X-RAY EMISSION FROM ROTATING ELLIPTICAL GALAXIES

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ABSTRACT

The slow inward flow of the hot gas in elliptical galaxy cooling flows is nearly impossible to detect directly because of instrumental limitations. However, in rotating galaxies, if the inflowing gas conserves angular momentum, it will eventually form a disk. The X-ray signature of this phenomenon is a flattening of the X-ray isophotes in the inner 1–10 kpc region. This effect is observable, so we have searched for it in X-ray observations of six rotating and nonrotating early-type galaxies, obtained mainly with the ROSAT PSPC and HRI imagers. The ellipticities of the X-ray emission never increase toward the central region, nor are the X-ray ellipticities significantly greater than the ellipticities for the optical stellar emission. Central ellipticities in excess of 0.5 were expected in rotating ellipticals, whereas values of 0–0.2 are measured. The failure to detect the expected signature requires a modification to the standard cooling-flow picture, possibly including partial galactic winds, rapid mass dropout, or turbulent redistribution of angular momentum.

Subject headings: galaxies: individual (NGC 1395, NGC 1404) — galaxies: kinematics and dynamics — galaxies: ISM — X-rays: galaxies

1. INTRODUCTION

Elliptical galaxies had long been thought of as purely stellar systems until observations using the Einstein Observatory (Giacconi et al. 1979) revealed significant X-ray emission from these objects (Forman et al. 1979). The emission has been attributed to a hot interstellar medium because of the brightness of the emission, as well as the softness of the spectrum. The gaseous component of the X-ray emission is dominated by the stellar component in only the most X-ray faint objects (Canizares, Fabbiano, & Trinchieri 1987; Irwin & Sarazin 1998). The comparatively faint X-ray brightness of individual galaxies relative to galaxy clusters made observations of extended objects difficult, and only six individual elliptical galaxies had Einstein high-resolution images that contained more than 150 photons (Fabbiano, Kim, & Trinchieri 1992). The ROSAT observatory was launched with instruments on board that were more sensitive and of lower background than those aboard Einstein, and thus it helps us gain greater insight into the hot interstellar medium in elliptical galaxies.

In the steady state cooling flow model, the source of the gas is stellar mass loss, which collides with and shocks gas lost by other stars, resulting in a medium at a temperature equivalent to the velocity dispersion of the stars (5–10 × 10^6 K; Thomas 1986; Loewenstein & Mathews 1987; Sarazin & White 1988; Vedder, Trester, & Canizares 1988; David, Forman, & Jones 1991). The cooling time of this gas is much shorter than a Hubble time, and because the radiative loss rate increases inward, the inner regions lose pressure support more rapidly. This effect leads to a slow inward flow of hot gaseous material, typically only ∼5–50 km s^{-1} (e.g., Thomas 1986; Loewenstein & Mathews 1987; Vedder et al. 1988; Sarazin & Ashe 1989).

Most steady state cooling flow models do not include large-scale rotation of the cooling system. Although optically luminous elliptical galaxies do not, in general, rely on rotation to support the stellar system, many galaxies have significant rotational velocities (Franx, Illingworth, & Heckman 1989; Davies & Birkinshaw 1988). We expected that as cooling gas flows inward, conserving specific angular momentum, the energy stored in rotation increases, so rotational support of the gas would eventually become significant. Subsequently, the hot gas flows more rapidly along the rotation axis than in the rotational plane, which produces a flattening of the cooling material. On the basis of this suggestion, we began an observing program to search for flattening of the X-ray isophotes toward the inner parts of elliptical galaxies.

In a series of papers, detailed models of rotating cooling flows have been developed by Kley & Mathews (1995) and Brighenti & Mathews (1996, 1997). Kley & Mathews (1995) examined the behavior of cooling flows for slowly rotating spherical elliptical galaxies. They found that as the gas flows inward, rotational support increases, eventually preventing the gas from further inward flow. This leads to the formation of a cooled disk, which is associated with a flattening of the X-ray isophotes. In addition, the X-ray luminosity is significantly lower than in models without rotation, which avoids the need for the distributed mass dropout assumed in other models.

