CHANDRA TEMPERATURE MAPS FOR GALAXY CLUSTERS WITH RADIO HALOS

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Abstract

This presentation is based on the paper by Govoni et al. (2004). We derived *Chandra* temperature maps for a sample of clusters with high-quality radio halo data, to study the origin of the radio halos. All the sample clusters exhibit distorted X-ray morphology and strong gas temperature variations indicating ongoing mergers. Some clusters, e.g., A520, A665, 1E0657−56, exhibit spatial correlation between the radio halo brightness and the hot gas regions. However, it is not a general feature. We find clear counterexamples (e.g., A754 and A773) where the hottest gas regions do not exhibit radio emission at the present sensitivity level. This cannot be explained by projection effects, and therefore argues against merger shocks — at least those relatively weak ones responsible for the observed temperature structure in most clusters — as the main mechanism for the halo generation. This leaves merger-generated turbulence as a more likely mechanism. The two clusters with the clearest radio brightness – temperature correlation, A520 and 1E0657−56, are both mergers in which a small dense subcluster has just passed through the main cluster, very likely generating turbulence in its wake. The maximum radio brightness and the hot gas are both seen in these wake regions. On the other hand, the halos in 1E0657−56, A520 and A665 (all three high-velocity mergers) extend into the shock regions in front of the subclusters, where no strong turbulence is expected. Thus, in high-velocity ($\mathcal{M} \simeq$ 2–3) mergers, both shock and turbulence acceleration mechanisms may be significant.

1 Introduction

Radio halos are extremely low-brightness, large-scale diffuse sources observed in some galaxy clusters. They often span the whole cluster and are unpolarized (for recent reviews see, e.g., Kempner et al. 2003; Feretti 2003). While the cluster X-ray emission is due to thermal electrons with energies of several keV, the radio halo emission at $\sim$ 1 GHz is produced by synchrotron radiation of relativistic electrons with energies of $\sim$ 10 GeV in magnetic fields with $B \simeq$ 0.5–1 μG. These electrons should coexist with the thermal population. Their origin is still uncertain; the difficulty in explaining their presence arises from the combination of the large sizes of halos ($r \sim$ 1 Mpc) and the short synchrotron lifetime of these electrons (10^7–10^8 yrs). One needs a mechanism by which these electrons are locally and simultaneously (re-)accelerated over the halo volume. Several such mechanisms of feeding energy to the relativistic electrons have been proposed (see, e.g., Enßlin 1999; Sarazin 2001; Brunetti 2002; Petrosian 2002 and references therein).

Halos are typically found in clusters with significant substructure in the X-ray brightness which indicates merger activity (e.g., Feretti 1999; Buote 2001). The radio power of a halo, if one is present, strongly correlates with the cluster luminosity, gas temperature (e.g., Feretti 1999; Colafrancesco 1999; Liang et al. 2000), or total mass (Govoni et al. 2001a). In a number of well-resolved clusters, a spatial correlation between the radio halo and X-ray brightness is observed (Govoni et al. 2001b). These observations indicate that radio halos are closely related to the intracluster thermal gas, its history and energetics. However, details

