Evidence for Shock Acceleration and Intergalactic Magnetic Fields in a Large-Scale Filament of Galaxies ZwCl 2341.1+0000

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Abstract

We report the discovery of large-scale diffuse radio emission from what appears to be a large-scale filamentary network of galaxies in the region of cluster ZwCl 2341.1+0000, and stretching over an area of at least $6\,h_{50}^{-1}$ Mpc in diameter. Multicolour CCD observations yield photometric redshifts indicating that a significant fraction of the optical galaxies in this region is at a redshift of $z = 0.3$. This is supported by spectroscopic measurements of 4 galaxies in the Sloan Digital Sky Survey (SDSS) at a mean $z = 0.27$. We present VLA images at $\lambda = 20$ cm (NVSS) and 90 cm, showing the detailed radio structure of the filaments. Comparison with the high resolution FIRST radio survey shows that the diffuse emission is not due to known individual point sources. The diffuse radio-emission has a spectral index $\alpha \lesssim -0.5$, and is most likely synchrotron emission from relativistic charged particles in an inter-galactic magnetic field. Furthermore, this optical/radio structure is detected in X-rays by the ROSAT all-sky survey. It has a 0.1–2.4 keV luminosity of about 10^{44} erg s^{-1} and shows an extended highly non-relaxed morphology. These observations suggest that ZwCl 2341.1+0000 is possibly a proto-cluster of galaxies in which we are witnessing the process of structure formation. We show that the energetics of accretion shocks generated in forming large-scale structures are sufficient to produce enough high energy cosmic-ray (CR) electrons required to explain the observed radio emission, provided a magnetic field of strength $B \gtrsim 0.3\mu$G is present there. The latter is only a lower limit and the actual magnetic field is likely to be higher depending on the morphology of the emitting region. Finally, we show results from a numerical simulation of large-scale structure formation including acceleration of CR electrons at cosmological shocks and magnetic field evolution. Our results are in accord with the observed radio synchrotron and X-ray thermal bremsstrahlung fluxes. Thus we conclude that the reported radio detection is the first evidence of cosmic-ray particle acceleration taking place at cosmic shocks in a magnetized inter-galactic medium over scales of $\gtrsim 5\,h_{50}^{-1}$ Mpc.

Key words: Acceleration of particles; Cosmic rays; Cosmology: observations; Galaxies: clusters: general; Large-scale structure of universe; Magnetic fields; Methods: simulations; Radio continuum: general; Shock waves
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1 Introduction

Recent advances in observational cosmology have revealed that the large-scale distribution of galaxies in the Universe has a honeycomb-like structure, where the principal morphological elements are interconnected networks of large filaments and sheets of galaxies surrounding huge regions almost devoid of galaxies (the 'voids') (Einasto et al. 1997, Bond, Kofman & Pogosyan 1996, Doroshkevich et al. 1996). The enduring quest has been to understand how such diverse structures emerge out of primeval density fluctuations that grew over time due to the effects of gravity.

An important role in the structure-formation process is played by the large-scale shocks that form as the primordial density fluctuations become non-linear and the accretion flows on collapsing structures become supersonic (Quilis, Ibnez, & Saez 1998, Miniati et al. 2000, Enßlin et al. 2001). Likely these shocks are responsible for heating of most of the diffuse intergalactic medium (IGM) up to $\approx 10^{5-7}$K (Cen & Ostriker 1999). Given their large sizes and long lifetimes, these shocks have also been proposed to be the sites for the acceleration of very high energy cosmic-rays up to $10^{18} - 10^{19}$ eV (Norman, Melrose & Achterberg 1995, Kang, Ryu, & Jones 1996). In addition, it has been recently pointed out that the cosmic-ray ions accelerated at intergalactic

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shocks could accumulate in the formed structure, storing a significant fraction of the total energy there (Miniati et al. 2001a). Exploration of such ideas through direct observations is truly important because even after close to a century since cosmic-rays were discovered by Victor Hess in 1912, we do not know how and where they are accelerated.

