X-ray isophote shapes and the mass of NGC 3923

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ABSTRACT

We present analysis of the shape and radial mass distribution of the E4 galaxy NGC 3923 using archival X-ray data from the ROSAT PSPC and HRI. The X-ray isophotes are significantly elongated with ellipticity $\epsilon_x = 0.15(0.09-0.21)$ (90% confidence) for semi-major axis $a \sim 10^{\pm 1}$ kpc and have position angles aligned with the optical isophotes within the estimated uncertainties. Applying the Geometric Test for dark matter, which is independent of the gas temperature profile, we find that the ellipticities of the PSPC isophotes exceed those predicted if $M \propto L$ at a marginal significance level of 85%(80%) for oblate (prolate) symmetry. Detailed hydrostatic models of an isothermal gas yield ellipticities for the gravitating matter, $\epsilon_{\text{mass}} = 0.35 - 0.66$ (90% confidence), which exceed the intensity weighted ellipticity of the R-band optical light, $\langle \epsilon_R \rangle = 0.30$ ($\epsilon_{\text{max}}^R = 0.39$).

We conclude that mass density profiles with $\rho \sim r^{-2}$ are favored over steeper profiles if the gas is essentially isothermal (which is suggested by the PSPC spectrum) and the surface brightness in the central regions ($r \lesssim 15''$) is not modified substantially by a multi-phase cooling flow, magnetic fields, or discrete sources. We argue that these effects are unlikely to be important for NGC 3923. (The derived $\epsilon_{\text{mass}}$ range is very insensitive to these issues.) Our spatial analysis also indicates that the allowed contribution to the ROSAT emission from a population of discrete sources with $\Sigma_x \propto \Sigma_R$ is significantly less than that indicated by the hard spectral component measured by ASCA.

Key words: galaxies: elliptical and lenticular, cD – galaxies: fundamental parameters – galaxies: individual (NGC 3923) – galaxies: structure – X-rays: galaxies.

1 INTRODUCTION

The structure of the dark matter halos of galaxies provides important clues to their formation and dynamical evolution (e.g. Sackett 1996; de Zeeuw 1996, 1997). For example, in the Cold Dark Matter (CDM) scenario (e.g. Ostriker 1993) there is evidence that the density profiles of halos have a universal form essentially independent of the halo mass or $\Omega_0$ (Navarro, Frenk, & White 1997; though see Moore et al. 1997). The intrinsic shapes of CDM halos are oblate-triaxial with ellipticities similar to the optical isophotes of elliptical galaxies (e.g. Dubinski 1994). The global shape of a halo also has implications for the mass of a central black hole (e.g. Merritt & Quinlan 1997).

At present accurate constraints on the intrinsic shapes and density profiles of early-type galaxies are not widely available (e.g. Sackett 1996; Olling & Merrifield 1997). Stellar dynamical analyses that have incorporated the information contained in high order moments of stellar velocity profiles have made important progress in limiting the uncertainty in the radial distribution of gravitating mass arising from velocity dispersion anisotropy (Rix et al. 1997; Gerhard et al. 1997). However, as indicated by the paucity of such stellar dynamical measurements, the required observations to obtain precise constraints at radii larger than $\sim R_e$ are extensive, and the modeling techniques to recover the phase-space distribution function are complex. It is also unclear whether this method can provide interesting constraints on the intrinsic shapes since only weak limits on the range of possible shapes have been obtained from analysis of velocity profiles out to $\sim 2 R_e$ (e.g. Statler 1994).

* The distribution of dark matter in spiral galaxies is also far from being a solved problem – see, e.g. Broeils (1997).
Interesting measurements of the ellipticity of the gravitating mass have been obtained for two Polar Ring galaxies (Sackett et al. 1994; Sackett & Pogge 1995) and from statistical averaging of known gravitational lenses (e.g. Keeton, Kochanek, & Falco 1997), but owing to the rarity of these objects it is possible that the structures of their halos are not representative of most early-type galaxies. Moreover, gravitational lenses, which are biased towards the most massive galaxies, only give relatively crude constraints on the ellipticity and radial mass distribution for any individual system and only on scales similar to the Einstein radius (e.g. Kochanek 1991).

The X-ray emission from hot gas in isolated early-type galaxies (Forman, Jones, & Tucker 1985; Trinchieri, Fabiano, & Canizares 1986; for a review see Sarazin 1997) probably affords the best means for measuring the shapes and radial mass distributions in these systems (for a review see Buote & Canizares 1997b; also see Schecter 1987 and the original application to the analogous problem of the shapes of galaxy clusters by Binney & Stimpyle 1978). The isotropic pressure tensor of the hot gas in early-type galaxies greatly simplifies measurement of the mass distribution over stellar dynamical methods. Moreover, since the shape of the volume X-ray emission traces the shape of the gravitational potential independent of the (typically uncertain) gas temperature profile (Buote & Canizares 1994, 1996a), the shape of the mass distribution can be accurately measured in a way that is quite robust to the possible complicating effects of multi-phase cooling flows and magnetic fields (see Buote & Canizares 1997b).

Presently, X-ray measurements of the mass distributions in early-type galaxies are inhibited by limitations in the available data. The ROSAT (Trümper 1983) Position Sensitive Proportional Counter (PSPC) (Pfeffermann et al. 1983) has inadequate spatial resolution (PSF $\sim 30''$ FWHM) to map the detailed mass distributions for all but the largest nearby galaxies, and the limited spectral resolution and band width complicates interpretation of the measured temperature profiles (Buote & Canizares 1994; Trinchieri et al. 1994; Buote & Fabian 1997). Although equipped with superior spatial resolution (PSF $\sim 4''$ FWHM), the ROSAT High Resolution Imager (HRI) (David et al. 1997) has too small an effective area and too large an internal background to provide images of sufficient quality for many galaxies for radii $r \gtrsim R_e$. Among the few galaxies with detailed measurements of their radial mass profiles are NGC 507 (Kim & Fabbian 1995), NGC 1399 (Rangarajan et al. 1995; Jones et al. 1997), NGC 4472 (Irwin & Sarazin 1996), NGC 4636 (Trinchieri et al. 1994), NGC 4649 (Brighenti & Mathews 1995), and NGC 5044 (David et al. 1994).

The shape of the gravitating mass has been measured via X-ray analysis for the E4 galaxy NGC 720 and the E7/S0 galaxy NGC 1332 and found to be at least as elongated as the optical isophotes (Buote & Canizares 1994, 1996a, 1997a). For NGC 720, which has more precise constraints, the ellipticity of the gravitating matter is $e_{mass} = 0.44 - 0.68$ (90% confidence) compared to the intensity weighted ellipticity of the optical light, ($e$) = 0.31 (Buote & Canizares 1997a). In addition, the X-ray isophotes of NGC 720 twist from being aligned with the optical isophotes within $R_e$ to a position $\sim 30''$ offset at larger radii. This twist, when combined with the ellipticities of the X-ray isophotes, cannot be explained by the projection of a reasonable triaxial matter distribution and thus may implicate a dark matter halo misaligned from the stars (Buote & Canizares 1996b; Romanowsky & Kochanek 1997).

