Structure and Dynamics in the Local Universe
CSIRO PUBLISHING
Publications of the Astronomical Society of Australia, 2004, **21**, 408–411
www.publish.csiro.au/journals/pasa

Light on Dark Matter

R. Brent Tully[A]

[A] Institute for Astronomy, University of Hawaii, Honolulu, HI 96822, USA. Email: tully@ifa.hawaii.edu

Received 2004 May 3, accepted 2004 September 27

Abstract: Galaxies are lighthouses that sit atop peaks in the density field. There is good observational evidence that these lighthouses do not provide a uniform description of the distribution of dark matter.

Keywords: dark matter: galaxies — clusters: galaxies — dwarf galaxies: luminosity function — dwarf galaxies: mass function

1 Let There be Light

In the beginning there was dark matter and gas but there were no stars. Today some of the gas that was once dispersed has transformed into stars, and we have light. In places the stars are young, hot, and bright, whereas elsewhere the stars are old, cool and faint. In places the stars have been scattered by violent collisions. In places the gas never coalesced and stars never formed. We have light, but light in selective places.

It has been pointed out that the abrupt cutoff of the luminosity function at the bright end and the flat slope at the faint end compared with the Press–Schechter mass function anticipated by the hierarchical clustering scenario suggests that there is a relative deficiency of light at high and low mass extremes compared with the situation at intermediate masses (van den Bosch et al. 2003; Yang et al. 2003). Semi-analytic models that follow the transformation of gas into stars lead to similar expectations (Blanton et al. 1999; Somerville et al. 2001; Ostriker et al. 2003). These same results are found directly in observations. A full discussion of the observational situation is provided by Tully (2005). A condensed version is presented here.

2 The High End of the Mass Spectrum

Two lines of evidence strongly indicate that the ratio of blue light to mass *decreases by about a factor of six in progressing from halos of mass* $10^{12}\,\mathrm{M}_\odot$ *to halos of mass* $10^{15}\,\mathrm{M}_\odot$.

2.1 Virial Analysis of Groups

Collapsed halos are the sites of groups and clusters of galaxies (where in some circumstances the 'group' may be a single object). The relative distribution and motions of the galaxies in a group or cluster provide an indication of the mass of the ensemble. Many groups are relatively young (crossing times are a substantial fraction of the age of the universe) so are not expected to be relaxed. As a consequence, mass estimations based on the virial theorem have uncertainties of as much as a factor of two. Nonetheless, bear with this analysis based on the virial assumption because the variances in mass to light with environment that will be demonstrated are much larger than a factor of two.

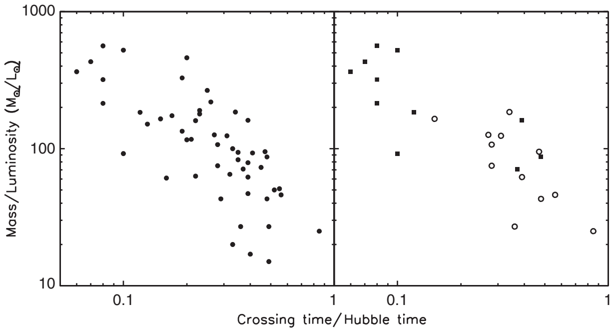

Figure 1 Correlation between mass/light ratio and group crossing time. *Left:* all groups with five or more members in the volume limited T87 sample. *Right:* Subset of groups with at least six members with $M_B < -17$ distinguished according to whether a majority are E/S0/Sa (filled squares) or Sab-Sc-Irr (open circles).

A volume-limited sample of groups in the Local Supercluster, extending to $25h_{75}^{-1}$ Mpc ($h_{75} = H_0/75$), was assembled by Tully (1987: T87), with the individual galaxies in the T87 groups identified in Table II of Tully (1988). The base galaxy catalog was considered complete to $M_B^\star$ within this volume. The group catalog consists of 179 groups of two or more galaxies, 50 with five or more.

The left panel of Figure 1 reveals a striking correlation between the virial mass M_V to blue light L_B ratio and the dynamical timescale of groups, as measured by crossing time t_X. There is an increase of an order of magnitude in M_V/L_B as t_X decreases from $\sim 0.5H_0$ to $<0.1H_0$. The right panel of the figure shows a subset of the sample, groups with at least six non-dwarf members, distinguished by whether the majority of the members are early or late type. There is a clear separation: the spiral rich groups have long dynamical times and low M_V/L_B values compared with the groups dominated by E/S0 galaxy types.

