ABELL 2218: X-RAY LENSING, MERGER, OR BOTH?

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ABSTRACT

Comparison of the high-resolution X-ray image of A2218 obtained with the ROSAT HRI with the optical HST image shows several interesting correlations. The X-ray emission within a 1’ radius core is resolved into several components; the central dominant galaxy does not coincide with either of them or with the emission centroid. The major X-ray peak is an elongated feature that lies between the two mass concentrations known from the optical lensing analysis, and coincides with optical arcs at \( r \approx 20'' \) from the cD galaxy. We speculate that this may be lensed X-ray emission, for example (but not necessarily) of the same object lensed in the optical. Alternatively, this feature may be a merger shock or a gas trail of an infalling subgroup. Two other X-ray enhancements are close to the two major mass concentrations. Both lensing and a merger are likely.

Previous X-ray derivations of the A2218 mass used a \( \beta \)-model fit to the data with angular resolution that blurred the features mentioned above into a broad constant core. As the HRI data show, such a core does not exist. Because of this, under certain assumptions and using only the improved imaging data, the hydrostatic estimate of the projected mass within the lensing radius can in principle be increased by a factor of \( \sim 1.4 \) (and the mass within a sphere of the same radius by a factor of 2.6) compared to previous analyses. However, for a merging cluster, the hydrostatic analysis is generally inapplicable. Most other lensing clusters are more distant than A2218, and obtaining adequate X-ray images and temperature maps of them is even more difficult. Together with the likely overestimation of mass by the lensing analysis (as in the simulations), oversimplification of the gas density and temperature models resulting from inadequate resolution may account for the mass discrepancy as suggested for A2218.

Subject headings: dark matter — galaxies: clusters: individual (A2218) — gravitational lensing — intergalactic medium — X-rays: galaxies

1. INTRODUCTION

A2218 at \( z = 0.175 \) shows a strong discrepancy between cluster masses derived from gravitational lensing in the optical (see review in Bartelmann & Narayan 1995) and from X-ray analysis (Miralda-Escude & Babul 1995; Loeb & Mao 1994). In A2218 as well as in some other clusters (e.g., Wu & Fang 1997 and references therein), lensing implies a projected mass within the cylinder delineated by the observed giant arcs up to 2–3 times greater than the value derived from X-ray data assuming hydrostatic equilibrium, isothermality, and spherical symmetry. Weak lensing results (e.g., Squires et al. 1996 and references therein) are consistent with strong lensing, although these results are still rather uncertain. Assuming that the mass from lensing is correct, Loeb & Mao (1994) proposed the existence of significant nonthermal gas support in the centers of clusters, due, for example, to gas turbulence or magnetic fields, which would compensate for the insufficiency of thermal pressure. A simple lensing mass estimate may be in error; cluster simulations by Bartelmann (1995) showed that the spherically symmetric lensing analysis should overestimate the true mass by an average factor of 1.6 due to the presence of substructure. The remaining discrepancy is still significant and requires further explanation.

Makino (1996) proposed a declining temperature profile to account for the mass discrepancy in A2218; Loewenstein (1997) detected a temperature decline in the outer region (\( r \) greater than a few arcminutes) of the cluster but found it insufficient to explain the discrepancy. A2218 has one of the largest values of \( \beta_T = \mu m_p \sigma_{gal}^2 / kT_e \approx 1.6 \) (where \( kT_e = 7.2 \text{ keV} \) [Mushotzky & Loewenstein 1997] and \( \sigma_{gal} = 1370 \text{ km s}^{-1} \) [Le Borgne, Pello, & Sanahuja 1992]), which is a likely indication of the cluster’s nonrelaxed state (see, e.g., simulations by Navarro, Frenk, & White 1995). Indeed, as Kneib et al. (1995) and Squires et al. (1996) noted, a ROSAT X-ray image of A2218 suggests an ongoing merger of subclusters. Below we discuss interesting details from a longer and better positioned ROSAT HRI exposure, comparing it with the optical HST image from Kneib et al. (1996) to investigate the nature of the mass discrepancy. Although strong temperature gradients in the inner region are likely if there is a merger, and a large-scale temperature gradient is detected, we will not consider their effects on the mass estimate and will limit the discussion to the imaging data.

2. HRI IMAGE

The ROSAT HRI performed four observations of A2218, two of which (with a total exposure of 35.6 ks) are on axis and two others offset by 12’. We use only the on-axis pointings in which the HRI point-spread function (PSF) at the position of interest has a half-power diameter of 4’ (David et al. 1996). A PSF of 20” in the offset pointings is insufficient to resolve the small-scale structure discussed below. Images for the two pointings with 5” pixels were generated using the software of S. Snowden and then co-added. There is a bright X-ray source 12” off-axis in the HRI field of view, coincident with the bright star SAO 17151. A ROSAT PSPC spectrum of this source is soft, which is typical of stars; thus the identification is firm. The proper motion of this star is negligible on the relevant timescales. This

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A star was used to correct for a $\sim 3''$ shift in the ROSAT sky coordinates in both pointings (such an error is well within the nominal range). Since there is only one reference source, a possible rotational error of the HRI pointing cannot be corrected in a similar way. However, A. Vikhlinin (1997, private communication) infers from the analysis of a large number of the PSPC observations that it is likely to be negligible. It is also rather improbable that, if any significant rotational error exists, the independent offset and rotation combine in such a way that the X-ray star coincides with its optical counterpart to a $3''$ accuracy before any correction. We therefore conclude that the corrected sky coordinates of the X-ray image are accurate to $\sim 2''$–$3''$.

