TRACING THE MASS PROFILES OF GALAXY CLUSTERS WITH MEMBER GALAXIES

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Abstract. The mass distribution of galaxy clusters can be determined from the study of the projected phase-space distribution of cluster galaxies. The main advantage of this method as compared to others, is that it allows determination of cluster mass profiles out to very large radii. Here I review recent analyses and results on this topic. In particular, I briefly describe the Jeans and Caustic methods, and the problems one has to face in applying these methods to galaxy systems. Then, I summarize the most recent and important results on the mass distributions of galaxy groups, clusters, and superclusters. Additional covered topics are the relative distributions of the dark and baryonic components, and the orbits of galaxies in clusters.

1 Introduction

Knowledge of the mass distribution within clusters, (also in relation to the distributions of the different cluster components), gives important clues about the formation process of the clusters and of the galaxies in them, as well as on the nature of dark matter. There have been many studies of the mass distribution in galaxy systems over the last decade, stimulated by the discovery of the ‘universal’ NFW mass density profile of dark matter haloes by Navarro et al. (1996, 1997).

A cluster mass distribution can be derived in three ways: 1) through the gravitational lensing of distant objects, 2) using the spatial distribution and temperature profile of the X-ray emitting, intra-cluster (IC hereafter) gas, and 3) through the kinematics and spatial distribution of ‘tracer particles’ moving in the cluster potential. Lensing mostly works for clusters at intermediate and large redshifts, and only few nearby cluster lenses are known (see e.g. Cypriano et al. 2004). X-ray observations only sample the inner (see, e.g., Pratt & Arnaud 2002) or, at best, the virialized (Neumann 2005) cluster regions. The third method is particularly suited for studying the mass profiles of relatively nearby galaxy clusters, out of reach for the other two methods.
to large radii, well beyond the virialized region (see, e.g., Reisenegger et al. 2000). Additionally, using galaxy distributions it is also possible to constrain the velocity anisotropies, and hence the orbits, of cluster galaxies (see, e.g., Biviano & Katgert 2004, BK04 hereafter).

In this paper, I review recent results on cluster mass profiles as obtained from the analysis of the spatial and velocity distributions of cluster member galaxies (see Biviano 2002 for another recent review on this topic).

2 Methods & Problems

In order to determine a cluster mass profile, $M(< r)$, using the projected phase-space distribution of its member galaxies we can use the Jeans analysis (see, e.g., Binney & Tremaine 1987, BT87 hereafter), or the 'Caustic' method recently introduced by Diaferio & Geller (1997; see also Diaferio 1999).

In the Jeans analysis the observable projected phase-space distribution of galaxies is related to the cluster $M(< r)$, using the Abel and Jeans equations (eqs. 4-55, 4-57, and 4-58 in BT97, for the simplified case of a stable, non-rotating, spherically symmetric system), through knowledge of the velocity anisotropy profile, $\beta(r)$, which characterizes the orbits of cluster galaxies.

In the Caustic method, one infers $M(< r)$ of a given cluster from the amplitude of the caustics in the plane of line-of-sight velocities vs. projected clustercentric distances. Formally, the caustic amplitude is related to the gravitational potential through a function $F$ of the potential itself, and of $\beta(r)$, (see eqs. 9 and 10 in Diaferio 1999). Numerical simulations indicate $F \approx \text{const}$, but only at radii larger than the cluster virial radius, $r_{200}$ (see Fig. 2 in Diaferio 1999). Hence, for $r < r_{200}$ the Caustic mass estimate is not very accurate. On the other hand, since the method does not rely on the assumption of dynamical equilibrium, it is a very powerful tool to constrain $M(< r)$ at large radii.

Note that both with the Jeans and the Caustic method one samples the total, not the dark mass of a cluster. This must be taken into consideration when observational results are compared with results from numerical simulations of collisionless dark matter haloes. Using X-ray data it is possible to subtract the baryonic component of the total mass and infer the dark mass distribution (see Lokas & Mamon 2003, LM03 hereafter), but this has not been done very often.