NGC 720 and NGC 1332 were selected for analysis since they are isolated, significantly elongated in the optical, sufficiently bright, and sufficiently dominated by emission from hot gas in the ROSAT band. In this paper we present X-ray analysis of the classic “shell” galaxy, NGC 3923, which is the last galaxy of which we are aware that satisfies these selection criteria and has deep ROSAT observations. This isolated E4 galaxy has both archival ROSAT PSPC and HRI data and its ASCA spectrum has been analyzed previously (Buote & Fabian 1997). This will serve as our final case study until the impending launch of AXAF revolutionizes this field.

The organization of this paper is as follows. In §2 we describe the ROSAT observations and the data reduction. We discuss removal of point sources in §3. Measurements of the ellipticities of the X-ray isophotes and the radial profiles are described in §4 and §5 respectively. Analysis of the PSPC spectrum is presented in §6. We give results for the Geometric Test for dark matter in §7 and constraints on the shape and radial mass distribution from detailed hydrostatic models in §8. Finally, in §9 we give our conclusions.

2 OBSERVATIONS AND DATA REDUCTION

2.1 PSPC

NGC 3923 was observed with the PSPC for 14.5 ks from 17-19 December 1991 and for 24 ks from 23-26 June 1993. Both observations were positioned at the field center where the point spread function is smallest. Since spatial resolution is of principal importance for our analysis of the shape of the X-ray surface brightness, we analyze only the PSPC data in the hard band (PI channels 42-201, $E \approx 0.4 - 2.0$ keV) to further optimize the size of the PSF; for details regarding the PSPC PSF see Hauser et al. (1993, updated 1994) and see Aschenbach (1998) for a description of the ROSAT X-ray telescope.

We reduced each observation separately with the standard XSELECT, FTOOLS, and IRAF-PROS software. Firstly, the events files were cleaned of after-pulse signals by removing any events following within 0.35 ms of a precursor. We then removed large fluctuations in the light curves indicative of scattered light from the Bright Earth, Sun, or SAA; this resulted in filtered exposures of 13.5 ks for the 1991 observation and 21.8 ks for the 1993 observation.

To optimize signal-to-noise (S/N) and bin-size requirements for computing ellipticities (see §3), we binned the cleaned events files into images with 5'' pixels. Exposure maps for the appropriate energy band (PI=42-201) were then generated for each image and were then used to create flattened images; note that the intrinsic resolution of the exposure maps is 15''. Finally, we aligned the images using bright point sources in the field and then combined the images. The final image is displayed in Figure 1.

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2.2 HRI

NGC 3923 was observed with the HRI for 45 ks from 10-17 January 1995 and for 26 ks from 22-26 June 1995. Both observations were positioned at the field center where the PSF is smallest (David et al. 1997). For detailed explanation of our reduction of HRI data we refer the reader to the related study of NGC 720 by Buote & Canizares (1996b).

We restricted the data to those in pulse-height analyzer (PHA) bins 2-8 since they maximized the S/N of the data of each observation. For each observation we binned the events into images with 1″ pixels to optimize determination of ellipticities within a 30″ radius of the galaxy center (§). Exposure maps were generated with the standard software for each image and then used to flatten the images.

An accurate aspect solution is critical to analysis of isophote shapes with the HRI on small scales (r ≤ 15″), with the amplitude of the asymmetrical distortion due to incomplete aspect correction typically being most important for (r ~ 5″ – 10″) (David et al. 1997). The S/N of each of the NGC 3923 observations are too small to usefully perform the aspect correction algorithm of Morse (1995). The low S/N also makes it difficult to make strong statements about the ellipticity of isolated point sources indicative of aspect error. As a result, following Buote & Canizares (1996b), we search for possible aspect errors by examining the positions of point sources for each of the OBIs; i.e. the time intervals during which the spacecraft continuously pointed on the target.

Three OBIs contain most of the “on time” of the January observation: 19 ks for OBI-6, 20 ks for OBI-11, and 9 ks for OBI-14; 28 ks is distributed fairly evenly among 12 other OBIs. Using OBI-11 as a reference, the bright point sources in the NGC 3923 field are displaced by 2″ ± 1″ for OBI-6, and 3″ ± 1.5″ for OBI-14. These shifts, though statistically significant, are very consistent with the expected aspect uncertainties for a typical observation. To register all of the OBIs to one coordinate frame, we binned together those OBIs that were observed close together in time; i.e. OBIs 1-5, 6-9, 10-11, 12-13, and 14-15. Once registered to the same coordinate frame, the images were all added. (Note that the image for each of these OBI groups was binned as above.)

The June observation proved to be problematic because none of the 19 OBIs had a long enough exposure to provide very accurate source positions. Hence, we were unable to perform a reliable test of the aspect solution. In order to make some estimate of the error, we grouped those OBIs closest together in time: OBIs 1-3, 4-12, 13-16, and 17-19. For three of these groups, less than 1″ shifts were required, but the OBI 4-12 group required an 8″ ± 1″ shift. This large shift is questionable since all but one source was too faint to even obtain a centroid measurement using the alignment software in IRAF.

As it is unclear from considerations of the OBIs how accurate is the aspect error for the June observation, we compared the ellipticity and orientations (computed as described in § of the surface brightness with those of the January observation. Unfortunately, we find significant disagreement between the two observations; note the disagreement occurs whether or not we include the OBIs 4-12 for the June observation. In particular, the position angles determined from the January observation are fully consistent with the PSPC data and the optical position angles for r ≤ 30″, which agrees with NGC 720 and NGC 1332 (Buote & Canizares 1996a,b); the ellipticities are also consistent with the PSPC data. The June observations, however, have position angles that differ by over 60° and the ellipticities, particularly for r ≥ 20″ – 30″ are less than 0.1 as opposed to ~ 0.25 for the January observation. Furthermore, the radial profile (see § of the June observation is significantly flatter for r ≤ 10″.

Thus, the isophote shapes and orientations are inconsistent for the two observations. The differences point to a serious aspect error in the June observations. That is, although we would expect aspect error to induce ellipticity in an intrinsically circular source, if the distortion occurs nearly along the minor axis of a moderately elliptical source, it will reduce the ellipticity of the source, as well as alter the position angle. The flatter inner radial profile of the June data is consistent with a much larger intrinsic ellipticity. For the June observations, this would require an ellipticity of ∼ 0.3 or larger. If we assume that the ellipticity is the same for both observations, we would make some estimate of the error, we grouped those OBIs closest together in time: OBIs 1-3, 4-12, 13-16, and 17-19. For three of these groups, less than 1″ shifts were required, but the OBI 4-12 group required an 8″ ± 1″ shift. This large shift is questionable since all but one source was too faint to even obtain a centroid measurement using the alignment software in IRAF.