Mass and luminosity are separated in Figure 2. It is seen that the E/S0/Sa dominated groups tend to be the most massive. Two concurrent trends are found — more massive

10.1071/AS04056 1323-3580/04/04408

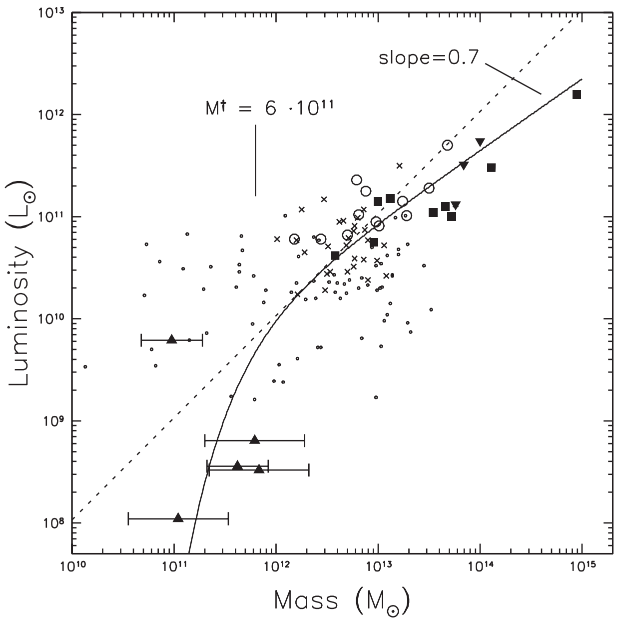

Figure 2 Mass versus light for groups over the full range of the observed mass spectrum. The large open circles and filled squares represent the same data seen in the right panel of Figure 1. The crosses represent the remainder of the groups with five or more members found in the left panel of Figure 1. The small open circles represent groups with only two to four known members. The three filled inverted triangles represent E/S0/Sa groups more distant than the volume-limited sample. The five filled triangles with error bars represent groups at the low end of the mass spectrum that are discussed separately. The $M_V/L_B = 94$ dotted line is the mean value for the sample reported by T87. The solid line is a fit constrained by the data with a high mass slope of $\gamma = 0.7$ and an exponential fall off at masses less than $M^\dagger = 6 \times 10^{11}\ M_\odot$.

groups tend to have fractionally less blue light and, at a given mass, E/S0/Sa groups have less blue light than their counterparts dominated by later morphological types.

The properties of groups from the volume-limited survey region with only two to four members are included in Figure 2 in order to explore conditions in a lower mass range. In these cases the errors in the mass estimates are very large, which accounts for the large scatter. The five data points with error bars in this Figure are discussed later.

2.2 *Numerical Action Methods*

Compatible results have emerged from the reconstruction of galaxy orbits with Numerical Action Methods (Peebles 1989; Shaya et al. 1995; Tully & Shaya 1998). These reconstructions extend dynamical studies to larger scales. One is considering the dynamical influence of groups on each other and potentially taking into account mass that extends beyond the groups. For this discussion, no attempt is made to model the complex orbits *within* groups. Groups are considered as ensemble halos and it is the orbits of the centres of mass of these ensembles that are reconstructed.

In fact it is not the specific orbits that are reconstructed that we take seriously but rather it is the mass requirements that are found to give good fits. The reconstruction is constrained by the need to match the angular positions and radial velocities of objects in a catalog. If the cosmology is set with a specified age then the main variable is the mass assignments. With a given set of mass assignments, orbits are found which leaves each entity today with six specified values in phase space, three of which rigorously match the observed boundary conditions. One of the other three phase space values — the distance — is subject to test. Our model constraint is a χ^2 comparison of model and observed distances. The orbits that are found are not unique given the limitations of the catalogs and the poor constraints on the three free phase space components, but *only models within a modest range of mass assignments give good* ξ^2 *fits to the distance constraints.* Basically, increasing mass forces objects with a given velocity to be farther removed from the main mass centres.

