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AN X-RAY TEMPERATURE MAP OF THE MERGING CLUSTER ABELL 2255

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ABSTRACT

We present a spatially resolved map of intracluster gas temperatures in the rich cluster Abell 2255, using *ROSAT* PSPC data. The intracluster gas is strongly nonisothermal and the temperature distribution supports the conclusions of Burns and coworkers that Abell 2255 is currently undergoing a merger. The hottest regions are near the core, northwest of the center. A map of the ratio of softer to harder X-ray photons reveals an anomalously soft region northeast of the center, coincident with a radio ridge discovered by Burns and coworkers in 1995. We suggest that this cooler region is associated with an infalling group of galaxies that is giving rise to the radio ridge. Meanwhile, a much more substantial recent merger between comparably sized subcluster components can account for the more global merger signatures, which include the extensive central radio halo, the large-scale gas temperature variations, the pair of central-dominant ellipticals, elliptical X-ray isophotes offset from these dominant galaxies, and the very high velocity dispersion of galaxies in the cluster.

Subject headings: galaxies: clusters: general — galaxies: clusters: individual (Abell 2255) — galaxies: interactions — galaxies: intergalactic medium — X-rays: galaxies

1. INTRODUCTION

Clues to the evolution of galaxy clusters can be found in the detailed dynamics of the hot gas and galaxies they contain. In hierarchical models for large-scale structure formation, clusters evolve by accreting small groups of galaxies and other clusters, a process that continues at the present epoch. X-ray signatures of a cluster merger include an X-ray peak offset from the peak of the galaxy distribution, an elongated X-ray core, nonisothermal and asymmetric temperature distributions, and the absence of a central cooling flow. These merger signs can be identified using *ROSAT* PSPC and *ASCA* data, which provide spatially resolved X-ray imaging and spectroscopy. Clusters thought to have X-ray evidence of a recent (or ongoing) merger include Abell 2256 (Briel et al. 1991), Abell 754 (Henriksen & Markevitch 1996; Henry & Briel 1995; Zabludoff & Zaritzky 1995), and Coma (White, Briel, & Henry 1993). X-ray temperature maps for Abell 2256 and Abell 754 show a complex temperature structure, which is most naturally explained if these clusters are undergoing a merger.

Abell 2255 is a rich cluster that shows several signs that it is undergoing a merger event. Some of the first evidence for a merger came from early *Einstein* X-ray data: Jones & Forman (1984) found that Abell 2255 has one of the largest X-ray core radii in their cluster sample. Stewart et al. (1984) further analyzed *Einstein* IPC data and concluded that Abell 2255 does not contain a cooling flow, which is unusual for a such a rich cluster (Edge, Stewart, & Fabian 1992). It is thought that a major merger would disrupt a preexisting cooling flow and increase the core radius (Roettiger, Burns, & Loken 1993). More recently, Burns et al. (1995) found from *ROSAT All-Sky Survey* (*RASS*) data that the X-ray peak of Abell 2255 is not centered on the brightest cluster galaxies but is offset by $\sim 2'$. Thus, the X-ray data indicate that this cluster has recently undergone or is currently undergoing a merger. Feretti et al. (1997) recently analyzed the *ROSAT* PSPC pointed observation of Abell 2255 and came to similar conclusions.

Abell 2255 has a very large velocity dispersion, ≈ 1200 km s^{-1}, which may indicate that it is dynamically unrelaxed, despite the lack of obvious spatial or kinematical substructure (Stauffer et al. 1979). Abell 2255 contains two comparably bright, central-dominant galaxies, which is reminiscent of the Coma Cluster. Having a pair of central-dominant galaxies is thought to be a sign that the cluster is the merger product of two similarly sized subclusters, each of which had its own central-dominant galaxy before the merger (Davis & Mushotzky 1993; Bird 1994).

