AN ULTRA-STEEP-SPECTRUM RADIO RELIC IN THE GALAXY CLUSTER A2443

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ABSTRACT

We present newly discovered radio emission in the galaxy cluster A2443 which (1) is diffuse, (2) has an extremely steep spectrum, (3) is offset from the cluster center, (4) is of irregular morphology, and (5) is not clearly associated with any of the galaxies within the cluster. The most likely explanation is that this emission is a cluster radio relic associated with a cluster merger. We present deep observations of A2443 at multiple low frequencies (1425, 325, and 74 MHz) which help characterize the spectrum and morphology of this relic. Based on the curved spectral shape of the relic emission and the presence of small-scale structure, we suggest that this new source is likely a member of the radio phoenix class of radio relics.

Key words: galaxies: clusters: general – galaxies: clusters: individual (A2443)

1. INTRODUCTION

A number of clusters of galaxies show extended synchrotron emission not directly associated with the galaxies, but rather diffused in the intra-cluster medium (ICM; Feretti 2005). These radio sources have low surface brightness, a variety of sizes up to ∼1 Mpc and a steep radio spectrum. They have been observationally classified as halos and relics. Halos are located at the cluster centers, and show a rather regular structure and little or negligible polarized emission. Relics are at the cluster peripheries, are generally elongated in shape, and are often highly polarized. Kempner et al. (2004) further classified radio relics into categories associated with extinct or dying radio galaxies (radio phoenix and active galactic nucleus relics) or those associated more generally with the ICM (radio gischt). About 60 clusters are known to contain halos and or relics (Ferrari 2009). The origin and evolution of this diffuse emission is still a matter of debate, though the existence of powerful diffuse sources only in clusters undergoing major mergers indicates that they are somehow related to the merger process. The detection and study of new objects of this class is of great importance to establish correlations between the radio source properties and the parent cluster properties, and to discriminate among the proposed theoretical models of their origins (see Ferrari et al. 2008, and references within).

2. THE GALAXY CLUSTER A2443

A2443 is a rich cluster at an intermediate redshift of z = 0.108 (Struble & Rood 1999) with a relatively low X-ray luminosity of \( L_x = 1.9 \times 10^{44}\) erg s\(^{-1}\) (Ebeling et al. 1998). It contains a radio source, cataloged as 4C+17.89. A multi-color photometric study of the system by Wen et al. (2007) identified 289 new cluster member galaxies. Combining these with the 12 known member galaxies revealed a northwest to southeast elongated galaxy distribution for the main cluster connecting to a group in the southeast (Wen et al. 2007, Figure 6) which they have identified with the galaxy cluster ZwCl 2224.2+1651. There is an X-ray peak in the vicinity of the southeast cluster but no redshift information is available. It is unclear whether the two cluster systems are in the process of merging or whether the images are just revealing the chance superposition of two systems at different redshifts.

Comparing the A2443 image in both the 1400 MHz NVSS (Condon et al. 1998) and 74 MHz VLSS (Cohen et al. 2007) indicated that A2443 contains diffuse steep-spectrum radio emission, but neither image provided the resolution or sensitivity to confirm its nature, or distinguish it from radio galaxy emission from cluster members. We therefore conducted a series of deeper, higher-resolution observations at 1425 MHz, 325 MHz, and 74 MHz using the National Radio Astronomy Observatory’s Very Large Array (VLA) radio telescope.

3. OBSERVATIONS

3.1. Low-resolution Observations

Our observations were designed to map the radio emission in A2443 at three low frequencies (1425, 325, and 74 MHz). By using different VLA configurations (C, B, and A, respectively), we obtained images of roughly equivalent resolution at each of these three frequencies. The resolution of between about 13′′ and 23′′ is optimal for surface-brightness sensitivity of the diffuse emission (see, e.g., recent papers by van Weeren et al. 2009; Giacintucci et al. 2009). The observational parameters are listed in Table 1, and the maps are shown in Figures 1–3, respectively.

