X-RAY OBSERVATIONS AND THE STRUCTURE OF ELLIPtical GALAXIES

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ABSTRACT

We compare optical and high-quality X-ray data for three bright elliptical galaxies in the Virgo Cluster, NGC 4472, 4649, and 4636. The distribution of total mass in NGC 4472 and 4649 determined from X-ray data is sensitive to the stellar mass over a considerable range in galactic radius extending to $r \approx r_e$, the effective radius. The agreement of X-ray and optically determined stellar masses provides a unique verification of the stellar mass-to-light ratio, which is essentially constant over the range $0.1 \leq r/r_e \leq 1$. However, for NGC 4636 the dark matter is important at all radii $\geq 0.35r_e$. Evidently, the dark to stellar mass ratio varies in quite different ways in elliptical galaxies of comparable optical luminosity, implying that the radial structure of dark halos may not be universal. There is some evidence in NGC 4636 for additional support of the hot interstellar gas at $r \approx 0.35r_e$; either a field $B \sim 10^{-4}$ G or a small (mechanically unstable) central region of high gas temperature ($T \sim 10^7$ K) is required. The global temperature structure in the hot interstellar medium of many recently observed elliptical galaxies is very similar, reaching a maximum near $3r_e-4r_e$. This feature, which may suggest a new structural scale in these galaxies, is inconsistent with current theoretical gasdynamical models.

Subject headings: cooling flows — galaxies: elliptical and lenticular, cD — galaxies: individual (NGC 4472, NGC 4636, NGC 4649) — X-rays: galaxies

1. INTRODUCTION

Elliptical galaxies are large, bright stellar systems with considerable structural regularity. The stellar light profiles are well fitted by the de Vaucouleurs law (Burkert 1993), and the stellar velocity dispersion, surface brightness, and effective radius $r_e$ are constrained to a fundamental plane (Djorgovski & Davis 1987; Dressler et al. 1987). In contrast, the X-ray emission from hot interstellar gas in elliptical galaxies exhibits enormous variations in $L_X/L_B$ (Eskridge, Fabbiano, & Kim 1995) and, to a lesser extent, in gas temperature (Davis & White 1996).

We have reexamined optical and X-ray observations of elliptical galaxies in preparation for a new series of gasdynamical studies of the evolution of the interstellar gas. Although current X-ray observations are sparse, we have found that they reveal more useful information about elliptical galaxies than is currently realized. Gas temperature profiles $T(r)$ for elliptical galaxies recently determined with ROSAT and ASCA reveal a surprising uniformity for radii $r \approx 10r_e$. The total mass and density of all gravitating matter, $M_{tot}(r)$ and $\rho_{tot}(r)$, can be found from the variation of temperature and density in the hot interstellar gas by assuming that the gas is in hydrostatic equilibrium in the galactic potential.

We show here that the total mass determined from the X-ray gas for two bright Virgo elliptical galaxies (NGC 4472 and 4649) is in excellent agreement with a de Vaucouleurs profile for $0.1r_e \leq r \leq r_e$ using optically determined mass-to-light ratios. Remarkably, in another bright Virgo elliptical galaxy, NGC 4636, dark matter contributes substantially to the total mass within $r_e$, and the total mass found from X-ray observations is lower than the known stellar mass for $r \approx 0.35r_e$, implying that thermal pressure is not the only support for the hot gas. These results suggest that AXAF X-ray observations of elliptical galaxies will provide powerful new constraints on both the interstellar physics and the nature of stellar populations in these galaxies.

2. SCALE OF THERMAL STRUCTURE IN ELLIPtical GALAXIES

Figure 1 shows a plot of the radial variation of gas temperature with projected galactic radius $R/r_e$ for six early-type galaxies. The remarkable feature that all galaxies share is a positive temperature gradient out to about $3r_e$ followed by a leveling off or gradual decrease toward larger radii. Data for Figure 1 are taken from the following sources: NGC 1399, Jones et al. (1997); NGC 5044, David et al. (1994); NGC 4636, Trinchieri et al. (1994); NGC 507, Kim & Fabbiano (1995); NGC 4472, Irwin & Sarazin (1996); NGC 4649, Trinchieri, Fabbiano, & Kim (1997). The temperature profile observed with the ASCA satellite by Mushotzky et al. (1994) for NGC 4636 is in excellent agreement with that of Trinchieri et al. (1994) for 20% solar abundance. Additional properties of these galaxies are listed in Table 1. It is remarkable that $T(R)$ is so consistent in spite of the wide range of luminosities and cosmic environments among these galaxies. NGC 4636, 4649, and 4472 are in the Virgo Cluster, while NGC 1399, 5044, and 507 are the brightest galaxies in small groups or clusters. NGC 507 has an exponential surface brightness profile that is consistent with a very massive, face-on S0 galaxy (Magrelli, Bettoni, & Galletta 1992).

