GROUPS OF GALAXIES

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I would like to report on some work that Ed Turner and I have done on groups of galaxies and how groups may be used to obtain useful cosmological information. Of course the classic study of groups of galaxies was done by de Vaucouleurs (1975) who made a catalogue of groups and loose associations of galaxies in the local supercluster. Partly to obtain a larger sample of groups with uniform and well defined statistical properties and partly to obtain a sample of denser groups suitable for virial analysis, Ed Turner and I decided to make a new catalogue of groups of galaxies based on picking the groups as surface density enhancements in the Zwicky catalogue (Turner and Gott 1976) (TGI).

The sample contains 1088 galaxies from the Zwicky et al. 1961-1968 Catalogue of galaxies with $b^{II} > 40°$, $\delta > 0°$, $m_{pg} < 14.0$. 103 groups are detected as surface density enhancements of a factor of 4.64 over the mean, leaving 350 galaxies not associated with groups. This procedure leads to identification of many real physical associations since inspection of the available redshift data indicates that 64% of the groups have velocity dispersions of less than 300 km s^{-1}, although the individual galaxies in the sample have velocities ranging from near zero to over 6000 km s^{-1}, Gott and Turner (1976) (GTIII). Turner and Gott 1976 (TGII) used this sample to determine the luminosity function of galaxies in small groups. They found it to be well approximated by:

$$\phi(L)dL \propto L^{-1}\exp(-L/L^*)dL \qquad \text{where} \qquad (1)$$

$$L^* = 3.4 \times 10^{10} \; L_\odot .$$

Combining this luminosity function with counts of galaxies from the Zwicky catalogue and correcting for the presence of the local supercluster Gott and Turner (1976) (GT) found the mean luminosity density in the universe to be

$$\rho_L = 4.7 \times 10^7 \; L_\odot \; Mpc^{-3} \qquad (2)$$

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requiring: $(M/L)_{crit} = 1500$ (for $\Omega = 1$) (3)

(i.e., the critical density required to close the universe). The groups showed a median crossing time $H_o \Delta t_{median} \sim 0.1$ indicating that one was typically observing groups that had just become virialized, (GTIII). Virtually no groups with $H_o \Delta t \sim 1$ were found, so these groups appear suitable for virial analysis. Taking the median value of M/L for all groups they find (GTIII)

$$(M/L)_{median} = 141 \quad (4)$$

and with eq. (3) giving $\Omega = 0.09$. It is hard to see how this number can be too high. No background or foreground galaxies have been removed from the groups although certainly a fraction (1/4.64) of the group members are expected to be background or foreground contamination. Also velocity errors can only boost the M/L value. As we shall show later, N-body simulations suggest that the median mass-to-light ratio is rather insensitive to a number of effects and this simple unbiased indicator may provide as accurate an M/L estimate as any available. We judge this M/L value to be accurate to a factor of two.

Analyzing groups one by one it is usually rather straightforward to eliminate background or foreground members. They usually give themselves away by quite different redshifts magnitudes and galaxy types. Groups cleared in this way have M/L values comparable to groups that had no significant contamination originally, and all really extreme M/L values are eliminated. With the background and foreground contamination removed one finds mean M/L values of

$$\langle(M/L)\rangle \sim 65 \quad \text{for L group} < 10L^* \quad (5)$$

$$\langle(M/L)\rangle \sim 200 \quad \text{for L group} > 10L^* \quad (6)$$

weighting by the fraction of light in small and large groups one finds:

$$\langle(M/L)\rangle \sim 90 \quad (7)$$

$$\Omega \sim 0.06 \quad (8)$$

with an accuracy of a factor of 2 for the first and four for the second. (GTIII)

How do these M/L values from groups compare with other determinations? Ostriker, et.al. (1974), Gunn (1974) found $(M/L) \sim 100$ for the Local Group from timing arguments; Turner (1975) found $(M/L) \sim 65$ from a study of binary galaxies. Geller and Peebles (1973) derived $(M/L) \sim 140$ from a statistical virial theorem method to estimate M/L values for groups without making membership assignments. Oemler (1974) found $(M/L) \sim 200$ from great clusters. Sargent and Turner (1976) developed a general statistical method based on plotting