Figures 1–3 are all shown at the same scale and are of roughly the same resolution. Together they demonstrate that the radio morphology of A2443 changes greatly from 1425 MHz to 325 MHz and then to 74 MHz. This is caused by drastically different spectra among the various radio sources within the cluster. The sources seem to be split into two main groups. First are the sources that appear to be head–tail radio galaxies. These sources are A, B, C, D, and E, which are best seen at 1425 MHz and 325 MHz maps (Figures 2 and 3, respectively) assuming typical spectral indices for radio galaxies of approximately \( \alpha \approx -0.7 \) (\( S \propto \nu^\alpha \)). The signal-to-noise ratio declines at lower frequencies because the map noise increases greatly (Table 1) due to the very high system temperatures. The second group of sources include sources F, G, H, and I (see also Section 3.2) which are best seen in the 325 MHz image (Figure 2). That they are seen in the 325 MHz image with higher signal-to-noise ratio than in the 1425 MHz image indicates a very steep spectrum. In fact, a point source would need a spectral index of \( \alpha \approx -1.89 \) to be better detected in the 325 MHz image.
than in the 1425 MHz image. Also seen in the 325 MHz image are additional steep-spectrum emission that extends the “global relic” both to the southeast, past source C, and to the west beyond source F, which is not seen at all in the 1425 MHz image. All the steep-spectrum emission combines to form a roughly east–west “arc” throughout a region indicated by the dotted rectangle in Figures 1–3. In the 74 MHz image, this steep-spectrum arc, which was barely seen at 1425 MHz, is the most prominent feature, with the flatter spectrum radio galaxies now relatively far fainter. Hereafter we refer to the steep-spectrum arc as the radio relic.

Table 1
VLA Observations of A2443

| Date          | Code | ν     | c     | TOS   | σ_{rms}  | Resolution        |
|---------------|------|-------|-------|-------|----------|-------------------|
| 2005 Jul 3    | AC786| 1425  | C     | 115   | 0.0493   | 13.4 × 12.2, −24  |
| 2006 Jul 24   | AC822| 325   | B     | 260   | 0.803    | 17.5 × 15.9, −67  |
| 2007 Sep 1    | AC882| 73.8  | A     | 344   | 29.4     | 23.4 × 22.9, −21  |

| Date          | Code | ν     | c     | TOS   | σ_{rms}  | Resolution        |
|---------------|------|-------|-------|-------|----------|-------------------|
| 2006 Jul 24   | AC822| 1425  | B     | 140   | 0.0372   | 4.00 × 3.74, −54  |
| 2007 Sep 01   | AC882| 325   | A     | 344   | 0.656    | 5.56 × 4.90, −62  |

Notes. For each observation: ν is the central frequency in MHz, c refers to the configuration of the VLA, TOS is the time on source in minutes, σ_{rms} is the map noise in mJy beam^{-1}, and resolution is the synthesized beam dimensions in arcseconds with the position angle in degrees.

3.2. High-resolution Observations

To further examine this steep-spectrum emission, higher resolution images (~5") were taken with the VLA. At 1425 MHz this was done in the B-configuration and at 325 MHz, this was done in the A-configuration. The existing 74 MHz image was already taken in the largest configuration (A), and therefore no higher resolution is possible at this frequency using the VLA. These observations served three purposes. First was to better determine the morphology of this very steep spectrum emission and determine if it is smoothly distributed or has finer scale structure. The second purpose was to distinguish this emission from the radio galaxies, especially source C. The final purpose was a better understanding of the morphology of the radio galaxies to better distinguish their cores, jets and lobes, and their possible relationship to the steep-spectrum emission. The observational parameters are listed in Table 1 and the images are shown in Figures 4 and 5.

From the higher resolution 1425 MHz image (Figure 4), we find that source A is apparently a narrow-angle-tail (NAT) source. This is indicative of a significant velocity difference...
between the source galaxy and the ICM. Source B appears as a single head–tail source with the tail in roughly the same direction as the tails in source A, indicating that source B may also have a similar velocity with respect to the ICM. Source B may also be a NAT, but with a smaller projected angular separation between the tails than can be resolved in this image. Even higher resolution would be needed to confirm this. The similar tail direction for sources A and B may be indicative of an on-going cluster merger (see, e.g., Loken et al. 1995; Gomez et al. 1997; Burns et al 2002). We note also that the optical galaxy distribution reveals a similar NE–SW elongation (Wen et al. 2007).

