JVL A S- and X-band polarimetry of the merging cluster Abell 2256

Takeaki OZAWA,1,* Hiroyuki NAKANISHI,1 Takuya AKAHORI,1 Kenta ANRAKU,1 Motokazu TAKIZAWA,2 Ikumi TAKAHASHI,3 Sachiko ONODERA,4 Yuya TSUDA,5 and Yoshiaki SOFUE6

1Graduate School of Science and Engineering, Kagoshima University, 1-21-35 Korimoto, Kagoshima, Kagoshima 890-0065, Japan
2Department of Physics, Yamagata University, 1-4-12 Kojirakawa-machi, Yamagata, Yamagata 990-8560, Japan
3Graduate School of Science and Engineering, Yamagata University, 1-4-12 Kojirakawa-machi, Yamagata, Yamagata 990-8560, Japan
4Department of Physics, Meisei University, 2-1-1 Hodokubo, Hino, Tokyo 191-8506, Japan
5Graduate School of Science and Engineering, Meisei University 2-1-1 Hodokubo, Hino, Tokyo 191-8506, Japan
6Institute of Astronomy, The University of Tokyo, 2-21-1 Osawa, Mitaka, Tokyo 181-0015, Japan

*E-mail: k5148776@kadai.jp

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Abstract

We report on polarimetry results of a merging cluster of galaxies, Abell 2256, with the Karl G. Jansky Very Large Array (JVLA). We performed new observations with JVLA at the S band (2051–3947 MHz) and X band (8051–9947 MHz) in the C array configuration, and detected significant polarized emissions from the radio relic, Source A, and Source B in this cluster. We calculated the total magnetic-field strengths toward the radio relic using revised equipartition formula, which is 1.8–5.0 µG. With dispersions of Faraday rotation measure, the magnetic-field strengths toward Sources A and B are estimated to be 0.63–1.26 µG and 0.11–0.21 µG, respectively. An extremely high degree of linear polarization, as high as ∼35%, about a half of the maximum polarization, was detected toward the radio relic, which indicates highly ordered magnetic lines of force over the beam sizes (∼52 kpc). The fractional polarization of the radio relic decreases from ∼35% to ∼20% at around 3 GHz as the frequency decreases, and is nearly constant between 1.37 and 3 GHz. Both analyses with depolarization models and Faraday tomography suggest multiple depolarization components toward the radio relic and imply the existence of turbulent magnetic fields.

Key words: galaxies: clusters: individual (Abell 2256) — galaxies: clusters: intracluster medium — magnetic fields — polarization
1 Introduction

A collision of galaxy clusters is one of the most energetic events, with kinetic energy of the order of $\sim 10^{58}$ erg in the Universe (Buote 2001). Shock waves and turbulence induced by the collision can convert a huge amount of kinetic energy of clusters into thermal/nonthermal energy of the intracluster medium (ICM). Cosmic rays injected into the ICM by active galactic nuclei (AGN) activities, star formations of galaxies, and structure formation shocks (Brunetti et al. 2001) can be re-accelerated by the shocks (Takizawa & Naito 2000; Ryu et al. 2008; Vazza et al. 2009) and turbulence (Brunetti et al. 2001, 2004; Petrosian 2001; Ohno et al. 2002; Fujita et al. 2003; Cassano & Brunetti 2005; Xu et al. 2009, 2010; Feretti et al. 2012; Donnert et al. 2013). The correlation between the X-ray luminosity of the ICM and the power of diffuse radio emission from cosmic rays is known for radio halos and relics (e.g., Feretti et al. 2012). It suggests a relationship between the cluster size and the magnitude of particle acceleration, in the sense that larger clusters can produce more powerful radio emission. However, the nature and evolution of the ICM and intergalactic magnetic field (IGMF), which determine the efficiency and the radio emission mechanisms, are poorly understood.

Turbulence is thought to play an important role in the evolution of the IGMF. It has been suggested that a turbulence dynamo can amplify the IGMF in a cosmological time (Ryu et al. 2008; Cho & Ryu 2009). Actually, the Kolmogorov index in the power spectrum of magnetic fields has been reported (e.g., Abell 2362, Guidetti et al. 2008), indicating the existence of turbulence and the amplification of the IGMF by turbulence in galaxy clusters.

One of the useful techniques to investigate turbulent magnetic fields is the depolarization, in which the observed polarized intensity becomes weaker than that at the origin, as a result of several mechanisms. Particularly, beam depolarization of internal Faraday dispersion (IFD) and external Faraday dispersion (EFD) becomes a significant effect, if structures of Faraday rotation measure (RM) inside and outside a polarized radio emission source, respectively, are not uniform within an observing beam, e.g., if small eddy-sized turbulent magnetic fields exist. Both IFD and EFD depend on the dispersion of RM within the beam. Burn (1966) analytically investigated the dependencies called Burn’s law, and Arshakian and Beck (2011) investigated the optimum frequency range for this technique.

Abell 2256 is known as a merging cluster of galaxies in which we expect turbulence of the ICM and turbulent magnetic fields in the cluster. In this paper, we report on results of linear polarimetry of the central part of Abell 2256 with the Karl G. Jansky Very Large Array (JVLA) at the S band (2051–3947 MHz) and X band (8051–9947 GHz) in the C array configuration. We obtained Stokes $I$, $Q$, and $U$ images in order to measure the total intensity, fractional polarization, and RM map. Using the obtained maps, we investigated IGMF structures in Abell 2256 by means of depolarization. The layout of this paper is as follows. In section 2, we introduce Abell 2256. In section 3, we describe the observations and data reductions in the JVLA. In section 4, we present the results, which include the total intensity, fractional polarization, and RM. In section 5, we discuss the magnetic field strengths toward the radio relic, Source A, and Source B, and discuss the fractional polarization of the radio relic. In section 6, we summarize our conclusions.