The HRI surface brightness contours are overlaid on the optical image in Figure 1. The image shows a complex multi-peaked X-ray structure in the inner $1''$–$2''$ of the cluster. Neither of the X-ray peaks coincides with the cD galaxy, whose J2000 coordinates from the Digitized Sky Survey image are $\alpha = 16^h35^m49.2^s$, $\delta = +66^\circ12'45''$. Because our reference star is approximately to the northwest of the cluster, any uncor-
rected rotation around the star could not make any of the brightness peaks coincident with the cD galaxy. Kneib et al. (1995), who used one-third of this HRI exposure, and Squires et al. (1996), using the same data set as here, reported approximate coincidence of the cD galaxy and the major X-ray peak. Our disagreement with the former authors apparently originates from their use of the incorrect cD galaxy coordinates (the coordinates listed in the NASA/IPAC Extragalactic Database with the reference to J. Le Borgne [1993, private communication] differ by 13° from the position given above). The X-ray image of Squires et al. (1996) appears inverted east-west with respect to the optical image, therefore it is likely that these authors have forced the coincidence between the X-ray peak and the cD galaxy. The poorer-resolution PSPC and offset HRI images agree with the HRI image presented here.

A standard β-model fit to the X-ray surface brightness profile centered at the overall emission centroid yields $a_0 = 58$ and $β = 0.63$, in agreement with the Einstein IPC (Birkingshaw & Hughes 1994) and ROSAT PSPC values (Squires et al. 1996). However, comparing the central 100° × 100° part of the image binned in 20° pixels to the two-dimensional β-model by means of a $χ^2$ test shows that this model is unacceptable at the 99.99% confidence level because of the structures seen in Figure 1.

3. DISCUSSION

3.1. X-Ray Lensing?

The major X-ray peak to the south of the cD galaxy has a bowlike shape and lies at the position of the brightest optical arc. Using the HST data, Kneib et al. (1996) found three pointlike counterparts to this arc, all four lying along the east-to-south segment of the 20° radius circle centered on the cD galaxy (see Fig. 1) and being lensed images of the same object at $z = 0.7$. The elongated X-ray structure covers about the same region. It is quite possible that lensed X-ray flux from the same object (or maybe other background X-ray sources; see discussion in Refregier & Loeb 1997) contributes to the central X-ray structure. The flux of the brightness excess is about 1% of the total cluster flux. At the redshift of the optical arc and assuming a magnification of 5–10 as for the optical arc, this would correspond to an X-ray luminosity of the lensed source of the order of $10^{39}$ erg s$^{-1}$. Presently, such an interpretation of the image is of course one of the many possibilities, since, for example, this X-ray peak is also coincident with a bright ringed galaxy (belonging to the cluster; Le Borgne et al. 1992) and a group surrounding it. The ROSAT HRI resolution is insufficient to determine whether this X-ray feature consists of point- or arclike sources (which would indicate lensing of a compact source) or is extended, but AXAF instruments will be capable of resolving X-ray lensing here. If lensing of background sources contributes any considerable X-ray flux near the cluster center, it could modify the derived gas density profile and hence the X-ray mass estimate. X-ray lensing has been observed with the HRI in another object (Chartas et al. 1995).

3.2. Subcluster Merger?

Another likely explanation of the observed X-ray structure is a subcluster merger, as noted by previous investigators. From the lensing data, Kneib et al. (1995, 1996) detected two major mass concentrations around the cD galaxy and the second brightest galaxy to the southeast. X-ray contours (Fig. 1) show extension and perhaps a local enhancement toward the second brightest galaxy’s concentration, while another X-ray peak lies ~10° to the northwest of the cD. These two mass concentrations must merge. If they are infalling head on, then the peak “behind” (to the northwest of) the cD galaxy may be offset from the cD by ram pressure. The central elongated structure, discussed in the previous section, lies between the mass concentrations perpendicular to the direction of the merger, and may be a shock such as those predicted in hydrodynamic simulations (e.g., Schindler & Müller 1993; Roettiger, Burns, & Loken 1993). Alternatively, this structure, together with its long northeastern extension not associated with any apparent galaxy concentration (Fig. 1), may be a gas trail of an infalling group originally not belonging to either of the two main subclusters. In the absence of a detailed gas temperature map in which merger shocks would be apparent, construction of such merger scenarios is highly speculative. Nevertheless, even the available X-ray image and optical lensing data strongly suggest that there indeed is a merger underway. AXAF will be able to obtain a temperature map and provide the missing information about the merger in this cluster.