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Table 1. Identified Point Sources

| Source | R. A. (J2000) | Decl. (J2000) |
|--------|---------------|--------------|
| 5      | 11h 50m 53s   | -28° 47′ 04″ |
| NWa    | 11 50 58      | -28 47 04    |
| NWb    | 11 50 58      | -28 46 30    |

These sources (expressed in J2000 coordinates) were identified from visual inspection of the PSPC image within a 10′ radius of the galaxy center. They were removed from the image for spatial analysis as described in §.

3 POINT SOURCES

It is readily apparent from inspection of Figure 1, particularly for the higher S/N PSPC data, that the X-ray emission of NGC 3923 is significantly contaminated by foreground/background point sources. Within a 10′ radius of the galaxy center at least 8 point sources are easily identified by visual inspection of the PSPC image. (Only r ≤ 3′ is shown in the Figure.) We list the positions of these sources in Table 1.

For our analysis of the isophote ellipticities and orientations (∈) and the radial profile (∂) of the X-ray surface brightness, we wish to analyze only the distribution of the diffuse emission associated with NGC 3923 and thus these contaminating sources must be removed. The most important contaminating source is number (1) (which lies along the optical major axis to the N-E) since it lies closest to the galactic center where the S/N, and thus constraints on the surface brightness, are best; this source is also apparent in the Figure.) We list the positions of these sources in Table 1.

Our preferred method for removing sources, which is well suited for analyzing quadrupole moments of X-ray images (Buote & Tsai 1996b), is to first choose an annulus around each source to estimate the local background. Then a second order polynomial surface is fitted to the background which then replaces the source. We removed sources 2-8 using this method, but sources (1) and NWa,b require some elaboration.

Since source (1) affects ellipticity measurements for r ≥ 100″ we examined how robust the ellipticity and position angle were to the method used to remove the source. Another method to remove sources is by “symmetric substitution” (see Strimple & Binney 1979; Buote & Tsai 1995; Buote & Canizares 1996a). This method exploits the assumed symmetry of the hot gas distribution. If the gas is approximately ellipsoidal, then we can replace source (1) with the corresponding emission obtained by reflecting the source over the galactic center; i.e. essentially on the other side of the major axis (a → −a). Fortunately, we find that the ellipticities and position angles are virtually the same whether we remove source (1) by subtracting a model for the local background or by symmetric substitution. (We use the former method for ensuing analysis.)

The emission associated with NWa,b cannot be so easily removed because it is extended, and it is not obvious how to define a background model. Fortunately this emission only begins to affect the ellipticities for semi-major axes ≳ 120″. At these distance the S/N does not allow accurate constraints. However, this emission does need to be removed from the radial profile, and thus we iterate the local background method to remove the emission associated with NWa,b. This method is suitable for the radial profile since the azimuthal averaging is not overly sensitive to small non-axisymmetric residuals. (We mention the effect of removing this emission on the radial profile in §.)

4 X-RAY ISOPHOTE SHAPES AND ORIENTATIONS

As is typical for current X-ray data of early-type galaxies the small number of counts (≤ 1000) for the PSPC and HRI images of NGC 3923 implies that we can only hope to measure with any precision the ellipticity and position angle of the aggregate X-ray surface brightness in a large aperture. The method we employ is an iterative procedure (Carter & Metcalfe 1980) and is analogous to computing the two-dimensional moments of inertia within an elliptical region where the ellipticity, θs, is given by the square root of the ratio of the principal moments and the orientation of the principal moments gives the position angle, θM, (see Buote & Canizares 1994 for application to ROSAT images). The parameters εs and θs are good estimates of the ellipticity (ε) and position angle (θ, or P.A.) of an intrinsic elliptical distribution of constant shape and orientation. For a more complex distribution εM and θM are average values weighted heavily by the outer parts of the regions.

We estimate the uncertainties on εM and θM using a Monte Carlo procedure described in Buote & Canizares (1996b). In sum, the procedure involves constructing 1000 realizations of the PSPC and HRI images taking into account statistical noise and unresolved sources; these unresolved sources are modeled according to the log N(> S) − log S distribution given by Hasinger et al. (1993) and their profiles are given by the appropriate PSPC or HRI PSF. The 90% confidence limits on εM, for example, are defined by the 5th and 95th percentile values computed from the 1000 simulations.

The profiles of εM and θM are listed for the PSPC in Table 4 and for the HRI in Table 5. We also display the εM profiles and their 68% uncertainties in Figure 4. The apertures listed in the tables are chosen so that each increment in semi-major axis a consists of approximately 100 source.
The values of $\epsilon_M$ (and confidence limits) are computed within an aperture of semi-major axis $a$ on the image with the background included; the counts, however, have the background subtracted. The values of $\theta_M$ are given in degrees N through E.

Table 3. HRI Ellipticities and Position Angles

| $a$ (arcsec) | $\epsilon_M$ | 68% | 90% | $\theta_M$ | 68% | 90% | Counts |
|--------------|--------------|-----|-----|------------|-----|-----|--------|
| 12, . . . . . | 0.25         | 0.21| 0.32| 42         | 44-83| 30-92| 309    |
| 17, . . . . . | 0.26         | 0.20| 0.31| 69         | 50-76| 43-88| 412    |
| 23, . . . . . | 0.22         | 0.18| 0.29| 66         | 47-81| 34-102| 506    |
| 32, . . . . . | 0.19         | 0.17| 0.27| 63         | 35-82| 15-107| 631    |
| 44, . . . . . | 0.14         | 0.12| 0.22| 76         | 41-87| 31-103| 735    |
| 60, . . . . . | 0.16         | 0.10| 0.20| 74         | 44-101| 33-123| 825    |

See Table 2.

5 RADIAL PROFILE OF X-RAY SURFACE BRIGHTNESS

In order to construct the azimuthally averaged radial profiles for the PSPC and HRI data we require measurements of their respective background levels. We selected annular regions centered on the galaxy that are sufficiently far from the galaxy center so that contamination from the galaxy is minimal. (Also, any point sources were removed.) We obtain a background rate of $2.4 \times 10^{-4}$ cnts s$^{-1}$ arcmin$^{-2}$ for the PSPC and a rate of $3.3 \times 10^{-3}$ cnts s$^{-1}$ arcmin$^{-2}$ for the HRI.

We binned the radial profiles so that each bin had approximately the same S/N. However, for the innermost bins the S/N is larger because we did not oversample the respective PSFs. The centers of the radial bins for both the PSPC and HRI data were determined by the centroid of the circular region containing $\sim 80\%$ of the total flux; in neither case did this choice critically affect the radial profile shape. We display the radial profiles in Figure 5 along the the PSFs; note that residuals of the emission near sources NWa,b may be seen in the PSPC profile for $r \sim 130'' - 150''$. The X-ray emission is clearly extended for both data sets.

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Figure 2. Moment ellipticities and $1\sigma$ errors for PSPC (left) and HRI (right) data. The isophotal ellipticities of the $R$-band light from Jedrzejewski (1987) are indicated by the dotted line. The dashed line represents the isopotential ellipticities of $\Phi_R$, the potential assuming $M \propto L_R$ (see §7).