Throughout this paper, we assume the following cosmological parameters: $H_0 = 70.5 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.27$, and $\Omega_{\Lambda} = 0.73$. The angular size of 1 arcmin corresponds to $\sim 67$ kpc at the redshift of Abell 2256, $z = 0.0581$, corresponding to a distance of $D = 247$ Mpc.

2 Cluster of galaxies Abell 2256

Abell 2256 is a nearby (redshift $z = 0.0581$) cluster of galaxies whose X-ray center is located at (RA, Dec) = (17$^h$04$^m$23.3, +78$^\circ$37′55″2) in the J2000.0 epoch (Ebeling et al. 1998). Berrington, Lugger, and Cohn (2002) investigated Abell 2256 with optical observations and found substructures of member galaxies with a peak radial velocity difference of $\sim 2000 \text{ km s}^{-1}$. Substructures of the ICM are also known in X-ray observations (Briel et al. 1991; Briel & Henry 1994; Sun et al. 2002). Using the X-ray satellite Suzaku, Tamura et al. (2011) estimated radial velocity difference of $\sim 1500 \text{ km s}^{-1}$ in gas bulk motions of the substructures. There are two distinct ICM components with temperatures $\sim 7 \text{ keV}$ and $\sim 4.5 \text{ keV}$ (Sun et al. 2002). These results suggest that Abell 2256 is a merging galaxy cluster.

Radio observations have discovered a radio relic and a halo in the central part of Abell 2256 (Bridle & Fomalont 1976; Bridle et al. 1979; Röttgering et al. 1994; Miller et al. 2003; Clarke & Ensslin 2006; Brentjens 2008; van Weeren et al. 2009, 2012; Kale & Dwarkath 2010; Owen et al. 2014; Trasatti et al. 2015). The radio relic located in the northwestern region of the cluster is $\sim 440$ kpc away from the X-ray center. The radio relic covers an area of $16.9 \times 7.8$ (1125 kpc $\times$ 520 kpc, Clarke & Ensslin 2006). Previous observations revealed that the radio relic includes filamentary structures (Clarke & Ensslin 2006; Brentjens 2008; Owen et al. 2014). The radio halo is located in the central region of the cluster. Clarke and Ensslin (2006) measured that the total flux of the radio halo is approximately 103 mJy at 1369 MHz.

There are also several radio sources in Abell 2256. Miller, Owen, and Hill (2003) identified the radio sources
Table 1. Details of the VLA and JVLA observations of Abell 2256.*

| Frequency (MHz) | Bandwidth (MHz) | Configuration | Date       | Time (hr) | Project |
|----------------|-----------------|---------------|------------|-----------|---------|
| VLA 1369/1417  | 25/25           | D             | 1999-Apr-28| 5.9, 5.9  | AC0522  |
| VLA 1513/1703  | 12.5/25         | D             | 1999-Apr-29| 3.5, 5.5  |         |
| VLA 1369/1417  | 25/25           | C             | 2000-May-29| 2.5, 2.5  | AC0545  |
| VLA 1513/1703  | 12.5/12.5       | C             | 2000-May-29| 3.6, 3.6  |         |
| VLA 1369/1417  | 25/25           | C             | 2000-Jun-18| 2.5, 2.5  |         |
| VLA 1513/1703  | 12.5/25         | C             | 2000-Jun-18| 4.1, 3.5  |         |
| JVLA S-band    | 128             | C             | 2013-Aug-25| 1.2       | 13A-131 |
| JVLA X-band    | 128             | C             | 2013-Aug-26| 1.2       |         |
|                |                 |               | 2013-Aug-29| 1.2       |         |

* Column 2: observing frequency; Column 3: observing bandwidth; Column 4: array configuration; Column 5: dates of observation; Column 6: time on source; Column 7: NRAO project code.

1. 2051/2179/2307/2433/2563/2691/2819/2947/3051/3179/3307/3435/3563/3691/3819/3947.

2. 8051/8179/8307/8435/8563/8691/8819/8947/9051/9179/9307/9435/9563/9691/9819/9947.

Associated with member galaxies of Abell 2256. Each radio source is labeled with letters (Bridle & Fomalont 1976; Bridle et al. 1979; Rottgering et al. 1994), and Sources A, B, and C are the remarkable bright sources. Sources A and B are linearly polarized sources which are suitable for our measuring of RMs. Source C is known as a head–tail galaxy which has a narrow straight tail extending for at least 480 kpc at 1.4 GHz across the radio relic (Rottgering et al. 1994).

3 Observations and data reductions

3.1 Radio observations

We carried out new observations of Abell 2256 using JVLA at the S band (2051–3947 MHz) and X band (8051–9947 MHz) in the C array configuration on 2013 August 18–30. Each band was separated into 16 spectral windows and each window had a bandwidth of 128 MHz (table 1). The pointing center was Source A (RA, Dec: 17h03m31.9s, +78°37′44.4″), since our observations primarily aimed to measure RMs toward Sources A and B in the central part of Abell 2256. We observed 3C 286 and 1803+784 as a flux and polarization calibrator, and a gain and phase calibrator, respectively.

