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A deep radio and X-ray view of cluster formation at the crossroads of filaments

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Abstract. Deep X-ray data from *Chandra* and *XMM-Newton*, and GMRT radio data are presented for ZwCl 2341.1+0000 , an extremely unusual and complex merging cluster of galaxies at the intersection of optical filaments. We propose that energetics of multiple mergers and accretion flows has resulted in wide-spread shocks, acceleration of cosmic ray particles and amplification of weak magnetic fields. This results in Mpc–scale peripheral radio relics and halo like non–thermal emission observed near the merging center.

Key words. Galaxies: clusters: general – Galaxies: clusters: individual: ZwCl 2341.1+0000 – X-rays: galaxies: clusters – Radio continuum: galaxies – Shock waves – Cosmology: Large-scale structure of Universe

1. Introduction

Galaxy clusters grow by mergers of smaller subclusters and galaxy groups as predicted by hierarchical models of large-scale structure (LSS) formation. For the most massive mergers a significant amount of energy is released; up to $10^{63} - 10^{64}$ erg, according to these models. All massive clusters have undergone several mergers in their history and presently clusters are still growing by matter accretion at the junction of large scale filaments of galaxies, mediated by the gravity of dark-matter component. Key properties for testing models of LSS formation include the total energy budget and the detailed temperature distribution within a cluster, which are both strongly affected by the cluster's merger history. Moreover, the physics

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of shock waves in the tenuous intra–cluster medium (ICM) and the effect of cosmic rays (CR, relativistic particles) on galaxy clusters are all fundamental for our understanding of LSS formation.

Diffuse radio sources with steep spectra ($\alpha \lesssim -0.5$), not directly associated with individual galaxies, are observed in a number of clusters (e.g. review by Ferrari et al. 2008). Large scale ($l \gtrsim 500$ kpc) diffuse radio sources in clusters are commonly divided into 'radio halos' and 'radio relics'. Radio halos have smooth morphologies, are extended with sizes $\gtrsim$1 Mpc, unpolarized, and are found at the centers of clusters, co-spatial with the X-ray emitting hot ICM gas. Giant radio relics are found on the cluster periphery, with sizes up to several Mpc, sometimes showing arc or ring-like structures, and are highly polarized (p$\sim$ 10-50% at 1.4 GHz). They are probably signatures of electrons accelerated at large–scale shocks. The vast majority of clusters with extended diffuse radio sources are massive, X–ray luminous and are merging systems. Although still under debate, shocks and turbulence, both caused by mergers, are thought to be responsible for (re)accelerating electrons to highly relativistic energies, and synchrotron radiation is produced in the presence of magnetic fields in the ICM. Therefore deep radio and X–ray observations of merging clusters may provide extremely important information on the dynamics of LSS formation.

ZwCl 2341.1+0000, discovered by Bagchi et al. (2002), is an extremely interesting and complex system of galaxies, composed out of several different subclusters arranged along a north–south filamentary axis extending up to at least ~4 Mpc. It is probably a very large and massive cluster coming together at the junction of supercluster filaments. A 2.5 Mpc scale diffuse radio emission was detected in the main filamentary structure (Bagchi et al. 2002; Giovannini et al. 2010) which makes it unique and a highly valuable source for cosmological studies. The system is located at a redshift of $z = 0.27$, based on SDSS DR7 spectroscopic redshifts of several galaxies in the vicinity. A galaxy isodensity map derived from SDSS imaging data shows an elongated cluster of galaxies, including several subclusters distributed roughly along a north-south axis, spanning $\gtrsim$4 Mpc. A network of several filaments of galaxies are seen branching off from the main structure towards the east and northeast forming a 'cosmic-web' (Fig. 1 and Fig. 2).

2. Radio and X-ray observations of ZwCl 2341.1+0000

For probing the Bremsstrahlung emission from the diffuse, hot ICM of this remarkable large-scale structure, deep X–ray observations with *Chandra* and *XMM-Newton* were obtained. The X–ray emission is detected for about 2.5 Mpc in the N–S direction and an extension towards the east is also visible, similar to the pattern of galaxy distribution. In Fig. 2 we also show the GMRT 610 MHz radio contours superposed on the *Chandra* ACIS-I X-ray image. In addition to the N–S X-ray emission roughly following the filament of galaxies visible in the optical image, embedded within the extended diffuse emission, we can identify several other prominent X–ray emitting systems, which most likely represent hot gas associated with merging groups and clusters (Fig. 1).

