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THE MASS FUNCTION OF NEARBY GALAXY CLUSTERS

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ABSTRACT

We present the distribution of virial masses for nearby galaxy clusters, as obtained from a data set of 75 clusters, each having at least 20 galaxy members with measured redshifts within 1.5 h^{-1} Mpc. After having accounted for problems of incompleteness of the data set, we fitted a power law to the cluster mass distribution.

Subject heading: galaxies: clustering

1. INTRODUCTION

The distribution functions of observational cluster quantities, such as velocity dispersions, radii, masses, luminosities, and X-ray temperatures, can provide strong constraints both on cosmological scenarios and on the internal dynamics of these systems. Theoretical as well as observational estimates of these distribution functions are presently being debated.

The theoretical mass distribution expected for groups and clusters in the hierarchical clustering scenario has been derived by several authors (see, e.g., Press & Schechter 1974; Cavaliere, Colafrancesco, & Scaramella 1991; Blanchard, Valls-Gabaud, & Mamon 1992). The distribution functions for mass, X-ray temperature, and velocity dispersion of rich clusters have been shown to provide important diagnostics for cosmological models (see, e.g., Edge et al. 1990; Henry & Arnaud 1991; Lilje 1992). In particular, the distribution function of cluster X-ray temperatures has been used to constrain the mass fluctuation spectrum (see, e.g., Henry & Arnaud 1991). Bahcall (1979) estimated the cluster luminosity function and first offered the possibility of evaluating the cluster mass function by adopting a constant mass-to-light ratio. At present both optical and X-ray data contribute to the description of the cluster mass function (Bahcall & Cen 1992). Recently Pisani et al. (1992) obtained the mass distribution function of groups of galaxies directly from their dynamics, while Ashman, Salucci, & Persic (1993) described a distribution function of galaxy masses.

Quite a large number of redshifts for cluster galaxies is now available, so that many cluster masses can be measured directly from dynamics. We collected from the literature 75 clusters, each having at least 20 members with measured redshift within 1.5 h^{-1} Mpc (we use $H_0 = 100\ h$ km s^{-1} Mpc^{-1} throughout). In Table 1 we list the clusters considered, the number N of cluster members with available redshift, and the richness classes R mainly taken from Abell, Corwin, & Olowin (1989, hereafter ACO).

In order to reasonably reduce evolutionary effects, we considered only clusters with mean redshift $z \leq 0.15$. In Biviano et al. (1992) and Girardi et al. (1993a, b) we describe the database and give the relevant references. In Girardi et al. (1993a) we detail the criteria used to define the clusters both in redshift space and in projected separation.

We have shown (Girardi et al. 1993a, b) that at least 20 galaxy redshifts are generally needed to describe cluster parameters (in particular the galaxy velocity dispersion and the virial radius) without heavy problems induced by undersampling. So, from our statistical point of view, the choice of a minimum of 20 redshifts per cluster seems to be an acceptable compromise between the need of having at disposal a large number of clusters and the possible presence of undersampling problems.

Girardi et al. (1993a) studied, in a homogeneous way, the velocity field of galaxy clusters. They evidenced that the distribution of galaxy velocities in clusters is quasi-Gaussian, which encouraged us to apply the virial theorem to estimate the cluster masses. Moreover, the estimates of cluster masses, via the virial theorem, have been widely debated and accepted in recent literature. As shown by, for example, Postman, Geller, & Huchra (1988), Perea, del Olmo, & Moles (1990), and Pisani et al. (1992), the virial theorem measures masses with confidence comparable to that of other methods, in particular the projected mass estimator (see Heisler, Tremaine, & Bahcall 1985).

Our virial masses have been obtained by using robust estimates of the velocity dispersions (Beers, Flynn, & Gebhardt 1990; Girardi et al. 1993a). The mass errors quoted are obtained via the jackknife method (see, e.g., Efron 1979 and Geller 1984 for an astrophysical application). In this *Letter* we evaluate the virial masses both using two apertures, 0.75 h^{-1} Mpc and 1.5 h^{-1} Mpc, that is, one-half and one Abell radius, respectively. We also computed the projected masses of our clusters, within the same aperture. Remarkably, the shape of the distributions of virial and projected masses is almost the same.