3.2 Data reductions

Data were reduced by the following procedures. Using National Radio Astronomy Observatory (NRAO) Common Astronomy Software Applications (CASA), we executed VLA calibration pipeline and task EXPORTUVFITS to convert JVLA measurement sets into FITS so as to allow us to calibrate the data with the NRAO Astronomical Image Processing System (AIPS). In AIPS, the data in each spectral window was averaged in frequency domain using the task AVSPC. Radio frequency interferences (RFIs) and spurious signals were flagged using the tasks CLIP and TVFLAG. We calibrated polarization using the tasks PCAL and RLDIF after we created calibration tables. The data separated into observed date are concatenated using the task DBCON.

The data at 2179, 2307, 3691, 3819, and 3947 MHz in the S band are affected by RFIs. The RFIs were satellite downlink and digital audio radio service in 2180–2290 MHz and 3700–4200 MHz, respectively. Therefore, we removed the data in these spectral windows from our analysis.

In addition to the observed data, we also utilized the archival data which were observed with the VLA in the C and D array configurations at the L band (1369, 1417, 1512, 1703 MHz). We calibrated these data using the same procedures described above.

We created Stokes I, Q, and U images using the task IMAGR with suitable tapers. In order to detect the radio relic and to resolve the individual polarized sources in the cluster, we made images of 47″ resolution for the L and S bands, and 15″1 resolution for the S and X bands (table 2). Note that in the following analyses, except subsection 4.1, we used the images of 47″ resolution for analyzing the radio relic and those of 15″1 for the individual radio sources.
Table 2. Image qualities of total intensity and polarization at L, S, and X bands.

| Frequency (MHz) | Beam ($'' \times''$) | $\sigma_I$ (mJy beam$^{-1}$) | $\sigma_Q$ (mJy beam$^{-1}$) | $\sigma_U$ (mJy beam$^{-1}$) |
|-----------------|----------------------|-----------------------------|-----------------------------|-----------------------------|
| VLA 1369        | 47 $\times$ 47       | 0.163                       | 0.028                       | 0.022                       |
|                 | 1417                 | 0.152                       | 0.031                       | 0.020                       |
|                 | 1513                 | 0.183                       | 0.041                       | 0.028                       |
|                 | 1703                 | 0.259                       | 0.046                       | 0.095                       |
| JVLA S-band 11 windows† | 47 $\times$ 47 | 0.159                       | 0.029                       | 0.029                       |
| S-band 11 windows† | 15.1 $\times$ 15.1 | 0.151                       | 0.013                       | 0.014                       |
| X-band 16 windows‡ | 15.1 $\times$ 15.1 | 0.053                       | 0.027                       | 0.028                       |

*Column 2: observing frequency; Column 3: beam size; Columns 4, 5, 6: rms noise of the Stokes $I$, $Q$, and $U$. We show the averaged rms noise in JVLA S-band 11 windows and X-band 16 windows.
†2051/2435/2563/2691/2819/2947/3051/3179/3307/3435/3563.
‡8051/8179/8307/8435/8563/8691/8819/8947/9051/9179/9307/9435/9563/9691/9819/9947.

Fig. 1. Total intensity map of Abell 2256 at 2051 MHz in the JVLA C array configuration. Contours are drawn at ($-3$, $3$, $6$, $12$, $24$, $48$, $96$, $192$) $\times$ 140 $\mu$Jy beam$^{-1}$ ($9.702 \times 10^{-23}$ W m$^{-2}$ Hz$^{-1}$ sr$^{-1}$). The beam size of the image is shown at the bottom left and is $25'' \times 21''$. Radio sources are labeled following the references (Bridle & Fomalont 1976; Bridle et al. 1979; Rottgering et al. 1994). The fractional polarization of the radio relic was measured in the dashed-frame region (subsection 4.3).

We excluded the data of the X band from the images of 47'' resolution since the radio relic is outside the field of view. The images were convolved with a Gaussian beam using task CONVL. The number of pixels was $87 \times 87$ for images of 47'' resolution, and $136 \times 136$ for images of 15.7''. Each pixel size corresponds to a half of each beam size.

4 Results

4.1 Radio images

Figure 1 shows the total intensity map of Abell 2256 at 2051 MHz. We detected several radio sources and the radio relic above $3\sigma_I$ significance, where the subscript “I” means the total intensity. All of them are known sources in previous works with different array configurations and/or frequency bands (e.g., Miller et al. 2003; Clarke & Ensslin 2006; Owen et al. 2014). In all of the created images in the S band, except the data affected by RFIs, we detected the radio relic, where an area of the relic above $3\sigma_I$ significance at 3563 MHz was smaller than that at 2051 MHz by a factor of $\sim 0.37$.

Figure 2 shows the total intensity map at 8051 MHz. We excluded the data of the X band from the images of 47'' resolution since the radio relic is outside the field of view. In all of the created images in the X band, we detected Sources A, B, and C. These radio sources are identified as radio galaxies (Miller et al. 2003).
4.2 Total intensity

The total 2051 MHz flux of the radio relic is estimated to be 286 mJy, based on the image. For calculating the total 2051 MHz flux, we integrated the pixels where the flux density is above 3σ limit significance on the radio relic in the image of 47″ resolution. If we consider the total 1369 MHz flux from the radio relic of 462 mJy, which is subtracted from the flux of the point sources (Clarke & Ensslin 2006), and adopt the spectral index (S ∝ ν^α) of α = -0.81 (van Weeren et al. 2012), the total 2051 MHz flux should be 330 mJy. The measured total 2051 MHz flux of 286 mJy is thus smaller than the expected total flux by ~13%. Note that the total 2051 MHz flux of 286 mJy is not subtracted from the flux of the tail of Source C, so that the total flux of the relic is smaller than 286 mJy.