The temperature maximum observed in elliptical galaxies at about $3r_e$ suggests a new, previously unrecognized structural scale length. This cooling of gas within $3r_e-4r_e$ is not a natural result of galactic cooling flows, as many have suggested. In theoretical models, the radial gas velocity in the hot interstellar gas is very subsonic, since otherwise the gas replenishment time would be impossibly short and $L_X$ would be much too low. Straightforward spherical models of the hot interstellar gas
all three galaxies, similar to the Malmquist-corrected value $D = 17.2 \pm 1.9$ Mpc of Gonzalez & Faber (1997). For any particular Virgo galaxy the distance is uncertain by about 20% because of the unknown location of the galaxy along the line of sight through the cluster.

The total mass $M_{\text{tot}}(r)$ in these galaxies can be found from the condition for hydrostatic equilibrium:

$$M_{\text{tot}}(r) = - \frac{kT(r) r}{G \mu m_p} \left( \frac{d \log \rho}{d \log r} + \frac{d \log T}{d \log r} + \phi_m \frac{d \log P_m}{d \log r} \right),$$

where the last term allows for the possibility of magnetic pressure $P_m = B^2/8\pi$, and $\phi_m = P_m/P$ is the ratio of magnetic to gas pressure. The proton mass is $m_p = 0.63$. The strong negative density gradient $d \log \rho/d \log r$ is expected to be the largest of the three derivatives. Only the shape of $\rho(r)$, not its absolute normalization, influences $M_{\text{tot}}(r)$.

The density distribution $\rho(r)$ in the hot interstellar gas can be found from the X-ray surface brightness distribution. $T(r)$ and possibly also $\phi_m(r)$ must be known to some precision in order to determine reliable total masses. The total mass density is $\rho_{\text{tot}}(r) = dM_{\text{tot}}/4\pi r^2 dr$.

Density profiles are available for all three elliptical galaxies from Einstein HRI observations (Trinchieri, Fabbiano & Canizares 1986) and from ROSAT PSPC (Trinchieri et al. 1994; Irwin & Sarazin 1996; Trinchieri et al. 1997). Fortunately, there is a substantial range of angular scale over which these data sets overlap, so values of $\rho(r)$ from Einstein and ROSAT data can be renormalized to agree. Having done this, we fit $n(r) = \rho(r)/m_p$ with a sum of functions $n(r) = 2n_i(r)$, where $n_i(r) = n_i(1 + [r/r_i]^q_i)^{-1}$, and the temperature is fitted with $T(r) = 2T_m[n_m/(r + r_m) + (r/r_m)]^{-1}$. The temperature $T(R)$ observed at any projected radius $R$ is an average along the line of sight weighted by $\rho^2$ and differs in principle from the temperature $T(r)$ at physical radius $r$. However, $\rho^2$ is a very steep function of galactic radius, and we find $T(r) \approx T(R)$ within 10%, sufficient for our purposes here, considering the observational uncertainties involved (Fig. 1).

Figures 2a, 2d, and 2g show our fits to the X-ray data. The parameters for these fits are as follows: NGC 4472, $n_i(0.095, 0.00597, -0.00004); r_i(0.17, 0.95, 10); p_i(2.0, 1.14, 1.19); T_m = 0.75; r_m = 0.5; r_e = 0.75; q = 0; NGC 4636, $n_i(0.151; r_i = 0.172; p = 1.57; T_m = 0.5375; r_m = 0.475; r_e = 0.6; q = 0; NGC 4649, $n_i(0.1, 0.0144; r_i(0.15); p_i(2.0, 3.0); T_m = 0.9; r_m = 0.9; r_e = 0.40; q = 0.0, with radii in $r_e$ densities in cm$^{-3}$, and temperatures in 10$^7$ K. Total masses $M_{\text{tot}}(r)$ (Figs. 2b, 2c, and 2h) and the corresponding total mass

3. COMPARISON OF X-RAY AND OPTICAL DATA FOR THREE VIRGO GALAXIES

NGC 4472, 4649, and 4636 listed in Table 1 are all members of the Virgo Cluster. We adopt a distance of $D = 17$ Mpc for