The presence of subclustering may bias cluster mass estimates. In particular the bias may be severe, and the mass may be overestimated, when the subclustering masks the presence of two or more unbound systems. In this case one should consider the clumps as isolated clusters or groups. We adopted the method of Dressler & Shectman (1988) to investigate the presence of subclustering in our sample. Actually this method (like other methods present in the literature) is efficient for a number of members $N \gtrsim 40$; for a lower number of members the efficiency decreases; therefore we considered only well-sampled clusters with $N \geq 40$. The probability of subclustering was computed using all the galaxies within 1.5 h^{-1} Mpc from the cluster center; a probability $\geq 95\%$ was taken to be significant.

The mass distribution of the 18 clusters without evidence for subclustering did not succeed to be significantly different (according to the Mann-Whitney U-test; see, e.g., Siegel 1956)

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TABLE 1

CLUSTER VIRIAL MASSES

Name (1)	N (2)	R (3)	log ($hM_{0.75}$) (4)	log ($hM_{1.5}$) (5)
ACO 85	123	1	15.07 ± 0.28	15.17 ± 0.18
ACO 119	21	1	...	14.70 ± 0.68
ACO 151	32	1	14.21 ± 0.41	14.39 ± 0.36
ACO 194	89	0	14.14 ± 0.28	14.20 ± 0.25
ACO 262	64	0	14.34 ± 0.33	14.47 ± 0.25
ACO 426 (Perseus)	197	2	15.01 ± 0.15	15.12 ± 0.14
ACO 496	34	1	14.54 ± 0.36	...
ACO 539	97	1	14.75 ± 0.24	14.73 ± 0.23
ACO 548	133	1	14.91 ± 0.19	15.04 ± 0.10
ACO 569	39	0	...	14.22 ± 0.44
ACO 576	48	1	14.74 ± 0.26	...
ACO 634	38	0	14.04 ± 0.64	14.20 ± 0.42
ACO 744	21	0	14.37 ± 0.56	...
ACO 754	83	2	14.61 ± 0.35	14.78 ± 0.25
ACO 957	35	1	14.53 ± 0.31	...
ACO 999	28	0	14.05 ± 0.95	14.05 ± 0.95
ACO 1016	24	0	13.48 ± 0.39	...
ACO 1060 (Hydra)	145	1	14.52 ± 0.12	14.59 ± 0.11
ACO 1142	45	0	14.50 ± 0.53	14.62 ± 0.49
ACO 1146	64	4	14.96 ± 0.25	15.12 ± 0.25
ACO 1185	52	1	14.45 ± 0.45	14.58 ± 0.37