We also estimated the upper limit of the total 2051 MHz flux of the radio halo, which is ~49 mJy, assuming that the radius of the radio halo emission is ~6′′1 (Clarke & Ensslin 2006) and the upper limit of the flux density is 606 µJy beam⁻¹ (10.296 × 10⁻²³ W m⁻² Hz⁻¹ sr⁻¹) which corresponds to 3σ limit significance at 2051 MHz. If we adopt the total 1369 MHz flux of the radio halo of 103 mJy (Clarke & Ensslin 2006) and the spectral index of α = -1.1 (van Weeren et al. 2012), the upper limit of the total 2051 MHz flux should be ~66 mJy. Thus, the estimated upper limit of the total flux of 49 mJy is smaller than the expected total flux by ~26%.

Figure 3 shows an example of the spectral energy distribution (SED) at a point (RA, Dec: 17°02′51″9, +78°42′26″7) in the radio relic, where the SED is made from the images of 47″ resolution. We obtained a spectral index of α = -1.98 from the surface brightness between 1369 and 3563 MHz (the dashed line in figure 3). We found that the observed flux density of the radio relic at the frequency above 2 GHz is smaller than the extrapolation of the flux density from the results in 1369–2051 MHz with the spectral index α = -0.81 (the solid line in figure 3).

A possible cause of such a decline is that we are missing the flux. In interferometry, we miss the flux from the diffuse emission which has a scale larger than the largest angular scale (LAS) of the interferometer. Actually, the scales of the major axis of the radio relic and halo are 1014″ and 732″ on the sky (Clarke & Ensslin 2006), while the LAS at 1.5 GHz and 3.0 GHz in the JVLA C array configuration were 970″ and 490″, respectively. This possibility is also supported by single-dish radio observations with the Green Bank (Owen 1975) and Effelsberg (Haslam et al. 1978) telescopes, which yielded the total fluxes of 570 and 666 mJy in the entire area of Abell 2256 at 2695 MHz, respectively, in agreement with the spectral index of α = -0.72 (Brentjens 2008).

Another possible cause of the decline would be a cutoff of cosmic-ray electrons at high energies. However, since the effect of missing flux could be significant, we could not argue the possibility of the energy cutoff.

4.3 Fractional polarization

We detected significant polarized emission from the radio relic, Source A, and Source B at the S band. At the X band, we detected the significant polarized emission only from Source A. With the Stokes I, Q, and U, the fractional polarization p is given by

\[ p = \frac{\sqrt{Q^2 + U^2}}{I} \]

The fractional polarization is created from the images of 47″ and 15″1 resolution to analyze the radio relic and the individual polarized sources. We calculated the fractional polarization only in the pixels where the flux densities of Stokes I, Q, and U are all above 3σ significance.

Figure 4 shows the fractional polarization spectra of the radio relic (open squares), and figure 5 shows the fractional polarization spectra of Source A (open circles), Source B (open triangles), and Source C (filled inverted triangles). Each data point represents a spatial average for the pixels within each emitting region. For the radio relic, we choose the region where the polarized emission is detected at 3563 MHz (the dashed-frame region in figure 1). We only plotted the data points which satisfy the requirement that the fractional polarization was obtained with at least 3 pixels within each emitting region in each frequency. The error bar indicates the standard deviation of the fractional polarization for the pixels. We found that the fractional polarization of the radio relic decreases from ~35%
that weak polarized emission exists at the X band, but we did not detect the accurate polarized intensity due to low sensitivity.

4.4 Faraday RM

Faraday RM is defined by the Faraday rotation of the linear polarization as

$$\phi = \phi_0 + \phi_{\lambda^2}, \quad \lambda = 2$$

where $\phi$ is the observed polarization angle in units of rad, and $\phi_0$ is the intrinsic polarization angle in rad. RM is given by

$$\text{RM} \approx \frac{812}{\mu} \int n_e B \sigma_{\lambda^2} dl,$$

in rad m$^{-2}$, where $n_e$ is the thermal electron density in cm$^{-3}$, $B$ is the magnetic fields parallel to the line of sight in $\mu$G, and $l$ is the path length in kpc.

The RM map was created according to the linear relation between $\phi$ and $\lambda^2$ in equation (2). We used the polarization angle images of $47\alpha$ and $15\alpha$ resolutions to analyze the radio relic and the individual polarized sources. We calculated RM only in the pixels which satisfy the following conditions: the flux densities of the Stokes $I$, $Q$, and $U$ are all above $3\sigma$ significance, and the pixels satisfying the first condition are available from at least four frequencies. The RM map of Abell 2256 is shown in figures 6 and 7.

To make sure that our RMS based on a linear fit between $\phi$ and $\lambda^2$ are reasonable, we examined the $\phi$-$\lambda^2$ relations toward the radio relic, Source A, and Source B. Figure 8 shows some examples for the positions inside them (see figures 6 and 7). We confirmed that the linear relation is roughly satisfied for the radio relic, Source A, and Source B. We also detected the RMs from Source C but did not use these RMs, since the polarized emission from Source C is not significant at the X band due to low sensitivity (see subsection 4.3).