A fundamental problem of the Jeans analysis (and, to a lesser extent, also of the Caustic method) is the 'mass–orbit' degeneracy, i.e. the solution obtained for $M(< r)$ is degenerate with respect to the solution obtained for $\beta(r)$. In order to break the degeneracy, $\beta(r)$ must be constrained independently from $M(< r)$. This can be achieved via the analysis of the shape of the galaxy velocity distribution, that contains the required information about the orbital anisotropy of cluster galaxies (Merritt 1987; van der Marel et al. 2000, vdM00 hereafter; LM03). Alternatively, if several tracers of the gravitational potential are available, the Jeans equation can be solved for $M(< r)$ independently for each of the tracers, thus restricting the range of possible solutions (BK04).
Another relevant problem in the Jeans analysis occurs if the cluster is not in steady state and dynamical equilibrium. Since clusters grow by accretion of field galaxies (e.g., Moss & Dickens 1977), they are not steady-state systems. Formally, inclusion of the time derivative in the Jeans equation (BT87, eq. 4-29c) is then needed. On the other hand, the fractional mass infall rate is estimated to be quite negligible for nearby clusters (Ellingson et al. 2001). Moreover, most of the mass is accreted in big, discrete clumps (Zabludoff & Franx 1993). Hence, those clusters undergoing substantial mass accretion can be identified through the presence of substructures in their galaxies distribution, and excluded from the analysis (vdM00; Biviano & Girardi 2003). The problem gets tougher when one is dealing with small galaxy systems (galaxy groups) most of which are probably still in a pre-virialized collapse phase (Giuricin et al. 1998).

Interlopers are another potential problem in cluster mass estimates. Cluster velocity dispersion estimates have been shown to be robust vs. modifications of the method of interlopers removal (Girardi et al. 1993), but estimates of the kurtosis of the velocity distribution (needed to constrain $\beta$, see LM03) are not. Hence, it is advisable to use other, more robust, estimators of the shape of a cluster velocity distribution (e.g., the Gauss-Hermite moments, vdM00). As the number of available redshifts for cluster galaxies increases, the interloper selection procedure becomes more robust. Since in practice spectroscopic samples of more than 100 member galaxies per cluster are rare, quite often a ‘composite’ cluster is built by stacking together the data for several clusters (see, e.g., Carlberg et al. 1997; vdM00; Katgert et al. 2004). The procedure is justified if clusters form a homologous family, as suggested by the existence of a fundamental plane of cluster properties (Schaeffer et al. 1993; Adami et al. 1998).

In the Jeans analysis it is generally assumed that clusters are spherical and do not rotate. The composite cluster is spherically symmetric by construction, and deviation from spherical symmetry is unlikely to be a major problem for individual clusters either (see vdM00; Sanchis et al. 2004). While evidence for cluster rotation has been claimed for a couple of clusters (see, e.g., Biviano et al. 1996; Dupke & Bregman 2001), the energy content in the rotational component is marginal. Finally, dynamical friction and galaxy mergers could in principle invalidate the use of the collisionless Jeans equation. However, the cluster velocity dispersion is too high for galaxy mergers to take place, and the dynamical friction timescale is too long for most cluster galaxies, except for very massive galaxies (e.g., Biviano et al. 1992). These can be removed from the sample (Katgert et al. 2004) prior to application of the Jeans analysis. Galactic mergers in low-velocity dispersion systems, like groups, can however be a critical issue.

3 Results

3.1 Small groups

Since groups contain only a small number of galaxies each, their mass profile can only be inferred by stacking several of them together. Results so far are
contradictory. Mahdavi et al. (1999) used 588 galaxies in 20 groups to conclude that their mass density profile is consistent with a Hernquist (1990) model, and that the mass-to-galaxy number-density profiles ratio is constant. Mahdavi & Geller (2004) used the RASSCALS sample (893 galaxies in 41 nearby groups) to determine a single power-law mass density profile, $\rho(r) \propto r^{1.9\pm0.3}$ over a wide radial range ($0\text{--}2r_{200}$). Finally, Carlberg et al. (2001) analysed $\sim800$ galaxies in $\sim200$ groups from the CNOC2 survey, at redshifts $z=0.1$--0.55. They found a cored mass density profile near the groups centres, decreasing outside with a shallow slope, hence implying a steeply increasing mass-to-light ratio with radius.

Despite these different results, all these studies conclude that galaxies in groups have, on average, nearly isotropic orbits, except late-type galaxies that are on mildly radial orbits (Mahdavi et al. 1999).

