A merger mystery: no extended radio emission in the merging cluster Abell 2146

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ABSTRACT
We present a new 400 ks Chandra X-ray observation and a GMRT radio observation at 325 MHz of the merging galaxy cluster Abell 2146. The Chandra observation reveals detailed structure associated with the major merger event including the Mach $M = 2.1 \pm 0.2$ bow shock located ahead of the dense subcluster core and the first known example of an upstream shock ($M = 1.6 \pm 0.1$). Surprisingly, the deep GMRT observation at 325 MHz does not detect any extended radio emission associated with either shock front. All other merging galaxy clusters with X-ray detected shock fronts, including the Bullet cluster, Abell 520, Abell 754 and Abell 2744, and clusters with candidate shock fronts have detected radio relics or radio halo edges coincident with the shocks. We consider several possible factors which could affect the formation of radio relics, including the shock strength and the presence of a pre-existing electron population, but do not find a favourable explanation for this result. We calculate a $3\sigma$ upper limit of 13 mJy on extended radio emission, which is significantly below the radio power expected by the observed $P_{\text{radio}} - L_X$ correlation for merging systems. The lack of an extended radio halo in Abell 2146 maybe due to the low cluster mass relative to the majority of merging galaxy clusters with detected radio halos.

Key words: X-rays: galaxies: clusters — Radio continuum: galaxies — galaxies: clusters: Abell 2146 — intergalactic medium

1 INTRODUCTION

Galaxy clusters are formed through gravitational infall and mergers of smaller subclusters, which collide at velocities of several thousand $\text{km} \text{s}^{-1}$. The total kinetic energy of these mergers can reach $\geq 10^{64} \text{erg}$, a significant fraction of which is dissipated by shocks and turbulence over the merger lifetime (for a review see Markevitch & Vikhlinin 2007). Shocks and turbulence generated by the merger are also expected to amplify cluster magnetic fields and accelerate relativistic particles. These non-thermal phenomena have been revealed through the detection of Mpc-scale synchrotron radio halos (for recent reviews see Feretti & Giovannini 2008; Ferrari et al. 2008) and inverse-Compton hard X-ray emission (eg. Fusco-Femiano et al. 2005 but see also Wik et al. 2009).

Major mergers can also produce observable separations between the intracluster medium (ICM), which represents the bulk of the baryons, and the dark matter halo. The combination of X-ray and gravitational lensing studies of these clusters has produced the most striking evidence for the existence of dark matter (eg. Clowe et al. 2004).

Shock fronts provide a key observational tool in the study of merging systems. They can be used to determine the velocity and kinematics of the merger and to study the conditions and transport processes in the ICM (eg. Markevitch & Vikhlinin 2007). Shock fronts are detected as sharp discontinuities in X-ray surface brightness maps and, with spatially resolved spectroscopy, provide a method for measuring the gas velocities in the plane of the sky. While many clusters are found to have shock-heated regions (eg. Henry & Briel 1995; Markevitch et al. 1996), the detection of a sharp density edge and an unambiguous temperature jump is rare and only a handful of shock fronts are currently known (the Bullet
cluster, Markevitch et al. 2002, Abell 520, Markevitch et al. 2005, two in Abell 2146, Russell et al. 2010, Abell 754, Macario et al. 2011 and Abell 2744, Owers et al. 2011).

All merging galaxy clusters with X-ray detected shock fronts also contain large, diffuse radio halos covering ~1 Mpc in size (eg. Feretti & Giovannini 2008). Due to synchrotron and inverse-Compton losses, the relativistic electrons have relatively short lifetimes, only $10^{-7}$–10$^{4}$ yr, which is significantly shorter than the diffusion time necessary to cover their observed extent. Therefore, a mechanism is required that produces local particle acceleration over the whole cluster volume (Jaffe 1977). The possibilities include 'primary' models, where a pre-existing electron population is reaccelerated by turbulence or shocks (eg.Brunetti et al. 2001; Petrosian 2001), and 'secondary' models, which rely on the continuous injection of relativistic electrons by hadronic collisions between thermal ions and cosmic rays (eg. Dennison 1980).

The observed correlations between extended radio emission and cluster mergers favour electron reacceleration models (eg. Buote 2001, Feretti et al. 2004, Feretti & Giovannini 2008). Recent observations suggest that radio halos are likely generated by turbulent processes induced by a merger (eg. Brunetti et al. 2008; Dolag et al. 2008) and radio relics, which are elongated structures located in the cluster outskirts, may be produced by Fermi-I diffusive shock acceleration of ICM electrons (Passlin et al. 1998). Keshet & Loeb (2010) proposed a hadronic model where magnetic fields are amplified by mergers and produce radio halos. However, recently Bonafede et al. (2011) found no difference in fractional polarization properties between clusters with and without halos implying there no difference in the magnetic fields between the two.