This initial effort by Kley & Mathews (1995) was improved by Brighenti & Mathews (1996), who used more realistic models for elliptical galaxies. These more realistic models use oblate ellipsoidal stellar density distributions with differing amounts of flattening and rotation. They calculate the time evolution of the hot gas distribution for massive elliptical galaxies of type E0–E4. They show that there is a significant flattening of the X-ray isophotes, from nearly spherical in the outer parts to high degrees of flattening near the location of the cooling disk (a flattening of approximately 5:1 near the disk in model E2; 0.25). The size of the disk depends on the details of the models, but for all rotating models considered, the disk radius is in the range 2–15 kpc at the present epoch. In their most recent paper, Brighenti & Mathews (1997) examined the evolution of cooling flows in less massive elliptical galaxies, where rotational support of the stellar system is relatively more important. For these models, the X-ray emission from the hot gas in rotating ellipticals is low (10^{38} ergs s^{-1}) and would be difficult to observe. The observations presented here should
TABLE 1

| Galaxy       | Type | $B''_9$ | Diameter (arcmin) | $v_{\text{rotation}}$ (km s$^{-1}$) | $\sigma$ (km s$^{-1}$) | $r_e$ (arcsec) | $d$ (Mpc) | $\log L_X$ (ergs s$^{-1}$) | $\log (L_X/L_B)$ (ergs s$^{-1}$ L$^\odot$) | Reference |
|--------------|------|---------|-------------------|-------------------------------|-------------------------|--------------|---------|--------------------------|--------------------------------|-----------|
| NGC 1395.....| E2   | 10.94   | 5.9 \times 4.5    | 93                            | 258                     | 45           | 28.4    | 43.42                    | 30.02                             | 1         |
| NGC 1404.....| E2   | 10.89   | 3.3 \times 3.0    | 90                            | 225                     | 27           | 20.3    | 43.15                    | 30.53                             | 1         |
| NGC 4374.....| E1   | 10.13   | 6.5 \times 5.6    | 8                             | 290                     | 54           | 19.0    | 43.40                    | 30.10                             | 2         |
| NGC 4472.....| E1   | 9.32    | 10.2 \times 8.3   | 27                            | 250                     | 104          | 19.0    | 43.72                    | 30.45                             | 1         |
| NGC 4552.....| S01  | 10.84   | 5.1 \times 4.7    | 13                            | 273                     | 30           | 19.0    | 43.11                    | 30.21                             | 3         |
| NGC 5322.....| E4   | 11.09   | 5.9 \times 3.9    | 40                            | 310                     | 35           | 23.7    | 43.21                    | 29.31                             | 3         |

References.—(1) Franx et al. 1989; (2) Vedder et al. 1989; (3) Roberts et al. 1991.

2. OBSERVATIONS AND INITIAL REDUCTION

To search for the X-ray signature of rotating cooling flows, we need to obtain the isophotal shape of the X-ray emission in a sample of galaxies that contains rotating systems and a control set of nonrotating systems. The optical morphology and rotation parameters for our sample can be found in Table 1. The optical diameters for the major and minor axes are from the NASA Extragalactic Database (NED); the magnitudes, $r_e$, and the distances are from Faber et al. (1989; using $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$); $L_X/L_B$ (where $L_X$ is for the 0.5–2.0 keV band) is from Brown & Bregman (2000); and the rotational data come from Franx et al. (1989), van der Marel (1991), and the compilation of Roberts et al. (1991).

For an observation to be useful for morphological analysis, there must be at least approximately 300 photons from the source, and the galaxy must be resolved. This number limits the sample to nearby galaxies that are both extended and X-ray bright. The galaxies in our sample have optical sizes of a few arcminutes (see Table 1) and optical effective radii of about 0.5–1'. The optical core radius, which is useful for comparison to an X-ray core radius, is an order of magnitude smaller than the effective radius, 3′–10′ for the galaxies in this sample. ROSAT PSPC observations do not resolve any X-ray emission within 30′ because of the instrumental point-spread function (PSF), so the regions resolved in the PSPC observations are generally beyond 10 optical core radii. The resolution of the HRI lets us examine the shape of the galaxy as small as $5′′$–1′′ but because of lower sensitivity and higher background, does not detect diffuse emission beyond 30′ for most of our observations.