![Table 1: Optical and X-Ray Properties of Six Elliptical Galaxies](image-url)
High quality (Figs. 2b, 1997). Sufficiently massive (Kormendy & Richstone 1995; Faber et al.) may account for this increase, but typical holes may not be region (e.g., Faber et al. 1997) are larger; central black holes generally, mass-to-light ratio values determined only in the core dark matter that can be checked a posteriori (see below). In LB in slowly rotating model galaxies. This “stellar” determined by comparing stellar velocities measured out to $r_{\text{d}}$ and solutions of the two-dimensional Jeans equations in slowly rotating model galaxies. This “stellar” $M_{\text{y}}/L_{\text{y}}$ ratio is sensitive to all mass within $r_{\text{obs}}$ and may contain a component of dark matter that can be checked a posteriori (see below). In general, mass-to-light ratio values determined only in the core region (e.g., Faber et al. 1997) are larger; central black holes may account for this increase, but typical holes may not be sufficiently massive (Kormendy & Richstone 1995; Faber et al. 1997). $M_{\text{y}}(r)$ and $\rho_{\text{y}}(r)$ in Figure 2 are evaluated with de Vaucouleurs profiles (Young 1976).

The Structure of NGC 4472 and 4649.—We find it quite remarkable that the total mass and density indicated by the X-ray observations agree almost exactly with stellar values in the range $0.1 \lesssim r \lesssim 1r_c$, where the observational data are of high quality (Figs. 2b and 2e). Discounting a conspiracy of compensating errors, this superb agreement is possible only (1) if the stellar mass-to-light ratio values determined by van der Marel (1991) are essentially correct and constant for stars out to about $1r_c$, and (2) if magnetic pressure or rotation contributes little or nothing to the total pressure support of gas in $0.1 \lesssim r \lesssim 1r_c$. The total masses of dark and stellar matter are equal at about $2.5r_c$, which includes $r_{\text{d}}$ so van der Marel’s $M_{\text{y}}/L_{\text{y}}$ values are likely to be totally stellar. Dark matter dominates at $r/r_c \approx 2.5$. At $r = 10r_c$, the total mass-to-light ratio is about 78 (NGC 4472) and about 110 (NGC 4649), and $M_{\text{obs}}/L_{\text{y}}$ is undoubtedly higher at $r/r_c \approx 10$. The stellar to dark halo transition is particularly striking in the density plots (Figs. 2c and 2f). None of the qualitative features in Figure 2 are changed if $(M_{\text{y}}/L_{\text{y}})_{\text{c}}$ values are used from Faber et al. (1997), but the overall fit in $0.1 \lesssim r/r_c \lesssim 1$ is of lower quality. The discrepancy $M_{\text{obs}} < M_{\text{y}}$ at $r \approx 0.1r_c$ may result from observational inaccuracies in this region, although $M_{\text{obs}}(r)$ would be underestimated if a large magnetic field were present.

The Structure of NGC 4636.—Our total mass $M_{\text{obs}}(r)$ for NGC 4636 (Fig. 2h) is in excellent agreement with the mass determined by Mushotzky et al. (1994), who also assumed $D = 17$ Mpc. A de Vaucouleurs profile is used to determine $M_{\text{y}}(r)$ and $\rho_{\text{y}}(r)$; we have verified that NGC 4636 satisfies a
de Vaucouleurs profile by plotting the surface brightness data of Peletier et al. (1990) against $r^{-1/4}$.

