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ROSAT HRI IMAGES OF ABELL 85 and ABELL 496 – EVIDENCE FOR INHOMOGENEITIES IN COOLING FLOWS

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ABSTRACT

We present ROSAT HRI images of two clusters of galaxies with cooling flows, Abell 496 and Abell 85. In these clusters, X-ray emission on small scales above the general cluster emission is significant at the $3\,\sigma$ level. There is no evidence for optical counterparts. The enhancements may be associated with lumps of gas at a lower temperature and higher density than the ambient medium, or hotter, denser gas perhaps compressed by magnetic fields. These observations can be used to test models of how thermal instabilities form and evolve in cooling flows.

1. INTRODUCTION

The existence of "cooling flow" - regions in the centers of clusters of galaxies has been well established over the past twenty years (see Fabian 1994). More recently there have been exciting (and controversial) claims of small-scale X-ray structure in four cooling flow clusters; Sarazin et al. (1992a,1992b) report the existence of filaments in the *ROSAT* HRI images of the clusters Abell 2029 and 2A 0335+096, David et al. 1993 describe a "cooling wake" in the NGC 5044 group of galaxies and Bohringer et al. show inhomogeneities in the X-ray emission from of NGC 1275 which are probably related to the radio lobes. These inhomogeneities are usually interpreted as regions of gas that are cooler than the surrounding ambient medium, and hence have higher X-ray emissivities. If this interpretation is correct, these observations are of crucial importance in testing detailed models of how thermal instabilities form and evolve in cooling flows.

In this paper we present *ROSAT* HRI images of two well known cooling flow clusters, Abell 85 and Abell 496. Our aim is to determine whether there are statistically significant emission enhancements in the X-ray images, and if they are associated with optical counterparts. In Section 2. of this paper we describe the X-ray and optical data, and in Sections 3. and 4. we discuss the statistical significance of the emission enhancements and compare our results with those of Sarazin et al (1992a, 1992b). In Section 5. we discuss the origin of the clumps, and in Section 6. their hardness ratios. Finally, in Section 7. we discuss the results and summarize our conclusions.

2. *ROSAT* and Optical Observations

The *ROSAT* High Resolution Imager was used to observe Abell 496 on 12-13 September 1992 for 14,493 s, and Abell 85 on 24-25 June 1992 for 17,308 s. There are 106,087 counts in the Abell 85 image and 81,181 counts in the Abell 496 image. The plate of the *ROSAT* HRI is $0.499 \pm 0.001''$ pixel^{-1}

Optical images of these clusters were obtained at the United States Naval Observatory 60" telescope in Flagstaff, AZ, using a TEK 2048×2048 CCD on 21-23 November 1992. The November 1992 nights were not judged to be photometric, so these composite galaxy frames were photometrically calibrated via ten faint (15-19th mag.) stellar images included in each of the cluster fields. These "secondary" standards were measured on UT 19 November 1993 at the USNOFS 1.0-m telescope during photometric conditions, using a thinned TI 800×800 CCD. Observations of 27 Landolt standards (Landolt, 1992) obtained throughout the night were used to transform the instrumental measures to the Kron-Cousins VI system. Details of the photometry will be given in a later paper; we estimate the uncertainty in the galaxy magnitudes to be ~ 0.037.

Contour maps of the central 150 arcseconds of the X-ray images are shown in Figure 1, overlaid on the optical images. The X-ray images have been deconvolved with the HRI point response function (using the IRAF task "LUCY") The positions (J2000) of the optical centroids of the central CD galaxies have been measured to within $\pm 2''$ to be $R.A. = 00^h41^m50^s.5$ and $decl. = -9°18'12''.2$ for Abell 85 and $R.A. = 04^h33^m37^s.72$ and $decl. = -13°15'43''.4$ for Abell 496. These positions are consistent with others in the literature (e.g. Huchra et al 1993, de Vaucouleurs et.al 1991). The optical posititions should be compared to those of the X-ray centroids; $R.A. = 00^h41^m50^s.94$, $decl. = -9°18'10''.7$ for Abell 85 and $R.A. = 04^h33^m37{\cdot}92$, $decl. = -13°15'42''.5$ for Abell 496, measured from the nominal HRI pointing. The discrepancies between the X-ray and optical centroids are within the known aspect uncertainties of the HRI. Figure 1 shows the X-ray peaks centered on the optical peak.

