JA

**ASCA OBSERVATION OF NGC 4636:
DARK MATTER AND METALLICITY GRADIENT**

**R.F. Mushotzky, M. Loewenstein, H. Awaki, K. Makishima,
K. Matsushita, and H. Matsumoto**

84 5.445

SCAN-9411049

CERN LIBRARIES, GENEVA

**LABORATORY FOR HIGH ENERGY
ASTROPHYSICS**

**National Aeronautics And Space Administration
Goddard Space Flight Center
Greenbelt, Maryland 20771**

ASCA OBSERVATION OF NGC 4636: DARK MATTER AND METALLICITY GRADIENT

R. F. Mushotzky¹, M. Loewenstein^{1,2}, H. Awaki³, K. Makishima⁴, K. Matsushita⁴,
and H. Matsumoto³

¹ Laboratory for High Energy Astrophysics, NASA/GSFC, Code 666, Greenbelt, MD 20771

² Also with the Universities Space Research Association

³ Department of Physics, Kyoto University, Sakyo-ku, Kyoto, 606-01, Japan

⁴ Department of Physics, University of Tokyo, 7-3-1 Hongo, Tokyo 113, Japan

accepted for publication in the *Astrophysical Journal Letters*
to appear in the special *ASCA* issue in slightly abridged form

ABSTRACT

We present our analysis of *ASCA* PV phase observation of the elliptical galaxy NGC 4636. SIS spectra in six concentric annuli centered on NGC 4636 are used to derive temperature, metallicity, and column density profiles for the hot ISM. Outside of the central 3' the temperature is roughly constant at ~ 0.85 keV, while the metallicity decreases from > 0.36 solar at the center to < 0.12 solar at $R \sim 9'$. The implications of this gradient for elliptical galaxy formation and the enrichment of intracluster gas are discussed. We derive a detailed mass profile consistent with the stellar velocity dispersion and with *ROSAT* PSPC and *ASCA* SIS X-ray temperature profiles. We find that NGC 4636 becomes dark matter dominated at roughly the de Vaucouleurs radius; and, at $r \sim 100$ kpc, the ratio of dark to luminous matter density is ~ 80 and $M_{\odot}/L_{B\odot} \approx 150$. Evidence for the presence of a cooling flow is also discussed.

Subject headings: dark matter – galaxies: abundances – galaxies: individual (NGC 4636) – galaxies: formation

1. INTRODUCTION

Spatially resolved X-ray spectra can greatly enhance our understanding of the structure and history of elliptical galaxies and their hot interstellar media. Temperature profiles are required for mapping the large-scale gravitational potential, and column density profiles trace the deposition of cold matter by cooling flows. Accurate and precise abundance gradients can be compared with models of the chemical evolution of the stars and the hot ISM. The broad bandpass, good spectral, and adequate spatial resolution of the *ASCA* instruments enable the determination of these quantities as well as detection of hard spectral components from X-ray binaries or intergalactic gas in projection.

Previous studies of elliptical galaxies utilizing X-ray data from BBXRT (Serlemitsos et al. 1993), *ROSAT* (Forman et al. 1993), and *ASCA* (Awaki et al. 1994) have shown that (1) Average temperatures (kT) are typically 0.6-0.8 keV except for NGC 1399 and NGC 4472 which are located at the center of the Fornax cluster and a Virgo subcluster, respectively, and are somewhat hotter. The stellar gravitational potential inferred from optical data is insufficient to bind the hot gas, so that the presence of dark matter is indicated. (2) Average metallicities (Z) are surprisingly low, ranging from ~ 0.1 -0.8 solar, and the O, Si, and Fe abundances are consistent with solar ratios. Enhancement of Fe in the hot gas by Type Ia supernovae must be very limited. (3) Column densities (N_H) consistent with the Galactic value are sometimes allowed but, generally, excess columns of ~ 3 -10 10^{20} cm $^{-2}$ are required. (4) A hard spectral component is often, but not always, detected. This component varies greatly in its relative strength, contributing up to one-half or more of the flux in the GIS bandpass (Matsushita et al. 1994).