We calculated the average, (RM), and the standard deviation of RM, $\sigma_{\text{RM}}$, for the radio relic, Source A, and Source B. The results are listed in table 3. We also show the results for the radio relic reported by Clarke and Ensslin (2006). Our results for the radio relic and Source B are broadly consistent with the previous estimates for the radio relic. In contrast, Source A has substantially smaller (RM) and much larger $\sigma_{\text{RM}}$ compared to the other positions. Murgia et al. (2004) reported that the simulated $\text{rms}/\sigma_{\text{RM}}$ ratio depends only on the magnetic field power spectrum slope, and it has a considerable scatter. We consider that the smaller (RM) and larger $\sigma_{\text{RM}}$ could be related to the magnetic field fluctuation in the cluster.
5 Discussion

5.1 Magnetic-field strengths in the radio relic

We calculated the magnetic field strengths of the radio relic in Abell 2256 using the revised equipartition formula from Beck and Krause (2005). The total equipartition magnetic field strength $B_t$ is given by

$$B_t = \left[ \frac{4\pi(1 - 2\alpha)(K_0 + 1)I_0E_1^{1-2\alpha}(\nu/2c_1)^{-\alpha}}{(-2\alpha - 1)c_2(\alpha)l_{c_4}(i)} \right]^{1/(3-\alpha)}, \quad (4)$$

Table 3. Average and standard deviation of RM.

| Target  | ⟨RM⟩* | σ_{RM}* | Reference            |
|---------|--------|----------|----------------------|
| Relic   | −44    | 7        | Clarke and Ensslin (2006) |
| Relic   | −34.5  | 6.2      | this work            |
| Source A| −24.9  | 63.5     | this work            |
| Source B| −34.1  | 10.5     | this work            |

*⟨RM⟩ and σ_{RM} are the average and standard deviation of RM, respectively.

Fig. 6. RM distribution of the Abell 2256 with the intrinsic B-vector. It is also overlaid with contours of the total intensity map at 2051 MHz in the JVLA C array configuration drawn at (−3, 3, 6, 12, 24, 48, 96, 192) × 201.9 µJy beam$^{-1}$ (3.432 × 10$^{-23}$ W m$^{-2}$ Hz$^{-1}$ sr$^{-1}$), convolved with a circular Gaussian beam with a FWHM of 47′′. The numbers represent the positions chosen in figure 8. (Color online)

Fig. 7. RM distribution of Sources A, B, and C. It is also overlaid with contours of the total intensity map at 8051 MHz in the JVLA C array configuration drawn at (−3, 3, 6, 12, 24, 48, 96, 192) × 48.4 µJy beam$^{-1}$ (7.976 × 10$^{-23}$ W m$^{-2}$ Hz$^{-1}$ sr$^{-1}$), convolved with a circular Gaussian beam with a FWHM of 15′.1. (Color online)

Fig. 8. Sample plots of the polarization angle $\phi$ against $\lambda^2$ for different positions in Abell 2256. Each position is shown in figures 6 and 7.
where $B_i$ is in units of G, $\alpha$ the synchrotron spectral index, $K_0$ the ratio of the number densities of protons and electrons, $I_v$ is the synchrotron intensity at frequency $v$, $E_p$ is the proton rest energy, and $l$ the path length through the radio relic. The constants $c_1$, $c_2$, $c_3$, and $c_4$ are defined as

$$c_1 = \frac{3e}{4\pi mc^2} = 6.26428 \times 10^{18} \text{ erg}^{-2} \text{s}^{-1} \text{G}^{-1}$$

$$c_2 = \frac{1}{4c_1} \left( \frac{\gamma + 7/3}{\gamma + 1} \right) \Gamma[(3\gamma - 1)/12]\Gamma[(3\gamma + 7)/12]$$

$$c_3 = \sqrt{3}e^3 \left( \frac{4\pi mc^2}{\sqrt{\sigma}} \right) = 1.86558 \times 10^{-23} \text{ erg}^{-2} \text{s}^{-1}$$

$$c_4 = [\cos(i)]^{(\gamma+1)/2},$$

where $e$ is the elementary charge, $m_e$ the electron mass, $c$ the speed of light, $\gamma$ the spectral index of the electron energy spectrum which relates to the synchrotron spectral index $\alpha = -(\gamma - 1)/2$, and $i$ the inclination of the magnetic fields with respect to the sky plane (Beck & Krause 2005).

We obtained an averaged synchrotron intensity $I_v$ of $6.27 \times 10^{-19}$ erg s$^{-1}$ cm$^{-2}$ Hz$^{-1}$ ster$^{-1}$ at 2051 MHz in the radio relic where the fractional polarization was measured (the dashed-frame region in figure 1). Since we could not measure the accurate spectral index from our JVLA data due to the missing flux (see subsection 4.2), we adopted the spectral index of $\alpha = -0.81$ measured by van Weeren et al. (2012). We assumed a ratio of the proton–electron number densities of $K_0 = 100$, which is consistent with the acceleration process of cosmic ray electrons for secondary particles and turbulence. Since the radio relic has a 25 kpc thickness at the minimum (Owen et al. 2014) and covers $\sim 1125$ kpc $\times$ 520 kpc (Clarke & Ensslin 2006), we assumed path length $l$ values of 25 kpc and 1125 kpc. For the inclination, we assumed a mid value of $i = 45^\circ$.

We obtained the total equipartition magnetic field strengths of the radio relic of $\sim 5.0 \mu$G with $l=25$ kpc and $\sim 1.8 \mu$G with $l=1125$ kpc. These values of the order of micro-Gauss are consistent with the values of $1.5^{+0.9}_{-0.6} \mu$G and $3.3^{+2.0}_{-1.6} \mu$G with $\alpha = -1.25$ found by using the classical and the hadronic minimum energy conditions, estimated by Clarke and Ensslin (2006), respectively.