The overall cluster temperature in a $r = 4'$ region (roughly 1 Mpc or close to r_{500}), measured from the Chandra ACIS–I observation, is 4.4 ± 0.6 keV. The corresponding X–ray luminosity within the same region in the 0.1–2.4 keV range is $L_X = 2.4 \times 10^{44}$ erg s^{-1}, and the bolometric X-ray luminosity being $L_{bol} = 4.6 \times 10^{44}$ erg s^{-1}($h = 0.71$, $\Omega_M = 0.27$, $\Omega_\Lambda = 0.73$). From the XMM–Newton combined PN and MOS observations, from the central $r = 4'$ region, we obtain an average temperature of 4.7 ± 0.5 keV. Thus both Chandra and XMM–Newton measured temperatures are consistent with each other.

Deep GMRT radio maps were published by us recently (van Weeren et al. 2009) at 610, 240 and 150 MHz. These maps (specially 610 MHz map shown here in Fig. 2) successfully resolved the compact sources from the extended diffuse emission of extremely low surface brightness (only 100–200 μJy/beam at 610 MHz), which was found to be located mainly

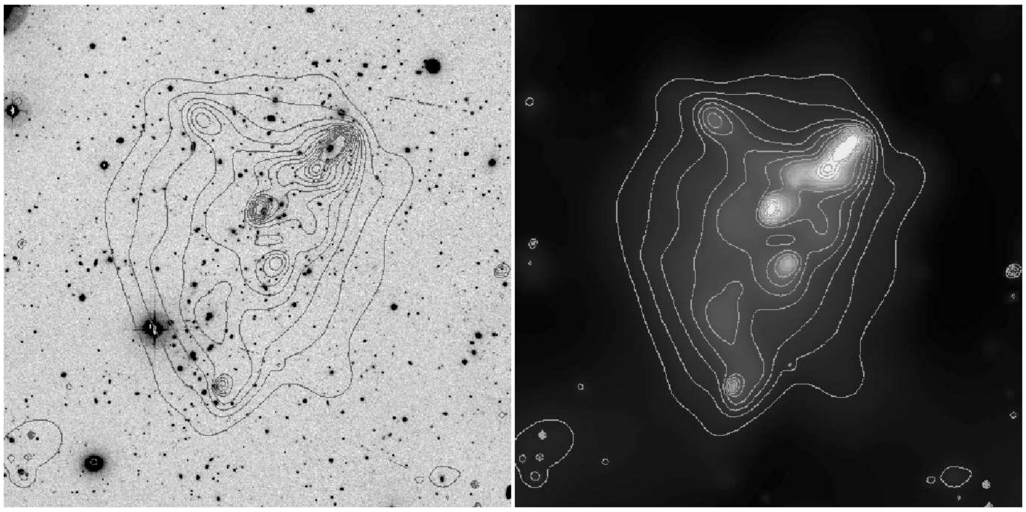

Fig. 1. Left panel: The optical R-band image of merging system ZwCl 2341.1+0000 obtained from WFI at the ESO 2.2m telescope. The overlaid contours show the thermal X-ray emission in the energy range 0.5–3 keV observed with *XMM-Newton*. Right panel: Grey-scale version of the same X-ray emission observed with *XMM-Newton*. Both images cover about 4 Mpc on a side at redshift z=0.27 (Raychaudhuri et al. 2011).

in two Mpc–scale radio structures to the north and south of the cluster, capping the two ends of X–ray emitting hot gas and the central optical filament. We interpret this structure as being a peripheral double radio relic, where the particles are accelerated by the diffusive shock acceleration (DSA or Fermi–I) mechanism in outward propagating shock waves generated in major cluster merger activity observed at the center (e.g. Bykov et al. 2008). The merger axis is clearly along the galaxy filament, with radio relics placed tangential to this axis, as expected in a merger-shock geometry. However, to the limits of surface-brightness sensitivity achieved ($\sim 30\,\mu$Jy noise for a $5''$ beam at 610 MHz, $\sim$12h on-source time), no central radio halo was detected in our GMRT observations. Possible reason is that some of the short baselines in the GMRT observations were affected by RFI and had to be flagged, which allowed imaging of spatial scales of $< 4'$ only (at 610 MHz). A very deep 327 MHz GMRT observation is in preparation to address this issue.