3. Statistical Significance of the Inhomogeneities

In this section, we investigate the statistical significance of the inhomogeneities by subtracting a two dimensional model of the cluster X-ray continuum emission from the data and examining the residuals (see also Davis and Mushotzky 1993) and comparing the number of clumps observed with that predicted assuming that the fluctuations are Gaussian. We also consider the structure of the emission enhancements.

The fit and model image construction were performed using the IRAF tasks "ellipse" and "bmodel" An ellipse center, ellipticity, position angle and the of major to minor axes was derived for a given radius using the iterative method described by Jedrzejewski (1987). A two dimensional model was then constructed from the fitted isophotes by spline interpolation. The overall "goodness of fit" of the two dimensional model was was evaluated by comparing the brightness profiles of the data and the model; an example of model/data brightness profile for Abell 85 is shown in Figure 2. The reduced χ^2 was 1.02 for Abell 496 and 0.4 for Abell 85. The resulting model was subtracted from the deconvolved image and the residuals are shown in Figure 3.

The statistical significance of the features in Figure 3 were determined by comparing the number of counts in the residual image within a given aperture (N_R) with the number of counts in the model image within the same aperture (N_M). The signal-to-noise ratio of a given feature is then given by N_R/z, where z is the uncertainty in N_R. This value has two components; Poissonian fluctuations and the error associated with N_R because of the statistical uncertainty in the model fit. The error in the model fit was estimated by scaling the model until the χ^2 of the surface brightness profiles changed by 1 σ. A 5% change in the model produced a 1 σ change in the χ^2 of both clusters. Combining these errors gives $z = (N_M + N_R + \delta N_M)^{1/2}$ and the signal-to-noise ratio of a given feature is $N_R/(N_M + N_R + \delta N_M)^{1/2}$

Table 1 shows the statistical significance of several of the bright emission features marked in Figure 3. Also shown are the apertures used and the total counts in the model and residual images. The counts given have been corrected for a small background factor ($\sim 10^{-3}$ counts pixel^{-1}); this was determined from a region at the edge of the field and is typically , $< 10\%$ of the counts in the residual image. The center of the Abell 85 image is 5' off axis and the center of the Abell 496 image is 1' off axis; hence telescope vignetting is $< 5\%$ for these features, and has been ignored. Features "1" in Abell 85 and "1" and "2" in Abell 496 are significant at approximately the 3 σ level. The other positive features are more marginal. The negative fluctuations are of smaller statistical significance.

The reality of the features observed in these clusters can be further investigated by comparing the number of clumps in 10 arcsec bins predicted by assuming that the fluctuations are Gaussian with the number of fluctuations observed. The solid line in Figure 4 shows the number of positive (or negative) fluctuations expected in the central 100×100 pixels greater than a given significance level (σ) plotted against σ The triangles show the number of observed positive clumps for Abell 496 and the squares the number observed for Abell 85. Most of the positive fluctuations are probably Gaussian. However, the features with higher statistical significance may be real. The prominent enhancement in Abell 85 to the SE of the X-ray centroid is significant at the 2.8 σ level, and there are two features in Abell 496 that are significant at the 3 σ level. Assuming Gaussian fluctuations one would expect 0.5 events greater with significance greater than 2.5 σ. Also shown in Figure 4 is the number of negative fluctuations, i.e. "holes" in the X-ray emission. The number of such holes is consistent with that predicted from Gaussian statistics.

The brightest enhancements in the residual images do not show any significant structure (the "connection" between clump 1 in Abell 85 and the X-ray centroid has a low formal statistical signifcance.) We therefore conclude that the inhomogeneities have spatial scales of ~ 5 arcseconds, comparable to the resolution of the ROSAT HRI. Neglecting projection effects these scales correspond to $\sim 10 - 15$ kpc at the distance of the clusters. Thus although we see evidence for statistically significant brightness enhancements we do not have evidence for filamentary structures.