Figure 4 also reveals a line of radio emission that crosses the tail of source B diagonally. This could be from another radio galaxy, or a population of charged particles that already existed at that location (perhaps from a past episode of activity from another cluster member) and has been re-energized by the passing of source B. A similar case has been seen in 3C129, another well-studied NAT source (Lane et al. 2002). This would indicate a supersonic velocity of source B with respect to the ICM. Source C is smaller, but has a distinct core and a small tail fading off to the northeast. Its velocity vector, if any, is significantly different than that of sources A and B. The steep-spectrum sources F, G, and H are all either barely detected or not detected at all. Sources D and E are outside the region shown in Figure 4, and also much farther from the cluster center. Source D appears to be comprised of two, roughly symmetric radio galaxies, and Source E is resolved out except for the core. These sources are visible in Figure 6 but will not be discussed further.

In the higher-resolution 325 MHz image (Figure 5), sources A, B, and C appear nearly identical to their 1425 MHz counterparts, but there is significant radio emission to the south and west of the radio galaxies that did not appear at 1425 MHz. The steep-spectrum sources F, G, and H are now prominently detected, with source G appearing as a narrow but highly elongated object. This image shows source G to be clearly distinct from source C. There is also a steep-spectrum source near the south portion of source B, which we have labeled source I. It is not clear if this emission is related to source B, though comparing the 1425 and 325 MHz images shows that it is much steeper than the rest of the tail of source B. If it is part of the tail, it seems like a discontinuous or irregular extension. The regions of flat spectrum and steep-spectrum emission can be divided roughly by the dotted line drawn in Figures 4 and 5.

Figure 4. A2443 at 1425 MHz with VLA B-configuration. Contours begin at ±0.112 mJy beam$^{-1}$ (3 $\times$ $\sigma_{\text{rms}}$) and increase by multiples of $\sqrt{2}$. The peak intensity is 12.2 mJy beam$^{-1}$.

Figure 5. A2443 at 328.5 MHz with VLA A-configuration. Contours begin at ±1.97 mJy beam$^{-1}$ (3 $\times$ $\sigma_{\text{rms}}$) and increase by multiples of $\sqrt{2}$. The peak intensity is 38.0 mJy beam$^{-1}$. The crosses indicate the locations of member galaxies and, by their sizes, the relative K-band brightness.

Figure 6. Three-color image showing a radio/optical overlay of A2443 with R mapped to the I-band BATC image of Wen et al. (2007), G mapped to the 1425 MHz B configuration VLA data, and B mapped to the 328.5 MHz A configuration VLA data. The optical identifications of sources A, B, and C are clearly visible, as is the lack of possible identifications for the diffuse sources F, G, and H. Source D is composed of two separate radio sources, each of which has an associated optical source but no ID. The core of source E is associated with a faint galaxy as reported by Slee et al. (1996).
Figure 7. Spectral index map (color scale) of A2443 between 325 MHz and 1425 MHz. The image at each frequency was convolved to a circular 5′6 resolution. Contours are for 325 MHz and begin at ±2.11 mJy beam⁻¹ (3 × σrms in the convolved 325 MHz map) and increase by multiples of √2. The peak intensity is 42.3 mJy beam⁻¹. The spectral index is only shown for regions detected above 5 × σ rms in both maps. For regions well detected at 325 MHz that are white, the spectral index is steeper than the lower color-scale limit of α_{325} ≥ −1.8. Because such regions are generally not detected or very weakly detected at 1425 MHz (Figure 4) the spectral index is not well determined below this upper limit.

Also plotted on the higher-resolution 325 MHz image (Figure 5) are the locations of galaxies found to be possible cluster members by a deep multi-band optical/IR study (Wen et al. 2007). The member galaxy positions are indicated by crosses, where the size of the cross increases with brighter K-band magnitude such that the cross size doubles with each magnitude of brightness. Sources A, B, and C are clearly associated with bright cluster member galaxies located predictably at their cores. One relatively fainter cluster member galaxy is located within source I and seems roughly at the same location as the compact source seen in that location in the 1425 MHz image (Figure 4).

In Figure 6, we show a three color image with the Wen et al. (2007) I-band image in red, the high resolution 1425 MHz VLA data in green, and the high-resolution 328.5 MHz VLA data in blue. Inspection of this overlay shows that source I and the possible optical counterpart are not quite aligned and therefore it is uncertain if they are related. We further see in Figure 6 that there are no optical counterparts in the remainder of the diffuse emission and thus the steep-spectrum sources located southwest of the dotted line in Figures 4 and 5 have no clear connection to bright member galaxies.