In this paper we present the results and implications of radial X-ray spectral analysis of the elliptical galaxy NGC 4636, based on *ASCA* SIS data acquired during

the PV phase. NGC 4636 is the best subject for such a study for several reasons. NGC 4636 is both close and large at optical ($R_e \approx 2'$) and X-ray wavelengths. Its large X-ray flux and angular size (radius $\sim 18'$ or ~ 6 *ASCA* SIS resolution elements; Trinchieri et al. 1994) ensure the detectability of gradients in kT and Z . NGC 4636 is ~ 3 Mpc from the center of the Virgo cluster in a region of relatively low galaxy density and its X-ray isophotes are much more regular than the other, more centrally located, Virgo giant elliptical galaxies NGC 4472 and NGC 4406. Finally, the hard component in NGC 4636 is weaker, relative to the dominant soft thermal component, than in any other galaxy of comparable flux yet observed with *ASCA* (Matsushita et al. 1994); this considerably reduces the uncertainties in measurements of Z and N_H .

NGC 4636 has been observed at X-ray wavelengths by the *Einstein Observatory* IPC and HRI (Trinchieri et al. 1986), and by the *ROSAT* PSPC (Trinchieri et al. 1994). The PSPC data are complementary to the *ASCA* SIS and GIS data since the PSPC offers superior spatial resolution and sensitivity below 0.5 keV, but cruder spectral resolution and no sensitivity above 2 keV.

2. SIS SPECTRAL ANALYSIS

The *ASCA* PV observation of NGC 4636 was conducted with the SIS in 4-CCD mode and resulted in a net exposure of ~ 40 ks. The observational details are in Awaki et al. (1994). We have fit the SIS-0 and SIS-1 spectra in six concentric annuli, centered on NGC 4636, that have approximately equal X-ray fluxes with an absorbed two-temperature Raymond-Smith thermal plasma (R-S) model. The best-fit parameters and 90% confidence errors for the primary component are displayed in Table 1 for each annulus (for fits to SIS-0 spectra – best fits to SIS-1 spectra are nearly identical). We emphasize the accuracy of the temperature measurements: the temperature derived from the ratio of the H-like and He-like lines of Mg is consistent, within 4%, with that

obtained by fitting the entire spectrum, and is also consistent with the temperature of the continuum beyond 2 keV. Allowing the abundance ratios to be non-solar does not significantly improve the spectral fits or alter the best-fit temperatures. There are significant gradients in N_H and Z ; but, kT is nearly constant. However, in the innermost two annuli there is strong evidence for line radiation at 0.71 keV, most likely a blend due to Fe XVI, Fe XVII, and O VII that cannot come from $kT \geq 0.4$ keV gas (Awaki et al. 1994).

In their PSPC investigation of NGC 4636, Trinchieri et al. (1994) were unable to distinguish single-temperature, low Z models from models with solar abundances that have a secondary hard component because of the limited bandpass and spectral resolution of the PSPC. With the SIS we have confirmed the presence of low abundances, and detect only a relatively weak and centrally concentrated hard component. The hard component emits, at most, 10% of the total flux in any annulus and is not required at all in the outermost three rings. The temperatures we derive are in excellent agreement with the $Z = 0.2$ solar model of Trinchieri et al. (1994) except that the spatial resolution of *ASCA* is too crude to detect the gradient inside $3'$ (see below). On the other hand, PSPC and SIS determinations of N_H are not consistent (see below).

In the following three sections we utilize the kT , Z , and N_H profiles to derive the dark matter distribution in NGC 4636, to extract clues about galaxy formation and chemical evolution of galaxies and intracluster gas, and to examine the properties of a possible cooling flow in NGC 4636.

3. TEMPERATURE MEASUREMENTS AND DARK MATTER

We have used the procedure described in Loewenstein (1994) to derive the dark matter distribution in NGC 4636 by fitting mass models to the observed temperature profile. To model the mass distribution of hot gas, we adopt a “ β -model” with $\beta = 0.52$