In this Letter, we present results from a deep Chandra observation of the merging cluster Abell 2146 and a GMRT radio observation at 325 MHz, which was aimed at detecting any extended radio emission. We assume $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.3$ and $\Omega_{\Lambda} = 0.7$, translating to a scale of 3.7 kpc per arcsec at the redshift $z = 0.234$ of Abell 2146. All errors are 1$\sigma$ unless otherwise noted.

2 CHANDRA X-RAY OBSERVATIONS

Abell 2146 was observed with the Chandra ACIS-I detector for a total of 377 ks split into eight separate observations between August and October, 2010. These new observations were combined with the archival ACIS-S observations, 42.1 ks, taken in April, 2009 (Russell et al. 2010). All datasets were reprocessed following the standard methods detailed in Russell et al. (2010) and using CIAO 4.3 and CALDB 4.4.0 provided by the Chandra X-ray Center. There were no major flares in any of the observations of Abell 2146 producing a final exposure of 418 ks. The cleaned events files were reprojected to the position of the obs. ID 12245 dataset.

Fig. 1 (left) shows an exposure-corrected X-ray image produced by combining all of the individual datasets. The X-ray morphology reveals a major merger where a subcluster containing a dense, cool core has recently passed through the centre of the primary cluster. The cluster gas is extended along the merger axis from the NW core collision site to the subcluster which is travelling towards the SE and disintegrating under ram pressure. The leading and SE edges of the subcluster core form a narrow, continuous cold front with a sharp density jump of a factor of ~3. In contrast, the deep Chandra observations have revealed complex structures in the tail of stripped gas from the subcluster core, including what appear to be developing Kelvin-Helmholtz (K-H) instabilities along the NW edge. There is also an extended cool plume of emission to the SW from the subcluster tail, ~45 arcsec in length, which appears perpendicular to the merger axis.

The two shock fronts, reported in Russell et al. (2010), are clearly visible in the unsharp-masked image (Fig. 1 centre) as surface brightness edges to the NW and SE. The SE edge corresponds to the bow shock, which has formed ahead of the subcluster core, and can now be traced over ~500 kpc in length. The NW edge corresponds to the upstream shock which has formed in the wake of the subcluster’s passage through the primary cluster core and is travelling in the opposite direction to the bow shock. By measuring the gas density and temperature on either side of each shock front and applying the Rankine-Hugoniot shock jump conditions (eg. Landau & Lifshitz 1959), we calculated the respective Mach numbers $M = v/c_s$, where $v$ is the velocity of the preshock...
gas with respect to the shock surface and \( \epsilon_s \) is the velocity of sound in that gas. At the bow shock, the density drops by a factor \( p_2/p_1 = 2.4 \pm 0.2 \) which gives a Mach number \( M = 2.1 \pm 0.2 \). For the upstream shock, the density decreases by \( p_2/p_1 = 1.8 \pm 0.2 \) producing \( M = 1.6 \pm 0.1 \). The shock fronts are confirmed by the detection of unambiguous decreases in the gas temperature coincident with the density drops. By using the bow shock velocity and estimating the distance between the subcluster core and the primary cluster centre, we can calculate the time since the subcluster passed through the primary cluster core. For a bow shock velocity \( v = 2800^{+400}_{-300} \) km s\(^{-1}\) and an estimated distance of \( \sim 350 \) kpc, the time since core passage is \( \sim 0.1 - 0.2 \) Gyr. This is likely to be an underestimate of the timescale as the subcluster velocity is presumably lower than the shock velocity (Springel \& Farrar 2007).

The deep Chandra observation of Abell 2146 presented here will be analysed in detail in a future paper (Russell et al. in prep).

3 GMRT OBSERVATIONS

GMRT radio continuum observations at 325 MHz of Abell 2146 were carried out on August 22, 2010. The GMRT software backend (OSB; Roy et al. 2010) was used in spectral line mode with 512 channels, 4 s integration time per visibility and recording RR and LL polarizations. The total on source time was 5.7 hr. The data were reduced with the NRAO Astronomical Image Processing System (AIPS) package. The data were visually inspected for the presence of radio frequency interference (RFI) and malfunctioning antennas. The visibilities were then calibrated for the bandpass response of the antennas using the calibrator source 3C286. The visibilities were carried out on August 22, 2010. The radio continuum observations at 325 MHz of Abell 2146 were analysed in detail in a future paper (Russell et al. in prep).