It is also possible that the absence of an X-ray peak centered on the cD galaxy is due to partial absorption by cold material, e.g., accumulated from a past cooling flow (White 1992). The absorbing column should be of the order of $10^{21}$ cm$^{-2}$ and higher to be noticeable in the 0.5–2 keV image. The ROSAT HRI data have no energy information, and the angular resolution of the PSPC is insufficient to test this possibility.

Note that a merger in A2218 would imply strong temperature gradients and the absence of spherical symmetry, making the Hubble constant estimates using this cluster (e.g., Birkinshaw & Hughes 1994; Saunders 1997) highly uncertain (see, e.g., simulations by Roettiger, Stone, & Mushotzky 1997).

3.3. Effect of Angular Resolution on Mass Estimate

Miralda-Escudé & Babul (1995) and Loeb & Mao (1994) noted that the presence of lensed images around the cD galaxy implies a mass distribution more centrally concentrated than, or, equivalently, a mass inside the 20° lens radius greater than, that derived from the hydrostatic isothermal X-ray analysis. The gas density profile they used was derived from the β-model fits to the cluster images obtained with the ROSAT PSPC and the Einstein IPC, respectively. Those fits have core radii $a_0$ around 1, consistent with the HRI result given above. Essentially, it is the absence of the radial gradient in the assumed gas density profile with $a_0 = 1'$ at the lens radius of 20° that gives rise to the discrepancy between the X-ray and lensing mass measurements. However, it is now apparent from the better resolution HRI data that in fact (1) the centroid of the X-ray emission is offset from the cD galaxy by about 20°, and (2) the “core” is a blend of previously unresolved brightness peaks. As is said above, the image strongly suggests a subcluster merger and hence violent gas motions and the likely absence of hydrostatic equilibrium, the basic condition for an X-ray mass estimate. The gas turbulence proposed by Loeb & Mao (1994) essentially means the same thing.

However, in addition to this likely breakdown of the equilibrium assumption, the limited angular resolution and the resulting oversimplification of the gas density model also have a significant effect on the A2218 mass estimate. If, for exam-
ple, one assumes that the head-on merger scenario is correct and the X-ray peak to the northwest of the cD galaxy has been centered on the cD in the past, then one may expect it to retain some information about the cD gravitational well (e.g., if the bulk motions are rapid enough, the gas density peak may not have had enough time to disperse completely after the removal of the cD potential). For a crude estimate, we fit a simple symmetric $\beta$-model centered on this brightness peak, excluding other parts of the image and not going too far off peak. The fit yields $a_{1} = 26^\circ$ and $\beta = 0.49$. For an isothermal spherically symmetric equilibrium model, this corresponds (see, e.g., Sarazin 1988) to a mass within a $20^\circ$ radius sphere $2.6$ times the mass from the "old" $\beta$-model, and to a factor of $1.4$ increase in the projected mass within the cylinder of the same radius. This increase is due to the greater observed density gradient at the lensing radius. This crude calculation illustrates the likely effect of the limited angular resolution of the previous X-ray measurements on the mass at small radii. Note that no temperature information exists for the central part of A2218, therefore this calculation has little physical meaning and is made solely for comparison with earlier analyses also performed under the isothermality and equilibrium assumptions.

Most other lensing clusters are more distant than A2218, and their X-ray images of sufficient quality are even more difficult to obtain. Still more problematic (practically impossible at present) is a detailed measurement of the temperature distribution for distant clusters. Both distributions are necessary, not only for an accurate hydrostatic analysis but also to judge its applicability. First attempts at restoring the cluster mass profiles that take into account real temperature distributions obtained by ASCA (e.g., Markevitch et al. 1996; Ikebe et al. 1996; Allen, Fabian, & Kneib 1996; Markevitch & Vikhlinin 1997) suggest that the mass is more centrally peaked compared to that derived assuming isothermality. It is therefore possible that, together with the substructure (Bartelmann 1995) and projection effects (e.g., Daines et al. 1997) which tend to increase the mass derived from lensing, inadequate modeling of gas density and temperature distributions can account for the lensing/X-ray mass discrepancy as suggested for A2218.

4. SUMMARY

The ROSAT HRI image of A2218 reveals complex structure in the cluster core region. One of the elongated brightness features is coincident with the bright optical gravitational arc and its counterparts. We speculate that some X-ray emission in this feature can also arise from lensing. Taking into account the detailed structure of the core can significantly increase the X-ray hydrostatic mass estimate at the lensing radius. Together with the expected mass overestimate by the lensing analysis, this can explain the previously reported lensing/X-ray mass discrepancy in A2218. Moreover, the image strongly suggests an ongoing subcluster merger, which makes the hydrostatic mass estimate inapplicable.

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