AN UNUSUAL DISCONTINUITY IN THE X-RAY SURFACE BRIGHTNESS PROFILE OF NGC 507: EVIDENCE OF AN ABUNDANCE GRADIENT?

R. P. KRAFT AND W. R. FORMAN
Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, MS-67, Cambridge, MA 02138

E. CHURAZOV
Max-Planck-Institut für Astrophysik, D-85740 Garching, Germany; and Space Research Institute (IKI), Moscow 117810, Russia

AND

N. LASLO, C. JONES, M. MARKEVITCH, S. S. MURRAY, AND A. VIKHLININ
Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, MS-67, Cambridge, MA 02138

Received 2003 April 18; accepted 2003 October 1

ABSTRACT

We present results from a 45 ks Chandra ACIS-I observation of the nearby ($z = 0.01646$) NGC 507 group. The X-ray surface brightness profile of the outer region of the group is well described by an isothermal $\beta$-profile consistent with earlier ROSAT observations. We find a sharp edge or discontinuity in the radial surface brightness profile 55 kpc east and southeast of NGC 507 covering an $\sim 125''$ arc. At the sharpest part of the discontinuity, the surface brightness declines by a factor of $\sim 2$ over a distance of 6.9 kpc ($\sim 15''$). The inner and outer gas temperatures across the discontinuity differ by only about 0.2 keV (interior and exterior gas temperatures are 1.2 and 1.4 keV, respectively). Spectral analysis indicates that there is a gradient in the elemental abundance across the discontinuity, and comparison with the low-resolution NRAO VLA Sky Survey radio maps suggests that the discontinuity is aligned with a low surface brightness radio lobe. We conclude that the appearance of this discontinuity may be the result of two phenomena: the transonic ($M \sim 0.75 - 1$) expansion/inflation of the radio lobe close to our line of sight and the transport of high-abundance material from the center of the galaxy due to this expansion.

Subject headings: galaxies: individual (NGC 507) — galaxies: ISM — X-rays: galaxies

1. INTRODUCTION

Chandra observations of early galaxies, groups of galaxies, and clusters of galaxies have demonstrated that the hot, X-ray-emitting coronal gas of these systems is often not resting idly in their gravitating dark matter halos and that many of these systems are far from relaxed. A variety of structures have been identified and studied in detail. Chandra observations of shocks and “cold fronts” associated with subcluster mergers have contributed to our knowledge of the formation of structure. Evidence for large-scale, coherent, nonhydrostatic motions of the central regions of clusters has also been reported (Vikhlinin, Markevitch, & Murray 2001; Markevitch, Vikhlinin, & Mazzotta 2001; Mazzotta et al. 2001). One of the most interesting, and to some degree unexpected, results from Chandra has been the study of diverse interactions between jets and radio lobes of radio galaxies and the ambient interstellar/intergalactic/intracluster medium (ISM/IGM/ICM) (Fabian et al. 2000; Finoguenov & Jones 2001; McNamara et al. 2000; Jones et al. 2002; Kraft et al. 2003). The study of these various motions and hydrodynamic interactions is of fundamental importance to several astrophysical and cosmological problems. These observations give us insight into the merger process and subsequent relaxation. By studying merger shocks, thermal histories, etc., we learn about the process of the formation of clusters. In addition, understanding the radio lobe/ICM interactions may be critical in understanding the life cycle of clusters, since there may be a cyclical relationship between cooling flows, nuclear activity, and nuclear outflow (see, for example, Owen, Eilek, & Kassim 2000; Churazov et al. 2001, 2002).

NGC 507 is the dominant, massive elliptical galaxy of a nearby ($z = 0.01646$) group/poor cluster (the so-called Pisces cluster). Previous ROSAT observations have shown that NGC 507 is one of the most X-ray–luminous early-type galaxies ($L_X \sim 10^{43}$ ergs s$^{-1}$) in the local universe with evidence of a large cooling flow (cooling rate of $30-40 M_\odot$ yr$^{-1}$) at the center (Kim & Fabbiano 1995; Paolillo et al. 2003). This group has an unusually large mass-to-light ratio ($\sim 125$), similar to that observed in the X-ray overluminous elliptical galaxies (OLEGs) (Vikhlinin et al. 1999). NGC 507 is also known to be an FR I radio galaxy (Fanti et al. 1986).