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galaxies in redshift space (each galaxy plotted at its redshift distance $d = H_o^{-1}V$). A virialized group will appear like a sausage pointing at the earth, while a group that has just halted its expansion will appear as a pancake. Calculating the mean angle between the line-of-sight to the earth and the line connecting a pair of galaxies as a function of the angular separation of the pair in the sky allows one to make a statistical M/L estimate for groups which have just halted their cosmological expansion. These are larger and looser associations than found by the group catalogue method. Sargent and Turner find $\Omega = 0.07$. From the observed smoothness of the Hubble flow within the local supercluster ($r < 20$ Mpc) Peebles (1976) deduces a best fit value $\Omega = 0.1$ (but is unable to rule out $\Omega = 1$ at the 2σ level). Gunn and Gott (1976) use the distribution of galaxies in the local supercluster to predict the velocity of our galaxy with respect to the blackbody radiation: $V_{gal} \sim 250$ kms^{-1} for $\Omega = 0.1$ and $V_{gal} \sim 1050$ kms^{-1} for $\Omega = 1$. Since current studies of the blackbody radiation suggest $V_{gal} < 300$ km s^{-1} in agreement with similar estimates from the smoothness of the Hubble flow in the local supercluster, this indicates $\Omega = 0.1$.

Kirshner (1976) has recently obtained complete redshift data for five groups in TGI, which previously had little redshift data. He also obtained significant redshift coverage for one further group. In addition to completeness, Kirshner's data has the advantage of uniformity and small measuring error (typically ~ 40 km s^{-1}). He finds it straightforward to separate out background and foreground galaxies. In the groups with complete redshift data only 9 of 35 galaxies are found to be probable contaminants or 26%, in line with the predicted number (1/4.64) = 22%. Kirshner finds a mean M/L $\sim 230 \pm 80$ for the six groups, two of which have $L > 10L*$ and four have $L < 10L*$. The M/L ratios found by Kirshner are higher than average relative to the previously available sample (GTIII) however within the envelope of observed values. It will be interesting to see whether or not the trend to somewhat higher M/L values continues as improved redshift data becomes available. Kirshner's data are definitely inconsistent with low M/L ~ 10 values (as claimed by Materne and Tammann (1974) for some groups), because Kirshner's velocity errors are much smaller than the observed velocity dispersions for these groups. Fall (1975) has developed a statistical technique for measuring Ω based on the covarience function. The covarience function $\xi(r)$ is the excess probability of finding a galaxy within a volume dV at a distance r from a randomly chosen galaxy

$$dP = \bar{n}\,(1 + \xi(r))\,dV \tag{9}$$

where $\bar{n}$ is the average number density of galaxies. Peebles (1974) shows $\xi(r)$ may be approximated by

$$\xi(r) \sim 68\, r_{Mpc}^{-1.77} \tag{10}$$

Fall (1975) has pointed out that the covarience function tells us the

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excess potential energy per unit mass W - associated with galaxy clustering. Numerical experiments suggest $T \sim 2/3\ W$ is approximately true for a variety of cosmological models. Taking the random velocity of galaxies relative to the black body radiation of $V_{rand} \sim 300$ km s^{-1}, Fall finds

$$\Omega = 0.05 \tag{11}$$

All these dynamical methods measure not only the mass in visible galaxies but also any invisible component of the universe (i.e., black holes, etc.) that is clustered like the galaxies. There are various theoretical difficulties with having a dominent component of mass not participating in galaxy clustering, Gott, Gunn, Schramm, and Tinsley (1974) so that the above values should give a good estimate as to the total mass density in the universe.