To obtain the uniform and random magnetic field strengths, we can use the relationship between the observed fractional polarization $p$ and the degree of uniformity $f$ of the magnetic fields (Segalovitz et al. 1976)

$$p = \frac{3\gamma + 3}{3\gamma + 7} \left[ 1 + \frac{(1 - f)\pi^{1/2}\Gamma[(\gamma + 5)/4]}{2f(\sin \theta)^{(\gamma+1)/2}\Gamma[(\gamma + 7)/4]} \right]^{-1},$$

where $\Gamma$ is the gamma function and $\theta$ is the angle between the line of sight and the uniform magnetic field. The ratio between the strength of the uniform magnetic field $B_u$ and total magnetic field $B_i$ is given by $B_u/B_i = f^2/(\gamma + 1)$ (Beck 1982). The random magnetic-field strength $B_r$ is $B_r = (B_i^2 - B_u^2)^{1/2}$.

In order to avoid the effect of the depolarization, we used the fractional polarization of high frequency, which is $p = 0.36$ at 3563 MHz. We also assumed the mid value of $\theta = 45^\circ$.

We obtained the degree of uniformity of $f \sim 0.56$, which indicates that there are uniform magnetic fields in the radio relic with random magnetic fields. The uniform magnetic-field strengths are $\sim 3.7 \mu$G with $l=25$ kpc and $\sim 1.3 \mu$G with $l=1125$ kpc, and the random magnetic field strengths are $\sim 3.4 \mu$G with $l=25$ kpc and $\sim 1.2 \mu$G with $l=1125$ kpc. However, $f \sim 0.56$ could be a larger value because equation (9) does not take into account the depolarization. We can see the ordered intrinsic magnetic fields over the beam size of $\sim 52$ kpc in figure 6 against $f \sim 0.56$. This could indicate that there are random magnetic fields along the line of sight toward the radio relic and that the depolarization occurred.

### 5.2 Magnetic-field strengths in the intracluster space

We estimated magnetic-field strengths in Abell 2256 using a traditional cell model (Lawler & Dennison 1982; Tribble 1991). In the model, we consider cells along the line of sight from the observer to the polarized source, and each cell consists of uniform size, uniform electron density, and uniform magnetic-field strength with a single scale and random field orientation. In this case, distribution of RM becomes Gaussian with a zero mean, and the variance of RM is given by

$$\sigma_{\text{RM}}^2 = \frac{812^2 \Lambda_B}{3} \int (n_e B_i)^2 \, dl,$$

where $\Lambda_B$ is the cell size in kpc. For the distribution of thermal electron density, we adopt the $\beta$-model:

$$n_e = n_0 \left( 1 + \frac{r^2}{r_c^2} \right)^{-3\beta/2},$$

where $n_0$ is the central electron density in cm$^{-3}$, $r$ is the distance from the X-ray center in kpc, and $r_c$ is the core radius in kpc. Adopting equation (11) into equation (10), we obtain

$$\sigma_{\text{RM}} = \frac{K B n_0 r_c^{1/2} \Lambda_B^{1/2}}{(1 + r^2/r_c^2)^{6\beta-1/4}} \sqrt{\frac{\Gamma(3\beta - 0.5)}{\Gamma(3\beta)}},$$

where $K$ is a constant.
where $B = \sqrt{3B_\parallel}$ considering isotropic fields, and $\Gamma$ is the Gamma function. $K$ is a constant which depends on the position of a backside polarized source along the line of sight; $K = 624$ if the source is located behind the cluster and $K = 441$ if the source is located halfway along the cluster (Feretti et al. 1995; Felten 1996; Govoni et al. 2010). Therefore, with $n_0$, $r$, $r_c$, $\beta$, and $\Lambda_B$, equation (12) leads the magnetic-field strength along the line of sight.

The adopted parameters and results are shown in table 4. Here, we consider $\Lambda_B$ from 5 to 20 kpc according to a dynamo theory (Cho & Ryu 2009). We obtained that the field strength toward Source A is $B = 1.26 \mu G$ with $\Lambda_B = 5$ kpc and $B = 0.63 \mu G$ with $\Lambda_B = 20$ kpc, and the field strength toward Source B is $B = 0.21 \mu G$ with $\Lambda_B = 5$ kpc and $B = 0.11 \mu G$ with $\Lambda_B = 20$ kpc.

5.3 Contribution of the Galactic magnetic fields

Table 3 suggests a shift of the mean of the RM from 0 rad m$^{-2}$ to about $-30$ rad m$^{-2}$ toward the Abell 2256 field. Figure 9 shows the histogram of RM in the Abell 2256 field. We obtained 355 pixels in figure 6, and they actually indicate a histogram centered at around $-36$ rad m$^{-2}$.

We consider that the shift is due to the Galactic contribution. In order to estimate the Galactic contribution to the Abell 2256 field, we examined the RM values of 28 polarized sources within $6^\circ$ around Abell 2256 using the all-sky RM catalogue (Taylor et al. 2009), and calculated an average of their RMs. We found that the average of the RMs for 28 polarized sources is $-30.0$ rad m$^{-2}$ with a standard deviation of 16.7 rad m$^{-2}$. The average is broadly consistent with the means of RM for the radio relic, Source A, and Source B.

5.4 Steplike variations of the fractional polarization

The fractional polarization of the radio relic varies at $\sim 3$ GHz and around $0.4$–$1.3$ GHz, and gives steplike variations as shown in figure 4. Such a decrease of the fractional polarization toward low frequencies implies that depolarization takes place. If that is the case, we could investigate turbulent magnetic fields along the line of sight, as introduced in section 1. We can analytically model the fractional polarization in the cases of the EFD and IFD using the Burn’s law (Burn 1966). The fractional polarizations of EFD and IFD can be written as

$$p_{\text{EFD}} = p_0 e^{-S},$$

and

$$p_{\text{IFD}} = p_0 \frac{1 - e^{-S}}{S},$$

respectively, where $p_0$ is the intrinsic fractional polarization and $S = 2\sigma_{\text{RM}}^2 \lambda^3$; $\sigma_{\text{RM}}$ is the standard deviation of RM within the field of consideration, and $\lambda$ is the wavelength. The Burn’s law is, however, a function which does not produce a steplike variation of the fractional polarization. Figure 4 shows an example of the EFD, and clearly indicates that a single depolarization component is not enough to explain the observed steplike variations of the radio relic.