4. ANALYSIS

4.1. Spectral Index Maps

We have produced spectral index maps of A2443 from our high- and low-resolution images. The high-resolution spectral index map is shown in Figure 7. This was produced by first convolving the 1425 MHz and 325 MHz images (Figures 4 and 5, respectively) to a common circular resolution of 5′6, and only calculating a spectral index for regions where the surface brightness was at least five times the map noise in both images. Most of the relic region was not well detected in the 1425 MHz image, and so the spectral index map does not cover that region. Because of the differences in sensitivity, regions that are detected in the 325 MHz image but not the 1425 MHz image have a spectral index of −1.94 or steeper. The radio galaxies (sources A, B, and C) all show significant steepening along their tails, with α_{325} ranging from roughly −0.4 near the core to −1 or steeper at the ends of their tails. This is again evidence that perhaps all of these sources are some kind of NAT systems. We also note that the line of emission that diagonally crosses the tail of source B has roughly the same spectral index as the region of the tail it crosses. This indicates that these two sources are of roughly the same age and probably became energized at roughly the same time.

We produced a lower resolution spectral index map by combining our low-resolution maps at 74 MHz and 325 MHz, and this is shown in Figure 8. This was produced by first convolving the 325 MHz and 74 MHz images (Figures 2 and 3, respectively) to a common circular resolution of 23′4, and only calculating a spectral index for regions where the surface brightness was at least five times the map noise in both images. The spectral index map shows quantitatively that the emission in the relic region (with the exception of source C) is significantly steeper than the other emission in the cluster. Also, the eastern end of the relic is steeper than the western end.

4.2. Spectral Index Measurements

Because of the stark differences in spectral indices, one can easily distinguish by eye between the flat-spectrum and steep-spectrum sources. Here, we present quantitative spectral index measurements of the various radio sources in A2443.
In the lower resolution images, sources A, B, and C are difficult to distinguish completely from each other and the steep-spectrum emission. This is much easier in the higher resolution images, and so we use these maps to measure the flux densities of these sources at 325 MHz and 1425 MHz. Because these are radio galaxies, rather than relic emission, we do not expect significant diffuse emission beyond the ∼5′′ scale of the higher resolution images, and therefore it is unlikely that measuring the flux density in the higher resolution images misses significant flux density. Because we have no high-resolution map at 74 MHz, we used the low-resolution 74 MHz image (Figure 3) to measure the flux densities of sources A, B, and C by summing the flux density within small boxes drawn around their known location from the higher resolution images. We note that this method is only an estimate of their flux densities, because this method, especially for source C, was more susceptible to contamination from nearby sources. However, the 74 MHz flux density of source C is only about 5% of the relic emission, so even a significant error here would not significantly contaminate the measurement of the relic flux density which follows.

Next we combine all the steep-spectrum emission into a single source that we simply call the “relic” source. The relic encompasses not just sources F, G, and H, but also all the steep-spectrum emission seen in the rectangular relic region indicated in Figures 1–3. The flux density of the relic was determined using the low-resolution maps (to avoid missing diffuse emission) by summing the flux density in the relic region and subtracting the flux density of the flat-spectrum source C.

The flux densities are plotted in Figure 9 and listed in Table 2 along with the resulting spectral index measurements. For the radio galaxies (sources A, B, and C), we find spectral indices between 325 MHz and 1425 MHz ($\alpha_{325}^{1425}$) ranging from $-0.637$ to $-0.813$, which is typical for radio galaxies. Between 74 MHz and 325 MHz, the spectra flattens a bit with $\alpha_{74}^{325}$ ranging from $-0.379$ to $-0.584$. This low-frequency flattening is also commonly seen in radio galaxies (Kellermann 1966). The relic emission is dramatically steeper with $\alpha_{325}^{1425} = -2.797$. This is steeper than the typical relic found in Feretti (2005), yet well within the range of the “extreme” relics found by Slee et al. (2001), which have $-4.4 < \alpha < 2.1$, measured at frequencies near 1400 MHz. In the lower frequency interval, the spectrum flattens for the relic also, but is still extremely steep at $\alpha_{74}^{325} = -1.737$. This curved spectral signature is characteristic of the radio phoenix class of relics (Kempner et al. 2004) which have experienced synchrotron and inverse-Compton radiation losses prior to re-energization by the passing shock (Enßlin & Gopal-Krishna 2001). Such curved spectra are difficult to produce for radio gischt, which are the result of shock acceleration from the thermal electron reservoir (Hoef & Brüggen 2007).