ACO 1367	88	2	14.71 ± 0.20	14.76 ± 0.21
ACO 1631	71	0	14.57 ± 0.27	14.80 ± 0.18
ACO 1644	91	1	14.88 ± 0.22	15.11 ± 0.20
ACO 1651	29	1	14.78 ± 0.30	...
ACO 1656 (Coma)	290	2	14.82 ± 0.14	14.94 ± 0.12
ACO 1736B	63	...	14.85 ± 0.20	14.99 ± 0.18
ACO 1750	47	0	14.76 ± 0.32	...
ACO 1795	40	2	14.63 ± 0.37	...
ACO 1983	81	1	14.31 ± 0.23	14.56 ± 0.23
ACO 1991	30	1	14.24 ± 0.41	14.24 ± 0.41
ACO 2052	41	0	14.58 ± 0.36	...
ACO 2063	48	1	14.08 ± 0.36	14.30 ± 0.49
ACO 2065	27	2	14.66 ± 0.45	14.88 ± 0.48
ACO 2092	22	1	...	14.50 ± 1.06
ACO 2147−52	45	...	...	15.48 ± 0.22
ACO 2151 (Hercules)	102	2	14.77 ± 0.15	14.94 ± 0.16
ACO 2197	45	1	14.50 ± 0.20	14.62 ± 0.22
ACO 2199	70	2	14.54 ± 0.26	14.68 ± 0.21
ACO 2255	31	2	15.01 ± 0.43	15.07 ± 0.32
ACO 2256	86	2	15.14 ± 0.15	...
ACO 2319A	22	1	14.71 ± 0.41	...
ACO 2538	42	1	14.68 ± 0.24	...
ACO 2593	37	0	14.35 ± 0.29	...
ACO 2670	230	3	14.87 ± 0.12	14.99 ± 0.11
ACO 2717	33	1	14.29 ± 0.28	...
ACO 2721	65	3	14.74 ± 0.36	14.87 ± 0.36
ACO 2877	97	0	14.70 ± 0.19	...
ACO 3112	32	2	...	15.47 ± 0.63
ACO 3158	35	2	14.51 ± 0.40	...
ACO 3266	130	2	15.06 ± 0.18	...
ACO 3376	77	0	14.58 ± 0.25	14.73 ± 0.22
ACO 3381	30	1	13.48 ± 0.33	13.74 ± 0.37
ACO 3391	66	0	15.12 ± 0.24	...
ACO 3395	146	1	14.96 ± 0.19	...
ACO 3526 (Centaurus)	232	0	14.83 ± 0.12	15.00 ± 0.10
ACO 3558	113	4	14.78 ± 0.14	...
ACO 3574	38	0	14.46 ± 0.40	...
ACO 3667	45	2	15.21 ± 0.39	...
ACO 3705	40	2	14.85 ± 0.21	...
ACO 3716	96	1	14.65 ± 0.18	15.01 ± 0.24
ACO 3854	36	3	15.15 ± 0.22	...
ACO 4067	30	1	14.45 ± 0.33	14.66 ± 0.29
ACO S301	29	0	14.19 ± 0.59	...
ACO S373 (Fornax)	57	0	13.97 ± 0.21	14.12 ± 0.17
ACO S463	85	0	14.51 ± 0.18	14.61 ± 0.15
ACO S753	34	0	14.36 ± 0.41	...
ACO S805	43	0	14.10 ± 0.39	14.16 ± 0.35
AWM 1	27	0	...	14.55 ± 0.37
AWM 7	33	0	14.64 ± 0.34	...
C67	28	1	14.70 ± 0.52	...
DC 0003−50	36	...	14.38 ± 0.47	14.53 ± 0.33
MKW 04	45	0	14.19 ± 0.24	14.19 ± 0.24
Pegasus I	57	0	14.35 ± 0.41	14.64 ± 0.33
Virgo	434	1	14.71 ± 0.08	14.93 ± 0.05