The observations of both instruments are needed to determine the ellipticities over a range of radii for a comparison to the predictions of Brighenti & Mathews (1996). A summary of the X-ray observations can be found in Table 2, which lists all the nearby galaxies with available low- and high-resolution X-ray data as well as published data pertaining to the rotation of the stellar system. All but two of the observations are from ROSAT; the HRI image of NGC 4472 and the IPC image of NGC 4374 are from Einstein, the

TABLE 2

| Galaxy       | Satellite | Instrument | Time (ks) |
|--------------|-----------|------------|-----------|
| NGC 1395.....| ROSAT     | HRI        | 16.3      |
| NGC 1395.....| ROSAT     | PSPC       | 21.0      |
| NGC 1404.....| ROSAT     | HRI        | 71.6      |
| NGC 1404.....| ROSAT     | PSPC       | 30.0      |
| NGC 4374.....| ROSAT     | HRI        | 26.5      |
| NGC 4374.....| Einstein  | IPC        | 35.0      |
| NGC 4472.....| Einstein  | HRI        | 33.8      |
| NGC 4472.....| ROSAT     | PSPC       | 26.0      |
| NGC 4552.....| ROSAT     | HRI        | 30.1      |
| NGC 4552.....| ROSAT     | PSPC       | 17.0      |
| NGC 5322.....| ROSAT     | HRI        | 20.3      |
| NGC 5322.....| ROSAT     | PSPC       | 35.0      |
second because a good ROSAT image was not taken during the lifetime of the PSPC.

To create the highest sensitivity HRI images, we used a subset of the photon event list of each observation. Of the 15 HRI energy bins, only the channels that contain photons from the galaxy were selected for our usable data set. These were generally channels 2–6 of the 15 HRI channels. To maximize the signal-to-noise ratio (S/N) of the observation, the value of the S/N for a source 10% as bright as the model background level was calculated, and then time bins with larger and larger background levels were added to the calculation until the S/N reached a maximum. All time bins with background levels higher than those that created the maximum S/N were omitted from the usable data set (Pildis, Bregman, & Evrard 1995). The edited data files were blocked to create a small image of 128 × 128 pixels for further analysis.

The ROSAT PSPC images were reduced in three steps. First, as with the HRI data, time intervals with high backgrounds were removed until a maximum S/N was achieved. An examination of the spectra of the central sources indicated that there were few source photons below energies of 0.4 keV, so an energy band of 0.42–2.0 keV was chosen to continue the analysis. Finally, the images were flattened using the program CAST_EXP (Snowden et al. 1994; bands 3–7 were used), which creates an accurate flat field by using the aspect and event-rate information from the observation, as well as the specific energy band and time filters. The resulting PSPC images were blocked to create 4′ × 4′ pixels, and the background was determined before creating a small image, usually of 128 × 128 pixels. The Einstein IPC data of NGC 4374 is an image file and does not contain time and energy information for each photon event, so all photons were used, a background was determined, and a smaller image was created.

The PSPC images, because of their wider field of view and greater sensitivity, often contain point sources not related to the central galaxy. These point sources have been edited and replaced with a background. This was accomplished by placing photon events randomly over the area in question, so that the average pixel count in the edited region would match the previously determined background count for the observation. When only the galaxy in question was left in the middle of the data frame, the initial data reduction was considered complete.

3. ANALYSIS

A morphological analysis of the data was carried out, following the processing of the data into blocked image files. One of the goals of the analysis is to determine a representative ellipticity for both the inner and outer regions of the six galaxies. Using the STSDAS package in IRAF, one can fit ellipses directly to the images. An advantage of this technique is the ability to map large or complicated changes in isophotal shape; we will use this technique for the PSPC data of NGC 1395. However, there are two disadvantages to fitting one elliptical isophote at a time. First, there are large errors due to the small photon count in most X-ray images; and second, the true shape of the galaxy is modified by the instrumental PSF. To perform a more accurate analysis, we will fit an elliptical “β” model to the data, taking into account the instrumental resolution and the Poisson statistics of the pixel values.

Since most X-ray images include 10²–10³.5 photons, one would like to consider as many photons as possible when trying to make statements about the morphology of the sources that we see. We perform this fit of the whole image (128 × 128 pixels) to a model surface brightness function,

\[
S(x, y) = \frac{S_0}{(1 + (1/a^2)(x^2 + [y^2/(1 - \epsilon^2)])^2 + S_b,}
\]

\[
x = x' \cos \theta + y' \sin \theta,
\]

and

\[
y = y' \cos \theta - x' \sin \theta,
\]

where \(S_0\) is the central intensity, \(a\) is the core radius along the major axis, \(\epsilon\) is the ellipticity of the isophotes, \(S_b\) is a flat random background, and \(x = 3\beta - 0.5\). This function is a standard elliptical β model used to fit the surface brightness profiles of elliptical galaxies (Cavaliere & Fusco-Femiano 1976), which leads to a single value for the ellipticity per fit. The rotation of the distribution through a position angle \(\theta\) is included in the calculation of \(x\) and \(y\) from the unrotated coordinates \(x'\) and \(y'\). Before any model surface brightness distribution is compared to data, it is convolved with the instrumental PSF of the observations modeled using a fast Fourier transform (FFT). The PSF is approximated by a two-dimensional Gaussian of the form \(e^{-x^2/2\sigma^2}\), where the width of the PSF depends on both the instrument and the off-axis angle of the target object (Hasinger et al. 1994).