In this paper, we present results from a Chandra ACIS-I observation of the hot ISM of this group. We detect a sharp discontinuity in the surface brightness profile at a distance of 55 kpc east and southeast from the galaxy center spanning a $125''$ arc. This discontinuity has been seen in XMM-Newton observations of NGC 507 as well (Fabbiano, Kim, & Brickhouse 2002). A more detailed discussion of the larger scale emission and the central cooling flow peak based on ROSAT HRI and Chandra ACIS-S observations is presented by Paolillo et al. (2003). Initially, it appears that this discontinuity was another example of a “cold front” as seen in clusters of galaxies. Such discontinuities have recently been detected in clusters of galaxies and are commonly attributed to either infalling subclumps or nonhydrostatic motions of the central core (e.g., A2142 [Markevitch et al. 2000], A3667 [Vikhlinin et al. 2001], A1795 [Markevitch et al. 2001]). However, there are significant problems with this interpretation of the discontinuity observed in NGC 507. In particular, the temperature jump across the discontinuity is small (0.1–0.2 keV), so the discontinuity should not appear sharp. The
size of the surface brightness discontinuity requires a large
density, and therefore large pressure, discontinuity. If the sharp
boundary is maintained by motion of the galaxy, a large, nearly
supersonic velocity of the galaxy with respect to the larger
scale halo is required. Spectral analysis indicates that there is
an elemental abundance gradient across the discontinuity. In
addition, the X-ray discontinuity is coincident with a radio
lobe detected in the NRAO VLA Sky Survey (NVSS) survey
(Condon et al. 1998). We suggest that the sharpness of this
discontinuity in the surface brightness is due to a combination
of the transonic expansion of the radio lobe and to turbulent
entrainment of high-abundance material from the center of the
galaxy to more distant regions caused by this expansion.

Throughout this paper, we use $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$,\n$\Omega = 0.3$, and $\Lambda = 0.7$. The observed redshift of NGC 507 then
corresponds to a distance of 65.5 Mpc, and $1' = 18.8$ kpc.

2. OBSERVATIONS

The central region of the nearby ($z = 0.01646, d = 65.5 \text{ Mpc}$)
NGC 507 group was observed twice by the Chandra X-Ray
Observatory. The first observation, taken 2000 October 11,
was made with the ACIS-S instrument, and the second, taken
2002 January 8, with the ACIS-I in Very Faint mode. The
particle backgrounds in both observations were examined for
periods of flares, and the average levels compared with the
nominal ACIS background rates. We found that the first
observation was contaminated by a steady but anomalously
high background, so we have used only data from the second
observation in all analyses presented in this paper. No flares or
periods of high background were found in the second data set.
Very Faint mode filtering was applied to this second event
file to reduce the background to the lowest possible level. A
background event file was created from the standard ACIS
background data appropriate for the date of the observation, and
Very Faint mode event filtering applied to these data as well. We
also have obtained archival data from the XMM-Newton
observation and have used these data to constrain spectral
parameters as described below.

A raw X-ray image in the 0.5–2.0 keV band is shown in
Figure 1. An adaptively smoothed, background-subtracted,
exposure-corrected image of NGC 507 is shown in Figure 2.
The complex azimuthal structure in the X-ray emission can be
seen in both figures. The large-scale coronal emission can
be seen in Figure 2 with the X-ray peak centered on NGC 507.
X-ray emission from the less massive NGC 508 is detected to

![Fig. 1.—Raw Chandra ACIS-I X-ray image of NGC 507 in the 0.5–2.0 keV band. The green wedge indicates the sector used to create the radial surface brightness profile in Fig. 3. The white arrows indicate the approximate position of the surface brightness discontinuity.](image)
some structure in the emission is seen to the west of NGC 507 and is most likely related to interaction between the radio lobe and the ISM.