### 3.2 Clusters

The Coma cluster, with its nearly 900 spectroscopically confirmed cluster members (Adami et al. 2005), is probably the best studied cluster in the Universe. Leaving apart historical studies (see Biviano 1998 and references therein), the first modern analysis of the Coma cluster mass profile was done by Merritt & Saha (1993). They found that the density profile is cuspy near the centre, $\rho(r) \propto r^{-2}$, and decreases as $\rho(r) \propto r^{-4}$, at large radii, if the orbits are isotropic. More recently, LM03 found that the NFW profile provides a good fit to the derived mass distribution, but other models are acceptable, and even a cored profile near the centre cannot be excluded. At variance with Merritt & Saha, and unlike most other studies, LM03 analysed the dark, not the total, mass profile of the cluster. Using the kurtosis profile of the galaxies velocity distribution, they obtained $-1.2 \leq \beta \leq 0.3$ for early-type galaxies, i.e nearly isotropic orbits.

The above results are in agreement with those obtained through the Caustic method (Geller et al. 1999; Rines et al. 2001). These studies also constrained the behaviour of the mass density profile at very large radii, $\rho(r) \propto r^{-\zeta}$ with $\zeta = 3$--4. The isothermal sphere model ($\zeta = 2$) is rejected, while both a NFW and a Hernquist (1990) model are acceptable. The mass-to-light ratio in the $K$-band is found to be nearly constant out to $\sim 6r_{200}$.

In a series of papers, Rines et al. (2000, 2003, 2004) have applied the Caustic technique to another 8 nearby clusters of the CAIRNS survey. The results are not very different from those found for the Coma cluster. Typically, $\rho(r) \propto r^{-1}$ near the centre, and the best-fit asymptotic slope of the mass density profile at large $r$ is either $-3$ (NFW) or $-4$ (Hernquist 1990). When the NFW profile is adopted, the best-fit values of the concentration parameter $c$ vary between 5 and 17. Using the mass profiles obtained from the Caustic technique in the Jeans analysis, $\beta \approx 0$ is obtained. The mass-to-light ratio in the $K$ band is approximately constant out to $r_{200}$, then decreases by a factor $\times 2$ out to the turnaround radius.

Following up a previous study by Carlberg et al. (1997), vdM00 stacked together 16 clusters at $z = 0.17$--0.55 from the CNOC survey, to build a composite cluster with $\sim990$ galaxies. Through the analysis of the shape of the galaxies
velocity distribution, vdm00 were able to constrain $-0.6 \leq \beta \leq 0.1$. From the Jeans analysis they then determined a mass profile which is fully consistent with a $c = 4.2$ NFW model. The ratio between the mass density profile and the galaxies number density profile was found to be nearly constant.

Biviano & Girardi (2003) analysed a composite cluster of 1345 member galaxies, obtained from the stacking of 43 clusters from the 2dFGRS. They performed a joint Jeans and Caustic analysis, using the former method to determine the mass profile in the virialized region ($\leq r_{200}$), and the latter to extend $M(< r)$ to $2 r_{200}$. I.e. they used each of the two methods in the cluster region where it is expected to perform best. They found that a $c = 5.6$ NFW profile fits the data over the whole radial range explored. Cored profiles are also acceptable but only for core radii $< 0.1 r_{200}$. The ratio of the mass density to the galaxy number density profiles was found to be constant out to $r_{200}$, and to decrease beyond that, mostly because of the contribution of late-type galaxies in the external regions.

![Figure 1](image_url)

Fig. 1. The average circular velocity profile, $V_c \equiv \sqrt{G M(< r)/r}$, of 59 clusters from the ENACS (points with 1-$\sigma$ error bars). The solid, dot-dashed, and dashed lines are the best-fit NFW, Burkert (1995), and softened isothermal sphere models, respectively.

Katgert et al. (2004) analysed a composite of 1129 galaxies from 59 nearby clusters from the ENACS. $M(< r)$ was determined in a fully non-parametric way. Only early-type galaxies were used in the analysis. Their velocity distribution was showed to imply nearly isotropic orbits, hence $\beta \equiv 0$ was adopted in the Jeans analysis. The resulting mass density profile has a slope of $-2.4 \pm 0.4$ at $r = r_{200}$,
fully consistent with an asymptotic slope of $-3$ at larger radii. Both a $c = 4 \pm 2$ NFW profile, and a Burkert (1995) profile with a rather small core ($\leq 0.1 r_{200}$) are acceptable (see Figure 1). The ratio of the mass-to-luminosity density profiles (in the $R$ band) is nearly constant out to $\sim 1.5 r_{200}$, when both the cD-like galaxies (that give an excess luminosity near the centre), and the late-type galaxies (that give an excess luminosity in the outer regions) are excluded.