The best fit to the surface brightness is achieved by minimizing a statistic that is analogous to \(\chi^2\), but takes into account the Poisson nature of the photon statistics. This maximum-likelihood statistic, \(\psi\), is

\[
\psi = -\sum_x \sum_y D_{xy} \ln [S(x, y)] + \sum_x \sum_y S(x, y),
\]

where \(D_{xy}\) is the image array of the X-ray data, and \(S(x, y)\) is the model, which depends on the parameters \(S_0\), \(a\), \(\epsilon\), \(\theta\), \(\sigma\), and \(S_b\).

To find the best-fit surface brightness distribution for any given image, a downhill simplex method was used to optimize the multiparameter function \(\psi\). This optimization routine can be used for any number of parameters. When first attempting to converge to an answer, the parameter \(S_b\), which was established using IRAF/PROS during the data reduction process, was kept constant. If the best-fit core radius, \(a\), is smaller than the half-width of the instrumental PSF, then it is fixed to a value smaller than the PSF. All images that were minimized were 128 × 128 pixels, with the exception of the PSPC image of NGC 4472, which was 512 × 512. The larger data array greatly slows the calculations, because of the FFTs performed during each evaluation of \(\psi\). For each ROSAT image, the simplex routine was used several times with different initial guesses at the correct parameter set, to ensure that the algorithm consistently converged to the correct answer.

Note that the center of the surface brightness distribution is not a floating parameter in the optimization routine. The minimized imaged must be chosen such that the center of the galaxy is the center pixel in the data array. The galaxy centers are determined using an iterative process. First, the galaxy centers are estimated by eye using the IRAF/PROS image display, and a minimized image is created. The optimization code is run on this image, creating a rough surface brightness model for the galaxy. To ensure that the center pixel of the image is truly the center of the galaxy, the fitted
surface brightness model is subtracted from the smoothed image. If the center of the image is offset from the center of the model, the residual image created by subtracting the model from the data will be asymmetrical. Since the central emission from the galaxy is dominated by a PSF that is several pixels wide, the initial estimates of the galaxy center were usually sufficient.

As a consistency check for our optimization method, the technique of simulated annealing (Goffe et al. 1994) was also used on some of our data. This method for finding the minimum of a function randomly samples the phase space created by the parameters of the function to be minimized. Because of the large sampling of phase space, this method is very robust and does an excellent job of finding the global extrema of a function. The main drawback of this method is that it is slow, requiring about an order of magnitude more computing time to perform a single optimization than the downhill simplex code. For the cases in which simulated annealing was used, the solution was consistent with the downhill simplex solution.

To calculate the errors in the best-fit parameters found by our optimization codes, a Monte Carlo method was adopted. For each best-fit surface brightness model, \( S_{\text{best}}(S_0, a, \alpha, \beta, S_{\text{sky}}) \), we have simulated a series of ROSAT observations of this optimal distribution convolved with a known PSF. The simulated observations have S/N, background noise, and total photon counts that match the ROSAT observation currently being modeled. Poisson deviates were taken from the convolved best-fit model surface brightness, \( S_{\text{best}} \), until the number of "photons" placed in the simulated image matched the photon count of the ROSAT data set in question.

For each ROSAT image and corresponding best-fit surface brightness distribution model, 50–100 of these simulated data sets were created and the parameters of their surface brightness distribution estimated by optimizing \( \psi \). Since all the simulated data sets came from the same surface brightness distribution, the variation in the calculated best-fit parameters is an estimate of the accuracy of the analysis method.

The standard deviation of the distribution of the best-fit parameters are used as error bars for the best-fit parameters of the real ROSAT observation.