3. ANALYSIS

The most striking feature of Figure 1 is the sharp discontinuity in the surface brightness approximately 120° to the east of the central peak spanning an angle of approximately 125° from the north through the east to the south. The radial surface brightness profile in the 0.5–2.0 keV band of the 60° wedge shown in Figure 1 is plotted in Figure 3. The discontinuity appears to be sharpest to the southeast, but in creating the surface brightness profile in Figure 3, we limited the wedge to the east and east-northeast of NGC 507 in order to avoid uncertainties associated with the CCD chip gap toward the southeast and NGC 508 to the north. The structure to the southeast is reminiscent of a Mach cone, but as we describe below, there is no evidence for shock-heated gas to support this hypothesis.

The temperature of the gas around NGC 507 was determined by two independent methods. First, we divided a 120° wedge (twice the angle of the sector shown in Fig. 1 to improve statistics) into eight regions, three to the west of the discontinuity, one straddling the discontinuity, and four to the east. An absorbed, single-temperature APEC model was fitted to both the Chandra and XMM-Newton data (independently) with the abundance as a free parameter. The absorption was held fixed at the Galactic value \( N_H = 5.5 \times 10^{20} \text{ cm}^{-2} \). The lower limit of the spectral fits was restricted to 0.8 keV to avoid uncertainties in the ACIS-I response due to the buildup of contaminants, although a correction also was applied to the response to account for this effect.

The best-fit Chandra and XMM-Newton MOS temperatures and abundances with 90% confidence intervals as a function of distance from the center of NGC 507 are plotted in Figure 4. Figure 4 shows only a small (0.1–0.2 keV) difference in the temperature between the regions interior and exterior to the discontinuity. The abundance increase from \( 0.3 \pm 0.1 \) to \( 0.6 \pm 0.1 \) toward the center is statistically significant at the 90% confidence level. If the abundance is held constant, the temperature difference between the interior region and the exterior region increases by only a small (~0.15 keV) amount.

We also created temperature maps from both data sets using the algorithm described in Churazov et al. (1996) and adapted to XMM-Newton as described in Churazov et al. (2003). The map created from the XMM-Newton MOS data is shown in Figure 5 and supports the conclusion of the spectral fitting that there is little change in temperature just across the discontinuity, but a small temperature decrease toward the center. Interestingly, the temperature is lowest in the region to the south-southeast, where the discontinuity appears sharpest.

4. INTERPRETATION

If the abundance is roughly constant across the discontinuity, there must be a large pressure jump due to the large density discontinuity, because the observed temperature jump across the boundary is small. We consider three possible interpretations to explain the observed surface brightness feature. In the first case, we consider the possibility that the edge is caused by motion of NGC 507 relative to the larger scale group dark matter potential. Second, we consider a scenario in which the pressure across the boundary is balanced by an unseen relic radio lobe left over from an earlier (and more
across the discontinuity to the ram pressure, the implied velocity of motion by equating the difference in pressure density, and therefore pressure, difference. If we estimate the temperature difference is not sufficient to balance the deprojected problems with this scenario for NGC 507. First, the temperature is roughly constant, to a large pressure discontinuity. The curve labeled "Model #2" consists of emission from a $\beta$-model density profile but with the emissivity of the gas interior to the discontinuity increased by a factor of 2.16 to account for the enhanced abundance and lower temperature derived from spectral fitting (see Fig. 4 below). This model can account for most of the observed structure of the discontinuity. The expansion of the radio lobe may also be important.