Figure 3. Radial surface brightness profiles of the PSPC (left) and HRI (right) data. The error bars indicate the data and the horizontal lines through each point show the bin sizes. The best-fit $\beta$ model (filled circles), the PSFs (crosses), and the $R$-band light convolved with the respective PSFs (boxes) are also shown. All of these quantities have been binned as the X-ray data.

A convenient parametrisation of the X-ray radial profiles of early-type galaxies is given by the "$\beta$ model", $\Sigma_x \propto (R^2 + R^4)^{-3\beta + 0.5}$ (Cavaliere & Fusco-Femiano 1976). The model assumes that the gas is isothermal and that the stars, considered as test particles, follow a King law. Although these assumptions are unlikely to be strictly valid for ellipticals, this model provides a reasonable description of the ROSAT radial profiles of both NGC 720 (Buote & Canizares 1996b) and NGC 1332 (Buote & Canizares 1996c), as well as many other galaxies (e.g. Forman et al. 1985). Moreover, for ROSAT data the $\beta$ model typically gives fits of quality very similar to more sophisticated mass models and thus it serves as a good benchmark for these more general models (as in §).

Table 4. Simple $\beta$ Model Fits to Radial Profile

| Data         | $R_c$ (arcsec) | $\beta$  | $\chi^2$ | dof | $\chi^2_{\text{red}}$ |
|--------------|----------------|----------|----------|-----|------------------------|
| PSPC         | $5.6^{+1.1}_{-1.0}$ | $0.47^{+0.02}_{-0.02}$ | 8.9 | 9 | 1.0 |
| HRI          | $5.1^{+1.6}_{-1.2}$  | $0.46^{+0.05}_{-0.04}$ | 1.4 | 4 | 0.4 |
| PSPC + HRI   | $5.4^{+0.8}_{-0.8}$  | $0.46^{+0.02}_{-0.01}$ | 10.7 | 15 | 0.7 |

The best-fit values and 90% confidence limits on one interesting parameter are listed for $R_c$ and $\beta$. The PSFs of each data set have been incorporated into the fits.

In Table 4 we list the results of fitting the $\beta$ model (convolved with the appropriate PSF) to the X-ray data;
only those bins with $S/N \gtrsim 5$ were included in the fits. When fitted separately to the PSPC and HRI data, the $\beta$ model gives a good quality fit and the derived $R_e$ and $\beta$ parameters are similar; note that if the emission from sources NWa,b is not removed from the PSPC data, the parameters of these fits are essentially unaffected but the value of $\chi^2$ increases to 17.4.

The best-fit model obtained from jointly fitting the PSPC and HRI data is shown in Figure 3. We have binned the optical data like the X-rays and have convolved with the appropriate PSFs; for radii larger than the limiting $a = 103''$ of Jedrzejewski, we extrapolate the data using the best-fitting De Vaucouleurs model. For radii larger than the PSFs, the shape of the optical profile, $\Sigma_O$, is very similar to the shape of $\Sigma_X$ in agreement with expectations from steady-state cooling flow models (e.g. Sarazin 1987). However, the X-ray and optical profiles disagree markedly for small radii ($r \lesssim 10''$) with $\Sigma_O$ being much more centrally peaked than $\Sigma_X$. Because of its smaller PSF this effect is more pronounced in the HRI data.

In particular, it is clear that a population of discrete X-ray sources distributed like $\Sigma_X$ cannot contribute significantly to the emission. If we assume that the hot gas is described by a $\beta$ model or related model (see §3.4) then adding such a discrete component only worsens joint fits to the PSPC and HRI data. We find that $f_{hg}/f_{disc} > 3.6$ (90% confidence), where $f_{hg}$ is the flux of the hot-gas component ($\beta$ model) and $f_{disc}$ is the flux of the discrete sources where the 0.4-2 keV flux is computed within a circle of $r = 2''$.

Spectral analysis of ASCA data of NGC 3923 by Buote & Fabian (1997) shows that two temperature models are required by the data with a cold component, $T_C = 0.55$ keV, and a hot component, $T_H = 4.2$ (> 2.2) keV (90% confidence); the ratio of the 0.5-2 keV flux of the cold component to the hot component is 1.9 (1.3-2.8) at 90% confidence. If the discrete sources are indeed distributed like $\Sigma_O$, then the emission of the hot component cannot be entirely due to discrete sources. This would indicate that the emission of the hot component is actually largely due to another phase of the hot gas and that $T_H$ is overestimated due to an artifact of fitting low S/N data as suggested by Buote & Fabian. (Note that the cold-to-hot flux ratio derived by Buote & Fabian in the 0.5-2 keV band remains essentially the same when computed in the 0.4-2 keV band analyzed in our paper.)

6 SPECTRAL ANALYSIS

Spectral analysis of the X-ray data is required for our study of the mass distribution in NGC 3923 to determine (1) how much of the emission is due to hot gas, and (2) the temperature profile of the gas. The superior spectral resolution of ASCA is better suited than ROSAT to address issue (1), and as discussed at the end of the previous section, the ASCA spectrum is consistent with $\sim 35\%$ of the X-ray emission in the 0.5-2 keV band arising from a population of discrete sources (Buote & Fabian 1997). Since this much discrete emission is inconsistent with the ROSAT radial profiles we shall neglect it and assume all of the emission arises from hot gas. This assumption does not seriously affect analysis of the mass distribution if the discrete contribution is $\lesssim 20\%$ (Buote & Canizares 1997a).

Unlike the ASCA data, the ROSAT PSPC data allows us to directly measure any temperature gradients. To investigate this issue we analyzed the PSPC spectra in a circular region with $r = 30''$ and an annular region with $r = 60'' - 120''$; the spectra of these regions are shown in Figure 4. We fit a model consisting of Galactic absorption ($N_H = 6.4 \times 10^{20}$ cm$^{-2}$ – Stark et al. 1992) and a thin
Results of fitting a MEKAL model modified by Galactic photo-electric absorption. We list 90\% confidence limits on one interesting parameter.

| Name | $T$ (keV) | $Z$ | $\chi^2$ | dof | $\chi^2_{red}$ |
|------|-----------|-----|----------|-----|----------------|
| $0^\circ - 30^\circ$ | $0.50^{+0.05}_{-0.04}$ | $0.44^{+0.23}_{-0.15}$ | 51.3 | 50 | 1.0 |
| $60^\circ - 120^\circ$ | $0.53^{+0.17}_{-0.15}$ | $0.09^{+0.67}_{-0.07}$ | 7.9 | 12 | 0.6 |
| BOTH | $0.50^{+0.04}_{-0.05}$ | $0.45^{+1.2}_{-0.16}$ | 61.6 | 64 | 1.0 |

7 GEOMETRIC TEST FOR DARK MATTER

The shapes of the X-ray isophotes allow the shape and radial distribution of gravitating matter to be probed in a way that is more robust than the traditional spherical approach (for a review see Buote & Canizares 1997b). Assuming the hot gas is approximately in hydrostatic equilibrium and that the emission is adequately described by a single phase, then the volume X-ray emissivity, $j_x$, obeys an “X-ray Shape Theorem” (Buote & Canizares 1994, §3.1; 1996a, §5.1) which states that $j_x$ and the gravitational potential, $\Phi$, have the same three-dimensional shapes independent of the temperature profile of the gas. One may thus make a “Geometric Test” for dark matter that is distributed differently from $L$ (with $L$ the luminosity distribution of the optical stellar light) by comparing the shape of $\Phi_L$ generated assuming $M \propto L$ with the shape of $j_x$ obtained from deprojecting the X-ray image data. As this comparison is independent of the poorly constrained temperature profile, $T(r)$, of the gas (see §3.1; 1996a), this test for dark matter is more robust than computing the radial mass distribution which is directly proportional to $T(r)$.

