MASS DISTRIBUTIONS IN ELLIPTICAL GALAXIES AT LARGE RADII

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ABSTRACT. Recently, x-ray observations have shown that elliptical galaxies generally contain large quantities of hot gas. Central dominant cluster ellipticals have even more gas, which they have accreted from the surrounding clusters. The mass distributions in these galaxies can be derived from the condition of hydrostatic equilibrium. M87, the best studied central dominant galaxy, has a massive, dark halo with a total mass of about 4×10^{12} $M_\odot$ within a radius of 300 kpc. The total mass-to-light ratio within this radius is at least 150 $M_\odot/L_\odot$. The x-ray observations of normal ellipticals also strongly suggest that they have heavy haloes, although the distribution of the mass is much less certain than in M87.

1. INTRODUCTION

Do elliptical galaxies have heavy haloes of optically dark matter? The rotation curves of spiral galaxies require that they possess such haloes (Rubin, Ford, and Thonnard 1980), but ellipticals generally lack extended disks of gas or stars which would allow a determination of their rotation curves at large radii. Recent x-ray observations show that these galaxies do generally have extensive coronae of very hot gas (Forman, Jones, and Tucker 1985; Trinchieri and Fabbiano 1985). If the profiles of gas density and temperature can be derived from the x-ray observations, then the mass distribution of the galaxy can be determined from the condition of hydrostatic equilibrium (Sec. 2). At least crudely, elliptical galaxies can be divided into two classes based on their x-ray properties. Many central dominant cluster galaxies are accreting large amounts of hot gas from their surrounding cluster, and are very luminous in x-rays. M87 in the Virgo

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cluster is the best studied example of this class, and its mass distribution (and that of other central dominant galaxies) is discussed in Sec. 3. Normal elliptical galaxies have quantities of hot gas in reasonable agreement with the expected rates of stellar mass loss within the galaxies, and as a result have lower x-ray luminosities than the central dominant ellipticals. The less complete information we have on the mass distributions of normal ellipticals is described in Sec. 4.

All numerical values quoted in this paper assume a Hubble constant of H_o = 50 km/s/Mpc and a distance to the center of the Virgo cluster of 20 Mpc.

2. HYDROSTATIC EQUILIBRIUM

Masses for elliptical galaxies can be derived by assuming that the x-ray emitting gas is in hydrostatic equilibrium with the gravitational field of the galaxy. This is a reasonable assumption as long as the galaxy is stationary (the gravitational potential does not change on a sound-crossing time), other forces (magnetic fields, etc.) are negligible, and the gas motions are significantly subsonic. This latter condition requires, first of all, that rotation in the gas be dynamically unimportant. This is consistent with the fact that neither large elliptical galaxies nor clusters of galaxies rotate significantly (see, for example, the paper by Davies in this Proceedings), and that the x-ray isophotes of central dominant and normal ellipticals are fairly circular, except in their outermost regions. The gas in these galaxies cannot be in supersonic inflow or outflow; since the sound crossing time for a galaxy is much shorter than gas cooling time, supersonic motions would remove the gas faster than it could radiate, and a very large source of gas would be required to explain the observed x-ray emission. In particular, the cooling inflows that are commonly seen in central dominant and normal ellipticals (see Secs. 3 and 4 and the paper by Fabian in this Proceedings) are very subsonic, except possibly in their innermost regions.

Under these circumstances, the gas obeys the hydrostatic equation

$$\vec{\nabla} P = -\rho \vec{\nabla} \phi \qquad (1)$$

where P and ρ are the gas pressure and density, and ϕ is the gravitational potential of the galaxy. The distribution of the total galaxy mass can then be derived from the variation of the gas pressure and density. This method has several advantages over stellar dynamic methods, using the radial velocity dispersion of stars or the individual radial velocities of globular clusters or companion galaxies, for determining the mass distributions of ellipticals at large radii. First, the gas is a collisional fluid, and the particle velocities are isotropically distributed. On the other hand, stars in galaxies (or globular clusters or companion galaxies) are collisionless, and uncertainties in the distribution of particle orbits can significantly influence the derived mass distribution (see, for example, Tonry 1983).