3. Discussion

The X-ray images clearly reveal a highly unrelaxed cluster experiencing a complex merger that is occurring preferentially along the NW-SE axis – i.e., along the major filament clearly seen in the distribution of galaxies. An additional arm of the X–ray emission extends from the middle of the cluster towards NE, roughly coinciding with another filamentary galaxy structure. ZwCl 2341.1+0000 may thus represent by far the most complex merger configuration found among galaxy clusters. Due to its highly unrelaxed dynamical state revealed by our X–ray data, this system may provide a rare glimpse into the early steps of assembly of a galaxy cluster at the junction of filaments. In addition, rare detection of diffuse radio emission from such system will throw much light on the dynamics of cluster formation. The optical, radio and X–ray observations presented in this paper firmly establish the link of this merger to the axis of a supercluster filament along which the merger takes place. This work represents a substantial advance in the field, because it probes several important components of the cosmic environment: intergalactic gas, magnetic fields, and cosmic rays. Large scale radio emission indicates that magnetic fields of appreciable strength are present not only in the ICM but also in the diffuse in-

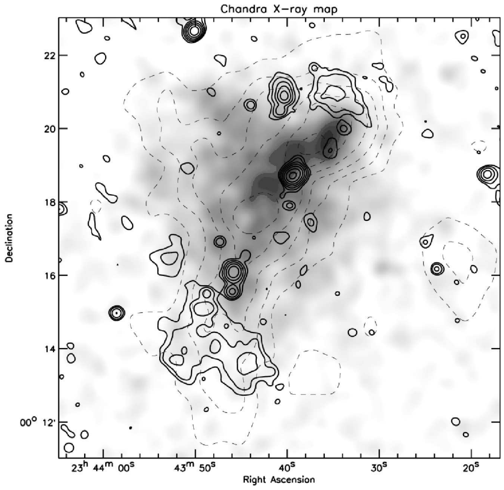

Fig. 2. A radio, optical and X-ray overlay map. The solid contours represent the radio emission at 610 MHz from the GMRT data (van Weeren et al. 2009). Broad beam of 15 ″ FWHM is used to better highlight the diffuse radio emission. The radio contours are drawn at $[1, 2, 4, 8, 16, 32, ...] \times 0.224$ mJy/beam. Dashed contours show the galaxy isodensity contours from SDSS, corresponding roughly to a limit of $M_V = -18.1$ (i.e., $M^* + 2.4$). The dashed contours are drawn at [2, 3, 4, 5,...] galaxies arcmin^{-2} with a redshift cut. Grey-scle image is smoothed, point source subtracted X–ray emission map from *Chandra* in the 0.5-3.0 keV energy band.

tergalactic medium, i.e., in the gas that will be shocked as it accretes onto collapsing structures – the precursors of virialized galaxy clusters. The search for magnetic fields in the intergalactic medium is of fundamental importance for cosmology (Bonafede et al. 2010; Dolag 2006).

In a recent deep 1.4 GHz VLA observation, Giovannini et al. (2010) present evidence of 2 Mpc-scale polarized radio emission, midway between the peripheral radio relics. The radio emission clearly follows the distribution of optical galaxies and X-ray emission which might suggest that it is similar to radio halos found in dynamically unrelaxed clusters (Ferrari et al. 2008). The polarization vectors (p$\sim$10 - 20%) are very regular, indicating an organized magnetic field pattern. This feature might result from the accretion flow shocks in filaments compressing the weak magnetic fields of the infalling IGM, which is consistent with a model proposed by Bagchi et al. (2002). An observation of large scale diffuse radio emission and magnetic fields in filamentary galactic environment also provides a foretaste of future detections, as a major goal of upcoming low frequency radio telescopes like the LOFAR and LWA is to probe the non-thermal processes in hundreds of merging clusters and in the filamentary cosmic-web of the near and distant Universe.

4. Conclusions

We have presented deep X–ray and radio observations which show that ZwCl 2341.1+0000 constitutes a complex, large–scale ensemble of clusters, which are merging at the intersection of filaments identifiable in optical and X–ray images. Energetics of multiple mergers and accretion flows has resulted in wide–spread shocks, acceleration of cosmic ray particles and amplification of weak magnetic fields. This is evident in a pair of giant, peripheral radio relics and a faint, diffuse radio halo extending more than $\sim$1 Mpc between the two relics, following the large–scale filamentary structure.

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