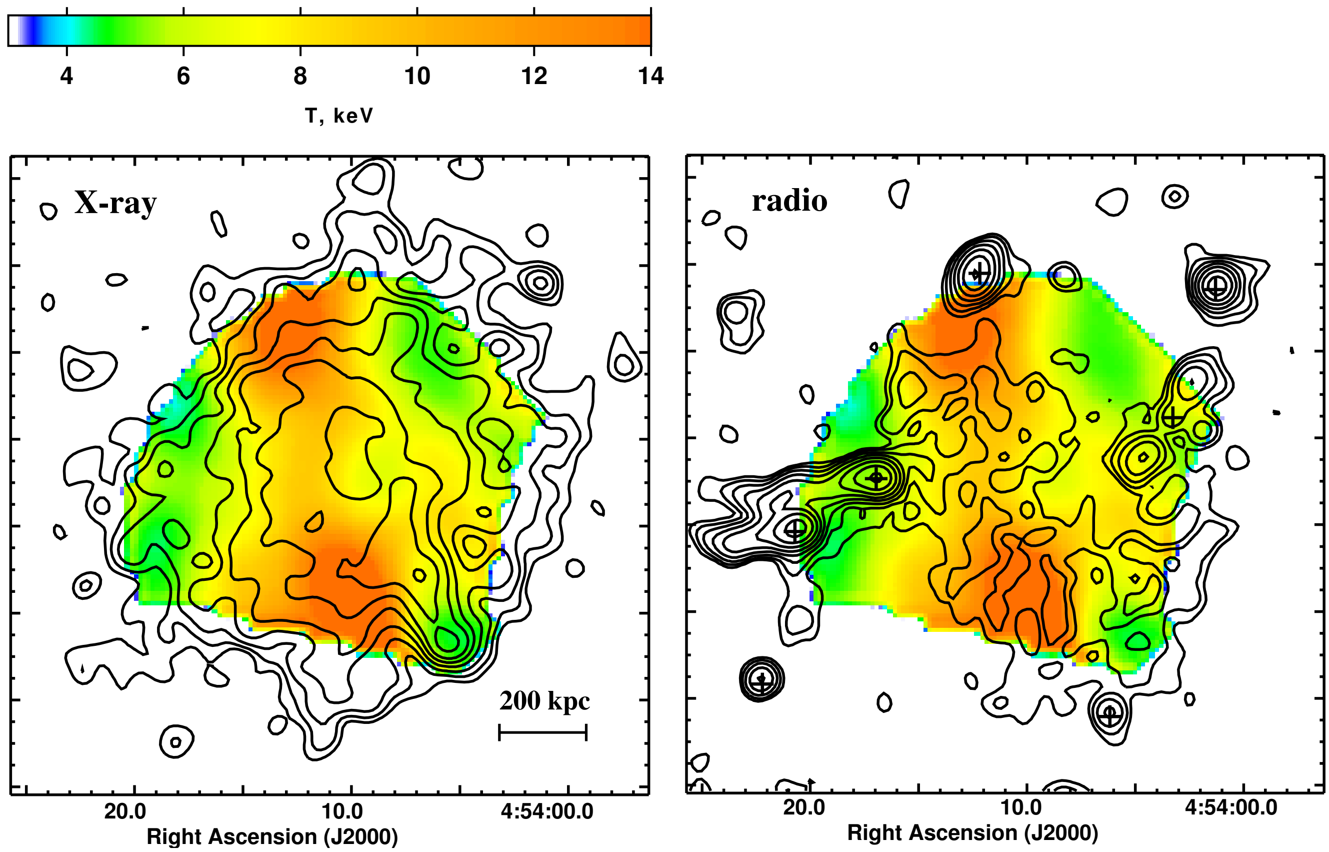

Figure 1: A520. *Chandra* temperature map (color) overlaid on the X-ray and radio contours. Crosses mark radio point sources. Linear scales are for $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_0 = 0.3$ and $\Omega_\Lambda = 0.7$.

of this connection need further investigations. Because the halos appear to be related to cluster mergers, cluster gas temperature maps can provide further information on their origin. Indeed, earlier *Chandra* studies of A2163, A665, 1E0657−56, and A520 (Markevitch & Vikhlinin 2001, hereafter MV01; Markevitch et al. 2002ab, hereafter M02a, M02b) revealed a possible spatial correlation between the high-temperature cluster regions and the diffuse radio emission, appearing to support a merger shock origin for the relativistic halo electrons.

Govoni et al. (2004) undertook an X-ray and radio study of a large cluster sample to see whether a spatial correlation between the radio halo and the gas temperature is a common feature. In this talk, we show the results from that paper, and refer to that paper for analysis details. Most of the presented X-ray maps are new, while the radio data were taken from previously published works.

2 Results

2.1 A520

The X-ray data show that A520 is in the middle of a merger. In Fig. 1, we compare an X-ray image and a temperature map (from M02b) derived from this *Chandra* observation to a Very Large Array (VLA) radio halo image at 1.4 GHz from Govoni et al. (2001a). The most prominent feature in the X-ray data is a dense, compact — but clearly extended — cool gas clump southwest of the center. Apparently, it has just passed straight through the main cluster from the northeast. The temperature map shows that the bright gas trail it has left behind is cool, and reveals a hot strip of apparently shock-heated gas along this trail. Most of the radio halo emission appears to follow this hot strip, and not the cool bright trail. The X-ray image hints at a possible bow shock in front of the dense clump, coincident with the southwest edge of the radio halo (a longer *Chandra* observation carried out since the Govoni et al. 2004 publication, has confirmed that this is

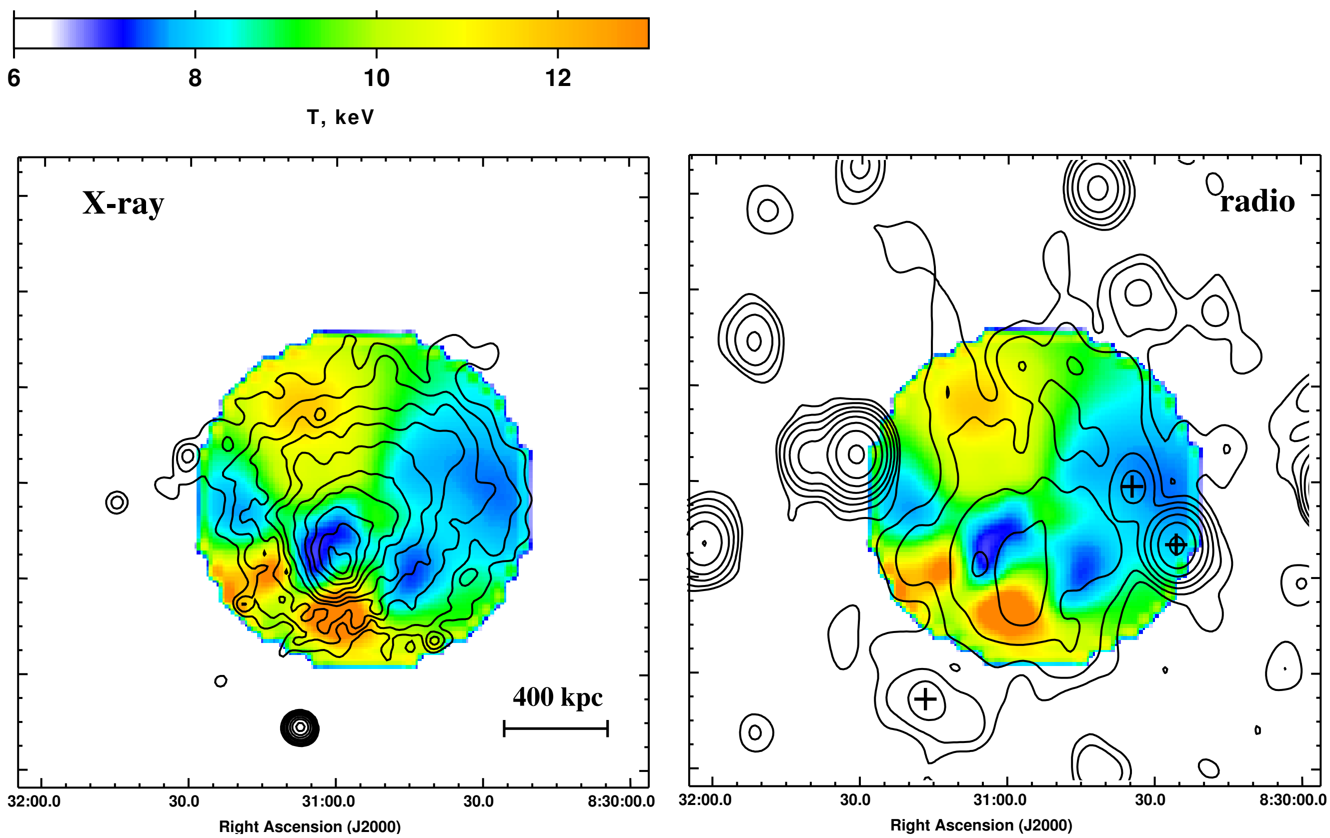

Figure 2: A665.

a shock). This cluster is one of the best examples of a spatial correlation between the radio halo brightness and the gas temperature. It is also one of only two clusters in our sample with a simple and clear merger geometry (the other being 1E0657−56).