One interpretation commonly invoked to explain the sharp discontinuities observed in galaxy clusters is that the central object is moving with a significant velocity relative to the larger halo (Vikhlinin et al. 2001; Markevitch et al. 2001). These are the so-called cluster cold fronts. There are several problems with this scenario for NGC 507. First, the temperature difference is not sufficient to balance the deprojected density, and therefore pressure, difference. If we estimate the velocity of motion by equating the difference in pressure across the discontinuity to the ram pressure, the implied velocity is approximately 450 km s$^{-1}$ (Mach 0.7) relative to the ambient medium. Such a large velocity relative to the dark matter halo is not reasonable, since NGC 507 is the largest galaxy in the group and lies at or near the center defined by the outer X-ray isophotes. An examination of archival ROSAT PSPC data indicates that NGC 507 is indeed lying at approximately the center of the larger scale halo, and therefore at the center of the dark matter potential. The large-scale gravitating mass of the NGC 507 group can be estimated from the parameters of the $\beta$-profile assuming the larger scale gas is in hydrostatic equilibrium. If we consider NGC 507 to be an undamped harmonic oscillator in this dark matter potential moving with a velocity of 450 km s$^{-1}$, it should reach a distance of $\sim$75 kpc from the center before falling back. Since there are no other known instances of the largest galaxy in a group or cluster being so far from the center of the gravitational potential, such a large velocity of the central galaxy relative to the larger scale halo is implausible. We therefore consider this possibility to be unlikely.

A second significant complication with this interpretation arises from hydrodynamic considerations and the sharpness of the discontinuity. There is no evidence for supersonic motions (i.e., hotter gas) around the discontinuity. We can place an upper limit on the temperature of any shock-heated gas, and therefore on the velocity of motion based on the uncertainties in the spectral analysis (see Fig. 4). We estimate an upper limit on the Mach number of $M \sim 1.2$ (relative to the ambient gas). This implies that the motion is subsonic or transonic at best (i.e., $M \sim 1$, consistent with the above analysis). However, since the pressure difference is due only to differences in density, the boundary should not appear sharp, as there must be a continuous and gradual pressure and density transition between the two regions. If the pressure difference were due to a temperature discontinuity (such as the cold front in A3667 [Vikhlinin et al. 2001]), a sharp boundary could be observable because the surface brightness is proportional to $n^2$.

In order to evaluate this phenomenon more quantitatively, we have modeled the subsonic/transonic flow of gas around a sphere using the VH-1 hydrocode (Colella & Woodward 1984). We have determined the density, temperature, and velocity of the gas for several flow velocities with Mach numbers between 0.05 and 1.2. Assuming that the emissivity of the gas is proportional to $n^2$, we then determined the projected surface brightness for a range of observing angles with respect to powerful) epoch of nuclear activity. Finally, we investigate the possibility that the discontinuity was created by the subsonic/transonic expansion of the relatively weak lobe currently observed lying interior to the discontinuity. This expansion has pushed or entrained higher elemental abundance gas out from the central region. The sharp appearance of the discontinuity is then a natural consequence of the compression of the gas due both to expansion of the lobe and to the increase in the abundance across the discontinuity.

One interpretation commonly invoked to explain the sharp discontinuities observed in galaxy clusters is that the central object is moving with a significant velocity relative to the larger halo (Vikhlinin et al. 2001; Markevitch et al. 2001). These are the so-called cluster cold fronts. There are several problems with this scenario for NGC 507. First, the temperature difference is not sufficient to balance the deprojected density, and therefore pressure, difference. If we estimate the velocity of motion by equating the difference in pressure across the discontinuity to the ram pressure, the implied velocity is approximately 450 km s$^{-1}$ (Mach 0.7) relative to the ambient medium. Such a large velocity relative to the dark matter halo is not reasonable, since NGC 507 is the largest galaxy in the group and lies at or near the center defined by the outer X-ray isophotes. An examination of archival ROSAT PSPC data indicates that NGC 507 is indeed lying at approximately the center of the larger scale halo, and therefore at the center of the dark matter potential. The large-scale gravitating mass of the NGC 507 group can be estimated from the parameters of the $\beta$-profile assuming the larger scale gas is in hydrostatic equilibrium. If we consider NGC 507 to be an undamped harmonic oscillator in this dark matter potential moving with a velocity of 450 km s$^{-1}$, it should reach a distance of $\sim$75 kpc from the center before falling back. Since there are no other known instances of the largest galaxy in a group or cluster being so far from the center of the gravitational potential, such a large velocity of the central galaxy relative to the larger scale halo is implausible. We therefore consider this possibility to be unlikely.