In addition to the depolarization, we suspect that the missing flux also affects the fractional polarization above $\sim 3$ GHz. If there is a large diffuse source larger than the LAS, we only detect the compact diffuse source smaller than the LAS. If the fractional polarization of the compact diffuse source is larger than that of the large diffuse source, then the fractional polarization could increase as the observing...
frequency increases. Therefore, the variation of the fractional polarization at 3–3.5 GHz may be partly due to the missing flux.

Since the fractional polarizations of Sources A and B, which are located near the radio relic, does not show the variation at ∼ 3 GHz, its origin should be significant for the emission from the radio relic. Indeed, because Sources A and B are compact sources, the effect of the missing flux is expected to be insignificant for the emissions from Sources A and B. Thus, to clarify the effect of the missing flux on the fractional polarization, single-dish observations at 3–3.5 GHz should be performed in future.

On the other hand, the variation of the fractional polarization expected at around ∼ 1 GHz could not be explained by the missing flux, since the LAS at ∼ 1 GHz or less is sufficiently larger than the the major axis of the radio relic.

5.5 Depolarization toward the radio relic

Hereafter, although the effect of the missing flux could be significant, we do not exclude the data above ∼ 3 GHz in our analyses. This aims at studying the case that the fractional polarization at ∼ 3 GHz is affected by the depolarization. Again, we suggest performing single-dish observations at 3–3.5 GHz in the future, to clarify the effect of the missing flux on the fractional polarization.

Figure 9 implies that the histogram of RM follows the Gaussian distribution, which is consistent when considering that the beam depolarization is induced by random (turbulent) magnetic fields (Lawler & Dennison 1982). As already described in subsection 5.4 and figure 4, it is hard to reproduce the observed fractional polarization of the radio relic with the Burn’s law with a single depolarization component. Therefore, we consider models with multiple depolarization components along the line of sight toward the radio relic. A weakness of adopting the Burn’s law is that we cannot extract information about magnetic fields. In order to understand the nature of depolarization as well as that of magnetic fields, we carried out simulations of depolarization using simple random-field models.

We calculated the intensity of the polarization which passed depolarization components. The components consist of grids, and each grid at the three-dimensional coordinates (X, Y, Z) = (N_X, N_Y, N_Z) has single-scale random magnetic fields with uniform strength. The electron density is uniform in the components. The polarized intensity in each cylinder at (x, y) is given by

\[ P(x, y) = \int p_0 e^{i2\phi(x,y)}dz, \]  

where \( p_0 \) is the intrinsic fractional polarization and \( e \) is the synchrotron emissivity at a depth along the line of sight.

\[ \phi(x, y) = \phi_0 + 812 \sum_{i=1}^{N_X} n_0 B_1 \Delta \lambda^2, \]  

where \( \phi_0 \) is the intrinsic polarization angle in rad, \( n_0 \) the thermal electron density in cm\(^{-3}\), \( B_1 \) the magnetic field strength parallel to the line of sight in \( \mu G \), \( \Delta \lambda \) the size of cells in kpc, and \( \lambda \) the observation wavelength in units of m. We obtain the polarized intensity \( P \) through the \( N_X \times N_Y \) cylinders as

\[ P = \sum_{x=1}^{N_X} \sum_{y=1}^{N_Y} P(x, y). \]

Our depolarization models include the following parameters: the magnetic-field strength of a cell, \( B \), the electron density, \( n_e \), the size of the cells, \( \Delta l \), the numbers of cells in the directions of the X, Y, and Z axes, \( (N_X, N_Y, N_Z) \), and the intensity of the polarized source or emitting depolarization source. Adapting suitable parameters, we can control the optimum frequency (Arshakian & Beck 2011) and the fractional polarization.

We consider two components, EFD and IFD, and develop two two-component depolarization models, EFD+IFD and IFD+IFD (figure 10). The order of the components along the line of sight from the observer is as follows:

- in the EFD+IFD model, we allocate the components in the order of a depolarization component, a polarized source, a depolarization component, and a polarized source;
- in the IFD+IFD model, we allocate the components in the order of an emitting depolarization component, and another emitting depolarization component.

Figure 11 shows the best-fitting lines for the two models. Each parameter is listed in table 5. The EFD+IFD and

![Fig. 10. (a) Depolarization model of EFD+IFD, which has two non-emitting depolarization components with two polarized sources. (b) Depolarization model of IFD+IFD, which has two emitting depolarization components. In each model, the cells constituting the depolarization components have single-scale random magnetic fields with uniform strength and uniform electron densities. (Burn 1966; Gardner & Whiteoak 1966; Sokoloff et al. 1998). The polarization angle \( \phi(x, y) \) is given by

\[ \phi(x, y) = \phi_0 + 812 \sum_{i=1}^{N_X} n_0 B_1 \Delta \lambda^2, \]  

where \( \phi_0 \) is the intrinsic polarization angle in rad, \( n_0 \) the thermal electron density in cm\(^{-3}\), \( B_1 \) the magnetic field strength parallel to the line of sight in \( \mu G \), \( \Delta \lambda \) the size of cells in kpc, and \( \lambda \) the observation wavelength in units of m. We obtain the polarized intensity \( P \) through the \( N_X \times N_Y \) cylinders as

\[ P = \sum_{x=1}^{N_X} \sum_{y=1}^{N_Y} P(x, y). \]  

\[ P(x, y) = \int p_0 e^{i2\phi(x,y)}dz, \]  

where \( p_0 \) is the intrinsic fractional polarization and \( e \) is the synchrotron emissivity at a depth along the line of sight.