The most surprising result evident from Figures 2h and 2i is the relative dominance of dark matter in NGC 4636 as compared to NGC 4472 and 4649. The dark mass $M_{\text{dark}} = M_{\text{tot}} - M_*$ in NGC 4636 becomes equal to the stellar mass $M_*$ at about $r = 1.2r_e$, and $M_{\text{dark}} \approx 0.83M_*$ at $r = r_e$, where the total mass-to-light ratio is 19. This large amount of dark matter may be unusual, since it has been difficult until recently to find evidence of dark matter in elliptical galaxies from stellar velocities measured within $r_e$ (e.g., Carollo et al. 1995). The "stellar" mass-to-light ratio $M_*/L_B$ from van der Marel is determined from velocity observations only out to $r_{\text{obs}}/r_e = 0.45$, where $M_* \gg M_{\text{dark}}$ (Fig. 2h). It is remarkable that there is no change in slope in Figure 2h as $M_*/L_B(r)$ crosses below $M_*(r)$ at $r \approx 0.33r_e$, since all observations should be reliable at this radius. This failure of the X-ray determined mass to detect the stellar mass suggests large magnetic fields, unusually high gas temperatures, or rotational support in this region. Magnetic fields $B \sim 9 \times 10^{-5}$ G would be required at $r = 0.1r_e$ to support the hot gas against the stellar mass within (see Mathews & Brighenti 1997), or a curious central temperature inversion may exist: a mean temperature within 1 kpc (0.20) of $0.9 \times 10^9$ K is implied. This inversion is constrained so that the mean projected gas temperature within $1.075 \times 10^9$ is within the observed limits $0.667 \pm 0.029 - 0.041 \times 10^9$. However, the high-temperature interpretation for $M_* < M_*$ in NGC 4636 is unlikely, since it is buoyantly unstable; $dT/dr$ is superadiabatic for $r \lesssim 0.08r_e \approx 0.7$ kpc. Alternatively, $M_*/L_B$ could decrease with galactic radius so that $M_* < M_{\text{dark}}$ is lower than we think near $r/r_e \approx 0.1$ in Figure 2h, but this seems unlikely in view of the uniform $L_*/L_B$ values implied by Figures 2b and 2e. None of these conclusions are changed if the core value $(M_*/L_B)_{\text{core}} = 12.69$ is used instead. The different distribution of dark matter at $r < r_e$ in NGC 4636 may provide evidence against a universal dark halo structure as proposed by Navarro, Frenk, & White (1996), but for $r \approx r_e$ the dark halos are all very similar, having slope $p_{\text{halo}} \propto r^{-1.9}$ at $r \sim 10r_e$. The total mass-to-light ratio near the outer limit of the X-ray observations shown in Figure 2e, $r_e = 12.5r_e$, is about 125.

How do these Virgo elliptical galaxies differ in other respects? NGC 4636 is a relatively isolated galaxy quite far ($\gtrsim 3$ Mpc) from the core of Virgo. Nevertheless, its X-ray image shows some azimuthal asymmetry at $r \approx 5r_e$, but this emission may arise from a different source (Trinchieri et al. 1994). It also has a broad, faint stellar distribution characteristic of CD galaxies. NGC 4472 is optically the brightest galaxy in the Virgo Cluster, lies within a small subgroup, and is interacting with a nearby dwarf irregular galaxy, UGC 7636. At radii $\gtrsim 3r_e$, the X-ray isophotes show a tail-like structure that may result from the motion of NGC 4772 through the Virgo Cluster medium (Forman, Jones, & Tucker 1985; Irwin & Sarazin 1996). NGC 4472 has a small kinematically decoupled (nonrotating) core within about 0.09$r_e$. NGC 4649 appears to be close to the center of Virgo. However, none of these galaxies show evidence of unusual X-ray or optical structure at $0.1 \lesssim r/r_e \lesssim 3$, where the difference in dark to stellar mass is so apparent in Figure 2.

4. CONCLUSIONS

(1) A previously unrecognized spatial scale at about $3r_e$ is suggested by the similarity of gas temperature profiles in many recently observed elliptical galaxies. (2) The stellar mass-to-light ratios for NGC 4472 and 4649 have been verified by X-ray observations; the interstellar gas temperature is also correct. (3) The mass-to-light ratios in NGC 4472 and 4649 determined from stellar motions are constant over the range $0.1r_e \lesssim r \lesssim r_e$. (4) In NGC 4472 and 4649 the hot interstellar gas is supported out to $r \sim r_e$ by thermal gas pressure; other means of support such as magnetic pressure or rotation are not evident. (5) Hot interstellar gas in the center of NGC 4636 may be supported by magnetic stresses ($B \sim 10^{-4}$ G), a transient unstable region of unexpectedly high temperatures ($T \sim 10^7$ K), or rotation. (6) Elliptical galaxies with comparable luminosities can have quite different distributions of dark matter relative to stellar matter. (7) In NGC 4636 the mass of dark matter is comparable to that in stars at $r \sim r_e$; in NGC 4472 and 4649 the mass of dark halo is negligible at $r < r_e$. (8) The "stellar" mass-to-light ratios for these three elliptical galaxies as determined by van der Marel (1991) are unlikely to be contaminated by dark matter from the galactic halos. AXAF observations will be useful in interpreting the variation of $M_*/L_B$ along the fundamental plane (Pahre & Djorgovski 1997) and in verifying central magnetically supported regions.

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