Second, the gas extends to large distances from the galaxy center, and it is easier to measure the density and temperature of the gas than it is to measure the velocity distribution of the stars in the outer regions of the galaxy. Third, the statistical errors in x-ray mass determinations are much smaller than those for globular clusters or companion galaxies. Finally, x-ray mass determinations are not very sensitive to the shape of the galaxy (Strimpel and Binney 1979; Fabricant, Rybicki, and Gorenstein 1984).

The first applications of x-ray distributions to derive mass distributions in galaxies were by Bahcall and Sarazin (1977) and Mathews (1978) in M87. The method has been developed extensively by Fabricant, Gorenstein, and collaborators (Fabricant, Lecar, and Gorenstein 1980; Fabricant and Gorenstein 1983; Fabricant, Rybicki, and Gorenstein 1984). Ideally, one would measure the spatially and spectrally resolved x-ray surface brightness of the galaxy $I_\nu(\vec{b})$, where $h\nu$ is the x-ray photon energy and $\vec{b}$ is the projected position relative to the center. This would be inverted to give the local x-ray emissivity $\varepsilon_\nu(\vec{r})$, where $\vec{r}$ is the position relative to the cluster center. This deconvolution is stable because the observed x-ray images of galaxies are quite smooth except in the outermost regions (Forman, Jones, and Tucker 1985; Trinchieri and Fabbiano 1985). To deconvolve the projected surface brightness one must assume that the actual gas distribution is spherical or spheroidal (Strimpel and Binney 1979) or, more generally, has an axis of symmetry in the plane of the sky (Fabricant, Rybicki, and Gorenstein 1984). However, the resulting mass distributions are not affected strongly by the shape. For a spherical cluster, the Abel integral inversion for $\varepsilon_\nu(\vec{r})$ is:

$$\varepsilon_\nu(\vec{r}) = -\frac{1}{\pi}\frac{d}{dr^2}\int_{r^2}^{\infty}\frac{I_\nu(b)\,db^2}{(b^2-r^2)^{1/2}} \quad . \tag{2}$$

The x-ray emissivity of a hot plasma depends on its electron density n_e, its temperature T, and its abundances (Sarazin and Bahcall 1977)

$$\varepsilon_\nu = n_e^2\,\Lambda_\nu\,(T,\ \text{abundances}) \quad . \tag{3}$$

Heavy elements mainly produce discrete line features in x-rays; the strength of these features determines the heavy element abundances. The x-ray continuum is exponential $\varepsilon_\nu \propto \exp(-h\nu/kT)$, and thus the spectral shape of the emissivity $\varepsilon_\nu(r)$ determines T(r), while its normalization gives $n_e(r)$. Then the hydrostatic equation gives the total mass M(r) interior to r as

$$M(r) = -\frac{k\,T(r)r}{\mu\, m_p\, G}\left\{\frac{d\log n_e}{d\log r} + \frac{d\log T}{d\log r}\right\} \quad , \tag{4}$$

where μ is the mean molecular weight. It is important to note that the mass depends only weakly on $n_e(r)$ (only on its logarithmic derivative), but depends strongly on the temperature profile T(r).

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3. M87 AND OTHER CENTRAL DOMINANT CLUSTER GALAXIES

Many central dominant cluster galaxies contain large amounts of hot gas, which they are accreting from the surrounding cluster. These cluster cooling flows have been reviewed by Fabian, Nulsen, and Canizares (1984), by Sarazin (1986a), and by Fabian in these Proceedings. The x-ray emission from this gas can be used to determine the distribution of mass around these central dominant galaxies.

M87 in the Virgo cluster is the nearest, brightest, and best studied example of a central dominant cluster galaxy with a cooling flow. (However, it has a much less x-ray luminous cooling flow than the typical, more distant, optically luminous central dominant cluster galaxy.) The most successful application of x-ray measurements for the mass determination of an elliptical galaxy has been to M87, because this galaxy has the best determined temperature distribution.

