OPTICAL STUDIES OF SMALL GROUPS OF GALAXIES

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INTRODUCTION

Galaxies occur in a wide variety of systems ranging from binary pairs through small groups to rich clusters. These systems in turn possess a wide range of densities, with typical separations between bright ($L \gtrsim L^* = 3.4 \times 10^{10}\ L_\odot$) galaxies varying from $\lesssim$ 10 kpc up to $\sim$ 1 Mpc. Among the most common of these systems are small, loose groups containing $\lesssim$ 10 bright galaxies with separations $\gtrsim$ 100 kpc. Such systems probably contain a substantial fraction of all galaxies (de Vaucouleurs 1975; van den Bergh 1962; Karachentseva 1973). Familiar examples include the Local Group and M81 group.

In this paper, the main results of a statistical study of small groups (Turner and Gott 1976a, 1976b; Gott and Turner 1977a, 1977b; hereafter TGI, TGII, GTIII, and GTIV, respectively) are reviewed and compared to N-body simulations of galaxy clustering.

CATALOG OF GROUPS

The problems in compiling a catalog of small groups arise both from the uncertainty in any particular group's membership and from the difficulty in consistently identifying each group's existence. De Vaucouleurs (1975) has suggested that such groups might be suitably defined as enhancements in the volume number density of galaxies and might be identified as enhancements in the surface number density of galaxies on the sky. Many group catalogs (de Vaucouleurs 1975; Holmberg 1937; Sandage and Tammann 1975) have been based on a detailed, but somewhat subjective, consideration of a variety of data (e.g., redshift, position, magnitude, appearance) concerning the candidate galaxies.

In TGI, a new catalog of groups is presented; this catalog, in contrast to earlier ones, has been generated by the "blind" application of a precisely defined group identification procedure. This procedure

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only considers the positions of galaxies in the sky. As a result, it sometimes makes absurd "mistakes" (e.g., assigning a dwarf spheroidal member of the Local Group to the same group as a galaxy with cz = 4000 km s^{-1}), but these are usually too obvious to be misleading. In addition, the shortcomings of the groups defined by our naive method are offset, we feel, by their objectivity (no unconscious observer biases), homogeneity, and completeness. These attributes are critical in any statistical study of group properties.

The sample of galaxies to be searched for groups is defined by:

$$\delta \geq 0^{\circ}, \quad b^{II} \geq 40^{\circ}, \quad m_{pg} \geq 14.0, \qquad (1)$$

with all positions and magnitudes taken from the Catalog of Galaxies and Clusters of Galaxies (Zwicky et al. 1961-1968, hereafter CGCG). The sample contains 1087 galaxies. This sample is likely to be quite homogeneous and complete since the CGCG extends well beyond each of the three limits (1).

The following group identification procedure has been applied to the sample defined by the limits (1):

1. For each galaxy in the sample, we consider the surface density

$$\sigma(\theta) = \frac{1}{2\pi}N(\leq\theta)/(1 - \cos\theta) \approx \frac{N(\leq\theta)}{\pi\theta^2}, \qquad (2)$$

where $N(\leq\theta) - 1$ is the number of galaxies within an angular distance θ of the galaxy being considered.

2. For each galaxy, we then choose the largest possible angle θ_c such that

$$\sigma(\theta \leq \theta_c) \geq f\bar{\sigma}, \qquad (3)$$

where $\bar{\sigma}$ is the mean surface density of galaxies in the sample (594 galaxies per steradian for our sample) and f is a surface density enhancement factor. Here we have used $f = 10^{2/3}$ in hopes of identifying groups with volume density enhancements ≥ 10 as suggested by de Vaucouleurs (1975). For computational reasons θ_c has only been determined to an accuracy of $0^{\circ}.25$.

3. For any galaxy with $N(\leq \theta_c) > 1$, a circle of angular radius θ_c centered on the galaxy is drawn on a map of the sky. Galaxies whose nearest neighbor is more distant than $\sim(\pi f\bar{\sigma}/2)^{-1/2}$ (about $0^{\circ}.75$ here) have $N(\leq\theta_c) = 1$ and have no circle drawn about them.