### 4.3. Small-scale Structure in the Relic

The best high-resolution image of the relic is at 325 MHz (Figure 5). This is because the relic spectral index is too steep for it to be well detected at 1425 MHz. At 74 MHz, the VLA is not capable of such high resolution. At 325 MHz, we see significant smaller-scale structure including isolated peaks and a roughly 1 arcmin arc of emission at the location of source G. The 1 arcmin extent corresponds to a projected physical size of roughly 120 kpc. The sum of the steep-spectrum emission is 205 mJy, which is roughly half of what was detected in the lower-resolution 325 MHz image (Figure 2). This indicates that about half of the emission is resolved out in the higher resolution...
image. We note that the extremely steep spectrum, the physical size and the small-scale structure in this relic makes this source very similar to previous extreme relics as examined by Slee et al. (2001).

In addition to showing that the relic emission is not smoothly distributed, the small-scale structure is possibly indicative of the origins of the relic. In particular, sources G and I appear to be extensions of sources C and B, respectively. However, in both cases, the extension seems discontinuous. Also, in both cases, this discontinuity occurs at the dividing line between the flat- and steep-spectrum emission in the cluster. Finally, in both cases, the discontinuity is the result of the emission on the steep-spectrum side seemingly being shifted to the southeast along this dividing line. An alternative scenario for sources G and I is that they are re-energized sources from adiabatic compression of the tail of source B which appears to be moving rapidly with respect to the ICM. The meaning of these observations is not clear, and it is likely that more extensive observations in both radio and X-ray will be necessary to explain the origin of these features.

4.4. X-ray Data

The best X-ray data available on this cluster comes from the ROSAT All Sky Survey (RASS; Voges et al. 1999). We show this map convolved to 120° overlaid on our low-resolution 325 MHz image of the cluster (Figure 10). This shows the center of the X-ray emission appears roughly at the location of source B, and that the relic emission is offset from the cluster center, which is typical of both the phoenix and gischt classes of radio relics. At its closest point, the relic emission is separated from the center of the cluster X-ray emission by a projected distance of 160 kpc.

The sensitivity and resolution of this X-ray image are not sufficient to indicate either merger activity or shock fronts in the ICM. In order to further investigate the nature of the radio relic and its relation to the cluster, it is extremely important to have a more accurate image of the X-ray emission.

4.5. Evidence for a Merger

There is no conclusive evidence that A2443 is experiencing or has recently experienced a merger or collision. The available X-ray data are not sufficient to show shocks or other asymmetries in the ICM. A multi-band optical/IR study of the galaxies in this region shows some evidence that another cluster, ZwCl 2224.2+1651, might be falling toward A2443 from the southeast (Wen et al. 2007), but the projected distance to ZwCl 2224.2+1651 is 2.5 Mpc, which makes it unlikely that this in-fall could have caused the relic we observe.

However, other evidence strongly suggests a major ongoing merger. First is the apparent high velocity difference between the ICM and the galaxies producing radio sources A and B. Second, the fact that there are three large and active galaxies (radio sources A, B, and C) is also suggestive of recent or ongoing merger activity since typical clusters are only expected to have 0–2 head–tail galaxies (Ledlow & Owen 1995).

5. CONCLUSION

We have presented deep radio images at 1425, 325, and 74 MHz of radio emission in the galaxy cluster A2443. These maps reveal a region of emission that (1) is diffuse, (2) has an extremely steep spectrum, (3) is on the cluster periphery, (4) is of irregular morphology, and (5) is not directly associated with any of the galaxies within the cluster. We conclude that this emission is most likely an ultra-steep-spectrum cluster radio relic. The high-resolution radio maps show morphology in the relic and member radio galaxies consistent with a recent or ongoing cluster merger. The curved spectral shape of the relic combined with the relatively small-scale and compact structure suggest that it is likely a member of the radio phoenix class outlined in Kempner et al. (2004). More accurate X-ray data are required to confirm the cluster dynamical state and establish the relation between the observed radio features and the merger-related activity within the ICM.

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