Originally, Bahcall and Sarazin (1977) and Mathews (1978) suggested that M87 must have a very high mass if it gravitationally binds its x-ray emitting gas. Bahcall and Sarazin found a mass of 1-6 × 10^{13} $M_\odot$ within several hundred kiloparsecs. However, the temperature distribution in the gas was not known at that time, and thus these estimates were very uncertain (Binney and Cowie 1981). Observations with the *Einstein* x-ray observatory permitted a definitive determination of the mass profile in M87 (Fabricant, Lecar, and Gorenstein 1980; Fabricant and Gorenstein 1983; Stewart *et al*. 1984). The results are shown in Figure 1. The hatched area gives the allowed area for the x-ray derived mass from Fabricant and Gorenstein (1983), while the solid curve is the best-fit mass model of Stewart *et al*. (1984). The dots give the mass determined from the optical velocity dispersion measurements of Sargent *et al*. (1978), assuming isotropic stellar velocities. The Stewart *et al*. model was constrained to roughly fit the optical data, and involved a comparison to low ionization x-ray lines that may help constrain the mass distribution at intermediate radii $10 \lesssim r \lesssim 100$ kpc.

Figure 1 shows that M87 has a very massive halo, with a total mass

$$M \approx 3\text{-}6 \times 10^{13}\ M_\odot \left(\frac{r}{300\ \text{kpc}}\right) \quad . \tag{5}$$

The material providing this mass is quite dark; beyond 100 kpc, the total mass-to-light ratio is $(M/L_B)_{tot} > 150\ M_\odot/L_\odot$, and the local value is $(M/L_B)_{loc} > 500\ M_\odot/L_\odot$.

The mass distribution in the outer regions of M87 is roughly consistent with $M \propto r$, implying an approximately constant velocity dispersion. However, the same proportionality between mass and radius that applies in the outer region overestimates the mass in the interior region ($r \lesssim 10$ kpc) by a factor of about 5. In other words, the implied radial velocity dispersion (assuming isotropic orbits) increases from ~300 km/s to ~600 km/s in the outer regions. This is a considerably different behavior than observed in spiral galaxies (Rubin, Ford, and Thonnard 1980), where the circular velocity remains roughly constant in the outer regions of the galaxy.

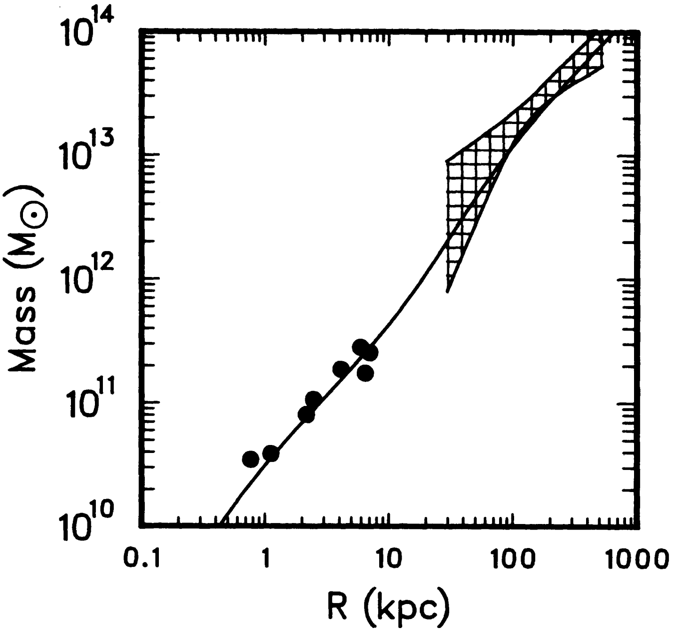

Fig. 1. The mass distribution in M87, assuming a distance of 20 Mpc. The hatched area gives the range of masses determined from the x-ray data by Fabricant and Gorenstein (1983). The solid line is the best fit model from Stewart et al. (1984). The filled circles are masses derived from the optical velocity dispersion measurements of Sargent et al. (1978), assuming isotropic stellar orbits.