4. When steps (1) through (3) are completed for each galaxy in the sample, a map of the sky showing all of the resulting circles is prepared. The circles fall into many (103) distinct (i.e., nonoverlapping) clumps; each clump contains from two up to ∿200 overlapping

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circles. The outside boundary of each clump of circles roughly approximates an iso-surface-density-enhancement contour; that is, the mean surface density of galaxies within the boundary is $\sim f\bar{\sigma}$. Each of these distinct clumps of circles is identified as a separate group with a boundary defined by the perimeter of the region of overlapping circles.

5. All galaxies lying within a particular group's boundary are considered (at least tentatively) to be members. Any galaxy lying outside all of the group boundaries is considered a field galaxy and not assigned to any group.

A total of 737 galaxies are assigned to groups, and 350 to the field. It should be noted that although the procedure was designed to locate loose groups, it also identifies large clusters, binary pairs, and generally any system which has a surface number density of galaxies $\geq f\bar{\sigma}$. All of these systems will hereafter be referred to as groups. This sample of small groups is well suited to statistical analyses because it is complete, well defined, and statistically homogeneous.

LUMINOSITY FUNCTION

Of the 103 groups identified in TGI, 63 have one or more members with measured radial velocities. Taking the mean radial velocity of each group (Table 3 of TGI) to indicate its distance, a determination of the individual group luminosity functions is possible. However, because most groups possess rather few members, these individual luminosity functions are not very informative. Therefore, in TGII, we have combined the 63 separate group functions into a single composite luminosity function. It should be remembered, of course, that by using only the groups with radial velocities, some unknown biases may have been introduced.

Before proceeding, several conventions should be specified. All quantities are calculated with $H_o = 50$ km s^{-1} Mpc^{-1}. Unless otherwise note, all magnitudes are from the CGCG. The accuracy of the CGCG magnitudes has been verified recently in an extensive study by Huchra (1976). Since the TGI groups all have $z << 1$ and $b^{II} \geq 40^o$, both absorption and K corrections are neglected. The Sun is assumed to have an absolute CGCG magnitude of 5.48.

Let $\phi_i(L)dL$ be the observed luminosity function of the ith group, that is, the number of galaxies in the ith group with luminosities between L and L + dL. Also let L_c be the faintest absolute luminosity which would be visible in a particular group. We then construct absolute luminosity which would be visible in a particular group. We then construct the function Y(L) according to

$$Y(L) = N_L^{-1} \sum_i \left[\phi_i(L)dL \Big/ \int_L^{\infty} \phi(L)dL \right], \quad (4)$$

where N_L is the number of groups with $L_c \leq L$. Suppose the brightest

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galaxy observed in any group has luminosity L'; then the composite group luminosity function $\phi(L)dL$ is

$$\phi(L > L')dL = 0, \qquad (5)$$

$$\phi(L')dL = 1, \qquad (6)$$

$$\phi(L < L')dL = Y(L)\int_L^{\infty} \phi(L)dL. \qquad (7)$$

In practice, the dL's in equations (4) through (7) are replaced by $\Delta \log L = 0.2$ (i.e., 1/2 magnitude bins), and equation (7) is solved numerically. Equations (5) and (6) amount to a normalization of $\phi(L)$ at the bright end. This procedure is preferable to simply adding the various $\phi_i(L)dL$ because it gives equal weight to each group. Simple addition gives more weight to the groups with more members; if applied to the present data, the result would primarily reflect the luminosity function of group 57 (the Virgo cluster) alone. Although our method could be used to determine the luminosity function of field galaxies, the presently available redshift data (TGI) is too meager for a good determination; rough consistency with the group luminosity function is indicated.

A weighted least-squares fit of the data to a functional form suggested by Schechter (1976),

$$\phi(L/L^*)d(L/L^*) = \phi^*(L/L^*)^{\alpha}e^{-L/L^*}d(L/L^*) \qquad (8)$$

yields $\alpha = -0.83 \pm 0.17$ and $M_{pg}^* = -20.59 \pm 0.26$. If, for simplicity, we constrain $\alpha = -1$, then the fit gives $M_{pg}^* = -20.85 \pm 0.13$, corresponding to $L^* = 3.4 \times 10^{10}\ L_{\odot}$. Both fits give a reduced chi-square of 0.63 and are, therefore, equally good. Since the analytic form of equation (8) is particularly convenient if $\alpha = -1$, the latter fit is adopted.