A second significant complication with this interpretation arises from hydrodynamic considerations and the sharpness of the discontinuity. There is no evidence for supersonic motions (i.e., hotter gas) around the discontinuity. We can place an upper limit on the temperature of any shock-heated gas, and therefore on the velocity of motion based on the uncertainties in the spectral analysis (see Fig. 4). We estimate an upper limit on the Mach number of $M \sim 1.2$ (relative to the ambient gas). This implies that the motion is subsonic or transonic at best (i.e., $M \sim 1$, consistent with the above analysis). However, since the pressure difference is due only to differences in density, the boundary should not appear sharp, as there must be a continuous and gradual pressure and density transition between the two regions. If the pressure difference were due to a temperature discontinuity (such as the cold front in A3667 [Vikhlinin et al. 2001]), a sharp boundary could be observable because the surface brightness is proportional to $n^2$.

In order to evaluate this phenomenon more quantitatively, we have modeled the subsonic/transonic flow of gas around a sphere using the VH-1 hydrocode (Colella & Woodward 1984). We have determined the density, temperature, and velocity of the gas for several flow velocities with Mach numbers between 0.05 and 1.2. Assuming that the emissivity of the gas is proportional to $n^2$, we then determined the projected surface brightness for a range of observing angles with respect to

**Fig. 3.**—Radial surface brightness profile of the X-ray emission in a 60\(^\circ\) sector (shown in Fig. 1) to the east and northeast of NGC 507 in the 0.5–2.0 keV band. The continuous curve labeled “Model #1” is computed from a model of the emission that consists of two components, an isothermal $\beta$-model beyond the discontinuity and a uniform density sphere inside the discontinuity. While reasonably consistent with the data, the model is physically unrealistic, since it attributes the discontinuity to a change in density and therefore, since the temperature is roughly constant, to a large pressure discontinuity. The curve labeled “Model #2” consists of emission from a $\beta$-model density profile but with the emissivity of the gas interior to the discontinuity increased by a factor of 2.16 to account for the enhanced abundance and lower temperature derived from spectral fitting (see Fig. 4 below). This model can account for most of the observed structure of the discontinuity. The expansion of the radio lobe may also be important.

**Fig. 4.**—Best-fit temperature and elemental abundances in a 120\(^\circ\) sector to the southeast, east, and northeast of NGC 507. The crosses and the triangles correspond to the Chandra ACIS-I and XMM-Newton MOS fits, respectively. The top set of points is the temperature (keV), and the bottom set is the elemental abundance (fractional relative to solar). All error bars are 90% confidence intervals for one interesting parameter.
the line of sight. By comparing these simulated profiles with that observed for NGC 507, we conclude that the velocity of motion must be transonic ($v/c_0 = 0.75 - 1.0$) and that the direction of motion must be relatively close ($< 20\degree$) to the line of sight for the observed surface brightness profile to be remotely similar to that observed. As stated above, such a large velocity for the central galaxy of the group is unrealistic, so we therefore reject the hypothesis of nonhydrostatic motions of the central galaxy.

For the sharp pressure discontinuity to exist in the absence of motion, additional pressure support could exist beyond the discontinuity. A large, unseen relic radio lobe could provide the needed pressure support beyond the discontinuity. NGC 507 is a known radio source and has been classified as an FR I radio galaxy (Fanti et al. 1986). Data from two radio observations are shown in Figure 6 overlaid onto an adaptively smoothed Chandra image. These radio observations detected a double lobe structure lying along the east-west axis of the galaxy. The eastern (weaker) radio lobe is contained inside the discontinuity. No evidence for radio emission beyond the X-ray discontinuity to the east has been reported in the literature. The morphology of the X-ray-emitting gas in the vicinity of the western lobe is complex suggesting a strong interaction in this region as well (Forman, Murray, & Canizares 2001).