2.2 A665

The X-ray image of A665 strongly suggests that the cluster is undergoing a merger. A *Chandra* temperature map revealed large variations and a possible shock with $\mathcal{M} \approx 2$ in the expected location (MV01). A luminous radio halo in A665 was discovered by Moffet & Birkinshaw (1989), confirmed by Jones & Saunders (1996) and further studied by Giovannini & Feretti (2000). Here we derive a more accurate temperature map than that presented in MV01, by including the recent longer exposure. In Fig. 2, the resulting map and an ACIS image are compared to the 1.4 GHz VLA image (Giovannini & Feretti 2000). The new map confirms the presence of hot — most probably shock-heated — gas south or in front of the cool core. The radio halo is very extended and elongated in the SE-NW direction, which is the apparent merger direction. As noted by MV01, the "leading edge" of the halo extends beyond the cool core and coincides with the shock region.

2.3 A754

Numerous optical and X-ray studies (e.g., Fabricant et al. 1986; Zabludoff & Zaritsky 1995) showed that A754 is undergoing a violent merger. Markevitch et al. (2003) noted that it is difficult to explain the complex details revealed by the *Chandra* X-ray image and temperature map (which we reproduce here in Fig. 3) with a simple two-cluster merger model. Krivonos et al. (2003) noted a possible weak bow shock east of the bright core in the *ROSAT* image; it is located approximately at the leftmost X-ray brightness contour in Fig. 3. A radio halo in A754 was discovered by Harris et al. (1980) and recently confirmed by Kassim et al. (2001) through radio observation at 0.3 GHz. In Fig. 3, we compare the *Chandra* X-ray image and temperature map with a 1.4 GHz VLA image from B03. The radio diffuse emission is complex and very ex-

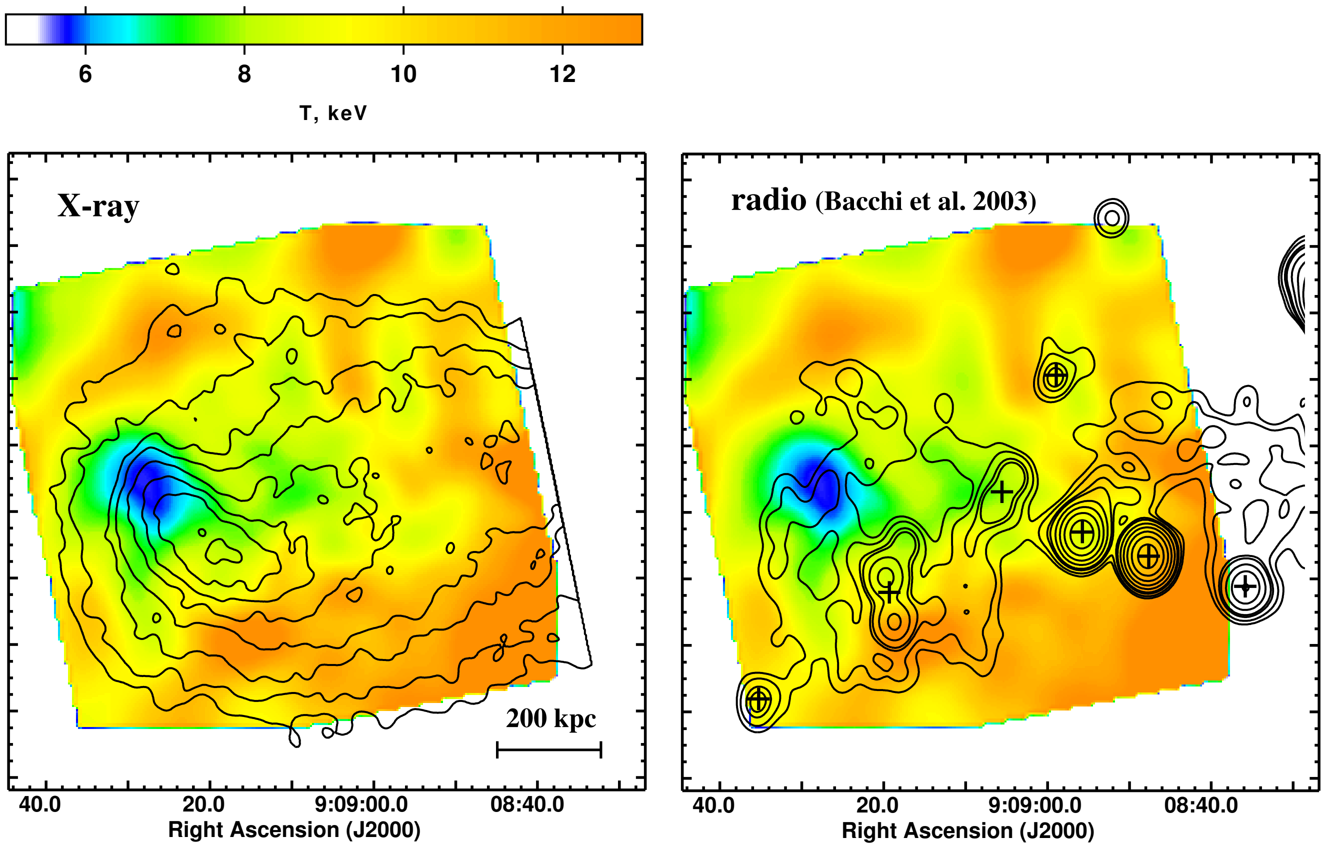

Figure 3: A754.

tended, consisting of two large components, roughly coincident with the two main galaxy concentrations. The temperature map shows strong spatial variations, such as a large hot area in the south and southwest and cool gas at the tip of the bright tongue-like structure. This structure appears to be the remains of the core of one of the subclusters, presently flowing in the northeast direction. The eastern diffuse radio emission is located around the eastern interface between the tongue and the surrounding gas. The western radio emission extends beyond the boundary of our temperature map. That region was covered by the *ASCA* map (Henriksen & Markevitch 1996) which showed hot gas. Significantly, the large, hot southern region in the present map does not exhibit radio emission at the present sensitivity level.