The dark matter is strongly concentrated to the center of M87; Stewart et al. (1984) find that the core radius of the dark matter is less than 50 kpc. This is smaller than the typical core radius determined for clusters of galaxies of ~250 kpc. Moreover, there are no other bright galaxies within the region of the x-ray measurements and M87 provides the great majority of the optical luminosity from this region, so it seems reasonable to associate the dark matter with M87.

The x-ray observations of other central dominant cluster galaxies suggest that they also have dark, heavy haloes, although the temperature profiles are not very well determined in these other cases. Matilsky, Jones, and Forman (1985) find a total mass of 2×10^{13} $M_\odot$ with 200 kpc for NGC 4696 at the center of the Centaurus cluster. This central dominant galaxy and cluster are very similar in most x-ray and optical properties to M87/Virgo. Fabian et al. (1981) find a total mass of ~7×10^{13} $M_\odot$ within 300 kpc of NGC 1275 in the Perseus cluster. Central dominant galaxies in poor clusters also show evidence for massive, dark haloes (Kriss, Cioffi, and Canizares 1983; Malumuth and Kriss 1986), with typical total mass-to-light ratios of ~100 $M_\odot/L_\odot$ at radii of ~100 kpc.

Central dominant cluster galaxies have many special properties (see the paper by Tonry in this Proceedings). Although these galaxies do appear to have heavy haloes, the dark halo material might be associated with the location of these galaxies near the kinematic centers of clusters. Thus it is important to determine the mass profiles of more isolated, normal elliptical galaxies.

4. NORMAL ELLIPTICAL GALAXIES

Recent x-ray observations indicate that essentially all elliptical galaxies that are not in the cores of rich compact clusters have extended x-ray emission (Forman, Jones, and Tucker 1985; Trinchieri and Fabbiano 1985; Nulsen, Stewart, and Fabian 1984). These galaxies have x-ray luminosities of $L_x \sim 10^{39}$–10^{42} ergs/s, and sizes of typically $R_x \sim 50$ kpc. There is a strong correlation between the x-ray and optical luminosities of the galaxies $L_x \propto L_B^{1.6-2.0}$, where L_B is the blue luminosity. It seems most likely that the x-ray emission is thermal with typical gas temperatures $T \sim 10^7$ K. The gas densities in the inner parts of the coronae exceed 0.01 cm^{-3}, and vary roughly as $r^{-3/2}$. The total gas mass is typically $M_g \sim 10^9$–10^{10} $M_\odot$, and the ratio of gas mass to luminous stellar mass M_* is typically $M_g/M_* \sim 0.02$. (See the papers by Fabian and by Canizares, Fabbiano, and Trinchieri in this Proceedings.)

The x-ray observations show that elliptical galaxies are gas-rich systems. Apparently, they do not have the global galactic winds suggested by Mathews and Baker (1971). Instead, the observations are basically consistent with a simple cooling flow model in which the x-ray emitting gas is the result of mass loss by stars. This gas is heated by the motions of the mass losing stars and by infall in the galactic gravitational potential, cools radiatively, and slowly flows inward in the galaxy (Nulsen, Stewart, and Fabian 1984; White and Chevalier 1984; Canizares 1987; Fabian 1987; Sarazin 1986b, 1987; Sarazin and White 1986; Thomas et al. 1986; Trinchieri, Fabbiano, and Canizares 1986).

The presence of this x-ray emitting gas means that mass profiles for these galaxies can be derived from hydrostatic equilibrium. Unfortunately, there is essentially no direct information about the temperature profiles T(r) in these galaxies; even the average temperatures for the x-ray image are very poorly determined. The main reason the temperature profiles are so poorly known is that these normal elliptical galaxies are much less luminous in x-rays than M87 (10^{41} versus 10^{43} ergs/s), but are typically at about the same distance.