(Trinchieri et al. 1994), and core radius (1.2 kpc) and central density ($1.2 \times 10^{-25} \text{ gm cm}^{-3}$) determined by the *Einstein* HRI (Trinchieri et al. 1986). The stellar light distribution is given by a “cored” de Vaucouleurs model (Mathews 1988) with $R_{\text{core}} = 255 \text{ pc}$ (Lauer 1985), $R_e = 8.4 \text{ kpc}$, and $L_B = 3.7 \times 10^{10} L_{B\odot}$ (Bender et al. 1992, $d = 17 \text{ Mpc}$). A stellar mass-to-light ratio of $11 M_{\odot}/L_{B\odot}$ is chosen to match the observed central velocity dispersion of 191 km s^{-1} (Bender et al. 1992). We model the dark matter with a “pseudo-isothermal” density distribution (e.g., Loewenstein & Mathews 1987) with an r^{-4} cutoff. The parameters of this model are α – the ratio of dark to luminous matter interior to 100 kpc, δ – the dark matter scale-length in units of R_e , and γ – the cutoff scale in units of R_e .

Figure 1 shows the predicted distribution of emission-weighted kT , averaged over the same six projected annuli that spectra were extracted from, for the best-fit model ($\alpha = 12.5$, $\delta = 1.0$, $\gamma = 5$) along with the observed SIS-0 (Table 1) and PSPC temperatures. The temperatures in the model for the inner two annuli are lower than those derived from the SIS; however beam dilution is a strong effect if the gas is not isothermal as these annuli are only $\sim 1.3'$ wide, which corresponds to the 68% enclosed energy radius. The PSPC kT measurements indicate that there is, in fact, a significant temperature gradient inside $3'$ that is reproduced by the model. Note that this gradient is not a result of a cooling flow, but of a transition from a stellar dominated gravitational potential to one dominated by dark matter.

Table 2 displays the nearly constant predicted projected stellar velocity dispersions, assuming isotropic orbits, and other quantities of interest. (Because the de Vaucouleurs stellar density profile is steeper than that of the hot gas, the stellar temperature is lower than the gas temperature.) Saglia et al. (1992) have argued for the presence of dark matter in NGC 4636 based on the flatness of the observed velocity dispersion profile inside R_e (Davies et al. 1993). Figure 2 shows the local ratio of dark matter

to luminous matter that increases monotonically, attaining a value of 84 at 100 kpc (roughly the farthest radius where hot gas has been detected). Figure 2 also shows the mass-to-light ratio as a function of radius – a ratio of nearly $150 M_{\odot}/L_{B\odot}$ is inferred at 100 kpc. These numbers fit in well with the standard picture of dissipative star formation occurring within an extended nonbaryonic halo; the total baryon fraction, 0.07, is consistent with standard big bang nucleosynthesis and $\Omega = 1$.

Because of the spatially resolved, unambiguous kT measurements, the range of acceptable model parameters is small, and the distribution as well as the total amount of dark matter is well-constrained. Models within $3\Delta kT$ of all four outermost SIS measurements, where ΔkT is the 90% error bars shown in Figure 1, have $\delta = 0.5$ -2.0, and $\alpha = 11.0$ -13.5 ($M/L_B = 126$ -153) and $\rho_{dark}/\rho_{lum} = 47$ -111 at 100 kpc. Models with $\delta \ll 1$ yield velocity dispersion profiles that exceed the optical observations (Davies & Birkenshaw 1988), while if $\delta \gg 1$, the model temperature profiles are not sufficiently isothermal to match the SIS data.

4. IMPLICATIONS OF THE HOT GAS METALLICITY DISTRIBUTION

The hot gas metallicity profile of NGC 4636 is shown in Figure 3a for R-S fits to SIS-0 and SIS-1 data. We have carefully verified the gradient in Z in the following manner. We have fitted both SIS and PSPC spectra with a model consisting of a thermal bremsstrahlung continuum plus lines, and then examined the equivalent width of the Fe L complex as a function of radius. For both detectors a negative gradient in equivalent width that echoes the gradient in Z determined from spectral fitting is measured.

The hot gas in elliptical galaxies originates as mass loss from evolved stars that are responsible for most of the galactic light, and so there should be a close correspondence between optical and X-ray abundance measurements. This assumes that the stellar mass loss is well-mixed into the X-ray emitting gas without any preferential “cooling

out” of higher metallicity inhomogeneities, and ignores any contribution from SNIa. SNIa explosions at $\ll 10\%$ of the standard rate are sufficient to account for all of the Fe in the hot gas. However we see no evidence for non-solar abundance ratios in the form of enhanced Fe – the relative abundances of the three best-measured elements (Fe, Mg, and Si) are consistent, at the $\sim 30\%$ level, with solar ratios.