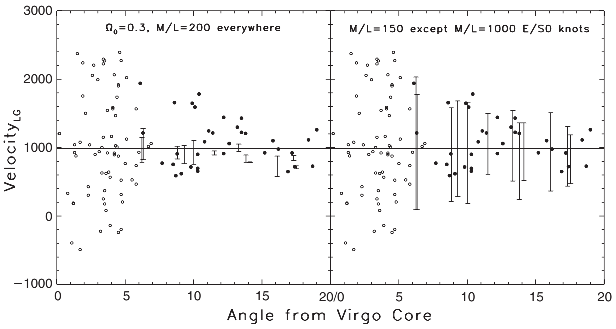

Figure 3 Virgo infall constraints from two Numerical Action models. Data points indicate the velocities and separations from the centre of the Virgo Cluster of individual galaxies. Galaxies within the 6° caustic of the cluster are indicated by open circles. Galaxies outside the caustic but associated with the infall region are indicated by filled circles. The vertical brackets are located at angles from the centre of the cluster that intersect infalling groups, so at lines-of-sight that have received attention in the Numerical Action models. The amplitudes of the brackets illustrate the range of infall velocities anticipated by the two models under consideration. *Left:* $M/L_B = 200$ assigned to all units. *Right:* $M/L_B = 1000$ assigned to the Virgo Cluster and other E/S0 knots and $M/L_B = 150$ otherwise.

In the earliest trials the minimalist assumption was made that M/L_B values are constant in all environments. The subsequent best fits were found for $M/L_B \sim 200 M_\odot/L_\odot$. However this modest M/L_B assignment fails utterly to account for the large infall velocities toward the Virgo Cluster that are observed. Rather, a value $M/L_B \sim 1000 M_\odot/L_\odot$ is required for the cluster. Figure 3 attempts to summarise the observational constraints. The amplitude of the envelope of observed infall velocities is closely governed by the mass of the cluster. A very high mass of $1.3 \times 10^{15}\ M_\odot$ is required to explain the velocity breadth of the infall region. Upon assigning the corresponding large mass to light ratio to the cluster (and other E/S0 dominated groups) it was found that the mass to light requirement for the remainder of the objects was reduced to $M/L_B \sim 150 M_\odot/L_\odot$.

The mass requirement found by the Numerical Action Method for the Virgo Cluster is 60% higher than found with the virial analysis, but applies to the cluster on a larger scale. The overall average M/L_B requirement of the action modelling is also higher than that found using the virial theorem for most groups but again refers to larger scales. Both the virial and action studies suggest that M/L_B values increase by a factor of five to seven in proceeding from the environments of spiral galaxies to the Virgo Cluster environment.

3 The Low End of the Mass Spectrum

The faint end of the luminosity function of galaxies in low density environments has a substantially flatter slope than the theoretical mass function of hierarchical clustering (Klypin et al. 1999; Moore et al. 1999). During a study of possible variations of the luminosity function with environment (Tully et al. 2002) the idea arose that groups with low mass with very little light might be common. It was recalled that during the construction of the T87 group catalog a number of entities that were called 'associations' had group-like qualities except in one respect. These entities had similar, though somewhat smaller, dimensions to loose groups and similar, actually smaller, velocity dispersions. If considered to be bound, then the inferred masses are low — in the range 10^{11}–$10^{12}\,M_{\odot}$. If one ignores the properties of the galaxies and regards them only as test particles probing a potential then one would conclude that these T87 associations are just the low mass end of a continuum of groups conditions.

The outstanding difference with familiar groups with higher mass is that these low mass entities have *very little light*. The candidate members of these groups are all dwarf galaxies. Though the inferred masses are low, the luminosities are *extremely low* and M/L_B values are high — so high that at the time of T87 there was a reluctance to conclude that the entities are bound (though there was a suspicion that this was the case!).

Today, with greater boldness, it is argued that these groups of dwarfs *are* bound. It is to be noted that candidate groups of dwarfs are not rare. Within the restricted domain of 5 Mpc, Tully et al. (2002) report four good examples. This number is comparable to the number of established groups within the same distance, and the census of dwarfs is surely incomplete at low Galactic latitudes. As discussed by Tully (2004), there is now a dramatic improvement in knowledge regarding the distances of nearby galaxies. Hubble Space Telescope observations resolves the brighter stars and permits a distance determination from the magnitude of the tip of the red giant branch (Karachentsev et al. 2003). Good distances now exist for almost all the dwarf group candidates and it is found that the spatial correlations are equally as good in distance as they were found to be on the plane of the sky and in velocity. One of the groups of dwarfs turned out to be considerably closer than suspected based on velocities, with all the observed distances concordant at the nearer position.

At this point the evidence very strongly suggests that the groups of dwarfs are bound. If so, mass estimates suggest $M/L_B \sim 1000 M_{\odot}/L_{\odot}$ for these groups. The structures are almost surely not virialised because crossing times are a substantial fraction of the Hubble time. Consequently, the derivation of masses are subject to large errors. The uncertainties can easily be a factor of two and conceivably as bad as a factor of three. However, the M/L_B values that are found are an order of magnitude larger than the values attributed to loose groups of spirals. There is little doubt that if the groups of dwarfs are bound then they are reservoirs of mostly dark matter.