NGC 3923 has negligible stellar rotation, but if rotation of the gas is dynamically important then we must replace $\Phi$ with the appropriate effective potential. Theoretically, even without strong stellar rotation one may or may not (Nulsen et al. 1984) expect a rotating cooling flow to develop depending on whether angular momentum of the gas is conserved. Highly flattened X-ray isophotes indicative of a cooling disk have not been observed in ellipticals and thus we shall ignore any contribution from gas rotation.

To apply the Geometric Test we constructed a constant $M/L$ potential using the $R$-band surface photometry, $\Sigma_R$, of Jedrzejewski (1987). The major-axis profile of $\Sigma_R$ is well fitted by a De Vaucouleurs Law with an effective semi-major axis, $a_e = 92^\prime\prime$. Taking into account the ellipticity of the isophotes, we fitted the De Vaucouleurs Law to the mean radial profile, where the mean radius is, $r = \sqrt{ab} = a\sqrt{q}$, where $a$ is the major axis and $q$ the axial ratio. This gives a mean effective radius, $R_e = 73^\prime\prime$. Since the 3-D density giving rise to a De Vaucouleurs Law is well approximated by the Hernquist profile, $\rho \propto r^{-1}(r + r_e)^{-3}$ (Hernquist 1990), we consider for our $M \propto L_R$ model a Hernquist profile with $r_s = R_e/1.8153 = 40^\prime\prime$. Furthermore, we take $q$ to be stratified on oblate or prolate spheroids of constant ellipticity, where we use the intensity weighted ellipticity of $\Sigma_R$, $(\epsilon_R) = 0.30$.

This simple prescription for the $M \propto L_R$ model is sufficient for comparison to the ROSAT X-ray data because of the relatively crude X-ray constraints: i.e. only a global constraint on the isophote shapes of the PSPC data over a small range in radius, $r \sim 70^\prime\prime - 90^\prime\prime$, is useful for the comparison -- as we show below, the HRI data do not provide interesting constraints over the PSPC data. With better quality data from future missions which accurately measure ellip-
ticity gradients over a large range in radius a more accurate $M \propto L_R$ approximation will need to be considered.

We show in Figure 4 the ellipticities of the isopotential surfaces of the potential, $\Phi_R$, assuming $M \propto L_R$ and edge-on oblate symmetry. These ellipticities are considerably smaller than those of the $R$-band light because the spherically symmetric monopole term in the potential dominates the isopotential ellipticities for $r \sim r_c$. The ellipticities of the X-ray surface brightness, particularly for the PSPC data for $a \sim 70'' - 90''$, appear to be significantly larger than the isopotential ellipticities and thus indicate a failure of the $M \propto L_R$ hypothesis.

However, to rigorously compare $\Phi_R$ to the X-ray data we must formally deproject $\Sigma_x$ to get the ellipticities of $j_x$. The procedure we adopt for this comparison, which is suitable for the relatively crude constraints provided by the X-ray data, is to first fit a simple model to the radial profile of $\Sigma_x$; for this purpose, the results of the $\beta$ model fit jointly to the PSPC and HRI data are suitable (see §4). This model for $\Sigma_x(R)$ is then deprojected to obtain $j_x(r)$. We then assign to $j_x$ the ellipticities of $\Phi_R$ which gives a spheroidal emissivity distribution, $j_x(r; \beta)$. This spheroidal $j_x$ is then projected back onto the sky plane, while adjusting $R_e$ and $\beta$ to maintain a best fit of the radial profile of $\Sigma_x$ (convolved with the appropriate instrument PSF), to yield a $M \propto L_R$ model of the X-ray surface brightness. We compute moment ellipticities, $\epsilon_x(\Phi_R)$, for 1000 Monte Carlo simulations of this model in analogy to the data (see §5).

The 1$\sigma$ error bars for $\epsilon_x(\Phi_R)$ as well as the observed X-ray ellipticities and the 3-D isopotential ellipticities of $\Phi_R$ are displayed in Figure 5. Although most of the measured X-ray ellipticities lie within the error bars, the best measured PSPC ellipticities from $a \sim 70'' - 90''$ exceed the values predicted by the edge-on oblate $\Phi_R$ at the 85% confidence level. The edge-on prolate $\Phi_R$ is formally discrepant at the 80% level at these radii.

Hence, the X-ray isophote shapes indicate that the $\epsilon_x(\Phi_R)$ model is either too round, too centrally concentrated, or both; i.e. dark matter is required which is flattened and probably more extended than $\Sigma_R$. This discrepancy, though formally marginal and of lesser significance than found for the other two early-type galaxies studied NGC 720 and NGC 1332 (e.g. Buote & Canizares 1997a,b), is of precisely the same character: i.e. flattened and extended dark matter is required in these ellipticals. Since the flattest optical isophotes of NGC 3923 are rounder than those of NGC 720 and NGC 1332, it is possible that the symmetry axis of NGC 3923 is inclined more along the line-of-sight than the other two. This would account for the marginal

** We caution that interpretation of the significance of this discrepancy must take into account the PSPC PSF as we have done; i.e. the two deviant data points for $a \sim 75'' - 100''$ are not simply random fluctuations weighted equally with other points over the radial range investigated. (Also, care is required in the interpretation of the last measured $\epsilon_m$ at $a = 110''$ for the PSPC data since its value depends on the bright point source that is removed – see Sections 3 and 4.) This point is illustrated in Figures 13 (a) and (b) of Buote & Canizares (1996) for a similar X-ray analysis of NGC 1332. That is, the X-ray ellipticity profiles produced by different models are smeared out by the PSPC PSF, and thus a discrepancy is only achieved at radii large enough so that the ellipticity differences between models exceeds the relatively large error bars of the measured ellipticity; of course, the radial range is limited from above by the decreasing S/N. Thus, the radii $a \sim 75'' - 100''$ are where the different models convolved with the PSPC PSF begin to show significant ellipticity differences and the X-ray data still have good constraints on the measured ellipticity. NGC 3923, NGC 1332, and NGC 720 are quite similar in this regard since they have similar length scales and similar S/N PSPC observations. However, the HRI data of NGC 720 are of sufficient quality so that the effect of the PSFs on the Geometric Test can be clearly seen: see Figure 2 of Buote & Canizares (1997a).
significance of the NGC 3923 result if the intrinsic shapes of the three galaxies are in fact similar.