Abell 2255 is also one of the rare clusters that contains a radio halo (Jaffe & Rudnick 1979; Hanisch 1982; Feretti et al. 1997). The most recent radio observations (Feretti et al. 1997) show that it is $\sim 1 h_{50}$ Mpc in diameter and unpolarized (which distinguishes it from the numerous polarized, tailed sources in this cluster). Accounting for the rarity of cluster radio halos as well as their varied morphologies and their energy source(s) have been long-standing puzzles. One of the main problems has been understanding how the relativistic electrons that power radio halos get into the outer regions of the clusters where radio halos tend to extend. Tribble (1993) recently proposed that cluster mergers can provide the energy source for accelerating electrons throughout clusters. Given the short lifetimes of relativistic electrons, it is thought that radio halos are indicative of very recent or *ongoing* cluster mergers.

We present *ROSAT* PSPC results that strengthen the case for a merger in Abell 2255. The PSPC data show that the cluster has a complex temperature structure, which indicates that the cluster is not in hydrostatic equilibrium. This, along with the gas and galaxy peaks being offset, the elongated X-ray isophotes in the inner region, and the existence of a radio halo, suggests that Abell 2255 is currently experiencing a merger. We describe the PSPC data in § 2 and § 3 and discuss the data analysis in § 4. In § 5 we discuss the implications of the data, review the merger evidence in this cluster, and summarize our conclusions.

2. X-RAY DATA

Burns et al. (1995) previously analyzed the 3.5 ks of *ROSAT All Sky Survey* PSPC data for Abell 2255. We analyze instead the *ROSAT* PSPC's 14.5 ks pointed observation of Abell 2255. We corrected the X-ray imaging data for spatial variations in the exposure and vignetting, using the procedures outlined in Snowden et al. (1994). The PSPC data were selected from observation times when the master veto rate (MVR) was within recommended bounds: $20 < \mathrm{MVR} < 170$. The spectra for each of the regions discussed below was extracted from the filtered data. The background for each spectrum was obtained from an annulus around the cluster extending from 30′ to 40′ from its center. All detectable point sources were excluded from both source and background spectra, using a region size appropriate for the off-axis angle of the source. Source and background spectra were also corrected for vignetting effects and for the residual particle background (in the manner prescribed by Snowden et al. 1994), the latter of which is proportional to the MVR. Finally, the extracted spectra were rebinned so that each channel has a minimum of 25 counts. We also investigated the effects of using background spectra extracted from regions farther from the cluster center, which reduces the cluster's contamination of the background but increases the vignetting correction; no significant difference was found in the results.

3. X-RAY MORPHOLOGY

The morphology of the X-ray gas in Abell 2255 can be seen in Figure 1, which shows the PSPC image lightly smoothed with a $\sigma = 30''$ Gaussian. The X-ray contours are elongated in an east-west direction in the center and appear to be more circular in the outer regions. The X-ray peak of this pointed observation is slightly offset from the brightest cluster galaxy. Fitting the X-ray surface brightness of the cluster confirms that the isophotes are offset from the central-dominant galaxies and are fairly flat, with an ellipticity of ~ 0.5. At larger radii from the center ($\sim 2'$–$15'$), we find the X-ray centroid is stable but offset from the brightest cluster galaxy by a larger amount, $\sim 1'$. The position angles