Is it feasible that such an unobserved, relic lobe is providing pressure support beyond the observed discontinuity? Relativistic electrons with $\gamma \sim 5 \times 10^2$ in a magnetic field of 50 $\mu$G (a typical value for the lobes of FR II radio galaxies) would radiate at $\sim 10$ MHz, which is unobservable. The density of such electrons can be estimated by requiring the pressure of the lobe to balance the pressure difference across the discontinuity. Assuming that the lobe has a $\sim 50$ kpc radius to cover the observed discontinuity, the total energy in the lobe would be about $5 \times 10^{50}$ ergs. This number is a factor of a few larger than the total energy in one of the lobes of the FR II radio galaxy Cyg A (Carilli et al. 1991), and would imply an energy deposition rate of approximately $10^{46}$ erg s$^{-1}$ for $10^7$ yr. The luminosity of inverse Compton–scattered cosmic microwave background photons would be considerable ($\sim 10^9 L_\odot$), but peaking in the EUV ($\sim 30$ eV), again difficult to observe. The existence of such an energetic but otherwise unobservable radio relic is not ruled out by this simple energy argument but is highly unlikely.

As a final possibility, we consider a scenario in which the inflation/expansion of the known radio lobe is creating the discontinuity. Such a scenario may explain all the observed features and has recently been investigated theoretically by Reynolds, Heinz, & Begelman (2001) to understand Chandra observations of cavities and cool shells seen around the lobes of several other FR I radio galaxies. We suggest that there is a low surface brightness radio lobe interior to the discontinuity, expanding to the south-southeast. Such a lobe is hinted at in the NVSS radio map (see Fig. 6). The relationship between the discontinuity and the smaller scale radio lobe presented in Fanti et al. (1986) is not clear. In this scenario, the subsonic expansion of the radio lobe, whether due to ongoing nuclear activity or buoyancy if the central source has shut off, gently pushes the lower temperature, higher abundance material from the cooling center of the galaxy out to more distant regions (Churazov et al. 2001; Nulsen et al. 2002).

We hypothesize that the sharp appearance of the discontinuity is due both to the combination of the motion of the radio lobe and to a significant abundance discontinuity across the
interface. At the observed ~1.2–1.3 keV temperature of NGC 507, the emissivity of the gas is a strong function of the heavy-element abundance, and there is an abundance gradient from the halo to the core (see Fig. 4). Material entrained from the central regions of NGC 507 would have higher abundance than that in the halo and would naturally give a sharp boundary if the emission were due to a cap surrounding a radio lobe. That is, the sharp abundance discontinuity (shown in Fig. 4) would naturally produce a discontinuity in the surface brightness and at the same time maintain pressure equilibrium without the need for a large temperature jump.

To demonstrate the effects of the enhanced elemental abundance interior to the discontinuity, we consider a model for the surface brightness in which the emissivity of the gas is determined by the extreme values of temperature and abundance in Figure 4. That is, the gas interior to the discontinuity has an abundance more than twice that of the material beyond the discontinuity, but with a 20% lower temperature. We assume that the gas density is described by a single $\beta$-profile and that there is no pressure discontinuity across the surface brightness discontinuity. The emissivity of the interior material is enhanced by a factor of 2.16 because of its higher abundance and lower temperature. We have overlaid the surface brightness profile from this model onto Figure 3. Such an idealized model closely approximates the observed surface brightness profile and can account for most, but not all, of the emission interior to the discontinuity.

Using the extremes of the abundance measurements probably overestimates this effect in the data, but the effects of projection and contamination by the X-ray binary population would tend to reduce the abundance jump across the interface. The true geometry of the motion is also unknown and is probably important in determining the observed morphology as well.