Direct evidence for the ability of cosmic shock waves to accelerate particles is given by the observed association of the so called 'cluster radio relic' sources with locations where shock waves are expected from X-ray observations (Enßlin et al. 1998). Diffusive shock acceleration may be operative at these locations and responsible for the radio emitting electrons. But also shock re-illumination of fossil radio plasma in remnants of former active radio galaxies is a viable explanation (Enßlin & Gopal-Krishna 2001). The latter mechanism seems to be the explanation of at least some of the cluster radio relics, since in some cases very filamentary and torus-like morphologies could be resolved. Such morphologies are predicted by numerical simulations of the shock passage of a fossil radio plasma bubble (Enßlin & Brüggen 2002). However it is quite possible that some of the cluster radio relic sources are caused by diffusive shock acceleration of thermal electrons (Miniati et al. 2001b).

In order for particles to be accelerated, magnetic fields have to be present at the shock waves. Magnetic fields are observed in the intra-cluster medium (ICM) of clusters of galaxies by Faraday rotation of polarized background sources (Clarke, Kronberg, & Böhringer 2001). They are further revealed by the presence of cluster-wide Mpc scale radio halos in some clusters of galaxies, believed to be the result of synchrotron emission of relativistic electrons accelerated in magnetic fields. The role of the magnetic fields in clusters is still a matter of debate, but some recent works indicate important dynamical influences in the ICM (Clarke, Kronberg, & Böhringer 2001, Vikhlinin, Markevitch, & Murray 2001). Outside clusters, no firm detections of magnetic field in the intergalactic medium (IGM) has yet been reported to our knowledge, but speculations on the magnitude of magnetic fields in IGM range from 10^{-7}G to 10^{-12}G.

The origin of cosmic magnetic fields is currently unknown and for this reason any observational evidence of them in the IGM environment is of great importance. Magnetic fields could have a primordial origin or they could have been seeded and amplified during the relatively recent history of large scale structure formation. In this latter scenario, the Biermann battery mechanism (Biermann 1950) operating at either large-scale shocks (Kulsrud et al. 1997, Ryu, Kang & Biermann 1998) or ionization fronts (Gnedin et al. 2000) has been proposed as a viable model for generating seeds of strength $10^{-19} - 10^{-23}$G, to be subsequently amplified by turbulent motions and/or galactic dynamos up to μG level. Alternatively, the origin of cosmic magnetic fields has been attributed to the pollution of the inter-galactic medium by winds and out-flows from primeval galaxies (Kronberg et al. 1999) and/or quasars and radio galaxies (Furlanetto & Loeb 2001, Gopal-Krishna & Wiita 2001). In most of these cases, magnetic fields would be expected to be present not only inside galaxy clusters, but also in filaments. There were earlier attempts to estimate the magnetization of the Universe from quasars (Daly & Loeb 1990, Medina-Tanco & Enßlin 2001).

The detection of magnetic fields in the IGM outside clusters of galaxies would help the understanding of the origin of magnetic fields within galaxies and galaxy clusters. At the same time, observational evidence for cosmic-rays in the intergalactic medium would allow us to further our understanding of high energy phenomena occurring in cosmic structures which have recently received much attention [see *e.g.,* Feretti & Giovannini (1996) and references therein]. Observationally exploring these issues would provide important clues for many physical problems, including, among others, the theories of ultra-high energy cosmic-ray acceleration and their intergalactic propagation, the origin of radio and hard X-ray emission from galaxy clusters, and the contribution to the diffuse gamma-ray background from shock-accelerated TeV cosmic-ray electrons (Loeb & Waxman 2000).

In this paper we report on the observational evidence of large-scale diffuse radio synchrotron emission (§ 4) over an extended region around ZwCl 2341.1+0000, which is likely to be a proto-cluster of galaxies containing several large filaments (§ 3). The ROSAT X-ray observation of this structure is presented in § 5. The result of a search for association of ZwCl 2341.1+0000 with other galaxy concentrations on a super-cluster scale is reported in § 6. Our observations imply the existence of magnetic fields and relativistic electrons at GeV energies over scales of several Mpc (§ 4 & § 7). The observed radio emission is compared with theoretical predictions from analytical (§ 7) and numerical modeling (§ 8) of particle acceleration at structure formation shocks. Finally in § 9 we discuss the implications of our results and the outlook for future work.

