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X-RAY MEASUREMENTS OF THE SHAPES OF CLUSTERS AND GALAXIES

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Abstract

We summarize a series of papers reporting studies of the ellipticities of X-ray images of five Abell clusters and two early type galaxies to learn about the shape of the gravitational potential and the underlying matter distributions. For the clusters we find the dark matter is centrally concentrated with ellipticity $\epsilon_{DM} \sim 0.5$. For the galaxies we find independent evidence for extended, flattened dark matter halos. One case of a clear isophotal twist in the X-rays may indicate a triaxial halo.

1. Introduction & Method

The shapes of X-ray images of clusters and early type galaxies provide information about presence and distribution of dark matter in those systems (see Binney & Strimpel 1978, Buote & Canizares 1992, 1994, 1996a, 1996b, 1996c, 1996d; Canizares & White 1987). Specifically, we can obtain independent, *geometrical evidence* for the presence of dark matter (independent of the X-ray temperature, for example), giving a robust test of the hypothesis that "mass follows light," and an independent measure of the ratio of luminous matter to dark matter. We can also learn about the shape of the overall distribution of matter, probing the two-dimension flattening or three-dimensional triaxiality and placing independent constraints on the radial distribution. Such information is valuable for constraining formation scenarios and for making comparisons to N-body codes, mass distributions deduced from gravitational lensing studies, and observations in other wavebands.

The key assumption is that the X-ray emitting gas that we are observing in these systems is in or near hydrostatic equilibrium. Recall that the timescales for equilibration in the centers of clusters and throughout elliptical galaxies are short compared to the lifetimes of the systems. The major threat to the method for clusters is the possibility that equilibrium has been disturbed by a recent merger. Other complications include the possible distortions in the outer parts of the interstellar medium (ISM) in galaxies due to external pressure from an intracluster medium (ICM), and possible emission from multiple phases in the ISM or ICM. One can minimize these by choosing cases with relatively smooth images to avoid obvious recent mergers, searching for temperature anomalies and testing for reflection symmetry. Also, since we use a low moment of the X-ray distribution, we are relatively insensitive to modest substructures. For galaxies, the possibility of flattening due to rotation and contamination from point sources need to be considered explicitly.

One can test susceptibility to substructure by exercising the method using N-body plus hydro simulations. Buote & Tsai (1995) analyzed a simulated cluster from Katz and White (1993) at various epochs. At late epochs, $z \leq 0.25$, when the simulated cluster looks relatively smooth, the X-ray gas appears to trace the gravitational potential, and our method does accurately measure the underlying matter distribution. At earlier epochs the gas is not relaxed and the X-rays themselves trace the matter distribution rather than the potential.

As a reminder, the traditional application of hydrostatic equilibrium to analysis of X-ray images relies on the radial distributions of X-ray surface brightness and temperature to deduce the radial distribution of the total gravitating mass (e.g. see Bohringer, this volume). The main difficulty is usually in obtaining a good temperature measurement at larger radii.

Our method instead exploits the fact that for gas in hydrostatic equilibrium the isopotential surfaces are also the isodensity and isotemperature surfaces (BC94, BC96). One can show that projection effects are generally not of concern, so that the projected X-ray surface brightness is a good tracer of the shape of the potential. In particular this provides a robust test of the hypothesis that mass follows light .

Qualitatively, the isopotential surfaces of an elliptical spheroidal shell of matter (a so-called homoeoid) are themselves elliptical spheroids which are confocal to the homoeoid (Chandrasekar 1969, Binney & Tremaine 1987). Thus the ellipticity of the isopotentials falls rapidly with increasing distance from the homoeoid. For example, the isopotentials of a mass shell with ellipticity $\epsilon \sim 0.7$ and semi-major axis a have $\epsilon \sim 0.24$ at $1.5a$ and $\epsilon \sim 0.06$ at $2.6a$ (see Binney & Tremaine 1987, fig. 2-9).

This means that if the visible light and X-rays come from roughly the same radius, as is roughly the case for clusters, then they should have similar ellipticities; if not, one can conclude that the light cannot be tracing the mass. Conversely, if the X-rays are more extended than the light, the X-ray isophotes must be nearly round if light traces mass; if the extended X-ray isophotes show sizeable ellipticity, this indicates presence of a dark matter component that is both elliptical and extended.