The Fe abundance of the stars in the nucleus of NGC 4636 is roughly solar (Worthey et al. 1992), in apparent disagreement with our innermost measurement. However, the crude *ASCA* spatial resolution – our central annulus extends out to 5.4 kpc – as well as beam dilution as discussed above, would mask the presence of solar abundance hot gas in the core if steep gradients in Z are present. In addition, if there is inflow and a gradient in Z in the source of gas (the stars), the central gas metallicity can be diluted with respect to the central stellar metallicity.

There is no published optical study of abundances beyond the de Vaucouleurs radius for NGC 4636. Inside R_e there is a typically mild negative metallicity gradient (Davies et al. 1993). Optically determined Fe abundances of ~ 0.3 solar at R_e and $\sim R^{-1/2}$ declines at large radii, as we have found in the X-ray emitting gas, are not unusual in elliptical galaxies (Schombert et al. 1993, Gonzales et al. 1994). (The significantly lower Z found in the elliptical galaxies NGC 1404 and NGC 4374 are more pathological; Loewenstein et al. 1994). However, our investigation demonstrates that these gradients persist to at least $5R_e$ where there is very little optical light, and that the mean Fe abundance is less than ~ 0.2 solar – comparable to the metallicity in the Virgo Cluster outside the central M87 region ($Z = 0.29 \pm 0.11$ based on analysis of an *ASCA* GIS spectrum from an area midway between M87 and M86). Moreover, in the overall spectrum of NGC 4636, we do not detect the two-to-one ratio of Mg to Fe inferred optically (Worthey et al. 1992), indicating that the Mg overabundance may be centrally concentrated.

These facts must be considered in any model that seeks to explain the formation of elliptical galaxies. In particular, the presence of persistent metallicity gradients when considered in conjunction with the extension of dark matter out to at least $9R_e$ underscores the importance of dissipation in the formation of the luminous parts of elliptical galaxies. The fact that NGC 4636 is optically diffuse (large R_e , low surface brightness at R_e) and seems to have a very massive, extensive nonbaryonic halo (inferred from the very extended, isothermal hot gas distribution) may indicate a link between the baryonic fraction and the amount of dissipation in elliptical galaxies. In Loewenstein et al. (1994) we speculate that this may explain the lower metallicities found in NGC 1404 and NGC 4374, galaxies that are more compact optically and in X-rays and presumably have more dissipation and higher baryon fractions. Because they have less dark matter, these galaxies had more difficulty in retaining gas as star formation proceeded and as a result might have had fewer star formation/enrichment cycles at large radius.

The implications of the low average Fe abundance for the enrichment of intracluster media (ICM) are also profound. Accounting for the Fe abundance in ICM via prolonged ejection of gas enhanced in Fe from SNIa (Renzini et al. 1993, Mihara & Takahara 1994) would imply a high Fe abundance in the remaining hot gas (Loewenstein & Mathews 1991), contrary to our observations, and is therefore ruled out. If early-type galaxies are primarily responsible for the enrichment of the ICM, as strongly suggested by the correlation between their cumulative luminosity and the mass of Fe in the ICM (Arnaud et al. 1992), SNII explosions during the early star-forming period of these galaxies must be the primary mechanism (Arnaud 1994). This is in accord with preliminary *ASCA* results on relative abundances in ICM (Mushotzky 1994). However, a comparison of the mean stellar Fe abundance we derive with the mass of Fe found in the ICM per mass of early-type galaxies implies that galaxies such as NGC 4636 must eject ~ 5 times more Fe than is locked up in their total stellar component without becoming unbound.

Moreover the star formation that results in the Fe production and ejection must occur after the main body of the galaxy has already formed; otherwise, these stars, and hence the hot gas, would have an average Fe abundance $\sim$ solar.

5. EVIDENCE FOR A COOLING FLOW

The gradient seen in the PSPC-derived temperature distribution does not necessarily imply the existence of a cooling flow and is consistent with a gas distribution in hydrostatic equilibrium with a gravitational potential that is dominated by stars for $r < 1$ kpc, and by dark matter for $r > 10$ kpc (§4). However, there are two pieces of evidence indicating the presence of a cooling flow. The first is the detection of an emission line blend at 0.71 keV that must be emitted by gas with $kT < 0.4$ keV (§2). This line is detected only in the central 2 annuli, which indicates that this cooler gas is centrally concentrated.