Unless stated otherwise, we adopt an $\Omega_m = 1$ Einstein-de Sitter cosmology and the Hubble constant $H_0 = 50\,h_{50}$ km s^{-1} Mpc^{-1}. The angular scale is $330\,h_{50}^{-1}$kpc per arcminute at a redshift z=0.3. The radio spectral index α is defined such that flux density F_ν is a power-law $F_\nu \propto \nu^\alpha$.

2 The ZwCl 2341.1+0000

The multi-Mpc scale filamentary network of galaxies in ZwCl 2341.1+0000 was discovered in an ongoing program to search for the large-scale diffuse radio emission (~ 1 Mpc or larger) originating in distant clusters of galaxies.

The primary aim of this program is to investigate the origin and evolution of high energy relativistic particles and magnetic fields in the IGM of large cosmic structures. To this end, we searched for the presence of diffuse radio emission in the field of several Abell and Zwicky clusters or groups with measured/estimated redshifts $\gtrsim 0.15$. Although not a statistically complete sample, it nevertheless contains many clusters that have no detailed information available so far. As a first step, we searched for radio emission in the 'New VLA All Sky Survey' (NVSS (`http://www.cv.nrao.edu/nvss/`)) images at the 1.4 GHz frequency (Condon et al. 1998). The NVSS survey uses the VLA's most compact D-array configuration and is well suited for detection of large structures of angular scales up to $\sim$ 15 arcmin in extent. The completeness limit for point sources is about 2.5 mJy and the angular resolution (beam size) is about 45 seconds of arc.

In the NVSS data, we discovered, among others, a large-scale diffuse emission feature in the region of galaxy concentration ZwCl 2341.1+0000 located at R.A. $23^h43^m39^s.7$ Dec. $+00°16'39''$. It is classified as a distant group 5 or "extremely distant" cluster with cluster diameter $22'$ by Zwicky et al. (1961-68)). Further literature and data search with the NASA Extragalactic Database (NED (`http://nedwww.ipac.caltech.edu`)) showed no additional information on this concentration of galaxies. However, the optical images of the Second Generation Palomar Digitized Sky Survey (DSS-2 (`http://archive.eso.org/dss/dss`)) revealed a very interesting cosmological scale (projected size $\sim$ 25 arcmin or $8h_{50}^{-1}$Mpc) filamentary network of faint galaxies, which had the distinctive non-relaxed morphology of a forming structure. Motivated by these findings, and with an aim to investigating the physical properties of this object in greater detail, we obtained several more detailed observations at radio and optical wavelengths. These observations and the results of their analysis form the subject matter of the following sections.

3 Optical data

3.1 CCD imaging and analysis

We obtained several deep optical and NIR images with the 1-m Carl-Zeiss reflector at the State Observatory, Nainital, India, in November 1999. Due to constraints of time and scheduling, only data in Johnson V, R, and I filters were obtained using a CCD camera equipped with a 2K $\times$ 2K pixels chip, giving a plate scale of 0.37 arcsec/pixel, and a field of view of about 13 arcmin at the f/13 Cassegrain focus. The gain and the read-out noise were 10 e^-/ADU and 13.7 e^- respectively. The sky conditions during the observations were photometric but the seeing was moderate at $\sim$2 arcsec FWHM. We took several frames in each filter with total exposure time sufficient for adequate photometric accuracy. Photometric zero points and colour transformations were defined by observing Landolt standards. The initial optical processing of the CCD frames was done using the IRAF software and the final object detection, magnitude evaluation and object (star/galaxy) classification was performed using the 'SExtractor' image analysis program (Bertin & Arnouts 1996).

The resulting source catalogue contains a total of 271 galaxies detected to a magnitude limit of $m_V = 21.9$, $m_R = 20.9$, and $m_I = 20.2$, and which were detected independently in all three passbands. The total magnitudes for galaxies at the faint end had typical errors of ∼0.05–0.10 mag. The extinction corrections are small ($A_B < 0.1$ mag over the area of observation) due to the high galactic latitude ($b = -58°$) position. The parameters for the extinction were obtained from the IRAS based galactic extinction estimates by Schlegel, Finkbeiner & Davis (1998). The astrometric conversion from the pixel to equatorial co-ordinates was performed with IRAF employing several bright astrometric stars identified on the CCD images.