Finally, it is likely that hydrodynamic details are also important. The hydrodynamic model that is commonly used to interpret motions in the cold front scenario is that of flow (either subsonic or supersonic) around a solid body of rotation (Vikhlinin et al. 2001). One important assumption in this model is that of steady flow. Given the complex X-ray morphology of the surface brightness discontinuity in NGC 507, this approximation is unlikely to hold. In addition, hydrodynamic simulations of supersonic subcluster mergers and the cold front phenomenon demonstrate that low-entropy material from the center of a colder subcluster can be transported to the edge of the front, thus enhancing the appearance of the front (Heinz et al. 2003). Whether such a transport process is important in a jet-driven front is unclear, but it seems that currents in the interior of the front can play an important role in the appearance of the discontinuity at the interface. We conclude that a model combining the effect of the enhanced abundances and compression from subsonic motion can match the observed surface brightness profile. Further detailed radio and X-ray observations combined with
hydrodynamic simulations are required to constrain the relationship between the lobe and this discontinuity.

5. CONCLUSIONS

We have observed a sharp discontinuity in the X-ray surface brightness profile in a Chandra observation of NGC 507. We conclude that this discontinuity is most likely not a cold front as has been observed in many clusters, nor is it due to nonhydrostatic motion of the group core. It is also highly improbable that this discontinuity is supported by an unseen relic radio lobe from an earlier epoch of galaxy activity. The appearance of this discontinuity probably arises from two factors. First, the \( M \sim 0.75 - 1 \) expansion/inflation of the radio lobe compresses the ambient ISM. Second, there is an abundance gradient across the boundary that creates a discontinuity in the surface brightness. We suggest that the inflation of the radio lobe has driven and/or entrained higher abundance material from the central regions within NGC 507 into the group halo. If the inflation of the lobe is the dominant factor in the appearance of the discontinuity, hydrodynamic simulations suggest that the direction of motion must be close to the line of sight. A much deeper XMM-Newton observation would be required to better constrain the abundance variations across the discontinuity to determine in detail the relationship between abundance gradients and hydrodynamic phenomena.

Chandra has now detected more than a dozen examples of active galaxies “blowing bubbles” into the ICM (Blanton et al. 2001; McNamara et al. 2000, among many others). In most cases, there is no evidence of shocks being driven into the IGM/ICM. This is clearly the case with NGC 507 as there is no evidence of hotter gas associated with either the discontinuity or any of the radio components. Sharp and morphologically complex structures appear to be common features in the observations of the nearer, brighter objects (such as M87 [Churazov et al. 2001], Per A [Churazov et al. 2003], and Cen A [Kraft et al. 2003]). The abundance and total mass of heavy elements (particularly Fe) required to account for the surface brightness discontinuity in NGC 507 are not unusually large. In some cases, heavy-element abundances greater than solar have been observed in the central regions of elliptical galaxies (Finoguenov & Jones 2000; Böhringer et al. 2001). In the case of NGC 507, it appears that the inflation of the lobe has disrupted the gas in the central region and may provide an efficient mechanism for mixing the higher abundance material at the center with the lower abundance material (presumably much older) in the halo. This suggests that the elemental abundance profiles of early galaxies are not solely a function of their star formation histories (David, Forman, & Jones 1991; Matteucci & Gibson 1995; Finoguenov et al. 1999).

It is unclear whether the phenomenon of “abundance fronts” is common or not, because it is most readily observable only in relatively cool (\( k_B T < 2 \) keV) galaxies and clusters where the emissivity of the gas is a strong function of the abundance. Such an abundance front could be generated in two ways; by the inflation of radio lobes and entainment of material from the central regions, as we have suggested for NGC 507, or by ram pressure stripping of the halo of an infalling elliptical galaxy during a merger. A significant fraction (>50%) of cooling flow clusters observed with Chandra exhibit sharp features (M. Markevitch 2003, private communication), and there is at least one cluster, A576, that shows evidence for a surface brightness discontinuity that is at least partially attributable to a gradient in the elemental abundance (Kempner & David 2003). Chandra observations of many merging elliptical galaxies and groups, including NGC 4472 (Biller et al. 2003), NGC 7619 (R. P. Kraft et al. 2004, in preparation), and NGC 1404 (E. Machacek et al. 2004, in preparation), have detected sharp surface brightness discontinuities that may in part be explained by abundance discontinuities. In these cases, the inner regions of the galaxy were removed by ram pressure stripping, leaving only the enriched cores. In such cases, the infall velocity of cool subclusters or the expansion velocity of radio lobe/ICM interactions would be overestimated, perhaps by as much as a factor of a few, because the pressure difference would be overestimated if the abundance differences were neglected.