The second is the detection of excess absorption seen in the inner 3-4 radial annuli. Figure 3b shows the radial distribution of N_H derived from spectral fits to the SIS-0 spectrum using two distinct models. One model is our standard two-temperature R-S model; the second a single-temperature R-S model with an additional bremsstrahlung component to model emission from X-ray binaries. N_H in the first model is systematically lower (kT and Z in the primary component are virtually unchanged). The total amount of cold material inferred from Figure 3b is given by the sum over annuli of $10^6(\pi\Delta R^2\Delta N_H) M_\odot$, where $\pi\Delta R^2$ is the projected area in kpc^2 and ΔN_H is the column in excess of Galactic ($1.9 \times 10^{20} \text{ cm}^{-2}$) in units of 10^{20} cm^{-2} . In NGC 4636 there is $6\text{--}20 \times 10^9 M_\odot$ of cold material, spread over 20-30 kpc, comparable to the amount of hot gas observed in this region. The upper limit in this same region from the PSPC is $\sim 3 \times 10^9 M_\odot$. This discrepancy between the values of N_H measured with the PSPC and the SIS has shown up in numerous systems; perhaps the inclusion of

more complicated models properly accounting for the cooling flow emission and partial covering will lead to reconciliation. As we have noted, the amount of excess absorption required is somewhat model dependent; and, the upper limit on optically thin cold gas from 21 cm emission line observations is $10^8 M_\odot$ (Roberts et al. 1991). Fixing N_H at the PSPC value does not significantly change our best-fit temperatures or metallicities.

6. SUMMARY

We have presented profiles of kT , Z , and N_H for the hot ISM in the elliptical galaxy NGC 4636 derived from spatially resolved X-ray spectroscopy with the *ASCA* SIS. Using the derived temperature profile in conjunction with the results of analysis of higher spatial resolution PSPC data by Trinchieri et al. (1994), we infer the presence of a non-luminous halo. The ratios of total integrated mass to light and local nonbaryonic to baryonic matter increase monotonically outward, attaining values of $145 M_\odot/L_{B\odot}$ and 84, respectively, at 100 kpc. There is a negative metallicity gradient in the hot gas with Z dropping from > 0.3 within $\sim 0.5R_e$ to ~ 0.1 at $\sim 5R_e$. Our results indicate the importance of dissipation in elliptical galaxy formation, raise new questions about the enrichment of the ICM, and suggest a fundamental connection between the amount of dissipation, baryon fraction, and metallicity in elliptical galaxies

We are grateful to the *ASCA* team for their efforts on the design and operation of *ASCA* hardware and software, to J. N. Bregman for a constructive referee's report, and to J. J. Gonzalez for communicating his results on optical line strengths in advance of publication.

REFERENCES

Arnaud, M. 1994, in proceedings of the XIVth Moriond Astrophysics meeting on

Clusters of Galaxies, in press

Arnaud, M., Rothenflug, R., Boulade, O., Vigroux, L., & Vangioni-Flan, E. 1992,

A&A, 254, 49

Awaki, H., et al. 1994, PASJ, in press (A94)