Forman, Jones, and Tucker (1985) estimated masses for several galaxies assuming that the gas temperature was isothermal at $T(r) = 1.2 \times 10^7$ K. The hydrostatic equation was applied out to the largest radius at which x-ray emission was observed. Table 1 lists the results of their analysis, including the average temperatures derived from the x-ray spectra, the radius of the x-ray image, and the derived mass and mass-to-light ratios. Note that the mass-to-light ratios range from roughly 5-100 $M_\odot/L_\odot$, with an average value of ~40 $M_\odot/L_\odot$. Based on these results, Forman, Jones, and Tucker suggested that elliptical galaxies did indeed possess massive dark haloes.

Table 1. Masses of Normal Elliptical Galaxies from Forman, Jones, and Tucker (1985).

Galaxy	Temperature (keV)	Radius (kpc)	Mass (10^{12} $M_\odot$)	M/L_B ($M_\odot/L_\odot$)
N315		110	5.7	26
N1316		34	2.0	8
N1332		36	2.5	62
N1395	0.51-0.90	98	5.1	88
N2563		80	4.1	60
N4374	0.93-1.32	15	0.9	14
N4382	>0.80	48	2.5	37
N4406	0.94-1.03	88	4.6	63
N4472	1.07-1.30	80	4.6	33
N4594	>1.6	32	1.7	8
N4636	0.78-1.21	44	2.3	87
N4649	1.78-4.12	36	2.1	24
N5128		20	1.2	7

Trinchieri, Fabbiano, and Canizares (1986) have described the effect of uncertainties in the temperature distribution on the mass estimates. They derived the range of average gas temperatures from the x-ray spectra, and assumed a power-law temperature distribution $T \propto r^\alpha$ for $-0.5 \lesssim \alpha \lesssim 0.5$. Because the outermost portions of the x-ray images of many galaxies are irregular, they assumed smaller radii than Forman, Jones, and Tucker in most cases. For most galaxies, a range of total mass-to-light ratios of $(M/L_B)_{tot} \approx 10$ to $100\ M_\odot/L_\odot$ was found. Since this range extends down to the mass-to-light ratios found in the centers of elliptical galaxies from optical velocity dispersions, this analysis suggested that the present x-ray data do not necessarily require heavy haloes.

Fabian et al. (1986; see also the paper by Fabian in this Proceedings) have derived a lower limit on the total mass surrounding an elliptical galaxy. They assume that the temperature at the outermost x-ray detected radius is given by the average gas temperature derived from the integrated x-ray spectrum, and determine the pressure at this point from the density derived from the x-ray image. They assume that the gas pressure decreases beyond this radius, the gas being gravitationally bound. Finally, the temperature decrease is assumed to be sub-adiabatic, so that the gas beyond the x-ray radius is convectively stable. These assumptions lead to a lower limit on the total mass, which is typically $M \gtrsim 5 \times 10^{12}\ M_\odot$. This implies a mass-to-light ratio $(M/L_B) \gtrsim 75\ M_\odot/L_\odot$, and strongly supports the existence of massive haloes around elliptical galaxies. Unfortunately, this limit provides no information about the distribution of the dark matter. For example, in principle, the binding mass might be associated with the group or cluster in which the galaxy is located.

The mass determinations of Forman, Jones, and Tucker (1985) and Trinchieri, Fabbiano, and Canizares (1987) assumed very simple temperature profiles. More realistic profiles might come from detailed numerical models for cooling flows in elliptical galaxies. Sarazin and White (1986) have calculated a grid of spherical, steady-state cooling flow models for the x-ray emission in these galaxies. In these models, the source of the gas is stellar mass loss, and the gas is heated by the motions of the gas-losing stars and by infall in the galactic gravitational potential. These models are in good general agreement with the x-ray luminosities, x-ray versus optical luminosity correlation, and gas temperatures observed in normal elliptical galaxies. Sarazin and White find that these models fit the observed radial distribution of the x-ray surface brightness in ellipticals if ellipticals have heavy haloes with $M \propto r$. In models in which ellipticals lack heavy haloes, the predicted x-ray surface brightness profile is more centrally peaked than is observed.