3.2 Optical morphology and luminosity

The Fig. 1 shows the R-band co-added image of the galaxy concentration. Morphologically it is best described as a long S-shaped main filament of galaxies extending over 12 arcmin ($\sim 4h_{50}^{-1}$ Mpc, which is the size of the CCD frame), and branching structures of several Mpc-scale galaxy sub-filaments mainly to the east and north-east of the main chain. The photometric redshift estimate places the structure at a redshift of z≈ 0.3, supported by spectroscopic evidence from the SDSS survey (see §3.4 below).

If the entire structure is actually a web-like formation at a single redshift and not an artifact of projection (evidence in support of this is presented below), the implications are clearly very important. The branching chain structure and multiple peaks in the galaxy distribution might indicate hierarchical merging of cosmic structures distributed on Mpc scales, at a moderately high redshift. This type of structure is to be expected in evolving Universe according to the "cosmic web" theory of structure formation (Bond, Kofman & Pogosyan 1996), and it is frequently seen in computer simulations such as the the Hubble-volume N-body simulation (Colberg et al. 2000), and also in observational surveys such as the Las Campanas redshift survey (Doroshkevich et al. 1996). These results predict that matter in the Universe should be concentrated along filaments, and clusters of galaxies should be found where these filaments intersect. It is interesting to note that the filamentary morphology of ZwCl 2341.1+0000 is quite similar to a more distant proto-cluster

RX J1716.6+6708 at $z=0.81$ (Henry et al. 1997).

The average integrated galaxy V luminosity of 12 randomly selected positions on the main filament and side chains, after correcting for the local background offset from main structure, yields a value of $2.7 \times 10^{11} L_{\odot}/\mathrm{arcmin}^2$ ($\pm 54\%$) for the observed average luminosity of the filament. The indicated dispersion about the mean value represents the fluctuation of the surface brightness occuring over the galaxy filaments, rather than the uncertainty of measurement.

3.3 Galaxy colours & estimating photometric redshifts

We estimated photometric redshifts for the galaxies in our catalogue to ascertain the mean redshift of the concentration, and to verify that most of the galaxies projected on the sky plane near this concentration represent an association in real space. This method is a powerful tool for detecting high spatial density regions such as clusters and groups and has recently been applied to the study of galaxy populations in high-z clusters of galaxies (Lubin et al. 2000, Gladders et al. 1998). From our photometric catalogue of galaxies in V, R and I bands, a set of 6 plots; three of colour-magnitude (C-M) diagrams and three of colour-colour (C-C) diagrams, were generated. Figs. 2 & 3 show the $(V-I)$ and $(R-I)$ colours vs. I magnitudes for all the galaxies. On both planes, a well defined linear sequence of early-type (E/S0) galaxies is clearly visible.

Early-type galaxies form the dominant population in cores of all clusters, rich or poor, and across a wide range of redshifts, low to $z > 1$ (e.g., Gladders et al. (1998)). Their ubiquitous colour-magnitude sequence, first noted locally by Baum (Baum 1959), is now well documented in many clusters, ranging from Coma to clusters at redshifts up to $z=1$ (Stanford, Eisenhardt, & Dickinson 1998, Ellis et al. 1997, Gladders & Yee 2000). The colours of elliptical galaxies become bluer as they become less luminous. We have detected this red C-M sequence on all three C-M diagrams, which shows that at least the dominant galactic population consists of early-type galaxies that are part of this filament at a single redshift. This is a good indicator of association of galaxies in a large-scale structure, as a random projection of field galaxies can not generate the red sequence which is characteristic of clusters. On the C-M diagrams, apart from E/S0s, a population of blue galaxies (late spirals and irregulars) can also be seen in the lower-right region.

From the position of each galaxy in a 3-dimensional colour space, consisting of orthogonal axes $(V-R)$, $(V-I)$, and $(R-I)$, the three colour-colour diagrams were obtained. These diagrams can be used to identify the galaxies of various Hubble types and to obtain the redshifts. The Fig. 4 and Fig. 5 show two of