4 DISCUSSION

We present the surprising result that our GMRT observation at 325 MHz did not show evidence for any extended radio emission associated with either shock front in the merging cluster Abell 2146. A deep Chandra observation confirms the strong dynamical disruption to the cluster cores and the presence of two shock fronts, each several hundred kpc across and with Mach numbers of \( 2.1 \pm 0.2 \) and \( 1.6 \pm 0.1 \). Observational results have so far suggested a strong connection between merging clusters hosting shock fronts and extended radio emission in the form of relics or halos (eg. Giovannini et al. 1992; Govoni et al. 2001a; Feretti et al. 2004; Venturi et al. 2007; Giacintucci et al. 2008; Markevitch 2011). We therefore consider possible explanations for the lack of extended radio emission in Abell 2146.

4.1 No radio relics

All other X-ray detected merger shock fronts, including those in the Bullet cluster (Liang et al. 2000; Markevitch et al. 2002), Abell 520 (Govoni et al. 2001b; Markevitch et al. 2005), Abell 754 (Kassim et al. 2001; Bacchi et al. 2003; Macario et al. 2011) and Abell 2744 (Govoni et al. 2001a), and shock front candidates are spatially coincident with radio relics or the edges of radio halos (eg. Markevitch 2010). The two shock fronts in Abell 2146 have comparable Mach numbers to the other clusters with detected radio relics or edges, such as Abell 754 \( M = 1.6 \) (Macario et al. 2011) and Abell 520 \( M = 2.1 \) (Markevitch et al. 2005). The lack of radio emission coincident with the shocks is a surprising result and indicates that other factors can determine the production of radio relics.

Direct acceleration of cosmic rays by these weak shock fronts is expected to be an inefficient process (eg. Gabici \& Blasi 2003; Hoeft \& Brüggen 2007). Therefore the observations support a scenario where the weak merger shocks are reaccelerating a pre-existing population of relativistic electrons (eg. Markevitch et al. 2005; Giacintucci et al. 2008) or, alternatively, re-energising a population of relativistic electrons trapped in a fossil radio bubble (Enßlin \& Gopal-Krishna 2001). Over the lifetime of a cluster, there will generally have been a large number of possible sources of these electrons, such as accretion shocks, supernovae and AGN. The pre-existing electron population could also have accumulated from previous mergers (eg. Sarazin 1999) or been generated by collisions between thermal protons and long-lived cosmic rays (Dennison 1980; Blasi \& Colafrancesco 1999).

Abell 2146 does not appear to be particularly atypical compared to the galaxy clusters with detected radio relics. The global ICM temperature, \( T = 6.75 \pm 0.06 \) keV, and luminosity, \( L_X = 6.60 \pm 0.02 \times 10^{44} \) erg s\(^{-1}\) (0.1 - 2.4 keV), indicate a substantial galaxy cluster which is likely to have experienced significant accretion and previous merger shocks during its assembly. Radio-loud AGN have been found generally to be common in cluster galaxies.
(eg. Best et al. 2005). Our observations of Abell 2146 also confirm the detection of two radio point sources, each associated with a cluster galaxy. The SE radio source (Fig. 1 right) is located in the subcluster BCG and coincides with a hard X-ray point source, which suggests it is likely to be AGN. Although there are no visible substructures or cavities in the Chandra observations indicating current AGN activity, the subcluster hosts a strong cool core where the gas temperature drops down to $\sim 1$ keV. Earlier episodes of AGN feedback could have produced radio bubbles to regulate this cooling. X-ray spectral fitting also shows that the ICM has been significantly metal-enriched by supernova activity (Russell et al. 2010). Abell 2146 appears to contain sufficient sources for producing a pre-existing electron population.

### 4.2 No radio halo

Large radio halos are found exclusively in disturbed and potentially merging clusters (eg. Feretti & Giovannini 2008). Strong correlations exist between the radio power of halos and the X-ray luminosity and temperature of their host clusters (eg. Colafrancesco 1999; Liang et al. 2004; Kemper & Sarazin 2001; Enßlin & Röttgering 2002; Cassano et al. 2006; Giovannini et al. 2009). Recent surveys with the GMRT have found a bi-modal behaviour where radio-halo clusters and clusters without radio halos are separated in the $P_{\text{radio}} - L_X$ plane (Fig. 2; Brunetti et al. 2009). Brunetti et al. (2009) argue that this bi-modal distribution suggests an evolutionary cycle where clusters that are undergoing mergers host radio halos for a period of time. Later, the clusters become dynamically relaxed and the relativistic particles cool, producing the observed upper limits. Fig. 2 shows the $3\sigma$ upper limit on extended radio emission for Abell 2146 overplotted on the $P_{1.4\,\text{GHz}} - L_X$ correlation. This upper limit on Abell 2146 is significantly below the expected radio power predicted by the observed correlation for merging systems.