As stated previously, the ROSAT PSPC image of NGC 1395 cannot be well fitted by a single ellipticity, and so the optimization code was not used. Instead, elliptical contours were fitted to the galaxy using the task ELLIPSE in the STSDAS package in IRAF. This task calculates the ellipticity and position angle, at some semimajor axis, of elliptical contours, given an initial position for the galaxy center, an initial guess for the semimajor axis, ellipticity, and position angle of the first contour. Because of the Poisson nature of the unsmoothed data, most of the pixels have zero values. The routine ELLIPSE relies on the assumption that the distribution to be fitted is one that changes fairly smoothly. Consequently, this routine is unsuccessful at fitting unsmoothed ROSAT data. However, when the data are smoothed with a Gaussian comparable to the instrumental PSF of a given image, the pixel-to-pixel variation is less severe, and ellipses can be fitted successfully.

Since a smoothed image is being used, one needs to consider how this will affect the results returned by the ellipse-fitting routine. An elliptical object that, on the sky, has a semimajor axis \( a \) and semiminor axis \( b \) is convolved with a Gaussian smoothing function that reflects the instrumental resolution aboard ROSAT. The observed axes of an elliptical isophote will be approximately the sum, in quadrature, of the true axes and the half-width of the smoothing function; for the semimajor axis,

\[
a_{\text{obs}}^2 \approx a_{\text{true}}^2 + r_{\text{PSF}}^2.
\]

Consequently, the ellipticity, \( \epsilon \), will be reduced by the instrumental resolution. The most severely affected case arises for a small, flattened ellipse; an ellipse observed to have an ellipticity of 0.5 and a semimajor axis \( a = 10'' \) will have a 12% error in the estimate of the ellipticity; i.e., the true ellipticity of the observed object would be 0.563. The above expression is applicable only to noiseless data, so a more reliable assessment of the ellipse-fitting procedure and the accuracy of the error bars is called for in the analysis of the ROSAT data. Again, we have performed Monte Carlo simulations for this purpose, using simulated images of the PSPC data for NGC 1395 and analyzing these simulated data with the task ELLIPSE. The ELLIPSE task fits isophotes at radii from 4'' to 40'', but we considered only the isophotes outside the instrumental PSF, trying to avoid one of the main pitfalls of this method of analysis. The uncertainty in the fit to NGC 1395 was determined from an ensemble of simulated data sets for an ellipticity of 0.1 and processed with ELLIPSE.

4. RESULTS

The processed X-ray observations are presented in Figures 1–13. Each processed model image was smoothed with a Gaussian that matches the instrumental PSF of the observation. For the PSPC data of NGC 1404, the PSF has a half-width of 3'', because the image of NGC 1404 is not in the center of the PSPC frame, but 10'' off-axis. Contour maps of the X-ray observations, both PSPC and HRI, are plotted with contours of 3 \( \sigma \), 9 \( \sigma \), 27 \( \sigma \), etc. above the local background. For the images with shallow surface brightness profiles, an extra contour that helps define the center of the X-ray emission was added.

![Fig. 1.—HRI contour map of NGC 1395. The pixels are 1'' × 1'' in size and the frame is 128 × 128 pixels. The cleaned data were blocked to an instrumental beam width of 3''.](image-url)
Model surface brightness distributions were fitted to the data using the optimization code described above. The best-fit parameters, along with their respective errors, are given in Table 3. Since the values of $\psi$ in phase space are symmetric about the $e = 0$ axis and periodic along the $\theta$ axis, the best-fit parameters are all shown with positive ellipticities and with position angles having a range of $0^\circ$–$180^\circ$. The position angles are set with $0^\circ$ pointing north and positive angle increasing counterclockwise. For most simulations, the core radius, $a$, often unresolved, was kept fixed and only changed in increments of 1.0 pixels in separate runs of the optimization code to determine the minimum value of $\psi$ that could be found in the parameter space. For the simulations of the HRI observation of NGC 1404 and NGC 4552, the errors were calculated using an optimization code that permitted $a$ to vary. The estimate of the errors in $a$, $\pm 1$ pixel (1"), come from these two sets of simulations; the values quoted in Table 3 are in arcseconds.

The shape of the X-ray emission as a function of radius is what we would like to compare to the predictions for rotat-