There is a simple argument that indicates why this is so. I have shown that the energy equation for a steady-state cooling flow leads to approximate thermal equilibrium in the flow, and that this implies that (Sarazin 1986b, 1987; Sarazin and White 1986)

$$I_x(r) \propto I_B(r)\, \sigma_*^2(r)\, \frac{\Lambda_x}{\Lambda}\,(T(r)) \quad , \qquad (6)$$

where I_x and I_B are the x-ray and (blue) optical surface brightnesses of the galaxy, σ_* is the stellar velocity dispersion, and (Λ_x/Λ) is the fraction of the radiative cooling that is emitted in the x-ray band. Now, if the velocity dispersion is roughly constant, then hydrostatic equilibrium implies that the temperature is nearly constant, and equation (6) implies that $I_x \propto I_B$. In fact, the observed x-ray surface brightness profiles fit this relationship quite well (Trinchieri, Fabbiano, and Canizares 1987). On the other hand, if elliptical galaxies lacked heavy haloes, $\sigma_*^2 \propto 1/r$ in the outer parts of the galaxy, and the x-ray surface brightness would drop with increasing radius at least as rapidly as I_B/r. This is much steeper than is observed.

Thus, the x-ray surface brightness profiles of normal elliptical galaxies strongly suggest that these galaxies have heavy haloes (Forman, Jones, and Tucker 1985; Fabian <u>et al</u>. 1986; Sarazin and White 1986), although this result is much less certain than in the central dominant galaxy M87 (Trinchieri, Fabbiano, and Canizares 1986). Moreover, we have at present very little information on the distribution of the dark matter in these heavy haloes.

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DISCUSSION

Richstone: Since most galaxies are better fit by models without constant density cores, and since counts in clusters of galaxies are well fit by a similar model, I wonder if you would have still needed to assign the dark matter near M87 to the galaxy if you had assumed a sharper dark matter distribution for the cluster.

Sarazin: Of course, this is largely a semantic issue. The real point is just that the dark matter is concentrated towards the center of M87, and that there are no other galaxies with any significant luminosity in the same region.

Binney: One of my students, Ian Pollister, has modeled Perseus in detail with cooling flows in $r^{1/4}$ models, and gets excellent fits for reasonable cluster parameters and no galaxy contribution to the potential. In fact, the X–ray profiles of cooling clusters are remarkably featureless, showing no core, and no separation of central–galaxy and cluster components.

Mould: Information on the M87 potential between the radii available from the galaxy light and the X–ray gas can be obtained from the kinematics of the globular clusters as shown elsewhere in this volume (p. 451). We find $\sigma = 370 \pm 50$ km/s for the velocity dispersion, which is different from 800 km/s (your equivalent velocity dispersion for the X–ray gas), but not significantly different from 300 km/s. Although the error bars are large as yet, there is at least no sign that the velocity dispersion is turning down, and our inferred mass–radius relation seems to connect the corresponding relations from the galaxy light and the X–ray gas.

Sarazin: Globular clusters offer a very exciting opportunity to bridge the gap in mass determinations between optical velocity dispersions and X–ray data. The present data give a velocity dispersion which is slightly higher than the stellar velocity dispersion at a slightly larger radius. Because there are many globulars extending out into the X–ray region in M87, I hope we will hear more about these measurements in the future.

van Gorkom: Is it not a bit worrying that NGC 4472 is always mentioned as *the* prototype of a normal elliptical galaxy? It is the brightest elliptical in the Virgo cluster and probably the dominant central elliptical in a separate group. For how many real normal ellipticals are the radial distributions known and similar to NGC 4472?

Sarazin: Of course, it is the fact that NGC 4472 is bright that allows it to be studied in detail. Good X–ray surface brightness profiles are available for another half dozen to dozen ellipticals. However, X–ray emission is found in essentially all nearby ellipticals, with the same relationship between L_X and L_B. The few undetected Es have upper limits consistent with this relationship. So, the X–ray emission does seem to be a very general property of ellipticals.