The derived values of Ω are in excellent agreement with a number of other independent lines of evidence (Gott, Gunn, Schramm, Tinsley 1974). As shown in that paper it is possible for a simple Friedman cosmology with $0.04 < \Omega < 0.08$ to explain the abundance of deuterium and helium, the age of the elements and the oldest globular cluster stars, the mass-to-light ratios in groups and clusters of galaxies, and give a prediction of the Hubble constant of $49 < H_o < 65$ km s^{-1} Mpc in agreement with the best recent determinations ($H_o = 55 \pm 5$ by Sandage and Tammann and $H_0 = 60 \pm 15$ by Kirshner and Kwan.) All these values of M/L and Ω are in reasonable agreement with each other.

One way to gain further insight into the galaxy clustering problem and the dynamics of groups of galaxies is to do N-body simulations of galaxy clustering in an expanding cosmology. Recently Sverre Aarseth, Ed Turner and I have begun a series of such simulations.

Consider as initial conditions a poisson distribution of galaxies with a luminosity function as given by eq. (1). The r.m.s. density fluctuations in a volume of space containing a total luminosity of NL* are the same as those from a poisson distribution of N equal point masses. Thus, with ρ_L as given in eq. (2) with N = 1000 we can simulate a spherical region with present radius of $r \sim 50$ Mpc. The initial density fluctuation spectrum is given by $(\delta\rho / \rho) \propto N^{-1/2}$ i.e., statistical fluctuations. These small density fluctuations grow by gravitational instability until they reach the non-linear regime. A region with enough excess density at the beginning will eventually halt its cosmological expansion and begin to collapse under its own gravitational attraction, eventually becoming a virialized group of galaxies: For an $\Omega = 1$ model an expansion by a factor of ~ 10 is

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sufficient to produce the observed amount of clustering. The initial conditions correspond to the point where the proto-galaxies have condensed sufficiently relative to the cosmological background to be considered point masses. This is approximately when $\delta\rho/\rho \sim 1$ on galactic mass scales and for the $\Omega = 1$ model occurs at a redshift of $(1 + z) \sim 10$. For an open model $\Omega = 0.1$ an expansion of the order of 30 is required. Bound groups with n members in the simulations correspond to bound groups in the universe of total luminosity nL*. With a luminosity function as given in eq. (1) the average luminosity of a galaxy seen in a magnitude limited survey is (3/2)L*, so the number of members in a group in the simulation is of the same order as the number of members seen in a corresponding group in the universe with a magnitude limited survey. We can observe the galaxies in the N-body simulation from a point on the edge of the spherical region. All galaxies within a cone of 45° are considered. This leaves some $\sim$750 galaxies in the sample. We then make a simulated catalogue of groups of galaxies exactly as done in TGI. We may now study the observed dynamical properties of these groups. We present here results for two cosmological models. An $\Omega = 1$ model with $(\delta\rho / \rho) \propto m^{-1/2}$ initial conditions which has expanded by a factor of 13, from the initial conditions; second, an $\Omega = 0.1$ model with $(\delta\rho / \rho) \propto m^{-1/3}$ initial conditions which has expanded by a factor of 32 from the initial conditions. The latter density fluctuation spectrum is expected from a standard hot big bang model (Gott and Rees 1975) and is achieved by building in some slight correlations among the point masses in the initial conditions.

The observations show (TGI, GTIII) 103 groups out of a sample of 1088 galaxies, while the two simulations detect 61 groups each for samples of $\sim$750 galaxies. Only 39 of the observed groups have sufficient redshift data to allow virial mass determinations; the observed values are shown in the first histogram of fig. 1, the median value is indicated by an arrow: $(M/L)_{median} \approx 0.09\ (M/L)_{crit}$. There is quite a range in observed M/L values. Several effects may be at work to produce this. Some groups have overestimated M/L values due to the fact that they have background and foreground contamination. Second, some groups, particularly binaries, may have systematically low M/L values because of selection effects due to their being picked as close pairs (Turner 1975). Finally in any small group there are large random statistical effects which give random errors in M/L (GTIII).