The mass and light values of the groups of dwarfs are shown in Figure 2 as the filled triangles with error bars. In fact, five points are plotted in this manner and one stands apart in terms of luminosity. This higher luminosity entity is the near side component of what is commonly referred to as the Sculptor Group, but which is probably two separate bound units. The near component includes NGC 55 and NGC 300 plus smaller objects. The dynamical properties (dimensions and velocity dispersion) suggest a very low mass for this proposed group, like that of the other four groups of dwarfs. However, the two NGC galaxies are intermediate luminosity galaxies, not dwarfs, so the group is not deficient in light. It is to be concluded that not all group halos in the mass regime 10^{11}–$10^{12}\,M_{\odot}$ lack light. However in the ensemble there seems to be a cutoff in light proceeding to low mass halos.

4 The Dark Side

The solid line in Figure 2 is a fit of the equation

$$L_B = C M^{\gamma} \mathrm{e}^{-M^{\dagger}/M} \tag{1}$$

This equation relates luminosity and mass with three constraints: a logarithmic slope at the high mass end γ, a low mass exponential cutoff set by $M^{\dagger}$, and a normalisation C. The fit minimises a χ^2 expression with uncertainties in mass. Perhaps a more dramatic presentation of the same information is seen in Figure 4, a plot of M/L_B versus mass (appreciating that the groups with two to four members represented by the small open circles have very large uncertainties in mass). It is seen that halos in the mass range 10^{12}–$10^{13}\,M_{\odot}$ manifest the most light. Groups with progressively more mass up to $10^{15}\,M_{\odot}$ have progressively smaller light fractions, with this trend particularly enhanced in the groups dominated by early type galaxies. At the other end of the mass spectrum, below $10^{12}\,M_{\odot}$ there is an abrupt cut-off, with M/L_B values becoming very large and perhaps going off to infinity. One can suppose that there are low mass halos completely devoid of stars.

The census of galaxies within $25h_{75}^{-1}$ Mpc of T87 that lead to the group catalog can be used to construct a halo mass function. This is seen in the top panel of Figure 5. The mass function is poorly constrained at the high mass end by the small number statistics in such a restricted volume. At the low mass end, the error bars only account for the $\sqrt{N}$ bin counting uncertainties. There are much larger horizontal errors associated with the uncertain masses of small groups. In the lowest mass bins the counts are dominated by individual galaxies outside of groups, in which cases it was assumed that $M/L_B = 100$.

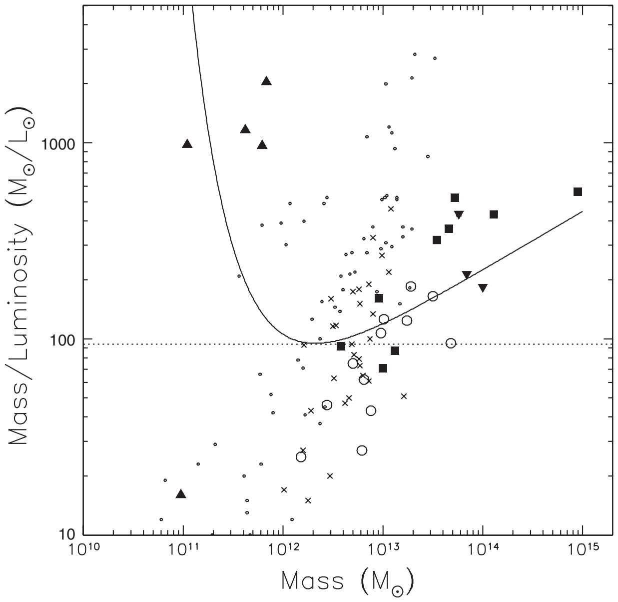

Figure 4 M/L_B versus mass over the full range of density regimes. The data are the same as in Figure 2. The solid curve and dotted line are transpositions of the curve and line in Figure 2.