from that of the 12 clusters with evidence of subclustering. We obtained again the same result when we compared the distributions of masses computed inside 0.75 h^{-1} Mpc (27 vs. 16 clusters). This result suggests that the effect of subclustering does not strongly affect our mass distribution, either because it is small, or because our selection criteria for cluster membership and our estimate of the velocity dispersions are statistically robust (see Girardi et al. 1993a). Therefore, no cluster has been rejected. In view of possible surviving cases in which subclustering effects produce mass overestimates, it is conservative to consider mass estimates obtained within small apertures. As a matter of fact, West & Bothun (1990) evidenced that only a few significant subclumps exist within 1 h^{-1} Mpc in $\sim$70 clusters analyzed.

Of course, other systematic errors in the mass evaluation may be present if light does not trace mass in our clusters (see, e.g., Merritt 1987; Watt et al. 1992 and references therein). Masses are in solar units.

2. THE DISTRIBUTION OF CLUSTER MASSES

In the above-mentioned Table 1 we also list the logarithms of the cluster virial masses log ($hM_{0.75}$), and log ($hM_{1.5}$) measured within apertures of 0.75 h^{-1} Mpc and 1.5 h^{-1} Mpc. In order to measure mass at a certain radius, we must have information on the galaxy velocity field and the gravitational potential up to the same radius. Therefore, we have estimated $M_{0.75}$ only for those 69 clusters which are actually well sampled up to 0.75 h^{-1} Mpc from the cluster center; these clusters contain $\geq$20 galaxies all located within 0.75 h^{-1} Mpc, and the most external of these galaxies is located, in each cluster, at $\simeq$0.75 h^{-1} Mpc from the center. Similarly, we have estimated $M_{1.5}$ only for those 47 clusters which are actually well sampled up to 1.5 h^{-1} Mpc from the cluster center; these clusters contain $\geq$20 galaxies all located within 1.5 h^{-1} Mpc, and the most external of these galaxies is located, in each cluster, at $\simeq$1.5 h^{-1} Mpc from the cluster center.

The masses $M_{0.75}$ and $M_{1.5}$ both contribute to describe the cluster mass distribution. In fact, fixed apertures may contain different fractions of cluster masses (depending on the intrinsic cluster sizes), and define two different cuts of the density peaks which identify the clusters in the cosmic density field. However, in this *Letter* we restrict our analysis to the galaxies contained within 0.75 h^{-1} Mpc, mainly because of the above-mentioned problem of subclustering. The distribution of $M_{0.75}$ is plotted in Figure 1.

Our sample, although quite extended, is not complete, either in richness or in mass. Therefore, we normalized the frequencies of clusters belonging to different richness classes to

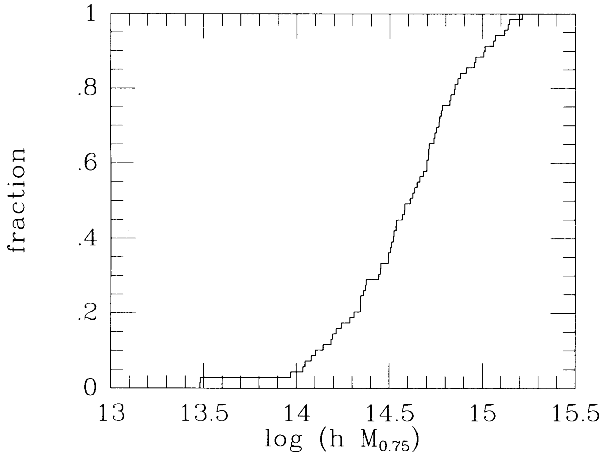

FIG. 1.—Cumulative distributions of log ($hM_{0.75}$) for our 69 clusters with data up to 0.75 h^{-1} Mpc.

the corresponding frequencies of the ACO catalog; the normalization procedure is described in Girardi et al. (1993a). However, since the completeness of ACO's catalog for $R = 0$ clusters is in question (see, e.g., Scaramella et al. 1991; Guzzo et al. 1992), we also considered the Edinburgh-Durham Cluster Catalogue (hereafter EDCC) of Lumsden et al. (1992), by rescaling their richness to ACO's. Moreover, using two catalogs also allows us to investigate the sensitivity of the results on the choice of the catalog. In Figure 2 we show the histograms of the ACO-normalized and EDCC-normalized mass distributions of our clusters.

3. THE MASS FUNCTION

As one can see in Figure 2, the mass distributions do not increase monotonically from high to low mass values. Two

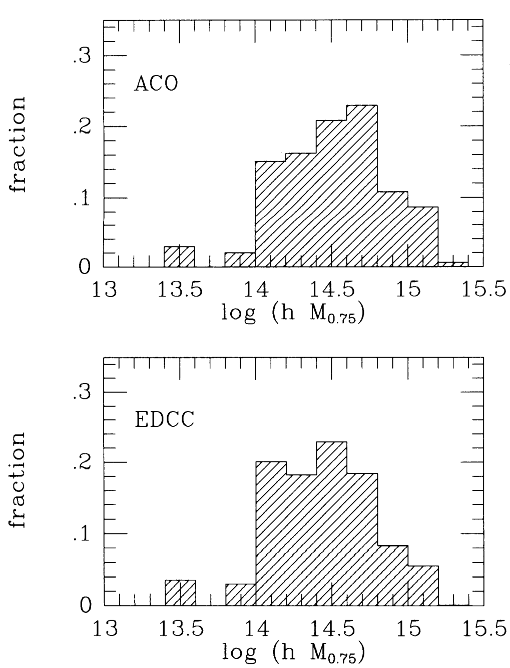

FIG. 2.—Histograms of the mass distributions of our clusters. Upper panel: ACO-normalized distribution; lower panel: EDCC-normalized distribution.