Schechter (1976) has fitted equation (8) to a composite luminosity function constructed from Oemler's (1974) data for rich clusters and obtained $\alpha = -1.25$ and $M_{B(O)} = -20.6$. These values are in fairly close agreement with the above results for small groups. The most significant difference ($\sim 2\sigma$) is in the value of α (slope of the low-luminosity tail). It is intriguing that some of Oemler's (1974) clusters seem to have relatively fewer low-luminosity galaxies than others (i.e., larger α's).

The composite luminosity function for early (E and SO) and late (S, SB, and Irr) type galaxies were determined by the same procedure as the total luminosity function. Fits of equation (8) yield $\alpha = -0.79 \pm 0.23$ and $M_{pg}^* = -20.49 \pm 0.30$ for late types and $\alpha = -1.27 \pm 0.24$ and $M_{pg}^* = -21.34 \pm 0.60$ for early types. These results are identical

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within the errors (2σ); but it is, again, intriguing that the α value for early-type galaxies agrees so well with Schechter's result for rich clusters (in which early-type galaxies are often concentrated).

The evidence for a "universal" luminosity function is sufficiently convincing to warrant the exploitation of equation (8)'s many convenient analytic properties in a wide variety of applications.

MASS-TO-LIGHT RATIOS AND CROSSING TIMES

In GT III, a detailed dynamical analysis of 39 TGI groups using available radial-velocity data has resulted in the following conclusions: The groups are characterized by typical velocity dispersions and sizes of $\sim$ 200km s^{-1} and $\sim$ 500 pc, respectively, and have typical total luminosities of several L*. Those groups contaminated by foreground or background objects can each be plausibly subdivided into one or more uncontaminated groups closely resembling the originally uncontaminated majority of the groups. For all 39 groups (uncorrected for contamination), the median (a very stable estimator) value of M/L is 141. When contamination correction and possible variation of M/L with total group luminosity are taken into account, a mean M/L of 90 (corresponding to 200 for $L > 10L^*$ and 65 for $L < 10L^*$) is obtained. The uncertainty in each of these values is roughly a factor of 2, and they all correspond to $\Omega_G \lesssim 0.1$. For these 39 groups, $\Delta t H_0 \approx 0.1$, indicating that collapse and virialization have just occurred. Taken together with the typical group density enhancement $\gamma \sim 950$, this very crudely implies $\Omega_G \approx 0.12$, in good agreement with the more rigorous M/L determination. In general, the data examined here offer little hope of closing the Universe with the mass associated with galaxies.

MULTIPLICITY FUNCTION

The spectrum of galaxy cluster sizes is a valuable cosmological datum. In GTIV the problem is formalized by defining the multiplicity function as the luminosity function of groups of galaxies which satisfy a surface density enhancement criterion, $\sigma \geq \sigma_g$.

The observed function is particularly simple $\eta_g(L)dL \propto L^{-1}dL$ for $L<L^*$, $\eta_g(L)dL \propto L^{-7/3}dL$ for $L^* < I \leq 350L^*$, $\eta_g(L)dL \sim 0$ for $L \geq 350 L^*$. The break in the function at L* (a typical bright galaxy luminosity) is presumably due to astrophysical processes related to galaxy formation.

The form of the multiplicity function for $L > L^*$ should reflect the initial conditions at recombination and should not depend on the specific value of σ_g. Since the covariance function of galaxies is a power law, it is reasonable to assume that the original density fluctuation spectrum at recombination was also a power law $(\frac{\delta\rho}{\rho}) \propto M^{-\frac{1}{2}-\frac{n}{6}}$, where n = 0 is a Poisson spectrum and n = -1 is the spectrum predicted by standard hot big bang cosmology (Gott and Rees 1975, Peebles 1974, Doroshkevich et al. 1974). Using the Press and Schecter (1974) theoretical multiplicity formulae, the observed multiplicity function can be fit to give an estimate of n. The formal best fit is $n = -1.3 \pm 0.3$.

A separate analysis of the observed distribution of binaries, triples, quadruples, etc. yields a crude estimate of $n = -1.2$. The relative frequency of Local Group and Coma cluster sized aggregates also gives a simple estimate of $n = -1.4$. We have also estimated the multiplicity function by a completely different method, using the nearest neighbor distribution for galaxies in the Zwicky catalogue and the hierarchical clustering model of Soniera and Peebles (1977). Here the best fit is $n = -0.9$. The latter three values are less certain than the first but provide independent supportive evidence.