The two histograms at the bottom of Figure 1 indicate M/L values for the two models assuming complete redshift data while the upper two histograms simulate incomplete redshift data as occurs for the observed groups. In general the models show that the incomplete redshift data picks a more or less random selection of the complete M/L histograms. Both the cosmological models produce a wide range of M/L values comparable to those obtained from the observations. The $\Omega = 1$ model has a true value of $M/L = (M/L)_{crit}$ while the $\Omega = 0.1$ model has a true value $M/L = 0.1\ (M/L)_{crit}$. The median values of M/L are within a

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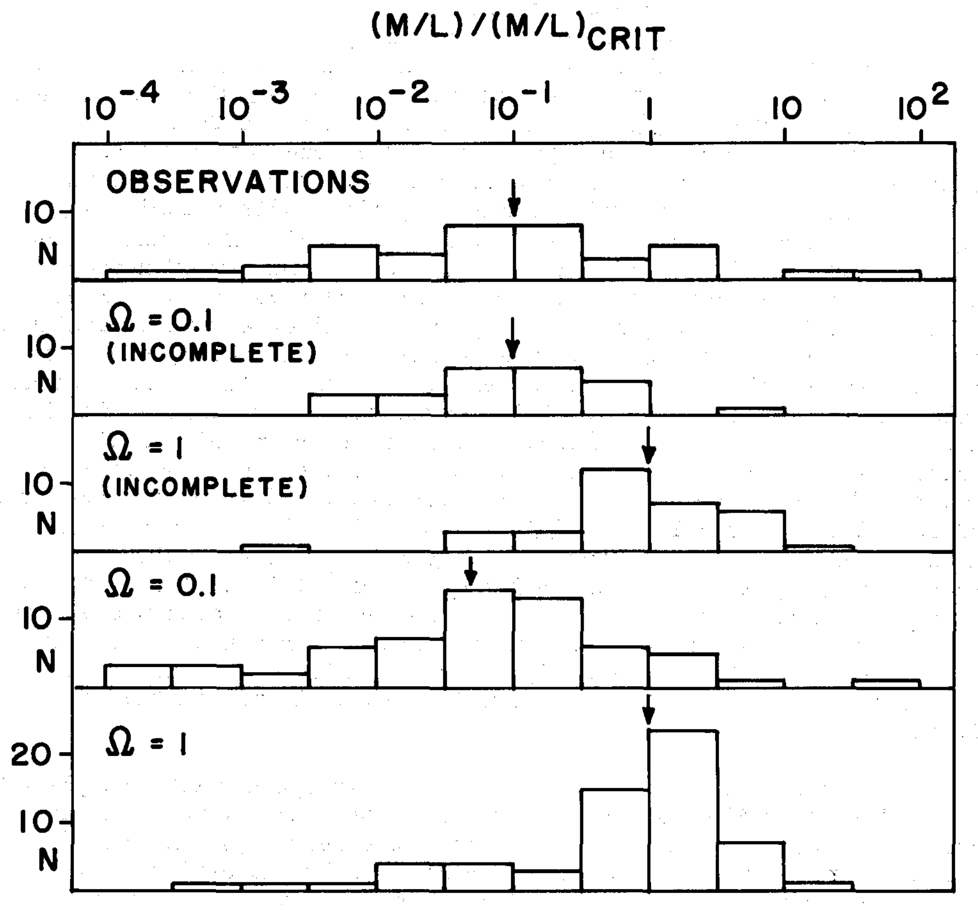

Figure 1. See Text For Description.

factor of 2 of the true values in all four simulated histograms. The median is thus a very stable indicator. The observations thus indicate $\Omega = 0.1$. Also, the shape of the $\Omega = 0.1$ model histogram is in qualitative agreement with the observations, while the shape of $\Omega = 1$ model is distinctly different. These studies illustrate the value of N-body simulations and support M/L determinations from complete samples of groups of galaxies (GTIII).

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