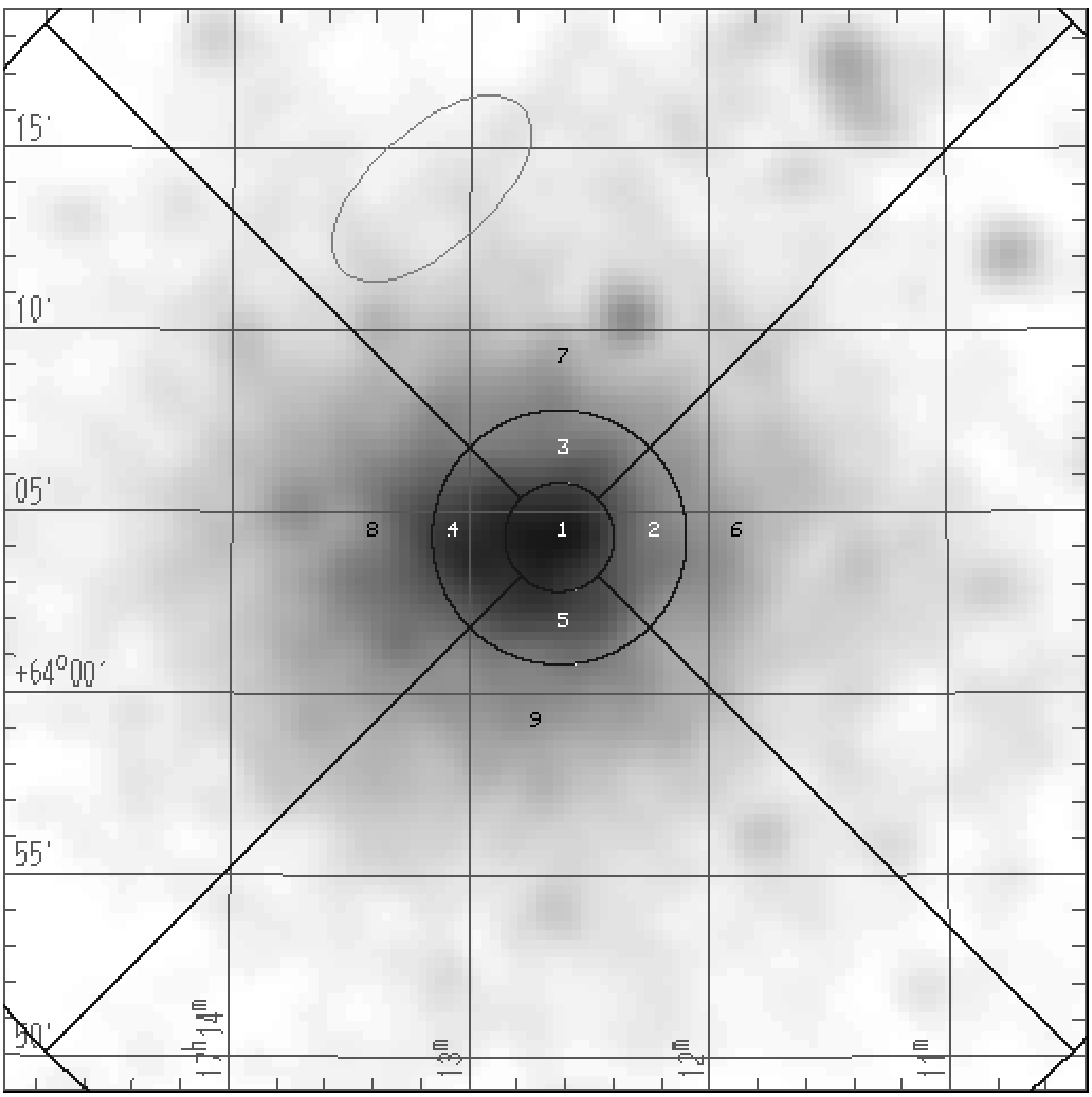

FIG. 1.—The regions for which the spectra are extracted for the PSPC-derived temperature map for Abell 2255 overlie the smoothed PSPC image of the cluster. The ellipse shows the position of the radio ridge and the cool X-ray feature found in the ratio map.

of the X-ray isophotes are predominately east-west, and the isophotal ellipticities are >0.25 inside 2′. Burns et al. (1995) report that the peak of the X-ray *RASS* image is displaced from the brightest cluster galaxy by about 2′. We do not find such a large offset in the pointed observations.