facts may contribute to the decrease at low mass values: (1) the possible incompleteness of the ACO and the Edinburgh-Durham Cluster catalog for low richness clusters; (2) the lack, in our sample, of rich galaxy groups, the masses of which are expected to fall partially in the low-mass region (in fact, completeness in richness does not necessarily imply completeness in mass).

The problem of the nonmonotonic behavior of the mass distribution will not be solved unambiguously until a complete sample of galaxy systems, spanning the range from small groups to rich clusters, is available. So, even if more data on poor cluster and rich groups (which are becoming available) were considered, we would still deal with an incomplete sample, and the renormalization problem would not be solved.

So we deemed it conservative to use only the high-mass (decreasing) part of the distribution in order to obtain the mass function of nearby clusters. Specifically, we set a lower bound of log ($hM_{0.75}$) = 14.6 to the mass distributions.

We fitted these two culled distributions with powers laws, $n(M_{15})dM_{15} = A(M_{15})^a dM_{15}$, where M_{15} is the mass expressed in units of $10^{15}\ M_\odot$. These power laws were convolved with lognormal functions whose dispersions were obtained from the median values of the cluster mass errors (quoted in Table 1). The best-fit values of a (obtained via the Maximum Likelyhood method) are $-2.3^{+0.6}_{-0.6}$ and $-2.6^{+0.7}_{-0.6}$ for the ACO-normalized and EDCC-normalized distributions, respectively. These a values are not different within the errors, and the result does not seem to be very sensitive on the choice of the reference catalog.

The volume density of ACO clusters has been estimated to be $2.5 \times 10^{-5}\ h^3$ Mpc^{-3} for $R \geq 0$ by Scaramella et al. (1991), and Zucca et al. (1993), and to be $8.6 \times 10^{-6}\ h^3$ Mpc^{-3} and $7.2 \times 10^{-6}\ h^3$ Mpc^{-3} for $R = 0$ and $R \geq 1$, respectively, by Peacock & West (1992). Thus the mass function, in the assumed range of completeness, is given by $n(M_{15}) = 5 \times 10^{-6}\ h^{1.7}(M_{15})^{-2.3}$ Mpc$^{-3}(10^{15}\ M_\odot)^{-1}$, if one considers the density estimate of Scaramella et al. (1992) and Zucca et al. (1993), or $n(M_{15}) = 3.2 \times 10^{-6}\ h^{1.7}(M_{15})^{-2.3}$ Mpc$^{-3}(10^{15}\ M_\odot)^{-1}$, if one considers the density estimate of Peacock & West (1992).

It is also possible to give an estimate of the exponent n of the power-law spectrum $P(k) \propto k^n$ of cosmic fluctuations. A way to do that is to compare the slope of the mass function with that one of the power-law representation of the temperature function of clusters given by Henry & Arnaud (1991) and Henry (1992). By making use of both of these functions we can better constrain the value of n than relying only on the mass function, which admittedly spans a short range in cluster masses. In the framework of self-similar clustering (Kaiser 1990), virial mass M and temperature T are linked by $T \propto M^{(1-n)/6}$. Comparing the slopes of the temperature function (-4.75 ± 0.50) and of the mass functions gives a spectral index $n = -1.1^{+0.9}_{-0.9}$ and $n = -1.6^{+1.1}_{-1.0}$ for ACO- and EDCC-normalized distributions, respectively.

In conclusion, we have presented a cluster mass function, obtained directly from the dynamics of these galaxy systems, which is described by a power law and which mainly refers to high-mass clusters. In the future we plan to extend this mass function to a larger mass range, including dynamical estimates of masses of poor clusters and groups of galaxies.

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