An $n = -1$ result finds observations andthe standard hot big bang theory in pleasant agreement, but it must be cautioned that the multiplicity function data and the Press and Schechter theory are still subject to a number of systematic uncertainties.

COMPARISON TO N-BODY SIMULATIONS

Computer N-body simulations of cosmological galaxy clustering in a comoving volume have been carried out by Aarseth, Gott, and Turner (1978). These simulations reproduce many of the observed properties of the galaxy clustering including the two point correlation function (Gott, Turner, and Aarseth 1978). Turner, Aarseth, and Gott (1978, hereafter TAG) have used the endpoints of these calculations to simulated galaxy catalogs similar to the CGCG and have identified groups in these simulated catalogs by the same procedure used to define the groups discussed in the preceeding sections of this paper. Examination and analysis of these simulated groups is instructive since complete information (position, velocity, and mass of each point) is available. TAG show that the simulated groups represent real spatial clusters, that $1/f$ is a good estimate of average contamination of groups by background and foreground objects, and that the dynamics of these simulated groups resembles that of the observed groups. In particular, the median mass per particle determined by a straightforward virial analysis of each group(analogous to the $M/L = 141\ M_\odot/L_\odot$ of G T III) is found to be within a factor of two of the true mean particle mass in every case examined. These results considerably strengthen one's confidence in the conclusions described in the previous sections.

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DISCUSSION

Davis: Do you assume the luminosity distribution of galaxies in your simulations to be a delta function, and if so, what would be the effect of using a realistic luminosity function?

Turner: Yes. The simulation represents a volume limited sample; the data are, of course, magnitude limited. We do not expect this effect to make a qualitative difference because the group identification procedure guarantees the same average fractional contamination ($\sim 1/f$) for simulated and observed groups.

Heidmann: Roughly are the examples of the simulations you showed representative of the differences in groupings between radial distance and radial velocity representations?

Turner: They are reasonably representative. Essentially all of the simulated groups show a real spatial cluster with more or less background/foreground contamination. In most cases, the reshift distribution is misleading in detail.

Zeldovich: What are the details of the simulations?

Turner: These will be given in detail by Dr Aarseth in a later paper.

Ekers: You discussed the expected bias in M/L for groups determined by various selection criteria by comparing them with simulations using $\Omega_g \gtrsim 0.1$. Presumably, simulations with smaller values of Ω_g would give more contamination and consequently even more bias. Shouldn't you also compare the observed distribution with such simulations?

Turner: Yes, examination of an $\Omega \approx 0.01$ simulation would be useful. They are computationally more expensive, and we have not yet produced one. The point here is that $\Omega = 0.1$ or even $\Omega = 1$ models might be taken for $\Omega = 0.01$ situations if groups are incautiously identified in redshift space (i.e. defined as having small velocity dispersions).

Rood: What is the mean number of galaxies in the simulated groups? Does the spread and shape of the histogram in M/L for the simulated groups depend on Ω? And if so, why?

Turner: The mean number of members is in the range of 5 to 10. The shape is affected because the masses of groups whose velocity dispersions are determined by background/foreground contamination does not depend on Ω. The relatively uncontaminated groups have masses proportional to Ω, naturally. These two distributions combine differently for different values thus giving rise to a variation in shape with Ω. The observed M/L distribution resembles that of the $\Omega = 0.1$ model in shape (as well as median) more than that of the $\Omega = 1$ model; I do not know how seriously this shape argument should be taken.

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Fessenko: According to my calculations, Turner's clusters contain about 40% or more false members which are foreground or background objects.

Turner: The contamination fraction should be $1/f \sim 20$ to 25%. This number is confirmed by the N-body simulations and, to some extent, by Kirshner's recent observations of real groups.

Holmberg: Shouldn't you use the arithmetic mean rather than the median in estimating average values of M/L?

Turner: True, but the mean is an unstable estimator if there are a few bad points.

Zeldovich: Kolmogorev taught me that the median is better than the mean. An example: if somebody says the time is 1 o'clock, another that it is five past one, and a third one 5 o'clock, obviously the median is better than the mean.

Turner: A perfect analogy! May I steal it for use on another occasion?

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