We note that, as explained in Section 5.1 of Buote & Canizares (1996a), if an ellipsoidal galaxy is inclined along the line of sight, then the Geometric Test results give a lower limit to the true discrepancy. That is, if mass follows light, then $j_x$ and $\Phi_L$ must be co-axial and thus share the same inclination angle, $i$. Since the projection of an ellipsoid with $i < 90^\circ$ is necessarily rounder than if the galaxy were viewed edge-on, deprojection of $\Sigma_x$ and $\Sigma_L$ assuming $i = 90^\circ$ will yield $j_x$ and $\Phi_L$ which are rounder than in reality. However, this edge-on deprojection of an inclined ellipsoidal galaxy only means that any differences in the inferred shapes of $j_x$ and $\Phi_L$ are smaller than if the true inclination angle were used.

8 DETAILED HYDROSTATIC MODELS

The results of the Geometric Test from the previous section suggest the presence of a dark matter halo that is flattened and more extended than the optical light. To generally constrain the allowed distribution of gravitating matter, we must employ explicit solutions of the hydrostatic equation. As the low S/N of the PSPC and HRI images does not justify a sophisticated non-parametric inversion of the data, we instead consider simple intuitive models to place constraints on the aggregate shape and radial distribution of gravitating mass. As in our previous studies (e.g. Buote & Canizares 1997b), we follow the pioneering approach of Binney & Strimpel (1978) and solve the hydrostatic equation assuming a single-phase, non-rotating, ideal gas,

$$\rho_g = \exp \left[ \Gamma \left( 1 - \frac{\Phi}{k_B T} \right) \right],$$

(1)

where $\Gamma = \mu m_p \Phi(0)/k_B T$ and where, $\rho_g = \rho_0(\vec{x})/\rho_0(0)$. Equation (1) assumes the gas is isothermal, but Strimpel & Binney (1979) and others (Fabricant, Rybicki, & Gorenstein 1984; Buote & Canizares 1994; Buote & Tsai 1995) have shown that the constraints on the shape of the gravitating matter distribution are not very sensitive to temperature gradients. Hence, we shall assume an isothermal gas which is consistent with the spectral constraints for NGC 3923 (§3) and the temperature profiles of other galaxies (e.g. Buote & Canizares 1994; for a review see Sarazin 1997).

Our procedure begins with a model for the gravitating mass. We consider spheroidal density distributions whose isodensity surfaces are concentric, similar spheroids. By examining oblate and prolate configurations we bracket the intermediate behavior of triaxial models; i.e. as our important constraints on the models are the X-ray isophote shapes for semi-major axes $a \sim 75''$, the detailed radial behavior of the isophote shapes and orientations which distinguish triaxial models cannot be usefully constrained by the NGC 3923 PSPC and HRI data.

Once the type of density model and its associated ellipticity, $\epsilon_{m,\alpha}$, are chosen, we compute $\Phi$ and $\rho_g$. (We initially focus on one-component models of the density of the gravitating matter and then consider separate density models for the dark and luminous matter.) The model X-ray surface brightness is then generated by integrating $\rho_g^2$ along the line of sight, assuming the galaxy is viewed edge-on. We model the radial mass as either a softened isothermal potential with mass density, $\rho \propto (a^2 + a'^2)^{-1}$, or a Hernquist profile, $\rho \propto a^{-1}(a + a')^{-3}$, where $a_\alpha$ is the appropriate mass scale length in each case. These models bracket the interesting range of densities in our previous X-ray analyses of NGC 720 and NGC 1332. We convolve the surface brightness with the PSF of the appropriate detector and evaluate the model on a grid of pixels identical to that used for analyzing the data (§4). We construct the radial profiles as for the data (§4) and determine $a_\alpha$ and $\Gamma$ by fitting the model profile jointly to the PSPC and HRI data. (The normalizations of the PSPC and HRI are free parameters.) By comparing the ellipticity of the model surface brightness to the data we constrain the input ellipticity of the gravitating mass.

In Table §7 we give the constraints on the shape of the gravitating matter obtained from these models. The mass is significantly flattened, $\epsilon_{m,\alpha} \approx 0.5$, with the derived shapes being essentially the same for both the $\rho \propto r^{−2}$ and Hernquist models. These ellipticities are inconsistent with the intensity-weighted ellipticity of the R-band light ($\langle \epsilon_R \rangle = 0.30$) at more than the 90% level and are marginally inconsistent with the flattest optical isophotes ($\langle \epsilon_{R,\alpha} \rangle = 0.39$). The derived range of values of $\epsilon_{m,\alpha}$, and the fact that they exceed the average ellipticity of the optical isophotes are consistent with the previous results we obtained for NGC 720 (and NGC 1332) (e.g. Buote & Canizares 1997a,b).

In Figure §4 we plot the radial profiles of typical $\rho \propto r^{−2}$ and Hernquist models. The $\rho \propto r^{−2}$ model fits are very similar in quality to those of the $\beta$ model (§3) but with slightly larger values of $\chi^2$. (The differences are not obvious from visual inspection.) However, the Hernquist fits are noticeably worse than the $\rho \propto r^{−2}$ model and have unacceptable $\chi^2_{\text{red}} \approx 1.9$. For $r \leq 15''$ the Hernquist model is too flat and then too steep out to $r \sim 100''$. At larger radii, the small fitted values of $\Gamma \sim 5.8$ force the Hernquist radial profile to be flatter than the data.

These deviations of the Hernquist model are most pronounced for the $M \propto L_R$ model (see §3) which has $a_\alpha = 40''$ and a best-fit $\Gamma = 5.5$ and $\chi^2 \approx 56.0$ (16 dof). The PSPC ellipticities of the $M \propto L_R$ model are 0.07 for $a \sim 70''$—90'', which is below the 90% confidence limits of the data (Table §3). Hence, by assuming the gas is isothermal we find that the $M \propto L_R$ model is inconsistent with the data at a significance level greater than indicated by the more robust Geometric Test (§4).

†† The plasma emissivity is a very weak function of temperature when convolved with the spectral response of either the PSPC or HRI.

‡‡ We assume the symmetry axis of the galaxy spheroid lies in the plane of the sky; i.e. we are not attempting in this analysis to uncover the true three-dimensional shape, though Binney & Strimpel (1979) have found that the X-ray analysis is not extremely sensitive to small inclination of the symmetry axis with respect to the sky plane. See Buote & Tsai (1994), for a thorough discussion of projection effects on X-ray shape analysis.

