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The distribution of mass in galaxy clusters

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Abstract. We determine the mass profile of an ensemble cluster built from combining together 59 galaxy clusters, observed in the ESO Nearby Abell Cluster Survey. The mass profile is derived from the projected phase-space distribution of elliptical and S0 galaxies, for which there is independent evidence that they move on nearly isotropic orbits in the cluster potential. Application of the Jeans equation yields a non-parametric estimate of the cumulative mass profile of the ensemble cluster. We compare our estimate with several analytical models from the literature, and find that a sizeable core in the cluster mass distribution is not required by our data. The total cluster mass density is well traced by the luminosity density of ellipticals and S0s, when the brightest ellipticals (with $M_R \leq -22 + 5 \log h$) are excluded from the sample.

Key words. Galaxies: clusters: general – Dark matter – Cosmology: observations

1. Introduction

The first determinations of galaxy cluster masses date back to the 1930's (see e.g. Zwicky 1937), and are remarkably close to current estimates, once they are corrected for today's value of the Hubble constant. Early estimates assumed that galaxies and the total cluster mass shared the same distribution, a reasonable assumption at a time when dark matter was yet to be discovered. Dropping this assumption can widen significantly the range of allowed cluster masses (as first shown by Merritt 1987). It is therefore essential to *measure* the distribution of the total cluster mass. This must then be compared with the distribution of galaxy light, in order to understand if galaxies are unbiased tracers of the cluster mass.

The cluster mass distribution has also recently become a useful test for the hierarchical paradigm of cosmological structure formation. In fact, cosmological numerical simulations have shown that dark matter halos have a universal mass density profile (Navarro, Frenk & White 1997, NFW hereafter), although the precise form of it near the cluster centre remains uncertain (see e.g. Power et al. 2003).

In this contribution, we present a determination of the cluster mass profile, based on spectroscopic data for about 3,000 galaxies in 59 rich nearby clusters of galaxies, observed in the ESO Nearby Abell Cluster Survey (ENACS, Katgert et al. 1998), which is currently the largest homo-

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geneous redshift data-set for cluster galaxies.

2. The cluster mass profile

In order to make the most efficient use of the ENACS data-set, we combine all 59 clusters together into an ensemble cluster, by scaling the projected clustercentric glaxy distances with the clusters virial radii, r_{200}'s (for which we use the definition of Carlberg et al. 1997), and the line-of-sight velocities (relative to the cluster mean) of cluster galaxies with the clusters velocity dispersions, σ_p. On average, for our 59 clusters, $< r_{200} >= 1.2\,h^{-1}$ Mpc, and $\sigma_p = 700$ km s^{-1}. We exclude galaxies in subclusters from our sample, because (by definition) they are not good tracers of the global cluster potential (for more details, see Biviano et al. 2002).

In Biviano et al. (2002) we found that among cluster galaxies outside substructures, 4 classes must be distinguished because they have different projected phase-space distributions: (i) the brightest ellipticals (with $M_R \leq -22 + 5 \log h$), (ii) the other ellipticals together with the S0 galaxies (referred to as 'Early-type' galaxies, in the following), (iii) the early spirals (Sa–Sb), and (iv) the late spirals and irregulars (Sbc–Ir) together with the ELG (except those with early morphology). Among these four classes, we choose the Early-type galaxies as tracers of the mass potential, because they are the oldest cluster population, and hence they are likely to have settled in equilibrium in the cluster potential by now.

In order to solve the Jeans equation for the determination of the mass profile, we make the usual assumption of steady-state, negligible net rotation, and spherical symmetry. Moreover, knowledge is needed of the velocity anisotropy of the galaxy population used as tracers. We analyse the shape of the velocity distribution of the Early-type galaxies, and, from a comparison with the velocity distributions of dynamical models (van der Marel et al. 2000),