2.4 A773

A radio halo in A773 was suggested by Giovannini et al. (1999) from the NVSS data and confirmed by Govoni et al. (2001a) through a dedicated VLA observation at 1.4 GHz. In Fig. 4, we compare this radio image with the *Chandra* image and temperature map. This is the first temperature map for A773; it reveals strong temperature variations in the 6–12 keV range. The optical and X-ray data suggests two galaxy subclusters, one in the center of the X-ray emission and another at the eastern outskirt. The eastern galaxy group appears to be exiting the merger site, having shed its gas due to ram pressure at the entry into the main cluster at its southwest side. The collision of the gas clouds has generated a shock-heated area there, seen in the temperature map.

The radio halo does not follow the X-ray brightness, nor temperature distribution – moreover, the hottest cluster region is not at all bright in the radio (although a more sensitive, lower spatial resolution radio image shows a faint extension mostly southward; Govoni et al. 2001a). Instead, the radio halo is centered in the relatively cool region between the two galaxy subclusters.

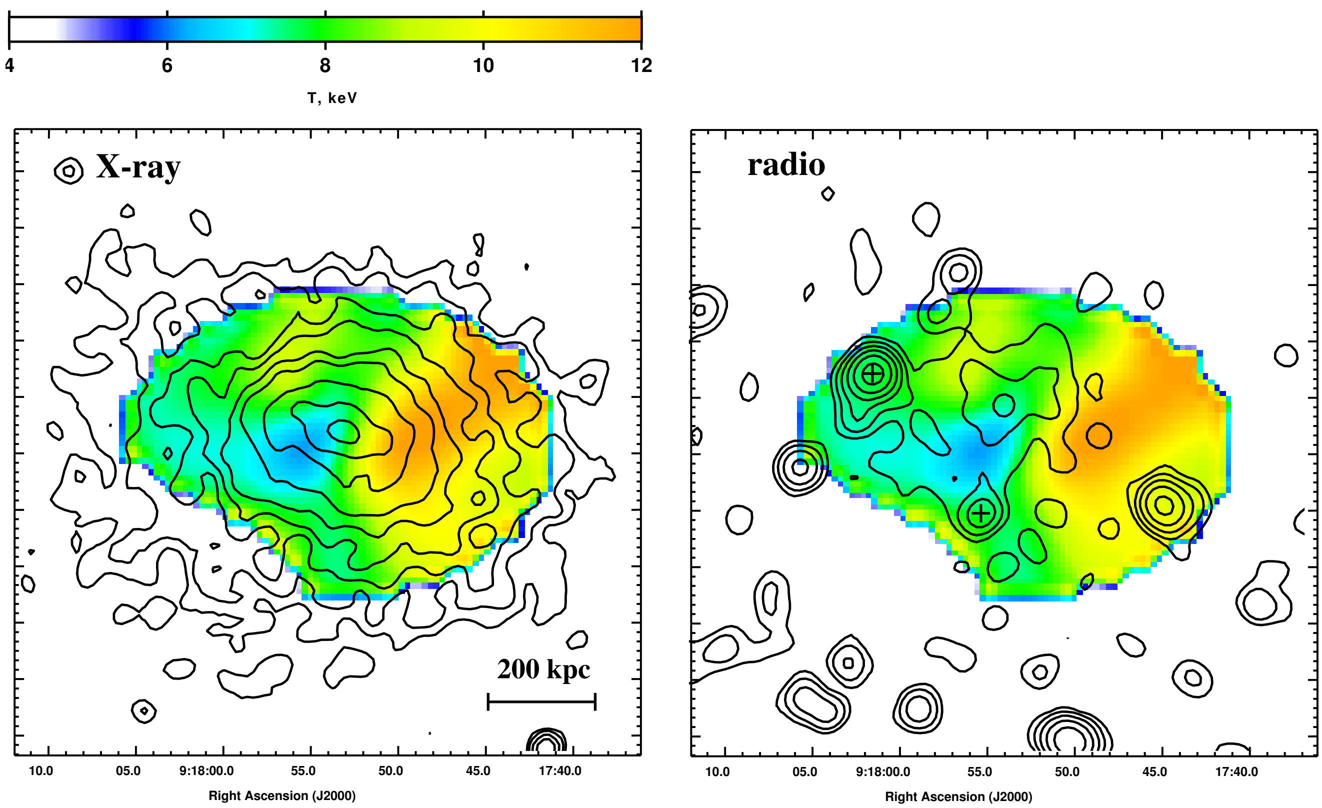

Figure 4: A773.