### TABLE 3

| Galaxy      | Instrument | $S_0(\sigma)$ | $a(\sigma)$ | $e(\sigma)$ | $\theta(\sigma)$ | $S_0(\sigma_b)$ |
|-------------|------------|---------------|--------------|--------------|------------------|-----------------|
| NGC 1395    | HRI        | 1.98 (0.40)   | 1.0 (1.0)    | 0.08 (0.08)  | 0.55 (0.04)      | 130 (60)        | 0.023 (0.006)   |
| NGC 1395    | PSPC       | ...           | ...          | 0.1 (0.08)   | ...              | ...             | ...             |
| NGC 1404    | HRI        | 17.42 (0.32)  | 4.5 (1.0)    | 0.09 (0.02)  | 0.935 (0.007)    | 165 (9)         | 0.107 (0.004)   |
| NGC 1404    | PSPC       | 141.00 (20.0) | 6.0 (4.0)    | 0.04 (0.08)  | 0.88 (0.04)      | 137 (20)        | 0.010 (0.001)   |
| NGC 4374    | HRI        | 2.53 (0.14)   | 4.8 (1.0)    | 0.14 (0.05)  | 0.80 (0.02)      | 108 (82)        | 0.004 (0.004)   |
| NGC 4374    | IPC        | 2.80 (0.12)   | 40.0 (8.0)   | 0.19 (0.06)  | 1.23 (0.06)      | 77 (10)         | 0.002 (0.003)   |
| NGC 4472    | HRI        | 14.18 (2.7)   | 4.0 (1.4)    | 0.08 (0.06)  | 1.00 (0.15)      | 185 (76)        | 0.66 (0.11)     |
| NGC 4472    | PSPC       | 61.14 (1.5)   | 8.0 (4.0)    | 0.26 (0.04)  | 0.78 (0.04)      | 49 (86)         | 0.0006 (0.0001) |
| NGC 4552    | HRI        | 5.24 (0.36)   | 5.0 (1.0)    | 0.23 (0.04)  | 0.98 (0.08)      | 179 (7)         | 0.019 (0.003)   |
| NGC 4552    | PSPC       | 4.90 (0.85)   | 12.0 (4.0)   | 0.24 (0.13)  | 2.34 (0.33)      | 182 (73)        | 0.0011 (0.0002) |
| NGC 5322    | HRI        | 0.88 (0.30)   | 3.0 (1.0)    | 0.11 (0.14)  | 1.14 (0.12)      | 48 (60)         | 0.016 (0.001)   |
| NGC 5322    | PSPC       | 5.76 (0.60)   | 12.0 (4.0)   | 0.22 (0.09)  | 1.67 (0.11)      | 92 (74)         | 0.0022 (0.0005) |
Fig. 5.—HRI contour map of NGC 4374. The pixels are $1'' \times 1''$ in size and the frame is $128 \times 128$ pixels. The cleaned data were blocked to an instrumental beam width of $5''$.

**TABLE 4**

| Galaxy   | $v_{rot}/v$ | $\epsilon_{opt}$ (10$''$) | $\epsilon_{opt}$ (30$''$) | $\epsilon_{HRI}$ | $\epsilon_{PSPC}$ |
|----------|-------------|-----------------------------|-----------------------------|------------------|------------------|
| NGC 1395 | 0.36        | 0.1 (0.02)                  | 0.18 (0.02)                  | 0.08 (0.08)      | 0.10 (0.1)      |
| NGC 1404 | 0.40        | 0.14 (0.02)                 | 0.14 (0.02)                 | 0.09 (0.02)      | 0.04 (0.08)     |
| NGC 4374 | 0.03        | 0.2 (0.02)                  | 0.12 (0.02)                 | 0.14 (0.05)      | 0.19 (0.06)     |
| NGC 4472 | 0.11        | 0.07 (0.03)                 | 0.15 (0.02)                 | 0.08 (0.06)      | 0.26 (0.04)     |
| NGC 4552 | 0.05        | 0.04 (0.02)                 | 0.08 (0.02)                 | 0.23 (0.04)      | 0.24 (0.13)     |
| NGC 5322 | 0.13        | 0.25 (0.02)                 | 0.20 (0.02)                 | 0.11 (0.14)      | 0.22 (0.09)     |
given in parentheses. Below is a list of how the optical and X-ray shape of each galaxy are related to one another.

**NGC 1395.**—This galaxy has one of the largest rotation velocities among the elliptical galaxies detectable by ROSAT, $93 \text{ km s}^{-1}$, and optical observations (Malin & Carter 1983; Forbes & Thomson 1992) of NGC 1395 show substructure in the form of shells. The PSPC data are not regular; i.e., a satisfactory best-fit parameter set could not be calculated, possibly in response to the event that created the shells, and we did not attempt to fit a single ellipticity to the observation. Note the large error on the position angle of the modeled PSPC surface brightness. The roundness of the galaxy and the low X-ray photon count in the HRI observation made the determination of a position angle very difficult. Given the uncertainty, both of the PSPC ellipticities are constrained with the HRI ellipticities, which are consistent with the shape of the optical ellipticities.