4. SPECTRAL ANALYSIS

We used XSPEC 9.0 software (Arnaud et al. 1996) to fit a Raymond-Smith plasma model to the extracted spectra. The temperature and abundance were allowed to vary in the global fit to the cluster. We also included a variable absorption component due to the column density of Galactic hydrogen in the line of sight. The redshift of the model spectrum was fixed to 0.081, which corresponds to the heliocentric velocity of the cluster given by Burns et al. (1995). The extracted spectra were fit between ∼0.2 and 2.0 keV, the exact energy boundaries being set by the channel grouping. Once a minimum in χ^2 was found, the 90% confidence errors were determined for the free parameters. A "global" spectrum extracted from within a radius of 20′ from the center yields a temperature of $3.71^{+2.22}_{-0.14}$ keV and a (poorly determined) metal abundance of less than 0.52 solar. This is in excellent agreement with the global temperature of 3.5 ± 1.5 keV found by Feretti et al. (1997), who assumed an abundance of 0.35 solar. The fitted value of $N_{\rm H}$ is $1.43^{+0.18}_{-0.14} \times 10^{20}$ atoms cm^{-2}, less than the Galactic value of 2.59×10^{20} atoms cm^{-2} (Dickey & Lockman 1990).

4.1. *Spatially Resolved Temperatures*

To examine the spatial distribution of temperatures, we extracted spectra from a central core region and from eight surrounding wedge-shaped regions (see Fig. 1). The radius of the central region was chosen to enclose the area where the (azimuthally averaged) cluster surface brightness profile shows an excess over the best-fitting analytic King model (we segregated this "excess" to optimize a search for the spectral signature of a cooling flow). This resulted in a circular region with radius 1.′5 from the cluster center. The radii of the surrounding annular wedges were chosen so that each region has ∼10,000 counts.

In fitting the spectra from the various subregions, we allowed the absorption column to vary, but we fixed the abundance at 0.3 solar (since the abundance was poorly determined in the global spectrum). The best-fitting temperature of the core region is $3.49^{+3.67}_{-1.38}$ keV and the fitted $N_{\rm H}$ is $2.56^{+0.37}_{-0.40} \times 10^{20}$ atoms cm^{-2}, both of which are consistent with the globally determined values. There is no sign of a central temperature drop that would indicate the presence of a cooling flow. Cluster cooling flows also tend to be associated with centrally enhanced X-ray absorption, of which we see no evidence. Our core temperature is consistent, within the errors, with the *RASS* PSPC spectral analysis by Burns et al. (1995), who found a core temperature of $1.9^{+2.3}_{-0.4}$ keV. The temperatures for all of the individual sectors are shown in Figures 2 and 3; three of the nine regions (regions 2, 3, and 9) have temperatures that are significantly hotter than the mean cluster temperature of $3.71^{+2.22}_{-0.14}$ keV (which is indicated in Fig. 3 by horizontal lines).

4.2. *The Spectral "Color" Map*

To search for complicated temperature structure in the cluster that may have been missed by using the regular regions in the spectral analysis above, we generated a spectral ratio map of the cluster. Relatively soft and hard images were constructed from 0.52–1.31 keV photons (PSPC bands R5 and R6) and 1.13–2.01 keV photons (band R7), respectively. We used spectral simulations to find that the ratio of these two bands offered the most dynamic range for a plausible range of temperatures in Abell 2255. After smoothing both images with a 1′ Gaussian, the softer image was then divided by the harder image to create a ratio map. We used XSPEC to determine the approximate temperatures corresponding to these ratios. Fixing the abundance to 0.3 solar and $N_{\rm H}$ to the best-fit value found in the global spectral fit, we find that these ratios are consistent with the temperatures found in the more detailed spectral analysis. This color map was generated in an attempt to trace the temperature structure of the cluster in more detail than was