§§ The Hernquist density gives fits to the density profiles of halos in Cold Dark Matter simulations that are very similar to the universal model of Navarro et al. (1997).
by magnetic fields. It should also be added that the hot gas is supported in the cores of clusters (Thomas, Fabian, & Nulsen 1987; Allen, Fabian, & Kneib 1996). Since no significant radio emission has been detected from NGC 3923 (e.g. Birkinshaw 

Table 6. Ellipticity of the Gravitating Matter

| Model     | Oblate $\epsilon_{mass}$ 68% | Oblate $\epsilon_{mass}$ 90% | Prolate $\epsilon_{mass}$ 68% | Prolate $\epsilon_{mass}$ 90% | $a_s$ (arcsec) | $|\Gamma|$ | $\chi^2$ | dof | $\chi^2_{red}$ |
|-----------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------|--------|--------|-----|--------------|
| $\rho \sim r^{-2}$ | 0.43-0.59                     | 0.35-0.65                     | 0.40-0.54                     | 0.33-0.58                     | 2.2-3.1     | 6.6-7.2 | 16     | 15  | 1.1          |
| Hernquist  | 0.45-0.61                     | 0.36-0.66                     | 0.42-0.55                     | 0.33-0.59                     | 53-75       | 5.7-5.8 | 28     | 15  | 1.9          |

Derived shapes of the gravitating matter for the spheroidal mass models assuming an isothermal gas (see §4). 90% confidence ranges are quoted for the scale length $a_s$ and $|\Gamma|$. Typical values of $\chi^2$ are listed in the 90% intervals. Note for the $M \propto L_R$ model we obtain $\chi^2 = 56.0$ for 16 dof.

Figure 6. Radial surface brightness profiles of selected oblate models fit to the PSPC (left) and HRI (right) data. The error bars indicate the data and the horizontal lines show the bin sizes. The filled circles represent the best-fit $\rho \sim r^{-2}$ model having $\epsilon_{mass} = 0.50$; the boxes represent the best-fit Hernquist model with $\epsilon_{mass} = 0.50$; the dotted line is the best-fitting constant $M/L$ model. The radial profiles of these models have been binned as the X-ray data.

For example, if we exclude the two inner bins for the PSPC ($r = 0\arcsec-30\arcsec$) and the three inner bins for the HRI ($r = 0\arcsec-15\arcsec$), we obtain a minimum $\chi^2$ of $\sim 10.0$ for the $\rho \sim r^{-2}$ model and $\chi^2 \sim 11.4$ for the Hernquist model. Since in these innermost regions the surface brightness profile could be modified by a multi-phase cooling flow or by magnetic fields, we suggest some caution in interpreting $\chi^2$ values of our models in these central regions until better data can distinguish between different scenarios.

However, there is reason for optimism on both of these accounts. The distortion due to a multi-phase cooling flow is likely to be insignificant since single-phase analyses generally provide good descriptions for multi-phase cooling flows in the cores of clusters (Thomas, Fabian, & Nulsen 1987; Allen, Fabian, & Kneib 1996). Since no significant radio emission has been detected from NGC 3923 (e.g. Birkinshaw & Davies 1985) it is unlikely that the hot gas is supported by magnetic fields. It should also be added that the $\rho \sim r^{-2}$ model appears to fit the radial profile better than the Hernquist model for $r \sim 100\arcsec - 300\arcsec$, but the effect is not highly significant because of the low S/N in this region.

If we fit the $M \propto L_R$ model and add dark matter following the $\rho \sim r^{-2}$ model, the fits are marginally improved over the single-component case with a minimum $\chi^2 = 13.3$ obtained for a ratio $M_{DM}/M_R = 10$ and $M_{DM}/M_R > 3$ (90% confidence). The ellipticity of the dark matter, $\epsilon_{DM}$, is essentially that of $\epsilon_{mass}$ for $M_{DM}/M_R = 10$ but increases systematically so that $\epsilon_{DM} \approx \epsilon_{mass} + 0.10$ at the lower limit $M_{DM}/M_R = 3$. Here it should be understood that $M_{DM}$ includes only dark matter that is distributed differently from $L_R$ and that the $\chi^2$ values from the radial profile fits for given ratios $M_{DM}/M_R$ depend on the assumed temperature profile.

The Hernquist profiles are only affected when $M_{DM}/M_R \sim 1$ at which point the fits are improved to minimum $\chi^2 \sim 21$ with large $a_s \sim 400\arcsec$. The dark matter in these models is required to be extremely flattened.

Similar to our analysis of the $\beta$ model (§8), we find that adding a discrete component with X-ray emission proportional to $L_R$ does not improve the fits for the $\rho \sim r^{-2}$ model; we place a slightly stricter limit of $f_{dm}/f_{disc} > 4.5$.

We remove a larger region for the PSPC because of its larger PSF.

Note that the limits on $\epsilon_{mass}$ are essentially unaffected when the central bins are excluded.
(90% confidence). The Hernquist models are actually improved by the addition of a discrete component such that $x_{\text{red}}^2 = 1.2$ for $f_{\text{halo}}/f_{\text{disc}} = 4.6$. However, essentially all of this improvement takes place for the central bins discussed above; i.e. if we exclude those bins from the fits, then the discrete model does not improve the fits significantly. Hence, a discrete component distributed like $L_B$ does not improve fits to $\Sigma$ with the $\rho \sim r^{-2}$ model, and the improvement observed for the Hernquist model occurs in the central bins for which other physics (e.g. multi-phase cooling flows, magnetic fields) may equally affect the models.

In Table 1 we give the spherically averaged masses corresponding to the models in Table 2. We only quote masses at a few interesting radii to emphasize that without precise constraints on the temperature profile (and only an aggregate constraint on the isophote shapes) we do not really constrain the detailed mass profile. (Note that the spectral constraints in §3 which indicate an approximate isothermal gas apply only for $r \lesssim 15h_{70}^{-1}$ kpc.) The masses of the $\rho \sim r^{-2}$ and Hernquist models agree very well within $10h_{70}^{-1}$ kpc as expected because over much of this region the large scale lengths of the Hernquist model imply an approximate logarithmic slope of -2. Assuming the gas to be isothermal out to $r > 50h_{70}$ kpc, the $\rho \sim r^{-2}$ model, with its flatter slope, has approximately twice the mass of the Hernquist model at that distance. The gas mass is less than 1% of the gravitating mass over the entire radius range investigated.

Using the total B-band luminosity from Faber et al. (1985) scaled to 30 Mpc, $L_B = 3.45h_{70}^{-2} \times 10^{43}$ erg cm$^{-2}$ s$^{-1} = 6.95h_{70}^{-2} \times 10^{10} L_\odot$, we have that the B-band mass-to-light ratio in solar units is $\sim 5h_{70}M_\odot/L_\odot$ at $10h_{70}^{-1}$ kpc for the $\rho \sim r^{-2}$ and Hernquist models. At $r = 50h_{70}$ kpc, the $\rho \sim r^{-2}$ model has $M/L_B \approx 32h_{70}M_\odot/L_\odot$ while the Hernquist model has $M/L_B \approx 17h_{70}M_\odot/L_\odot$. These $M/L_B$ values within $10h_{70}^{-1}$ kpc are very consistent with stellar dynamical studies of ellipticals (e.g. van der Marel 1991). The larger (extrapolated) $M/L_B$ values at $50h_{70}^{-1}$ kpc agree with previous X-ray studies of ellipticals (e.g. Sarazin 1997) indicating that NGC 3923 has a mass distribution typical for a galaxy of its luminosity.