**NGC 1404.**—This galaxy is near the center of the Fornax cluster (within 10' of the central galaxy, NGC 1399) and has a rotation velocity of $90 \text{ km s}^{-1}$. The HRI ellipticity does not differ from the PSPC ellipticity to within the error.

**NGC 4374.**—M84 is a member of the Virgo cluster and has a very low line-of-sight rotation velocity ($8 \text{ km s}^{-1}$). NGC 4374 is also a radio galaxy (3C 272.1), with jets that...
have position angles of $-5^\circ$ and $170^\circ$ (Laing & Bridle 1987) and that are linear for $40^\circ$ before they are engulfed by a larger diffuse radio emission. The core of this galaxy also contains dust lanes (Goudsouzian 1994), situated at a position angle of $80^\circ$. The HRI ellipticities are not significantly rounder than the IPC ellipticities. The position angle of the HRI emission puts it in areas that avoid the radio emission, as seen by Laing & Bridle (1987). The optical and X-ray ellipticities agree with one another.

NGC 4472.—The X-ray bright galaxy NGC 4472 (M49) is a luminous Virgo cluster member with a moderate rotation velocity of 27 km s$^{-1}$. The PSPC ellipticities are flatter than the HRI ellipticities and flatter than the optical isophotes of the galaxy at the same radii. The HRI and optical ellipticities are similar.

NGC 4552.—M89, like NGC 1395, is a shell galaxy (Malin 1979), but with a low rotation velocity (15 km s$^{-1}$). The PSPC and HRI ellipticities are the same within calculated errors, but the X-ray emission is significantly flatter than the optical emission at all radii; this is the only galaxy for which this occurs. We note that this is the only S0 galaxy in the sample.

NGC 5322.—This X-ray faint galaxy has a rotation velocity of 40 km s$^{-1}$. All of the ellipticities are the same to within the uncertainties. The HRI observation has only 360 photons from the source in the $128'' \times 128''$ field, and this paucity of counts is reflected in the large error in the optimized ellipticity.

5. DISCUSSION AND CONCLUSIONS

A primary goal is to examine whether the X-ray emission from rotating ellipticals provides insight into the flow of the hot gas, so we review the qualitative predictions of the models and compare them to our observations. The predictions for the model depend on a variety of important issues, such as whether rotation is responsible for the optical ellipticity, which we examine first. In low-luminosity galaxies, rotation can account for the observed ellipticity of the optical isophotes, while in the high-luminosity galaxies, rotation is insufficient, so an anisotropic velocity dispersion is required (Davies et al. 1983; Binney & Tremaine 1987). These galaxies have an average optical luminosity that is a bit higher than galaxies whose flattening is due to rotation, but by examining the properties of the galaxies in more detail, more definitive statements about rotational support can be made.

The two fastest rotators are NGC 1404 and NGC 1395, so they have the greatest probability of having rotation contribute to their flattening. The galaxy NGC 1404 appears to have an optical ellipticity that is close to the value expected from rotation. For elliptical galaxies whose isodensity surfaces are coaxial oblate spheroids (Binney & Tremaine 1987), the observed ratio of the mean rotational velocity to the line-of-sight velocity dispersion, $v/\sigma = 0.37-0.40$ (Davies et al. 1983; Franx et al. 1989), would lead to an expected ellipticity of 0.08–0.09. Since the observed optical ellipticity is 0.12–0.14, much of it could be due to rotation. However, in the central $15''$ of the galaxy the rotational velocity decreases sharply, so the mean $v/\sigma$ in this region is 0.20, which would produce an ellipticity of 0.02. Since the observed optical ellipticity in the center is significantly greater ($\epsilon = 0.14$), the flattening must be largely due to an anisotropic dispersion.

The other rapidly rotating galaxy, NGC 1395, a system of similar optical luminosity, has a rotation curve that rises to a value of 93 km s$^{-1}$ at a radius of 15'. Beyond this radius, the value of $v/\sigma$ is 0.36–0.45, depending on which weighting of $v$ or $\sigma$ is used (Davies et al. 1983; Franx et al. 1989); within 15' the mean $v/\sigma$ is 0.15–0.20. The ellipticities associated with these values of $v/\sigma$ for the rotational flattening model (above) are $\epsilon = 0.01-0.02$ at $r = 10''$ and $\epsilon = 0.08-0.11$ for $r > 15''$. However, the optical ellipticity is observed to have a mean value of $\epsilon = 0.15$ for $r \leq 10''$ and $\epsilon = 0.18$ for $r > 15''$. Evidently, an anisotropic velocity dispersion is responsible for the flattening in the center and for about half of the flattening in the outer regions.