Quantitatively, we construct an extensive grid of models based on a variety of assumed matter distributions, characterized by radial distribution and shape. We compute the potential, fill it with gas and compare the resulting model X-ray distribution to the observations. There is only one adjustable parameter beyond those that characterize the matter distribution, and that is the ratio of the specific gravitational energy to thermal energy at the center, $\Gamma = \frac{\mu m \Phi_0}{k T_x}$, where μm is the mean mass per particle, Φ_0 is the central potential, k is Boltzmann's constant and T_x the gas temperature. We can constrain Γ observationally by fitting the observed X-ray radial profile; no actual temperature measurement is required (although it can be used separately with the derived Γ to constrain Φ_0). We iterate many times to explore whole families of models and map out the permitted values of the shape parameters. Generally we assume the gas is isothermal, as is generally consistent with observations. We have also explored temperature gradients, and find that they have small effect on the shape of the permitted matter distributions but can alter their radial profiles.

One sidelight is that these shape studies provide interesting tests of the alternate explanation of the "dark matter problem" known as Modification of Newtonian Dynamics or MOND (e.g. Milgrom 1986). MOND attributes the well-know flat rotation curves to a break down of Newtonian dynamics at very small accelerations. We have argued that MOND cannot explain mismatches in the *shapes* of visible and X-ray isophotes (BC94).

2. Clusters of Galaxies

We applied our method to five, well known, rich Abell clusters, A401, A1656 (Coma), A2029, A2199, and A2256 (BC92, BC96b), all of which have flattened galaxy distributions on the sky, with $\epsilon \sim 0.4 - 0.6$. We first used Einstein images (BC92), but the improved angular resolution of more recent ROSAT data has led us to modify our original conclusions. The ROSAT data reveal a significant ellipticity gradient in four of the five clusters (the exception is Coma, which is large enough that we would not see a similar gradient). Examples are shown in Figure 1a. Typically, we find $\epsilon_x \sim 0.25 - 0.3$ at $0.35 h_{80}^{-1}$ Mpc falling to $\epsilon_x \sim 0.15$ at $1 h_{80}^{-1}$

Fig. 1. The observed ellipticity of X-ray isophotes for several Abell clusters vs. radius from the ROSAT PSPC (BC96b).

Mpc. In all cases, the position angles of the X-ray and optical distributions are within the XXX degree uncertainties.

One conclusion is that the matter giving rise to the potential, which for clusters is known to be mostly dark matter, is more centrally concentrated than the X-ray gas. Qualitatively, this follows from the fact that the X-rays and galaxies occupying roughly the same regions have different ellipticities. The quantitative analysis supports this conclusion – for example a distribution with density falling like r^{-2} (as in a self-gravitating isothermal spheroid) cannot explain the data. A flattened spheroidal mass distribution with $\epsilon \sim 0.5$, as observed for the galaxies, but falling more steeply, like r^{-4}, does work (the exact radial shape depends on the assumed temperature gradient). Therefore (contrary to our original conclusions in BC92 which assumed constant ϵ_x) we find that the *shape* of the dark matter distribution can be similar to the shape of the visible matter, though they likely have different radial distributions. Our analysis also gives revised values of gas and baryonic mass fractions that are consistent with previous results (e.g White & Fabian 1995).

3. Early Type Galaxies

We studied two flattened, early type galaxies, inconclusively with Einstein (Canizares & White 1987), then with ROSAT and now ASCA (BC94, BC95, BC96c). Optically, NGC 720 has $\epsilon \sim 0.4$ and NGC 1332 has $\epsilon \sim 0.7$. Both are relatively isolated galaxies, and both are relatively slow rotators. Therefore they are unlikely to be significantly disturbed by external pressure or nearby companions. Both are at distances of approximately 20 Mpc. The best results are obtained for NGC 720, which is brighter; NGC 1332 gives a consistent picture at somewhat lower significance.

We find X-ray ellipticities of $\epsilon_x \sim 0.2 - 0.3$ out to 10 kpc and beyond. As for most ellipticals, the visible light is very concentrated, with core radius $\leq 1 kpc$, so the potential from any mass distribution traced by the visible light would be nearly spherical at 10 kpc. Thus, the ellipticity of the X-ray isophotes alone constitutes *geometrical evidence* for the existence of a flattened dark matter halo. NGC720 shows an intriguing isophotal twist, described below,

Fig. 2. The position angle of the elliptical isophotes of NGC 720 vs. radius from the ROSAT HRI (BC96d). The solid and dashed lines, respectively, indicate the position angles and approximate radial ranges for the optical isophotes and for X-ray isophotes at larger radii from the ROSAT PSPC.

which is further evidence for dark matter.

Quantitatively, we explored a wide range of models for comparison to the observations, adding progressively more and more dark halo until we can account for the observed X-ray ellipticities at large radii. The models include a mass component distributed like the stars, a dark halo, and, in some cases, X-ray emission from discrete sources distributed like the stars. We also considered effects of rotation at the stellar velocity, which are negligible for NGC 720 but could each account for approximately $\epsilon = 0.1$ in NGC 1332. We find that the dark halo must contain at least four times the mass component distributed like the stars (out to 25 kpc). The overall mass to light ratio is 30-50, and the ellipticity of the dark matter distribution is $\epsilon_{DM} \sim 0.5$.

