity distribution of galaxies in the environs of a supercluster, where the Hubble flow is distorted by up to 100 percent, we should be able to infer Ω. The models should be simplest in regions where virialization cannot yet have occurred. The relative mass excess must be larger within a given region in order to account for a given Hubble flow distortion if Ω is small: this is because in this case the Hubble flow is kinetic energy-dominated, and a larger potential fluctuation is required. In the simplest model of spherically symmetric infall, the idealized "zero velocity" shell of matter contains an average density contrast, or mass "excess" relative to the local background, $1 + \delta\ell/\ell = \pi^2(H_o t_o)^{-2}(8\Omega)^{-1}$, where $1 \geqslant H_o t_o \geqslant 2/3$ and $\Omega \leqslant 1$.

Some notes of cautions are in order before observers rush to obtain redshifts. The density gradients around superclusters are extremely insensitive to Ω; the perturbed Hubble flow combined with the average density contrast within a shell surrounding a supercluster are required. Luminosity-weighted galaxy counts actually yield a measure of the luminosity rather than the density contrast, and a systematic gradient in M/L (for example an inverse correlation with distance from the supercluster center) could frustrate attempts to determine Ω: actually only a lower limit on Ω would be obtained. Finally, the observer should use isolated clusters for this test. Gross distortions of the Hubble flow can be induced by tidal interactions between neighbouring clusters. This is particularly likely to have occurred at a redshift of 1 or 2, and could result in anisotropic structure of the galaxy distribution on very large scales.

M. S. Longair and J. Einasto (eds.), The Large Scale Structure of the Universe, 281-286.

Tully: The most uncertain assumption to applying this method must be that there is a close correlation between the observed and actual distributing of matter.

Peebles: We have heard of the problems of defining groups of galaxies and how different workers can obtain different results from analyses of basically the same data. We should therefore use all the possible methods of analysing the problem until, hopefully, we get a consistent answer. My favourite method at present is to use the relative velocities of all pairs of galaxies in a properly selected sample and to relate this to the mass distribution. This method has the great advantage that only the relative velocity of one galaxy with respect to another is required. The mean square relative velocity of galaxies is related dynamically to statistics we can hope to measure - in fact, the three point correlation function for galaxies which we think we know. I come up with the plea that we know the right-hand side of the equation from integrals over the three-point correlation function. What we don't know is the left-hand side, the mean square relative velocities for good random samples of galaxies. The determination of velocities for complete random samples of galaxies down to 15th magnitude would give us a credible value for $\langle \Delta v_r^2 \rangle$. We would dearly like to have it.

Fall: I have been asked to make some remarks on dynamical methods for estimating the local mean density of matter. (In this context "local" refers to scales larger than individual galaxies but smaller than the horizon.) Let me first emphasize that all of these methods apply only to matter clustered in the same way as galaxies and that they tell us nothing about any uniformly distributed hot components of the Universe. Traditional methods of this sort are based on the usual virial theorem for individual groups and clusters. Recently, Geller and Peebles and Peebles have developed statistical versions of this method which average over groups and clusters. Like the ordinary virial theorem methods they are restricted to scales small enough that clustering can be considered stationary. As Peebles has already remarked, these "statistical" or "cosmic" virial theorems have the advantage that the required velocities are easily measured.

The other class of dynamical methods for estimating the mean matter density includes both the motions of galaxies in the relaxed parts of clusters and also the decelerated motions of galaxies in the outer parts of clusters; they rely upon deviations from perfect Hubble flow on a variety of scales. They are based on the idea that we can measure relative deviations from Hubble flow $\delta H/H$ and relative deviations from a uniform distribution of galaxies $\delta\rho/\rho$ on different scales. Relating $\delta H/H$ and $\delta\rho/\rho$ by some model for clustering then gives us the mass of clusters and hence the (dimensionless) mean density Ω.

The methods involving deviations from Hubble flow also take both a statistical form and a form applicable to individual clusters. The simplest of the second type is a model introduced by Silk for the non-linear evolution of a uniform density spherical cluster. Peebles' version applies to the linear development of a spherical but non-uniform cluster. On the theoretical side, we need more realistic models for the development of clusters in the regime where $\delta\rho/\rho \gtrsim 1$, i.e. where expansion has been halted and reversed. On the observational side, we need more and better distance and velocity estimates of the type Abell discussed in his talk. Regions within 10 or 20 Mpc of the centres of several large clusters such as Coma and Virgo are especially promising.