The $M(<r)$ solution obtained for the early-type galaxies was later confirmed by using a different tracer of the gravitational potential, early-type spirals (Sa–Sb; BK04). Inverting the Jeans equation (via the method of Solanes & Salvador-Solé 1990, developed from Binney & Mamon 1982), BK04 found that also early-type spirals have nearly isotropic orbits in the cluster potential. On the other hand the late spirals (Sbc–Sd) plus irregulars have $\beta \approx 0$ only near the centre, and increasingly radial orbits outside. Galaxies in substructures were found to have tangential orbits at all radii.

Work is in progress (Biviano & Salucci in preparation) to determine the relative distributions of the different mass components, namely the baryonic matter (in galaxies and in the intra-cluster gas), the dark matter in subhaloes, and the diffuse dark matter. Preliminary results indicate that once the baryons and the dark matter subhaloes are subtracted from the total mass profile, the remaining diffuse dark matter profile is still consistent with both a Burkert (1995) and a NFW model, but the concentration is a factor of two higher than for the total mass profile. The galaxy baryonic mass profile is found to be similar to the total mass profile, but the total baryonic mass is more widely distributed, because of the dominant contribution by the IC gas.

3.3 Superclusters

Superclusters are not virialized systems. It is then impossible to determine their mass profile other than by the use of the Caustic method. Reisenegger et al. (2000) and Rines et al. (2002) applied this method to the Shapley and the A2197/A2199 supercluster, respectively. The superclusters mass profiles are well fit by both a NFW and a Hernquist (1990) model.

4 Summary and perspectives

Useful constraints can be put on the mass distribution within clusters from the analysis of the projected phase-space distribution of their member galaxies. The constraints are poor near the centre, $\rho(r) \propto r^{\xi}$ with $-2 \leq \xi \leq 0$, because of an intrinsic finite resolution (the size of the cD galaxy). Cored profiles are allowed, but only for core sizes below this resolution size, $\leq 0.1 r_{200}$. Stronger constraints are obtained at large radii, and they are stronger than those obtained with any other methods, $\rho(r) \propto r^{\zeta}$ with $-4 \leq \zeta \leq -3$. In summary, the isothermal sphere is ruled out, while the NFW, Burkert (1995) and Hernquist (1990) models are acceptable.
When comparing a cluster mass density profile with the galaxy number (or luminosity) density profiles, it must be realized that the result of this comparison depends upon which cluster galaxy population (or, almost equivalently, which photometric band) is considered. More relevant is the comparison of the total mass distribution with the baryonic mass distribution. The galaxy baryonic mass profile is similar to the total mass profile, but the total baryonic mass distribution (including the IC gas) is more extended.

As far as the orbits are concerned, ellipticals, lenticulars, and early-type spirals (Sa–Sb) are all found to be on nearly isotropic orbits. Late-type spirals (Sbc-Sd) and irregulars have increasingly radial velocity anisotropy with increasing radius, and galaxies in substructures seem to be characterized by tangential orbits. The implications of these results for the evolution of galaxies in clusters is discussed in BK04.

Very little is known about the evolution of cluster dynamics with redshift. The average mass profile and the orbital characteristics of galaxies of nearby clusters (ENACS, CAIRNS, 2dFGRS) are similar to those of medium-distant clusters (CNOC). Hence, little or no evolution over \(z \sim 0–0.5\) is implied (see also Girardi & Mezzetti 2001).

In the near future it will be possible to use the SDSS products (see e.g. Goto 2005) to reduce the current uncertainties on the dynamics of nearby clusters. It is also urgent to improve our understanding of the dynamics of small galaxy systems (groups). A promising data-set in this respect is the GEMS groups sample of Osmond & Ponman (2004), for which also X-ray temperatures are available. These can provide robust scaling parameters for the build-up of a composite group sample. Determining the average mass profile (and galaxy orbits) of distant clusters (\(z > 0.5\)) is a more demanding task. Distant clusters are likely to be in a more turbulent phase of their evolution than nearby clusters, making the dynamical analysis even more difficult. As a consequence, a deeper sampling of the projected phase-space distribution of member galaxies is needed, with a strong investment in terms of observing time (e.g. Demarco et al. 2005).

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