2.5 A1914

The presence of a radio halo in A1914 was suggested by Giovannini et al. (1999) from an NVSS search. It was detected by Kempner & Sarazin (2001) in the WENSS at 0.3 GHz, and confirmed by B03 in deep VLA observations at 1.4 GHz. In Fig. 5, we compare the radio image from B03 with our *Chandra* X-ray image and temperature map. This temperature map, the first for A1914, provides a likely merger scenario, not at all obvious from the X-ray and optical images alone. In this scenario, the NE-SW arch-like hot region through the cluster center, which coincides with a distinct component in the X-ray image, is a shock between the two infalling subclusters. One of them has arrived from the southeast, where the map shows cool gas probably stripped from that subcluster. Its gas core was partly shocked and stopped by the collision around the position of the present X-ray brightness peak. This gas is currently squirting sideways along the hot arch, creating the prominent cooler elongation to the east. The other colliding subcluster arrived from the west; its cooler core was left behind and is currently seen as a western cool extension, some of it possibly squirting along the western side of the shocked region, similarly to the situation on the southeastern side of the cluster. If this merger had a smaller impact parameter and occurred closer to the sky plane, we would now see a classical picture from the simulations with two subclusters just before core passage and a shocked region between them.

The diffuse radio emission in A1914 is unusual in that it has a distinct, bright, elongated region, approximately along the presumed path traveled by the eastern subcluster. It is accompanied by a more typical, diffuse, low-brightness halo in the cluster center. The bright feature is clearly extended (B03). It would be interesting to determine if this region is physically distinct from the rest of the halo. The remaining low-brightness region of the radio halo approximately coincides with the hot central region of the X-ray cluster and may even follow the presumed streams of the gas of the two subclusters. However, a detailed comparison requires better accuracy and a removal of the radio sources in the south and the resolution of the nature of the bright feature.

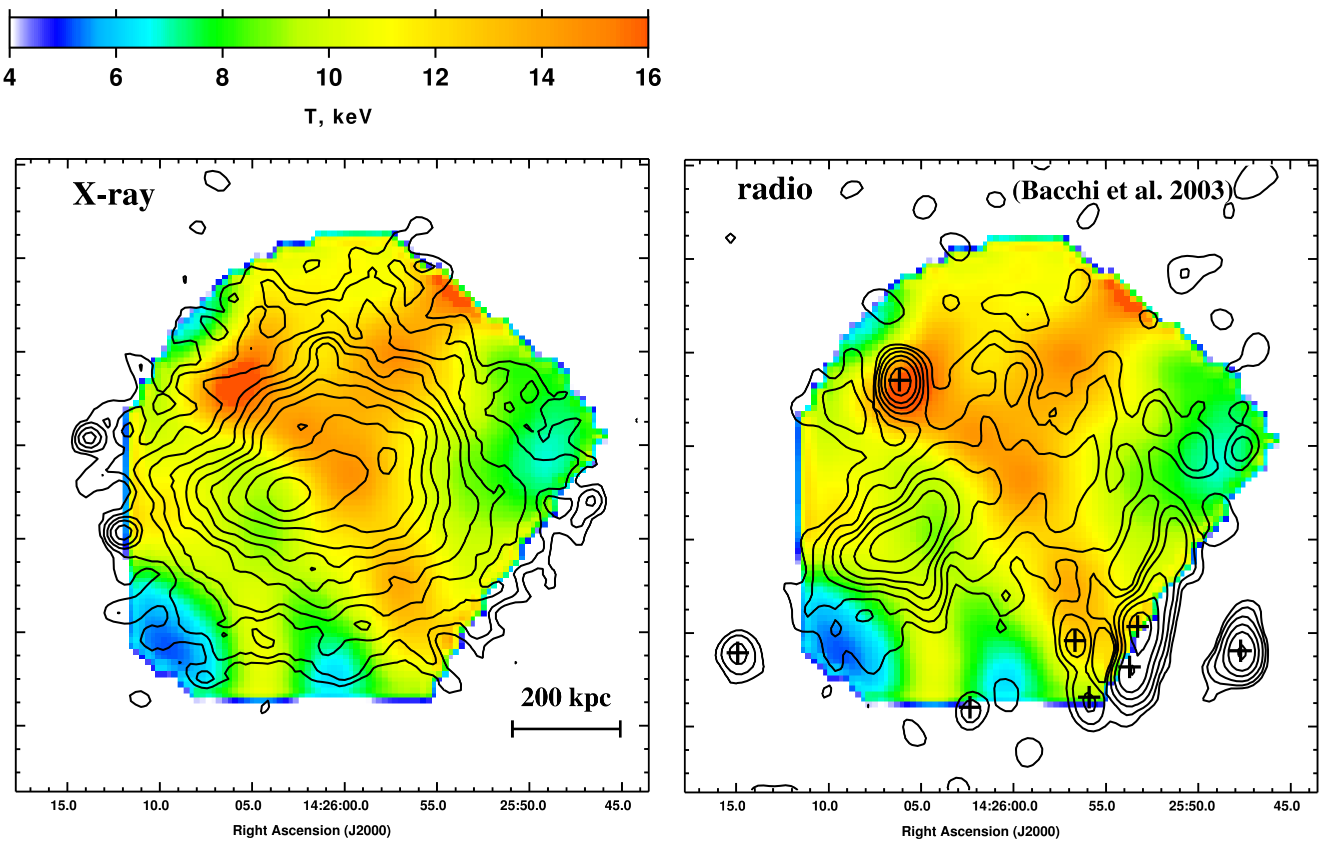

Figure 5: A1914.

2.6 A2319

Optical and X-ray analysis of the bright nearby cluster A2319 suggested that it consists of two components, with a smaller subcluster projected about $10'$ northwest of the cluster center. A2319 exhibits an extended and powerful radio halo (Harris & Miley 1978) with an irregular morphology well correlated with the X-ray brightness (Feretti et al. 1997). Our detailed *Chandra* temperature map of A2319 is shown in Fig. 6 along with our X-ray image and a 1.4 GHz VLA image from Feretti et al. (1997). The most prominent feature seen in the X-ray data is a sharp cold front southeast of the cD galaxy, such as those discovered by *Chandra* in many other merging clusters (e.g., Markevitch et al. 2000; Vikhlinin et al. 2001). The central cool gas cloud is clearly moving southeast with respect to the ambient hotter gas. The cD galaxy is neither at the centroid nor at the coolest spot of the cluster, suggesting that the cool gas core is moving independently of this galaxy. We can also see a cool arm extending around the cluster center from the tip of the cold front in the general direction of the northwestern subcluster. It may either be a tail of that subcluster, or gas stripped from the cold front cloud, unrelated to the subcluster. Overall, the picture suggests a later stage of a merger, well past the initial encounter.