Bender, R., Burstein, D., & Faber, S. M. 1992, ApJ, 399, 462

Davies, R. L., & Birkinshaw, M. 1988, ApJ Suppl., 68, 409

Davies, R. L., Sadler, E. M., & Peletier, R.F. 1993, MNRAS, 262, 650

Forman, W., Jones, C., David, L., Franx, M., Makishima, K., & Ohashi, T. 1993,

ApJ, 418, L55

Gonzalez, J.J, Faber, S. M., & Worthey, G. 1994, in preparation

Lauer, T. R. 1985, ApJ, 292, 104

Loewenstein, M. 1994, ApJ, in press

Loewenstein, M., et al. 1994, ApJ Lett., in press

Loewenstein, M., & Mathews, W. G. 1987, ApJ, 319, 614

Loewenstein, M., & Mathews, W. G. 1991, ApJ, 373, 445

Mathews, W. G. 1988, AJ, 95, 1047

Matsushita, K., et al. 1994, ApJ Lett., in press

Mihara, K., & Takahara, F. 1994, preprint

Mushotzky, R. F., 1994, in Proceedings of the New Horizon of X-ray Astronomy

meeting, in press

Renzini, A., Ciotti, L., D'Ercole, A., & Pelligrini, S. 1993, ApJ, 419, 52

- Roberts, M. S., Hogg, D. E., Bregman, J. N., Forman, W. R., & Jones, C. 1991,
ApJ Suppl., 75, 751
- Saglia, R. P., Bertin, G., & Stiavelli, M. 1992, ApJ, 384, 433
- Schombert, J. M., Hanlan, P. C., Barsony, M., & Rakos, K. D. 1993, AJ, 106, 923 (S93)
- Serlemitsos, P. J., M. Loewenstein, R. F. Mushotzky, Marshall, F. E., & Petre, R.
1993, ApJ, 413, 518
- Trinchieri, G., Fabbiano, G., & Canizares C. R. 1986, ApJ, 310, 637
- Trinchieri, G., Kim, D.-W., Fabbiano, G., & Canizares C. R. 1994, ApJ, in press
- Worthey, G., Faber, S. M., & Gonzalez, J. J. 1992, ApJ, 398, 69

<p>Table 1</p> <p>Best Fit Parameters</p>							
R_{in}^1 (arcmin)	R_{out}^1 (arcmin)	kT (keV)	δkT^2 (keV)	Z ($Z_{\odot}$)	δZ^2 ($Z_{\odot}$)	N_H (10^{22} cm^{-2})	δN_H^2 (10^{22} cm^{-2})
0.0	1.1	0.790	0.020	0.360	0.07	0.080	... ³
1.1	2.5	0.790	0.020	0.294	0.05	0.083	0.020
2.5	4.4	0.830	0.020	0.266	0.04	0.086	0.014
4.3	6.7	0.867	0.015	0.185	0.03	0.055	0.020
7.0	12.	0.874	0.012	0.097	0.02	0.000	0.012
12.	18.	0.756	0.012	0.097	0.04	0.000	0.012

- 1) $1' = 4.9 \text{ kpc}$ ($d = 17 \text{ Mpc}$)
- 2) Symmetrized 90% confidence errors
- 3) complexity of multi-component model did not allow accurate error determination

Table 2 Mass Model Quantities of Interest				
R (R_e^3)	σ^1 (km s ⁻¹)	ρ_{dark}/ρ_{lum}^2	M_{total} ($M_\odot$)	M/L_B ($M_\odot/L_{B\odot}$)
0.5	217	0.57	1.1 10 ¹¹	13
1.0	221	2.1	2.7 10 ¹¹	18
4.0	228	18.	1.6 10 ¹²	55
8.0	228	52.	3.8 10 ¹²	101
12.0	228	84.	5.1 10 ¹²	145

- 1) model predicted projected stellar velocity dispersion for isotropic orbits
- 2) ρ_{lum} includes hot gas and stars
- 3) $R_e = 8.4$ kpc (Bender et al. 1992, d=17 Mpc)

FIGURE CAPTIONS

Fig. 1.— Emission-averaged, projected kT in best-fit mass model ($\alpha = 12.5$, $\delta = 1.0$, $\gamma = 5$) (discs), kT derived from spectral fits to SIS-0 data (boxes), and kT derived from spectral fits to PSPC data for 0.2 solar abundance model from Trinchieri et al. 1994 (triangles) vs. projected radius. Symmetrized 90% confidence error bars are shown for the SIS fits; horizontal error bars represent the extent of the annuli.

Fig. 2.— Ratio of dark to luminous mass density (solid line) and integrated mass-to-light ratio (broken line) vs. radius in the model described in Fig. 1.

Fig. 3— (a) Metallicity in solar units vs. projected radius derived from spectral fits to SIS-0 (boxes) and SIS-1 spectra (filled circles). (b) Column density in units of 10^{22} cm^{-2} vs. projected radius derived from spectral fits to SIS-0 spectra; filled circles: single-temperature R-S plus thermal bremsstrahlung model, boxes: two-temperature R-S model. 90% confidence limits are shown.

FIG. 1

FIG. 2

FIG. 3A

FIG. 3B