9 CONCLUSIONS

We have analyzed the gravitating matter distribution of the E4 galaxy NGC 3923 using archival X-ray data from the ROSAT PSPC and HRI. Analysis of the PSPC data, which allows more precise constraints than the HRI data, demonstrates that the X-ray isophotes are significantly elongated with ellipticity $\epsilon_e = 0.15(0.09 - 0.21)$ (90% confidence) for semi-major axis $a \sim 10h_{70}^{-1}$ kpc and have position angles aligned with the optical isophotes within the estimated uncertainties. A bright point source located $\sim 100^\prime$ along the major axis inhibits reliable ellipticity constraints for larger radii.

By applying a "Geometric Test" for dark matter, which essentially compares the shapes of the observed X-ray isophotes to those predicted if mass traces the optical light $L$ (independent of the poorly constrained temperature profile of the gas), we found that the ellipticity of the PSPC X-ray surface brightness exceeds that predicted by the constant $M/L$ hypothesis at the 80%-85% confidence level. The "Geometric Test" result is conservative since it only considers signatures of dark matter that are distributed differently from the optical light.

Although the evidence for dark matter from the Geometric Test is marginal, the results from models which employ an explicit solution of the hydrostatic equation assuming an isothermal gas (which is supported by the PSPC spectrum — $\chi^2$ indicate that $M \propto L$ is highly inconsistent with the radial profiles of the PSPC and HRI data ($\chi^2_{\text{red}} = 3.5$ for 16 dof). This particular discrepancy arises because $L$ is too centrally concentrated: the derived scale length of the gravitating matter is approximately 1.5-2 times that of $L$.

The ellipticities predicted by this $M \propto L$ model fall below the PSPC data at a significance slightly greater than the 90% level. Modeling the gravitating mass with a density run $\rho \sim r^{-2}$ or with a Hernquist profile we find that the ellipticity of the gravitating matter is, $\epsilon_{\text{max}} \approx 0.35 - 0.65$ (90% confidence), which is larger than the intensity weighted optical ellipticity ($\epsilon \approx 0.30$).

This evidence for dark matter which is more flattened and more extended than $L$ is similar to our conclusions from previous X-ray studies of two other ellipticals, NGC 720 and NGC 1332, but at somewhat smaller significance level than for NGC 720 (e.g. Buote & Canizares 1997b). These results are consistent with analyses of known gravitational lenses (e.g. Keeton, Kochanek, & Falco 1997), two polar ring galaxies (Sackett et al. 1994; Sackett & Pagge 1995), and flaring disks in spiral galaxies (e.g. Olling 1996). The ellipticities of the gravitating matter derived from our X-ray analyses and these other methods are consistent with those of halos produced by CDM simulations (e.g. Dubinski 1994).

If an isothermal gas is assumed then models with matter density $\rho \sim r^{-2}$ are favored over Hernquist models (and similar models like the universal CDM profile of Navarro et al. 1997). For $r \sim 100^\prime - 300^\prime$ the $\rho \sim r^{-2}$ model marginally fits the data better than the Hernquist model. However, most of the difference in these models occurs in the central radial bins where the effects of multi-phase cooling flows, magnetic fields, and discrete sources could affect the surface brightness profiles, though we have argued the effects are unlikely to be important (see §3). (The derived shape of the gravitating mass is mostly robust to these issues – Buote & Canizares 1997b.) This support for nearly $r^{-2}$ profiles agrees with previous studies of gravitational lenses (e.g. Maoz & Rix 1993; Kochanek 1995), although a recent paper finds that density profiles with changing slopes (e.g. Hernquist and NFW) are preferred (Williams 1997).

An emission component that is proportional to $L$ cannot contribute significantly to the ROSAT X-ray emission of NGC 3923, and thus discrete sources should not affect our constraints on the gravitating matter (Buote & Canizares 1997a). However, the ASCA spectral data when fitted with two thermal components yield a cold component, $T_c = 0.55$ keV, and a hot component, $T_H \approx 4$ keV, where the relative flux of cold-to-hot is $\sim 1.9$ in the ROSAT band (Buote & Fabian 1999). The conventional interpretation of the hot component (e.g. Matsumoto et al. 1997; Loewenstein & Mushotzky 1997) is that it arises from discrete sources. But our analysis (§4) shows that $\sim 35\%$ of the $0.5-2$ keV emission cannot be distributed like the optical light which would be expected of discrete sources. Hence, either the emission from discrete sources is not distributed like $L$, or the hot compo-
The constraints we have obtained for NGC 720, NGC 1332, and now NGC 3923 from analyses of their X-ray isophote shapes and radial surface brightness profiles provide an initial demonstration of the power of X-ray analysis for probing the shape and radial distribution of gravitating matter in early-type galaxies. The next generation of X-ray satellites, particularly AXAF and XMM, have the capability to accurately map X-ray isophote shapes and orientations from the cores ($r \sim 1''$) out to $10s$ of kpc for many galaxies. The spatially resolved spectra provided by these future missions will allow more precise constraints on temperature gradients and the contribution from discrete sources. Thus, unlike most other methods, obtaining interesting X-ray constraints on the shape and radial density profile of the gravitating matter will be possible for a large sample of early-type galaxies since the X-ray analysis is applicable to any isolated early-type galaxy whose soft X-ray emission ($\sim 0.5 - 2$ keV) is dominated by hot gas.

Table 7. Gravitating Mass and Gas Mass

| Model      | $5h_{70}^{-1}$ kpc | $10h_{70}^{-1}$ kpc | $50h_{70}^{-1}$ kpc |
|------------|---------------------|---------------------|---------------------|
| $\rho \sim r^{-2}$ | $(1.1 - 2.8) \times 10^{11} h_{70}^{-1} M_{\odot}$ | $(2.4 - 6.0) \times 10^{11} h_{70}^{-1} M_{\odot}$ | $(12.2 - 30.5) \times 10^{11} h_{70}^{-1} M_{\odot}$ |
| Hernquist   | $(1.3 - 3.3) \times 10^{11} h_{70}^{-1} M_{\odot}$ | $(2.6 - 7.1) \times 10^{11} h_{70}^{-1} M_{\odot}$ | $(6.0 - 18.1) \times 10^{11} h_{70}^{-1} M_{\odot}$ |
| Gas        | $0.14 \times 10^{8} h_{70}^{-5/3} M_{\odot}$ | $0.45 \times 10^{8} h_{70}^{-5/3} M_{\odot}$ | $6.4 \times 10^{8} h_{70}^{-5/3} M_{\odot}$ |

90% confidence values of the gravitating mass corresponding to the oblate and prolate models in Table 7 which include 90% uncertainties in the (isothermal) temperature. The statistical errors on the gas mass are less than 10%.

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*** The vastly improved spatial resolution of AXAF over the ROSAT PSPC will allow easy exclusion of the bright point source (1) (see Table 1) which hindered the present analysis of NGC 3923.

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