The radio halo follows remarkably closely the distribution of the cool gas in the core, except for two low-brightness extensions into the hotter gas northeast and southwest of the cold front. The radio halo is more extended southwest of the X-ray brightness centroid — toward the cooler gas that we observe there.

2.7 1E0657−56

1E0657−56 is one of the hottest, most luminous clusters known which also contains the most luminous radio halo (Liang et al. 2000). An early *Chandra* observation revealed a spectacular bow shock propagating in front of a dense, cool bullet-like subcluster exiting the site of the collision with a bigger subcluster (M02a). Those authors derived an approximate temperature map of this merger and noticed that the radio halo brightness peaks at the hottest cluster region. In Fig. 7, we compare the Liang et al. (2000) 1.3 GHz ra-

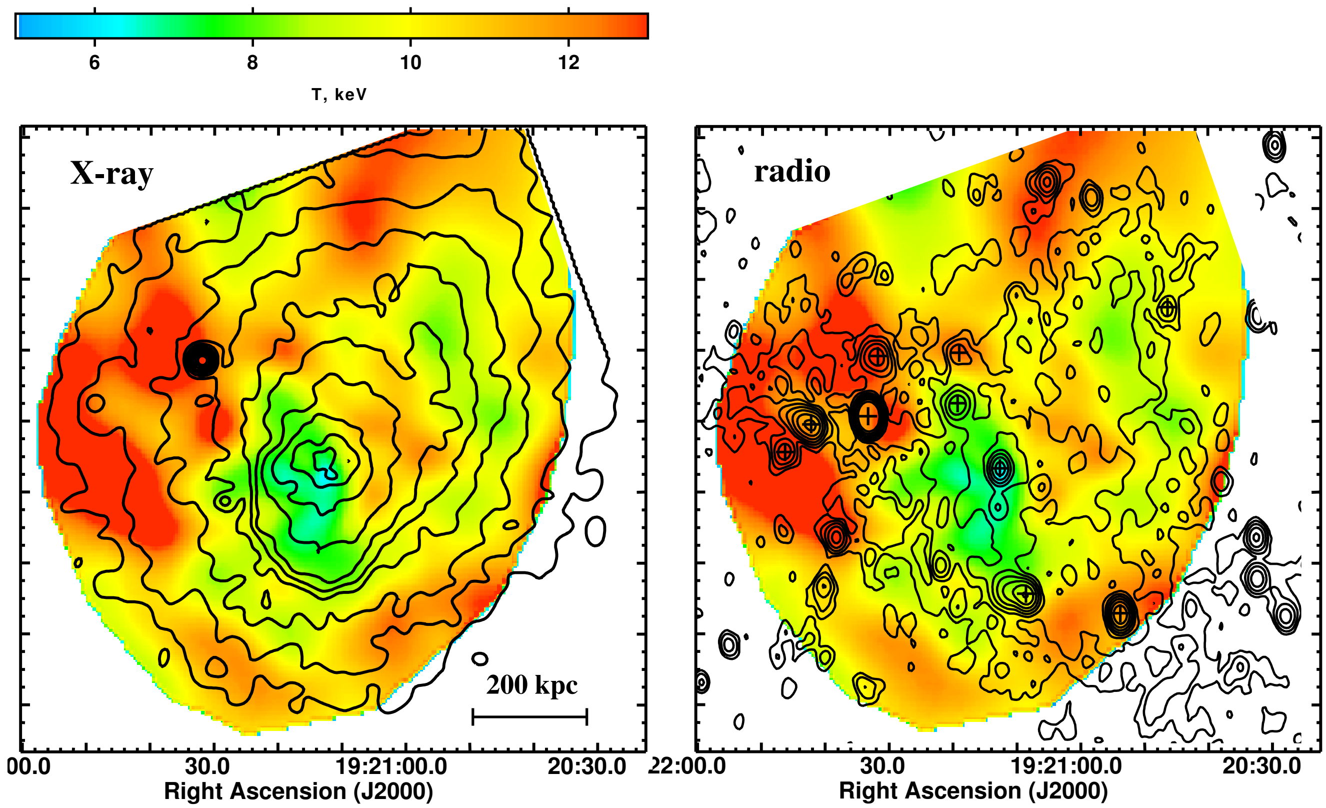

Figure 6: A2319.

dio image with a new, more accurate temperature map obtained from a deeper *Chandra* exposure. That map and the X-ray image suggest that the smaller subcluster has arrived at the collision site from the southeast. Most of its outer gas was shocked and stripped during the collision with a bigger subcluster. This stripped gas, together with the shocked gas from the other subcluster, form the north-south bar-like structure seen in the X-ray image, which is probably a pancake in projection. Shocks could not penetrate and stop the dense core of the subcluster, and it is now continuing to the west, preceded by a bow shock with $\mathcal{M} \approx 3.5$. This subcluster should be generating vigorous turbulence in its wake.

The radio halo peak is clearly offset from the X-ray brightness peak (in the region that excludes the bullet), and instead is centered in the hottest cluster region. The halo's eastern part is elongated along the presumed infall trajectory of the subcluster. Interestingly, the western part of the halo extends all the way to the bow shock.