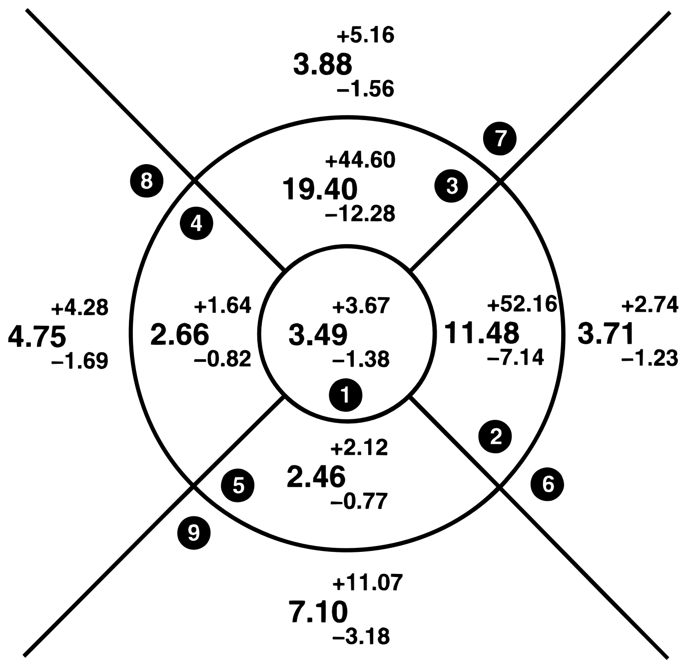

FIG. 2.—The best-fit temperatures are shown on a region map like that in Fig. 1.

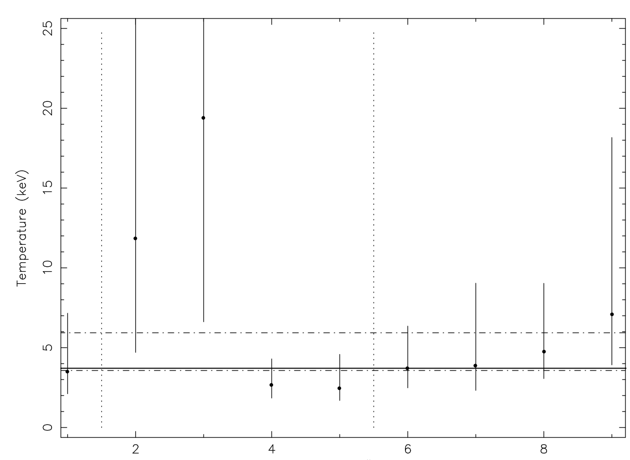

FIG. 3.—The temperature for the regions shown in Fig. 1 are shown here. The error bars are the 90% confidence intervals. The vertical dotted lines delimit the boundaries between the sectors seen in Fig. 1. The solid horizontal lines show the average cluster temperature, while the dash-dotted lines show the upper and lower limits.

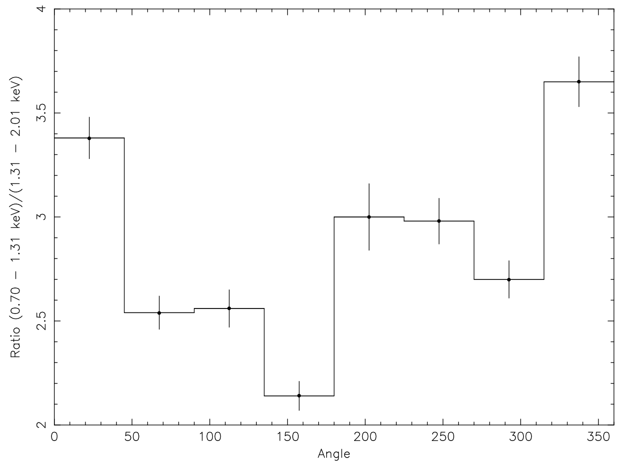

FIG. 4.—The color ratios for an annular region (6′.5 –13′) around the cluster center. A cool region (large ratio) can been seen in the two northern sections.

possible with the large regions used for the previous spectral analysis. However, because the global gas temperature (3.7 keV) is so far outside the *ROSAT* bandpass (0.1–2.0 keV), any detail that this method might have revealed is lost in statistical noise. Only one relatively soft feature, northeast of the cluster center, stands out as statistically significant in the color map; we describe this soft feature below.