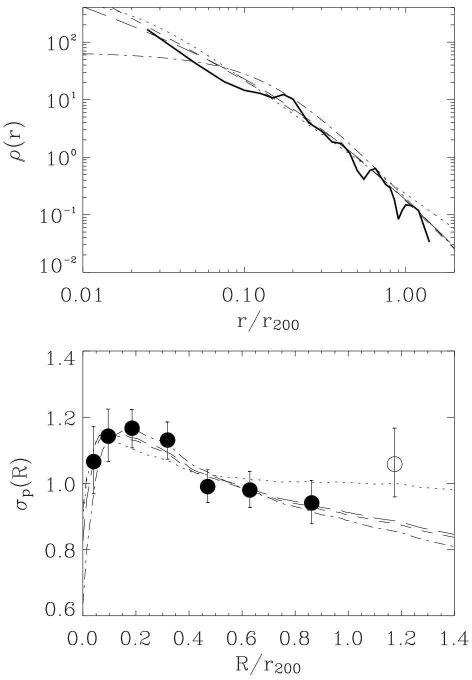

Fig. 1. Top: the observed mass density profile $\rho(r)$ (solid line) compared with 4 models (see text): NFW (long-dashed), M99 (short-dashed), SIS (dotted), B95 (dot-dashed). The vertical scale units are arbitrary. Bottom: the observed velocity dispersion profile of the Early-type galaxies (points with error-bars) and the 4 best-fit model velocity dispersion profiles (same coding as above). Note that the fits do not include the outermost point (open symbol). The vertical scale is in normalised units (each galaxy velocity has been rescaled with the global velocity dispersion of its cluster).

we conclude that the velocity anisotropy of Early-type galaxies is consistent with zero. We therefore assume that Early-type galaxies move on isotropic orbits in the cluster potential.

For the Early-type galaxies, we obtain non-parametric estimates of the projected number-density, and velocity-dispersion profiles, which we de-project using the Abel equations (see, e.g. Binney & Tremaine 1987). The mass profile $M(<r)$ then follows directly from the de-projected profiles, and their logarithmic derivatives (for details see Katgert et al. 2003). The mass density profile, $\rho(r)$, obtained by differentiating the observed $M(<r)$, is shown in the top panel of Fig. 1 (solid line).

We compare our observed mass density profile with four popular mass density models, viz. those of NFW, Moore et al. (1999, M99, hereafter), Burkert et al. (1995, B95, hereafter), and the softened isothermal sphere, SIS herafter (see, e.g. Geller et al. 1999). All these models are characterized by a single parameter, the linear scale. We perform the comparison of these models with our mass profile in the domain of observables, viz. the projected velocity dispersion profile $\sigma_p(R)$. For this we use the Abel projection equations and the inverse Jeans equation (see van der Marel 1994) to calculate $\sigma_p(R)$ given the mass profile $M(<r)$ and the galaxy number density profile. The observed $\sigma_p(R)$ of the Early-type galaxies is shown in the bottom panel of Fig. 1, with the velocity dispersion profiles obtained for the four best-fit mass density models (which are shown in the top panel of Fig. 1). The goodness of fit in the $\sigma_p(R)$ domain is estimated via a standard χ^2-analysis, using only the points within r_{200}, because galaxies at larger radii may not have relaxed to dynamical equilibrium yet. We find that all four models are acceptable. The best-fit values and 68% confidence levels (c.l.) for the scale parameters of the NFW, M99, and B95 models are $0.25^{+0.15}_{-0.10}$, $0.45^{+0.30}_{-0.15}$, and $0.15^{+0.03}_{-0.05}$, respectively, in units of r_{200}. On the other hand, for no value of the scale parameter is the SIS model acceptable at the 68% c.l. or better. The best-fit value for the scale parameter of the SIS model is $0.02\,r_{200}$, i.e. not much larger than the size of a galaxy. If we define the 'core radius' as the radius where the density equals half the central density, we can exclude core radii $> 0.13\,r_{200}$ at $> 99\%$ c.l. for our core models (SIS and B95). This sets an interesting upper limit on the scattering cross-section of any Self-Interacting Dark Matter dominating the cluster potential (Meneghetti et al. 2001).