3 Discussion

Mergers dissipate enough kinetic energy — simultaneously over a megaparsec-scale volume — for the maintenance of a radio halo. However, it is not clear how exactly the relativistic particles are accelerated. In-situ acceleration (or re-acceleration) of relativistic electrons during a merger can occur in shocks (e.g., Sarazin 1999, Fujita & Sarazin 2001) or in the gas turbulence (e.g., Schlickeiser et al. 1987; Brunetti et al. 2001; Ohno et al. 2002, Fujita et al. 2003). There are theoretical arguments against the shock hypothesis. Most importantly, a relatively strong shock with $\mathcal{M} >$ 4–5 is believed to be necessary for generation of an observable halo (e.g., Brunetti 2002). Such high Mach numbers should be very rare, as most merger shocks should have $\mathcal{M} \sim 1$ at the cluster center. Gabici & Blasi (2003) argued that shocks expected in mergers of clusters with comparable masses are too weak to result in significant non-thermal emission. Moreover, such radio emission should look more like radio relics at the cluster periphery than radio halos (Miniati et al. 2001). However, physics of collisionless shocks in clusters is not well understood, and so at present even relatively

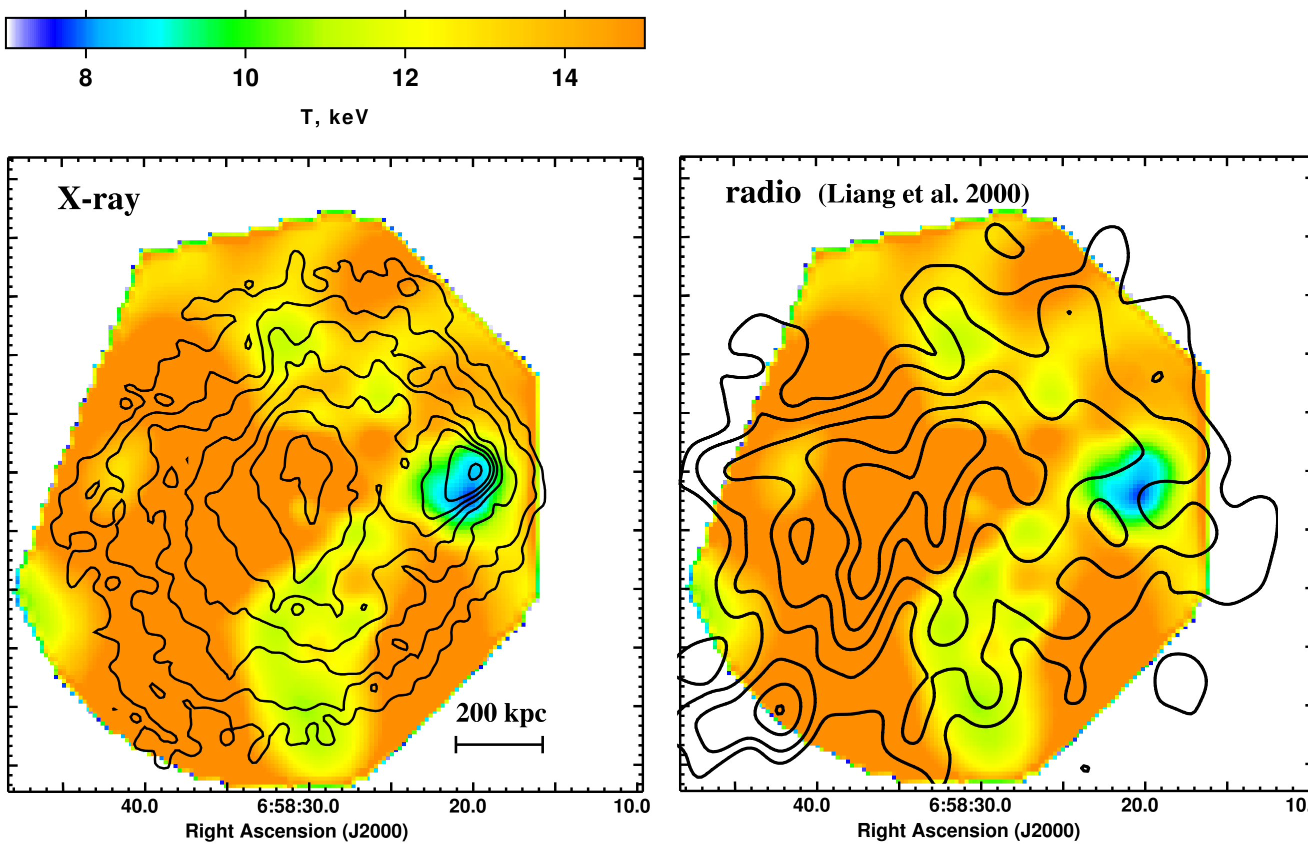

Figure 7: 1E0657−56.

weak merger shocks cannot be completely ruled out as an acceleration mechanism.

Indeed, comparison of the radio halo and gas temperature maps for a few merging clusters (MV01, M02ab) hinted at their spatial correlation, which could be easily explained if electrons were accelerated in shocks. After a shock passage, regions of shock-heated gas are mixed by large-scale gas motions, resulting in patchy temperature structure which persists for a considerable time in the absence of thermal conduction. Any relativistic electrons accelerated as the shock passes through the gas, will be prevented from diffusing far from their origin by the magnetic fields and will follow the bulk motion of their host gas. Thus, if relativistic electrons are accelerated by merger shocks, one expects strong spatial correlation between the radio halo brightness and the hottest gas regions (in the absence of strong projection effects, of course).

On the other hand, the gas turbulence, although not directly observable at present, is expected to exist throughout the merging clusters, including shock-heated and cooler gas regions. Therefore in the turbulence scenario, there should be no strong correlation between the radio brightness and the temperature.

Our analysis is a qualitative attempt to distinguish between the shock and turbulence acceleration mechanisms by means of a systematic comparison of radio halo maps with the temperature maps for a sample of halo clusters with good radio and X-ray data. All clusters studied here reveal clear signs of ongoing mergers and the accompanying strong spatial temperature variations. Although in most of these clusters, the merger geometry is ambiguous and the likely projection effects complicate comparison with the radio data, we can draw several conclusions.

We confirm the previously reported spatial coincidence of bright radio features with the high temperature regions in A520, A665 and 1E0657−56. 1E0657−56 and A520 are the best examples of this temperature-radio connection. This spatial "coincidence" is not quite a "correlation", but in the presence of projection effects, exact correlation is not expected. These examples appear to argue for the shock acceleration mechanism.