ASCA is particularly helpful in constraining the possible contribution of discrete sources, which could be contributing to the apparent X-ray ellipticity in NGC 1332 (but is probably negligible in NGC 720). Our observation shows clearly that NGC 1332 does have excess emission above 3 keV that could not be from the hot, ISM and is most plausibly from the discrete source population (BC96d). This constitutes approximately 25-50 % of the 0.4-2.4 X-ray keV flux of the galaxy.

Our original ROSAT PSPC image of NGC720 just barely resolved what appeared to be a "twist" of about 30 degrees in the isophotal position angle at a radius of about an arc minute (BC94). We subsequently obtained ROSAT HRI data that confirms the twist (BC96c). Figure 2 shows that the X-ray emission is aligned with the stars at small radii but then twists to the same value measured with the PSPC. Dark matter, possibly in a triaxial distribution, is clearly indicated.

4. Conclusion

Our analyses of the ellipticities of five flattened clusters and two flattened early type galaxies with ROSAT and ASCA lead us to the following conclusions: For the clusters of galaxies:

- the mass is not distributed like an isothermal sphere
- the dark matter distribution is steep ($\sim r^{-4}$) at large radii (for isothermal gas)
- the dark matter is flattened with $\epsilon_{DM} \sim 0.5$
- the ellipticity and position angle of the dark matter are consistent to those of the galaxy distribution

For the early type galaxies:

- the bulk of the mass does *not* follow the light
- dark matter halo is extended and flattened
- spectral studies constrain the contribution from discrete sources to the observed X-ray ellipticity
- the observed position angle twist may indicate triaxiality

The cluster findings complement and are consistent with what is being learned from gravitational lensing studies of arcs and arclets (e.g., Allen, Fabian & Kneib 1996, Pierre *et al.* 1996) and with expectations from N-body simulations (e.g., Efstathiou *et al.* 1988, Navarro, Frenk & White 1995). Similarly, the galaxy results add support to we know about flattening from polar ring galaxies and agree with expectations of dissipationless collapse (e.g., Dubinsky & Carlberg 1991, Rix 1994, Sacket 1995). We believe that MOND cannot obviate this *geometrical evidence* for the presence of large quantities of dark matter in clusters and galaxies. Finally, we suggest that the method can be powerfully applied to many more systems using the quality of data that will be obtained by AXAF.

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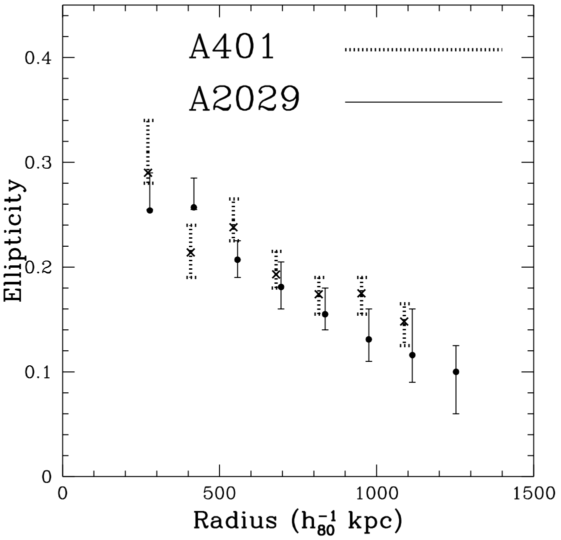
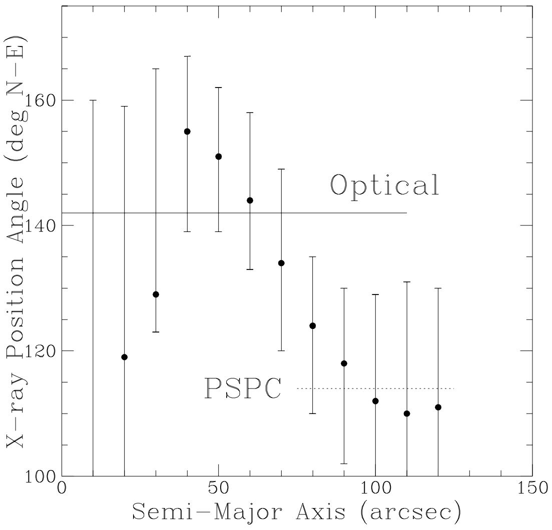

A401
A2029
Ellipticity
0
0.1
0.2
0.3
0.4
0
500
1000
1500
Radius (h_{80}^{-1} kpc)


X-ray Position Angle (deg N-E)
100
120
140
160
0
50
100
150
Semi-Major Axis (arcsec)
Optical
PSPC