3. The mass-to-light ratio profile

We compare the total cluster mass density profile with the deprojected 3-D luminosity density profile of the galaxies. The latter, $\mathcal{L}(r)$, is constructed for all galaxies, including those in substructures, since they also contribute to the total cluster luminosity. The average absolute magnitude of our ensemble cluster galaxies is $< M_R >= -21$. Since we are not interested in deriving the absolute value of the cluster mass-to-light ratio, but only its radial behaviour, we do not correct for the unseen cluster members, not sampled by the ENACS. Even if the ENACS is not magnitude-complete, it was shown by Katgert et al. (1998) that the ENACS sampling is independent of radius, apart from the geometric effect related to the observational set-up, which is well known, and corrected for, in the determination of $\mathcal{L}(r)$.

In the top panel of Fig. 2 we show the ratios of the NFW and B95 best-fits to the total cluster mass density profile, to the luminosity density profile of all cluster galaxies. The 68% c.l. account for uncertainties in the profile ratio, as computed for the best-fitting NFW and B95 mass density models. The mass-to-light ratio shows a rapid increase from $r/r_{200} \simeq 0$ to $r/r_{200} \simeq 0.2$, followed by a mild decrease to $r/r_{200} \simeq 0.6$. The reason for the lower mass-to-light ratio in the central regions is the central concentration of the brightest ellipticals (with $M_R \leq -22 + 5 \log h$), while the decrease of the mass-to-light ratio out to $r/r_{200} \simeq 0.6$ is due to the presence of spirals in the outer cluster regions. Once we exclude the bright ellipticals as well as the spirals from the sample on which we compute $\mathcal{L}$, the mass-to-light ratio becomes essentially constant (see bottom panel of Fig. 2).

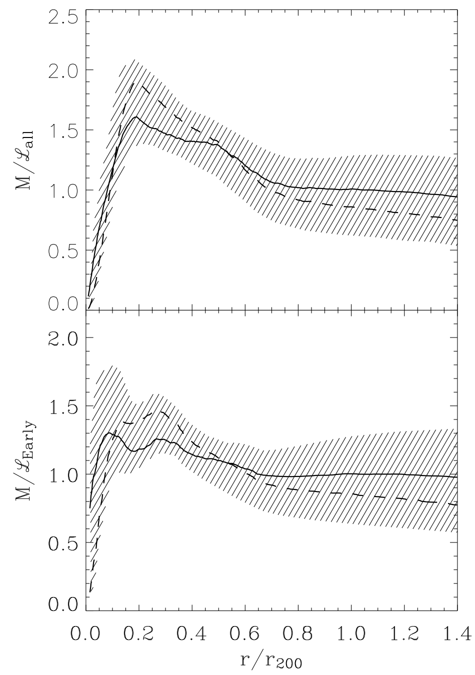

Fig. 2. Top: Differential mass-to-light profile, expressed in normalized units and calculated as the ratio between the cluster total-mass density, $\rho(r)$, and the deprojected 3-D luminosity density profile, $\mathcal{L}_{all}(r)$, of all cluster galaxies. The solid (respectively, dashed) line shows the mass-to-light profile computed using the NFW (respectively, B95) best-fit to $\rho(r)$. The shaded region denotes the 68% uncertainties in the profile ratio, as calculated for the best-fitting NFW and B95 models. The vertical scale units are arbitrary. Bottom: Differential mass-to-light profile, expressed in normalized units and calculated as above, except that the luminosity density profile, $\mathcal{L}_{Early}(r)$ is computed using the Early-type galaxies only. The 68% uncertainties in the profile ratio are calculated as described above.

4. Conclusions

We determine the total mass profile of an ensemble galaxy cluster built from the combination of 59 galaxy clusters observed in the ENACS. We find that both cuspy mass density profiles and profiles with a core provide acceptable fits to our data, but the core radius has to be small ($< 0.13\,r_{200}$ at $> 99\%$ c.l.). The total-mass density is traced remarkably well by the luminosity density of elliptical and S0 galaxies together, but it is less concentrated than the luminosity distribution of the very bright ellipticals, and more concentrated than the luminosity distribution of spirals.

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