Figure 4 shows the color ratios for an annular region, 6′.6–13′ about the cluster center, which has been divided into eight equal segments. All detected point sources were excluded from the calculation, using radii appropriate to the off-axis angles of the sources. A relatively soft (larger ratio) component is clearly seen in the northern portion of the annulus (0°/360°). The position of this soft region, at R.A. $17^h13^m15^s$, decl. $+64°13'$ (J2000), is not associated with any optical object but is coincident with the diffuse radio ridge discovered by Burns et al. (1995). The rough shape of the radio ridge is also seen in the color map and is indicated schematically as an ellipse in Figure 1. The value of the ratio in this region (5.00 ± 1.26) corresponds to a temperature of ~ 1 keV, which is much cooler than the bulk of the cluster. Using an elliptical aperture matched to the shape of the radio ridge, we find that the count rate from this region is 1.1×10^{-2} counts s^{-1}, which at the distance of the cluster corresponds to a luminosity of 3.6×10^{42} ergs s^{-1}.

We propose that this cool region is associated with an infalling group of galaxies. The temperature and luminosity of this cool region are consistent with those of the gas in a poor group of galaxies (Mulchaey et al. 1996). The shocks associated with the entry of a group of galaxies into the cluster can generate the relativistic electrons that power the radio ridge.

5. DISCUSSION AND CONCLUSIONS

Abell 2255 shows many signs of an ongoing major merger: a large X-ray core radius, noncircular X-ray isophotes, a complex temperature structure, the lack of a cooling flow, a large galaxy velocity dispersion, a pair of central-dominant galaxies, and a radio halo. All of these signs are found in the Coma Cluster as well. Simulations of cluster mergers show that strong shocks can heat the gas to ~ 10 keV (Evrard 1990; Roettiger et al. 1993; Schindler & Müller 1993). Our PSPC temperature map of Abell 2255 is too coarse to allow a detailed comparison with merger simulations, but it clearly indicates that there are large, asymmetric temperature variations in the cluster gas. The gas is particularly hot to the northwest of the core region.

We confirm previous work (Burns et al. 1995; Feretti et al. 1997) that showed that the X-ray isophotes in the cluster core are also consistent with an ongoing merger: the isophotes are offset from the central-dominant galaxies and are fairly flat, with an ellipticity of ~ 0.5; the isophotal ellipticity decreases outward until the outer regions are consistent with being round. A numerical simulation of this proposed merger shows that the X-ray isophotes should be elongated in the direction of the merger (Burns et al. 1995).

While there are many signs of a major merger in Abell 2255, we also find X-ray evidence of a smaller ongoing merger event: $\sim 13'$ northeast of the cluster center is a relatively cool (~ 1 keV) region, with a luminosity comparable to a poor group of galaxies. This cool region is coincident with a diffuse radio ridge discovered by Burns et al. (1995); the relativistic electrons that power this radio source may themselves be powered by shocks driven by an infalling group of galaxies. We suggest that a large sample of galaxy velocities (Ganguly, Hill, & Oegerle 1996) should be searched for kinematic evidence of such an infalling group in the vicinity of R.A. $17^h13^m15^s$, decl. $+64°13'$(J2000). Abell 2255 has evidently joined the ranks of clusters that are known to be undergoing major mergers and, like the Coma Cluster, has a diffuse radio halo, a pair of dominate central galaxies, and a cool group of infalling galaxies. In future work, we will use spatially resolved *ASCA* spectra to prepare a more accurate temperature map for this cluster in order to better determine whether Abell 2255 is indeed a site of ongoing major and minor subcluster merger events.

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