4. Comparison with Abell 2029 and 2A 0335+096

We have analysed the ROSAT HRI images of Abell 2029 and 2A 0335+096 using the techniques described in Sections 2. and 3.. We find that the most significant feature in the central region of Abell 2029 is 1.5 σ. The "bar" in 2A 0335+096 is significant at the 2σ level. The "bar" may be a real feature, however we do not find any convincing evidence for statistically significant structure in Abell 2029. These results are hard to reconcile with the claims of Sarazin et al 1993a that the features in Abell 2029 are significant at the 5-10 σ level.

5. Origin of the Clumps

The clumps described above may be background sources unconnected with the cluster, they may be associated with individual galaxy cluster members, they may be associated with the HRI flat-field, or they may be genuine inhomogeneities in the cluster X-ray emission. Assuming that the X-ray emission in the central part of the cluster is described by a 2 Kev Raymond-Smith plasma we find that the flux (0.5-2 keV) of the individual clumps is $\sim 10^{-13}\, ergs\, cm^{-2}\, s^{-1}$. The soft X-ray logN-logS function of Hasinger et al. indicates that the density of sources with fluxes $> 10^{-13}\, ergs\, cm^{-2}\, s^{-1}$ is $\sim 4\, deg^{-2}$, making it very unlikely that these enhancements are background sources. Visual inspection of our V-band images does not reveal any faint galaxies at the positions of the X-ray clumps. If the X-ray enhancements are due to elliptical galaxies we would expect to see optical counterparts with a B-magnitude of $\sim 10 - 15$ (Fabbiano, Kim and Trinchieri, 1992). This corresponds to a V-magnitude range of $11 - 16$, assuming $B - V = 1$. No such galaxies are seen at the positions of the X-ray clumps, even though fainter galaxies ($V = 18.6$ mag) are clearly detected. Finally, they are unlikely to be features in the HRI flat-field. The variation of the HRI Quantum Efficiency does not vary by more than 10% across the field of view of the detector (David et al 1993).

6. Hardness Ratios of the Emission Features

One possible interpretation of these X-ray clumps is that they are regions of gas that are cooler and denser than the surrounding cluster medium, and hence should have softer X-ray spectra. We have used the (very limited) spectral response of the *ROSAT* HRI (David et al 1993) to investigate the spectrum of these clumps; a more detailed spectroscopic study using the *ROSAT* PSPC or *ASCA* is not possible because of the small angular scale of the clumps ($< 10''$).

The spectrum of the clumps can be parameterized by a hardness ratio, defined as the ratio of the number of counts in HRI pulse height channels 6-16 to those in channels 1-5. The background in the HRI has a characteristic tail that extends to higher pulse height bins (David et al 1993); these bins have been included here because we are dealing with the central region of the cooling flow where the the source dominates the background. The hardness ratio of the central 50 arcsecs in Abell 85 is 0.3 ± 0.01, and 0.21 ± 0.01 in Abell 496. The hardness ratios of all the clumps in Abell 85 that have a statistical significance $> 2\sigma$ are greater than 0.3, and the average value is 0.5 ± 0.07. Similarly, the hardness ratios of the two brightest clumps in Abell 496 > 0.2, and the average is 0.32 ± 0.04. A similar effect also has been noted by Sarazin et al (1992) for the "bar" in 2A 0335+096. There is no known instrumental effect that can account for this result. Pre-flight calibration measurements show that the HRI response has two energy dependent components; mirror scattering tends to broaden the response at higher energies while a "halo" (David et al 1993) is more prominent at lower energies. However, in-flight measures of the point response does not show significant energy dependence, and certainly cannot account for the effect seen here where 30-50% of the soft photons would need to be scattered outside of $\sim 5"$ for the clumps to have the same hardness ratios as the central $50 \times 50"$ region. The detector gain does not vary significantly over scales $< 1'$, nor does the variation in the centroid of the of the pulse height distribution of ground-based calibration sources.