On the other hand, A2319 exhibits a radio halo whose brightest part follows rather closely the distribution of the *cooler* gas in the core (although at a lower brightness level, the halo's NE-SW extension appears to coincide with the outlying hotter regions). Moreover, in A754 and A773, the hottest cluster regions do not show radio emission, at least at the present sensitivity, while there is radio emission elsewhere in these clusters. While radio emission from cooler areas can be explained by projection effects, projection cannot explain the absence of the radio emission from the hottest cluster regions. We believe that this is a strong observational argument against merger shocks, at least the relatively weak ones expected in most mergers, as the main acceleration mechanism.

This leaves turbulence as a more viable mechanism. Indeed, all clusters in our sample where the merger geometry is tractable — 1E0657−56, A520, A2319, and A665 — exhibit relatively small, dense, cool moving clouds which are likely to generate turbulence in their wake. The radio halos are observed along the path of these moving clouds. The remaining clusters have sufficiently uncertain merger geometries to be consistent with the possibility of strong turbulence in the right regions.

However, with turbulence alone, it is difficult to explain the observed extension of the radio halo in 1E0657−56 ahead of the gas bullet all the way to the bow shock, a similar extension into the shock region ahead of the core in A520 and A665. Turbulence caused by these cores cannot precede the fast-moving core, especially in such a high-velocity merger as 1E0657−56. Thus, in systems like these, at least some of the relativistic electrons should be accelerated in shocks. Incidentally, 1E0657−56 has a shock with the highest-known Mach number ($\mathcal{M} \approx 3.5$, M02a).

We conclude that in most clusters, the radio halo electrons are probably accelerated by turbulence, but in those rare cases when shocks with $\mathcal{M} \simeq 2$–3 are present, these shocks also appear to contribute in the acceleration. Maps of the spectral index of the radio halo emission would be invaluable for pinpointing the electron acceleration sites (because the halo spectrum steepens as the relativistic electrons lose energy). Such data would be especially illuminating in clusters such as 1E0657−56, A520 and A665 (Feretti et al., these proceedings), where both turbulence and shocks are likely to be present and can be separated spatially.

References

Bacchi, M., Feretti, L., Giovannini, G., Govoni, F. 2003, A&A, 400, 465 (B03)

Brunetti, G., Setti, G., Feretti, L., Giovannini, G. 2001, MNRAS, 320, 365

Brunetti, G. 2002, astro-ph/0208074

Buote, D. A. 2001, ApJ, 553, L15

Colafrancesco, S. 1999, in Ringberg workshop on Diffuse Thermal and Relativistic Plasma in Galaxy Clusters, MPE report 271, 269

Enßlin, T. A. 1999, astro-ph/0001433

Fabricant, D., et al. 1986, ApJ, 308, 530

Feretti, L., Giovannini, G., Böhringer, H. 1997, New Ast., 2, 501

Feretti, L. 1999, astro-ph/0006379

Feretti, L. 2003, astro-ph/0309221

Fujita, Y., Sarazin, C. L. 2001, ApJ, 563, 660

Fujita, Y., Takizawa, M., Sarazin, C. L. 2003, ApJ, 584, 190

Giovannini, G., Tordi, M., Feretti, L. 1999, New Ast., 4, 141

Giovannini, G., Feretti, L. 2000, New Ast., 5, 335

Govoni, F., et al. 2001a, A&A, 376, 803

Govoni, F., Enßlin, T. A., Feretti, L., Giovannini, G. 2001b, A&A, 369, 441

Govoni, F., Markevitch, M., Vikhlinin, A., VanSpeybroeck, L., Feretti, L., Giovannini, G. 2004, ApJ, 605, 695

Harris, D. E., Miley, G. K. 1978, A&AS, 34, 117

Harris, D. E., Kapahi, V. K., Ekers, R. D. 1980, A&AS, 39, 215

Henriksen, M. J., Markevitch, M. L. 1996, ApJ, 466, L79

Kassim, N. E., Clarke, T. E., Enßlin, T. A., Cohen, A. S., Neumann, D. M. 2001, ApJ, 559, 785

Kempner, J. C., et al. 2003, astro-ph/0310263

Kempner, J. C., Sarazin, C. L. 2001, ApJ, 548, 639

Krivonos, R. A., Vikhlinin, A. A., Markevitch, M. L., Pavlinsky, M. N. 2003, Astr. Lett., 29, 425

Liang, H., Hunstead, R. W., Birkinshaw, M., Andreani, P. 2000, ApJ, 544, 686

Markevitch, M., et al. 2000, ApJ, 541, 542

Markevitch, M., Vikhlinin, A. 2001, ApJ, 563, 95 (MV01)

Markevitch, M., et al. 2002a, ApJ, 567, L27 (M02a)

Markevitch, M., Vikhlinin, A., Forman, W. R., 2002b, astro-ph/0208208 (M02b)

Markevitch, M., et al. 2003, ApJ, 586, L19

Miniati, F., Jones, T. W., Kang, H., Ryu, D. 2001, ApJ, 562, 233

Moffet, A. T., Birkinshaw, M. 1989, AJ, 98, 1148

Ohno, H., Takizawa, M., Shibata, S. 2002, ApJ, 577, 658

Petrosian, V. 2002, astro-ph/0207481

Jones, M., Saunders, R. 1996, in Röntgenstrahlung from the Universe, MPE Report 263, 553

Sarazin, C. L. 1999, ApJ, 520, 529

Sarazin, C. L. 2001, astro-ph/0105418

Schlickeiser, R., Sievers, A., Thiemann, H. 1987, A&A, 182, 21

Vikhlinin, A., Markevitch, M., Murray, S. S. 2001, ApJ, 551, 160

Zabludoff, A. I., Zaritsky, D. 1995, ApJ, 447, L21