Finally, the statistical version of these methods is most naturally expressed in terms of energies. With the deviations from Hubble flow one can associate the kinetic energy $T \equiv \frac{1}{2}\langle v^2\rangle$ where v is a non-Hubble velocity and the average is over all galaxies. Similarly, one can associate with clustering the potential energy $W \equiv \frac{1}{2}\rho\int d^3r(-G/r)\xi(r)$ where ξ is the galaxy pair-correlation function. The relation between T and W then comes from a "cosmic energy equation" which simply expresses the conservation of gravitational energy in an expanding system but does not require the assumption of a stationary state as in all virial theorem methods. The method is not sensitive to the shape of ξ nor is it sensitive to the adopted cosmological and clustering models: $T = -dW$ with $\frac{1}{2} \lesssim d \lesssim 2/3$. Thus, the major uncertainties of the method may be collected into the expression $\Omega \propto \langle v^2\rangle/(\text{amplitude of } \xi)$.

At first sight it might seem that estimating the velocities required for this statistical energy condition would be difficult. As Gott has emphasized in his talk, however, there is good reason to believe that $\langle v^2\rangle$ is simply related to the relative velocities of galaxy pairs in the models of interest. On the theoretical side it will be important to see if this relation holds up on very large scales. The first estimate of ξ came from magnitude-limited samples using no velocity data and their major uncertainty results from uncertainties in the galaxy luminosity function. As I hope Davis will explain in his talk, estimates of ξ can be improved using redshift data from a large sample of galaxies. On the observational side it will be important to extend existing redshift samples to volumes of space which are large enough that they are likely to be representative of the Universe as a whole. A fairly complete sample of galaxies to 15th magnitude would probably be adquate for this purpose.

Binney: If one confines oneself to scales too large to have virialized, one should be able to obtain an estimate of Fall's peculiar velocity from timing arguments applied to the known spatial distribution and an assumption of homogeneity at recombination. The problems which one encounters when carrying through this programme with spherically symmetric infinite models should not arise in more realistic cosmologies.

Peebles: I think knowledge of "initial and final positions" with time is not adequate to determine final velocities - one needs also the curvature between, that is, Ω.

Davis: One should note that there are difficulties in applying both of the two new virial theorems described by Drs Peebles and Fall. In one,

https://doi.org/10.1017/S0074180900144729 Published online by Cambridge University Press

there are problems in determing the kinetic energy terms and, in the other, the potential energy terms in the cosmic energy equation. In Fall's case, it is difficult to derive the single particle velocity dispersion from the relative velocity dispersions. In Peebles' case, the integral over the three-point correlation function is tricky and very sensitive to the observations. It may be possible to overcome these difficulties when we have magnitude-limited samples to 15th magnitude.

Turner: It might be worth mentioning that the value of peculiar v_{rms} could, in principle, be obtained directly from observations without intervening analytic or N-body models relating it to relative velocity dispersions $<\Delta v_r>^{\frac{1}{2}}$. This could be accomplished by comparing the spatial clustering deduced from the distribution of galaxies on the sky to the clustering in "redshift space"; the characteristic distortions of the galaxy distribution caused by non-Hubble flow motions reflect the value of peculiar v_{rms}. Thus, the Fall-type cosmic virial theorems are not intrinsically model dependent. The very great practical difficulty is, of course, that one would need a redshift survey considerably deeper than the largest scale on which coherent non-Hubble motions occur.

Tammann: There has been much discussion about determining redshifts for large samples of galaxies. Let me remind you that available redshifts are very poor. Few are determined with precision much better than 100 km s^{-1} mean error. Some recent compilations have greater errors. Therefore, you should also specify that you want good redshifts.

Komberg: It seems to me that even if we have a sufficient number of redshifts for galaxies in groups and clusters, we shall not be able without inclusion of additional considerations to decide which objects are physically connected with particular complexes. Such additional considerations might include for example (1) the relative abundance of gas, (2) the rate of star formation and resulting from that the colours of galaxies, (3) morphological peculiarities and peculiarities of the distribution of various types according to the radius of the cluster or according to the velocity dispersion, (4) the activity of nuclei and its connexion with the fraction of gas in galactic clusters.

Longair: Can each of the proponents of the new methods estimate the quantity and quality of data required to obtain a good result from the methods, i.e. precision of redshifts, number of galaxies to be measured to what magnitude, and so on?