The interpretation of these results are ambiguous because of the uncertainties associated with the HRI spectral response. If the inhomogeneities are due to clumps of cool gas, one might expect the hardness ratio of the blobs to decrease relative to the surrounding gas. The fact that the hardness ratio increases argues that the clumps are hotter and denser than the surrounding gas, perhaps compressed by radio jets or magnetic fields. Another possibility is that lumps are in fact cooler (≤ 1 kev) and the hardness ratio is skewed by emission lines (principally Fe) at ~ 1.1 kev. A more quantitative analysis can be made when a reliable spectral response matrix is available.

7. Summary and Discussion

One explanation of these bright X-ray features is that they are regions of cooler gas that have condensed out of the cooling flow. If this is the case, then (as pointed out by Sarazin et al 1992 and Bohringer et al. 1993) they have electron densities of $\sim 0.1\,cm^{-3}$, and rapid cooling times; $\sim 10^8$ years. Such inhomogeneities are therefore either short lived or supported by forces other than thermal pressure of the ambient medium (Sarazin 1992 and references therein). Another possibility is that the brightest feature in Abell 85 and possibly the clump to the east of the X-ray centroid in Abell 496 are "cooling wakes" of the type described by David et al 1993 in the NGC 5044 group of galaxies. The interpretation of these features as cool inhomogeneities or cooling wakes would imply that they have softer X-ray spectra than the surrounding ambient gas. All of the lumps studied here that are statistically significant at the 2σ level or above have harder hardness ratios than the average for the central cooling region. This result, if confirmed, would suggest that the lumps arise in regions of hotter, denser, gas perhaps compressed by magnetic fields or radio jets. However, the spectral response of the *ROSAT* HRI is currently not well determined, and a more quantitative analysis of the X-ray spectra of the clumps is needed to be able to reject the cool gas hypothesis.

In summary, we have found homogeneities in the *ROSAT* HRI X-ray images of two well known cooling flows, Abell 496 and Abell 85. These clumps have spatial scales of ~ 10 ", or (neglecting projection effects) 10-15 kpc. A quantitative analysis of the images indicates that while most of the clumps visible in the X-ray images are consistent with Gaussian noise, two or three of the lumps are significant at the 3σ level. Assuming Gaussian fluctuations one would expect 0.5 events with significance greater than 2.5 σ, further suggesting that these features are real. We do not find any evidence for X-ray filamentation described by Sarazin et al (1992a). Comparison with optical images shows that they are not associated with faint galaxies, and they are highly unlikely to be background sources.

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Table 1

Statistical Significance of Emission Features

Cluster	Feature	Offset[a] arcseconds	aperture radius (pixels)	Model Counts	Residual Image Counts Counts	Significance
Abell 85	1	10E 11S	10	60	28	2.8
	2	23E 20N	8	14	9	1.8
	3	23W 22N	8	18	11	2.0
	4	7W 19S	8	29	12	1.8
	5	12E 44S	5	4	4	1.4
	6	8	16	11	2.0	
Abell 496	1	12E 2N	8	33	27	3.4
	2	22W 7N	8	22	17	2.7

a: Offset is in arcseconds from the X-ray centroid

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10. Figure Captions

Figure 1: Optical images of Abell 85 (Figure 1a) and Abell 496 (Figure 1b) with X-ray contours superimposed

Figure 2: Radial brighness profiles of the central portion of Abell 85 (points) and the model (line). The axes are radial distance (measured in 0.5 arcsecond pixels) and counts pixel^{-1}. Each radial bin contained > 100 counts. Figure 3: Residual X-ray images for Abell 85 and Abell 496 The residual images were generated by subtracting a two-dimensional elliptical model to the cluster emission, as described in the text. The pixel size is 0.5 arcseconds. Bright portions in the image correspond to emission enhancements. The darkest pixels correspond to ~ -0.1 counts/pixel, and the brightest pixels to ~ 0.1 counts/pixel. The source marked "1" in Abell 85 residual image and sources "1" and "2" in Abell 496 are signifcant at the 3σ level.

Figure 4: The number of clumps expected at a given significance level (σ) vs. σ for Gaussian statistics, Abell 85 and Abell 496. Both positive and negative fluctuations are shown.