The absence of a radio halo in Abell 2146 could be related to the low cluster mass relative to the majority of the clusters in the GMRT radio halo sample (Venturi et al. 2007; Brunetti et al. 2009). Observations have found that radio halos are more common in clusters with higher X-ray luminosity and temperature, which both trace the mass (eg. Giovannini et al. 1999; Buote 2001; Cassano et al. 2006, 2008). The energy available to accelerate relativistic particles during a merger is a fraction of the gravitational potential energy that is released. Collisions between more massive galaxy clusters are therefore more likely to produce radio halos. The X-ray luminosity and temperature, both relating to the cluster mass, will also vary over the merger timescale. Simulations of cluster mergers show that the shocks and compression produced during core passage can temporarily boost the X-ray luminosity by a factor of a few (eg. Ricker & Sarazin 2001; Poole et al. 2007). This bias will affect all the merging systems in Fig. 2 to some degree but has no impact on systems that are closest to core passage, such as Abell 2146. For a head-on collision between two subclusters with mass ratio of 3:1 observed only $\sim 0.1 - 0.2$ Gyr after core passage, the boosts to the temperature and bolometric X-ray luminosity could produce an increase of a factor of $\sim 2 - 3$ in the observed $L_X$ (Poole et al. 2007). If we ‘correct’ for this factor, the upper limit for Abell 2146 in Fig. 2 is then approximately consistent with the observed $P_{\text{radio}} - L_X$ correlation. However, after the maximum around core passage, this boost to the X-ray luminosity decays rapidly. For Abell 2146, the time since core passage has likely been underestimated (section 4) and therefore the estimated factor of $\sim 2 - 3$ is an upper limit. More accurate measurements of the mass of Abell 2146 will be provided by weak-lensing results using Subaru Suprime-Cam observations (King et al. in prep).

Using the GMRT radio halo survey (Venturi et al. 2007), Cassano et al. (2010b) confirmed that radio halos are located preferentially in dynamically disturbed clusters and identified several clusters with a disturbed X-ray morphology but no radio halo. These ‘outliers’ have a relatively low X-ray luminosity $L_X \lesssim 8 \times 10^{44}$ erg s$^{-1}$, similar to Abell 2146, or are at a relatively higher redshift, which implies stronger inverse-Compton losses. The turbulent reacceleration model for radio halo formation predicts the existence of very steep spectrum halos with a spectral cutoff frequency that is dependent on the fraction of the turbulent energy channelled into electron reacceleration and therefore the cluster mass (eg. Cassano et al. 2006; Brunetti et al. 2008). Lower frequency observations, with LOFAR for example, could detect radio halos generated in lower mass mergers, such as these ‘outlier’ clusters or Abell 2146 (eg. Cassano et al. 2010b; Venturi et al. 2011).

### 5 CONCLUSIONS

The deep 400 ks Chandra observation of Abell 2146 reveals a major merging event with two shock fronts detected in the X-ray. The bow shock, located ahead of the subcluster core, can now be traced to over $\sim 500$ kpc in length and has a Mach number $M = 2.1 \pm 0.2$. This cluster also contains the first known example of an upstream cluster merger shock front, which we determine has a Mach number $M = 1.6 \pm 0.1$. Using a new GMRT radio observation at 325 MHz, we found no evidence for extended radio emission such as a radio relic associated with either shock or a large radio halo in the merging cluster Abell 2146. The absence of radio relics coincident with the shock fronts is a surprising result. All other clusters with unambiguous X-ray detected shock fronts, including the Bullet cluster, Abell 520, Abell 754 and Abell 2744, and clusters with likely shock front candidates have radio relics or radio halo edges. We have considered several possible factors which could affect the formation of...
radio relics, including the shock strength and the presence of a pre-existing electron population, but do not find a favourable explanation. The lack of an extended radio halo in Abell 2146 is likely due to the low cluster mass relative to the majority of merging galaxy clusters with detected radio halos. Using the GMRT radio halo cluster sample, Cassano et al. (2010b) identified several clusters with a disturbed X-ray morphology but no radio halo. The majority of these clusters have a relatively low X-ray luminosity and therefore low mass, similar to Abell 2146. Lower frequency observations, with LOFAR for example, could in the future detect radio halos generated in lower mass mergers like Abell 2146, which should have ultra-steep radio spectra.

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