Peebles: First, if you want to decide whether Ω is closer to 0.03 or 0.3, in the latter case the velocity dispersion of galaxies separated by 1 Mpc should be at least 300 km s^{-1}, perhaps even greater. Thus a precision of 100 km s^{-1} is adequate to test which is the better value of Ω.

Second, Zwicky's catalogue of galaxies to 15th magnitude seems to be a fair sample of the Universe and hence several Zwicky plates would probably be sufficient.

https://doi.org/10.1017/S0074180900144729 Published online by Cambridge University Press

Silk: I have been very impressed by Tully's data which represents a major advance over previous knowledge of the dynamics of galaxies in the vicinity of the local supercluster. Continued efforts in this direction may provide us with a good estimate of Ω as I outlined in my earlier remarks.

Tammann: This raises an interesting question. Are you happy only to get the redshifts for spiral galaxies since elliptical galaxies are weak emitters of 21-cm radio emission?

General reply from audience: No!!

Fall: In addition to measuring redshifts in the "representative" samples for the statistical methods, I would also urge continued work in fields near clusters such as Virgo and Coma.

Peebles: In the method using the dynamics of galaxies in the local supercluster, we need distances as well as redshifts unless you are prepared to build a very detailed model of the velocity field.

Davis: I would like to note that a group at Harvard is planning to measure the redshifts of all galaxies in the northern sky down to about 14.5 magnitude. It is estimated that 4000 galaxies will be measured and it will take a few years.

Jones: Are magnitudes important?

Tammann: Only as far as they effect distances.

de Vaucouleurs: 1. We are mapping the velocity field in the local supercluster within 40 Mpc from 300 spirals with good distances.

2. We are reducing (with H. Corwin and collaborators) the magnitudes in the Zwicky catalogues to a proper magnitude scale; corrected magnitudes will have mean errors ∿ 0.15 - 0.20 mag.

3. Measurements of ∿ 300 redshifts of bright galaxies are in progress.

4. Question to theorists: how important is the spherical approximation in the cosmic virial theorem; can you take into account sheet or string-like structures?

Peebles: In my version of the statistical virial theorem, these complications are automatically taken into account through using the 3 point correlation functions.

van der Laan: We need clarification on the relative value of 21 cm (spiral)redshifts and redshifts of ellipticals. Are they required equally badly, is there a trade-off, are they interchangeably useful?

Huchra: Optical redshifts can be as good as 21-cm redshifts if you use a high enough dispersion, say using 50 or 100 Å mm^{-1} rather than 300 Å

mm^{-1}. Furthermore, if the nucleus of the galaxy has an emission line spectrum, you can determine a very good redshift. There may be asymmetries in the 21 cm line emission.

Ekers: Is it also useful to have rotation curves and hence mass estimates for spiral galaxies since this can be done with synthesis telescopes at 21-cm? It would be very time consuming but it is possible.

Fall: In their present form, the methods we have been discussing make no explicit use of information on the masses of individual galaxies. If this information were readily available, however, it could certainly be incorporated into these methods.

Ginzburg: It is not clear why at a discussion of the value of Ω nobody touched upon the density of the intergalactic environment (primarily gas). It is natural that in a mathematical simulation all the mass between the clusters is considered. However, when the dynamics of clusters is discussed and large superclusters are not considered, the case will be different. According to the estimates that we made, the density of the intergalactic gas may be great enough to increase the value of $\Omega \sim 0.1$ many times. What is the new evidence here and what are the restrictions to the amount of the intergalactic gas?

Silk: In fact, the intensity and spectrum of the X-ray background would be consistent with the breumsstrahlung emission of hot intergalactic gas of density $\Omega \approx 1$ if its temperature were $\approx 3 \times 10^8$ K.

Tinsley: Intergalactic matter is counted in the cosmic virial theorems provided it is distributed like galaxies.

Gott: Statistical virial theorem estimates made by measuring velocity differences between pairs of galaxies separated by 1 Mpc give information on the mass distribution on scales of this order. Group catalogue techniques give similar information. The tests discussed by Silk on uniformity of the Hubble flow in the Local Supercluster measure mass distributions on scales of 20 Mpc. With the large space telescope, accurate distances will become available throughout the supercluster and the uniformity test can be carried out with confidence. It will be quite interesting to see if this test gives a value of Ω in agreement with that deduced from the group catalogue and statistical virial theorem methods.

Tinsley: In response to Dr Ekers' question, one should note that the masses of galaxies are of the greatest interest for many other reasons, for example for understanding their stellar populations and their values of M/L.

https://doi.org/10.1017/S0074180900144729 Published online by Cambridge University Press