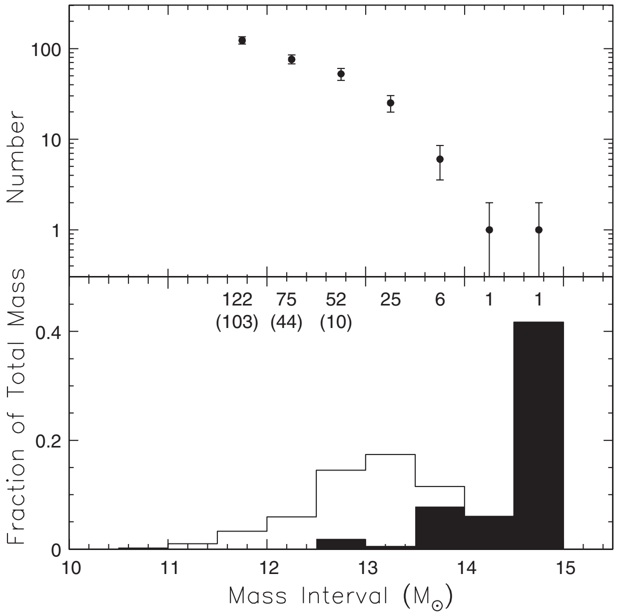

Figure 5 *Above:* Observed mass function in the volume within $25h_{75}^{-1}$ Mpc and $|b| > 30$. The numbers of objects in each bin are given along the top of the lower panel. In brackets are the numbers of individual galaxies (i.e., galaxies outside of groups). *Below:* Fraction of the total mass associated with the mass function in half-dec bins. The mass associated with the groups of predominantly early types is indicated by the filled histograms. The open histograms correspond to the mass found in the groups with predominantly late types.

Admitting that there are considerable uncertainties in this mass function because of the restricted sample and low mass cutoff, perhaps the greater interest is in the lower panel of Figure 5. Here one sees the fraction of the total mass found in the separate mass bins. The filled part of the histogram is contributed by the E/S0/Sa groups, while the open part represents the contribution by the groups dominated by spiral and irregular galaxies. One entity, the Virgo Cluster, contains ~40% of the mass in the survey volume (although it contains only 15% of the light!). The groups of early types together contain 60% of the mass. Considering groups of all type, 90% of the mass is in groups with $M > 3 \times 10^{12}\,M_{\odot}$.

The groups of dwarf galaxies have only been discovered within a restricted 5 Mpc volume. Within this space, though they appear to be numerous, they only contain ~10% of the mass associated with luminous galaxies. Yet the luminous groups within 5 Mpc lie on the tail of the histogram in Figure 5 just above $10^{12}\,M_{\odot}$. It is concluded that these groups of dwarfs, though they are dominated by dark matter, make only a minor contribution to the total mass budget of collapsed dark matter halos. From a cosmological perspective, it is the high mass-to-light ratios in massive clusters with short dynamical timescales that have greater implications. The force is with this dark side.

Acknowledgments

The work involving the Numerical Action Method was done with Jim Peebles and Ed Shaya, while the work on the faint end of the luminosity function was with Neil Trentham. Support has been provided by JPL Contract 1243647, the STScI award HST-GO-09162.01A, and the NSF award AST-0307706. This paper is the extract of a talk given on a special occasion for me, a workshop in my honor, and I am indebted to all those that participated and made the event possible, especially Joss Bland-Hawthorn.

References

Blanton, M., Cen, R., Ostriker, J. P., & Strauss, M. A. 1999, ApJ, 522, 590
Karachentsev, I., et al. 2003, AA, 398, 479
Klypin, A., Kratsov, A. V., Valenzuela, O., & Prada, F. 1999, ApJ, 522, 82
Moore, B., et al. 1999, ApJ, 524, L19
Ostriker, J. P., Nagamine, K., Cen, R., & Fukugita, M. 2003, ApJ, 597, 1 (astroph/0305203)
Peebles, P. J. E. 1989, ApJ, 344, L53
Shaya, E. J., Peebles, P. J. E., & Tully, R. B. 1995, ApJ, 454, 15
Somerville, R. S., et al. 2001, MNRAS, 320, 289
Tully, R. B. 2005, ApJ, in press (astro-ph/0312441)
Tully, R. B. 1987, ApJ, 321, 280 [T87]
Tully, R. B. 1988, Nearby Galaxies Catalog (Cambridge: CUP)
Tully, R. B., & Shaya, E. J. 1998, Proc. Evolution of Large Scale Structure (astro-ph/9810298)
Tully, R. B., Somerville, R. S., Trentham, N., & Verheijen, M. A. W. 2002, ApJ, 569, 573
van den Bosch, F., Yang, X., & Mo, H. J. 2003, MNRAS, 340, 771, 2003
Yang, X., Mo, H. J., & van den Bosch, F. 2003, MNRAS, 339, 1057, 2003