For the three galaxies with $\epsilon \approx 0.10$, NGC 4374, NGC 4472, and NGC 4552, the observed $v/\sigma$ is low, 0.03–0.11, whereas rotational flattening would require $v/\sigma \approx 0.4$, so the flattening in these systems must be dominated by the anisotropic velocity dispersion. Similarly, for NGC 5322, $v/\sigma = 0.13$, but for rotation to produce the observed optical ellipticity of $\epsilon \approx 0.4$, a value of $v/\sigma = 1$ would be needed. To conclude, velocity anisotropy rather than rotation is the likely cause of the observed optical flattening for the galaxies in our sample. This indicates that the most appropriate models are those for the higher mass galaxies (Brighenti & Mathews 1996), and it is for systems like these that they developed their models.

The basic expectations from the models were that the X-ray isophotes in the inner 1–10 kpc region would be flatter than either the stellar distribution or the X-ray iso-
photos in the outer part of the galaxy (beyond 10 kpc). These predictions are not supported by our data. For the most rapid rotators, NGC 1395 and NGC 1404, the X-ray isophotes are no more elliptical than the optical isophotes, and the ellipticities for the PSPC and HRI data are indistinguishable. One would expect these rapid rotators to have their rotation axis close to the plane of the sky, so the degree of flattening should be similar to that shown by Brighenti & Mathews (1996), approximately \( \epsilon = 0.5-0.8 \) (model E2; 0.25), while the observed ellipticities are typically 0.1 (Table 4). In the other four more slowly rotating galaxies, none show a significant increase in the ellipticity of the HRI relative to the PSPC.

A difference between the HRI and PSPC ellipticities occurs in only one case, NGC 4472, but it is in the sense that the ellipticity becomes greater at radii beyond 3′. Irwin & Sarazin (1996) have discussed this flattening in the outer part of NGC 4472, and they attribute it to the interaction of the galaxy with the environment of the Virgo cluster. Such interactions have been noticed previously in the Virgo cluster, such as in the case of NGC 4406 (White et al. 1991). Interactions of this type may explain why NGC 4552, also a Virgo cluster member, has PSPC and HRI ellipticities slightly flatter than the optical ellipticities.

The basic angular momentum cooling flow model appears to be ruled out, but it is difficult to determine whether one should consider entirely different models or whether modifications to this model are possible. There are a few possible explanations for the absence of the flattening predicted in the X-ray isocontours, most of which are discussed in Brighenti & Mathews (1996). In order to avoid the expected flattening, it is necessary that the gas fails to move inward to a fraction of its initial radius. Galactic winds will naturally prevent inflow, but unless the outward flow of the gas is halted by a surrounding medium, the X-ray luminosity will fall far below the observed levels. Partial winds are another possibility, where some gas flows outward beyond a stagnation radius while the gas interior to that radius flows inward. To assess the viability of this picture, one would need to calculate whether the predicted flattening within the central region is consistent with the limits set by the HRI (within 10\(^{-5}\)) or about 0.1–0.3\(R_e\) for these galaxies while still producing the observed X-ray luminosity. In support of the total or partial galactic wind picture, we note that Davis & White (1996) find that the hot gas temperature is significantly above the stellar velocity dispersion temperature, as might be expected if a wind or breeze were present. Alternatively, the relatively high X-ray temperatures may be due to deeper potential wells due to extended massive dark halos.

Another possibility for avoiding flattened disks is that the gas cools before it falls to a fraction of its original size. In several cooling flow models, distributed mass dropout is included and is attributed to the development of thermal instabilities. Unfortunately, the physical basis for this is questionable, since linear thermal instability modes generally are not unstable in this environment (Balbus 1991). In addition, thorough angular-momentum mixing could prevent disk formation. Fabian & Nulsen (1994) considered this possibility for cooling flows during the early stages of galaxy formation, but it might be applicable today as well. They suggest that turbulence (and shocks) create an effective viscosity that mixes the angular momentum. While this is not meant to be a definitive discussion of alternative models, it shows a range of possibilities that must be considered before we have a thorough understanding of the phenomenon. Several of these models make predictions that might be possible to test with more detailed measurements of the density and temperature distribution, as well as of the metallicity of the X-ray gas, and such observations are likely to be undertaken with the new generation of telescopes such as Chandra and XMM.

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