This work was supported by NASA contracts NAS8-38248 and NAS8-39073, the Chandra X-Ray Center, and the Smithsonian Institution.

REFERENCES

Biller, B. A., Jones, C., Forman, W. R., Kraft, R., & Ensslin, T. 2003, ApJ, submitted
Blanton, E. L., Sarazin, C. L., McNamara, B. R., & Wise, M. W. 2001, ApJ, 558, L15
Böhringer, H., et al. 2001, A&A, 365, L181
Carilli, C. L., Perley, R. A., Dreher, J. W., & Leahy, J. P. 1991, ApJ, 383, 554
Churazov, E., Gilfanov, M., Forman, W., & Jones, C. 1996, ApJ, 471, 673
Churazov, E., et al. 2001, ApJ, 554, 261
———. 2002, MNRAS, 332, 729
———. 2003, ApJ, 590, 225
Colella, P., & Woodward, P. R. 1984, J. Comput. Phys., 54, 174
Condon, J. J., Cotton, W. D., Greisen, E. W., Yin, Q. F., Perley, R. A., Taylor, G. B., & Broderick, J. J. 1998, AJ, 115, 1693
David, L., Forman, W., & Jones, C. 1991, ApJ, 380, 39
de Ruiter, H. R., Parma, F., Fanti, C., & Fanti, R. 1986, A&AS, 65, 111
Fabbiano, G., Kim, D.-W., & Brickhouse, N. 2002, AAS Meeting, 201, 14.04
Fabian, A. C., et al. 2000, MNRAS, 318, L65
Fanti, C., Fanti, R., de Ruiter, H. R., & Parma, P. 1986, A&AS, 65, 145
Finoguenov, A., Forman, W. R., Jones, C., & David, L. 1999, ApJ, 514, 844
Finoguenov, A., & Jones, C. 2000, ApJ, 539, 603
Finoguenov, A., & Jones, C. 2001, ApJ, 547, L107
Forman, W., Murray, S., & Canizares, C. 2001, in Clusters of Galaxies and the High Redshift Universe Observed in X-Rays, Recent Results of XMM-Newton and Chandra, ed. D. M. Neumann & J. T. T. Van Heinz, S., Churazov, E., Forman, W., & Briel, U. 2003, MNRAS, 346, 13
Jones, C., et al. 2002, ApJ, 567, L115
Kim, D.-W., & Fabian, D. G. 1995, ApJ, 441, 182
Kempner, J., & David, L. 2003, ApJ, submitted
Kraft, R. P., Vázquez, S. E., Forman, W. R., Jones, C., Murray, S. S., Hardcastle, M. J., Worrall, D. M., & Churazov, E. 2003, ApJ, 592, 129
Markevitch, M., Vikhlinin, A., & Mazzotta, P. 2001, ApJ, 562, L153
Markevitch, M., et al. 2000, ApJ, 541, 542
Matteucci, F., & Gibson, B. K. 1995, A&A, 304, 11
Mazzotta, P., et al. 2001, ApJ, 555, 205
McNamara, B. R., et al. 2000, ApJ, 534, L135
Nulsen, P. E., et al. 2002, ApJ, 568, 163
Owen, F. N., Eilek, J. A., & Kassim, N. E. 2000, ApJ, 543, 611
Paolillo, M., et al. 2003, ApJ, 866, 850
Reynolds, C. S., Heinz, S., & Begelman, M. C. 2001, ApJ, 549, L179
Vikhlinin, A., Markevitch, M., & Murray, S. S. 2001, ApJ, 551, 160
Vikhlinin, A., McNamara, B. R., Hornstrup, A., Quintana, H., Forman, W., Jones, C., & Way, M. 1999, ApJ, 520, L1