\[ \phi(x, y) = \phi_0 + 812 \sum_{i=1}^{N_X} n_0 B_1 \Delta \lambda^2, \]  

where \( \phi_0 \) is the intrinsic polarization angle in rad, \( n_0 \) the thermal electron density in cm\(^{-3}\), \( B_1 \) the magnetic field strength parallel to the line of sight in \( \mu G \), \( \Delta \lambda \) the size of cells in kpc, and \( \lambda \) the observation wavelength in units of m. We obtain the polarized intensity \( P \) through the \( N_X \times N_Y \) cylinders as

\[ P = \sum_{x=1}^{N_X} \sum_{y=1}^{N_Y} P(x, y). \]  

\[ P(x, y) = \int p_0 e^{i2\phi(x,y)}dz, \]  

where \( p_0 \) is the intrinsic fractional polarization and \( e \) is the synchrotron emissivity at a depth along the line of sight.
IFD+IFD models can nicely reproduce the fractional polarization of the radio relic. We confirmed that we need two depolarization components to produce the steplike variation of the fractional polarization. In addition, we found that the $\sigma_{\text{RM}}$ of the foreside depolarization component viewed from the observer has to be smaller than the that of the backside depolarization component.

We could interpret the two depolarization components of the models as follows. The foreside depolarization component viewed by the observer could be the magneto-ionic plasma in the cluster or the Galaxy. The backside depolarization component should be magneto-ionic plasma inside the radio relic, according to the fact that the fractional polarization of Sources A and B does not show the same variation as the fractional polarization of the radio relic. Otherwise, if the cluster or the Galaxy depolarizes the relic’s polarization, the fractional polarizations of Sources A and B should also show the steplike variations. However, as seen in figure 5, the fractional polarizations of Sources A and B are nearly constant. The $\sigma_{\text{RM}}$ for the radio relic is larger than that for the cluster or the Galaxy.

Although we can explain observed fractional polarization of the radio relic with our depolarization models as presented in this section, we should note that there should be a more realistic model to match the observational data. For instance, Murgia et al. (2004) shows a realistic model obtained by numerical simulations, including the magnetic-field strength, radial profile, and magnetic-field power spectrum of clusters of galaxies, which is successfully applied to individual clusters (e.g., Govoni et al. 2006; Guidetti et al. 2008; Bonafede et al. 2010; Vacca et al. 2012).

### 5.6 Faraday tomography

We also carried out Faraday tomography to make sure of the existence of multiple components toward the radio relic. We apply the so-called QU-fit, in which a model is fitted with the data in Stokes $Q$ and $U$ spaces (see, e.g., Ideguchi et al. 2014). We perform the QU-fit using a Markov chain Monte Carlo (MCMC) approach, so as to explore the best set of model parameters. As for structures of Faraday components, we consider a delta function or a Gaussian. Here, the delta function consists of the three parameters: the Faraday depth $\phi$, the amplitude, and the intrinsic polarization angle $\chi_0$; the Gaussian function consists of these three parameters plus the width of the Gaussian (the standard deviation of the normal distribution). We consider five models—one delta function, one Gaussian, two delta functions, two Gaussians, and one delta function plus one Gaussian. We then find the best model according to the Bayesian information criterion (BIC). We also check the reduced chi-square (RCS) of the best fit for each model.

The results are shown in figure 12 and table 6. We find that one-component models poorly reproduce the observed $Q$ and $U$, and apparently the two-component models are better fitted with the data. Actually, two-component models dramatically improve BICs and RCSs (table 6). We do not conclude which model is best, since BICs of the two-component models are similar to each other. RCSs of the two-component models are a bit far from unity. To improve the fit, data below $\sim 1500$ MHz are essential.

The results fitted with the two-component models commonly suggest that there are components at the Faraday depth $\phi\sim -50$ rad m$^{-2}$. This would be the radio relic, since the depth and the thickness are respectively close to the average and the standard deviation of RM for the radio relic (table 3).

### Table 5. Parameters for the depolarization models.

| Model  | Component | $B$ (\$\mu$G) | $n_e$ (10$^{-3}$ cm$^{-3}$) | $\Delta l$ (kpc) | $N_X \times N_Y$ (kpc $\times$ kpc) | $N_Z$ (kpc) | Intensity | $\sigma_{\text{RM}}$ (rad m$^{-2}$) |
|--------|-----------|---------------|-----------------|-----------------|-----------------|----------------|------------|-------------------|
| EFD+EFD| Foreside  | 0.2           | 1.0             | 1$^*$           | 50 $\times$ 50$^*$ | 600            | 1          | 3.2               |
|        | Backside | 2.3           | 3.0             |                 |                 | 600            | 3          | 111               |
| IFD+IFD| Foreside  | 0.2           | 1.0             | 5$^*$           | 50 $\times$ 50$^*$ | 500            | 1          | 4.1               |
|        | Backside | 2.3           | 3.0             |                 |                 | 600            | 3.5        | 164               |

*We assume 50 $\times$ 50 kpc since the beam size of 47$^\circ$ corresponds to $\sim$ 52 kpc.*
Table 6. The reduced chi-square (RCS), the Bayesian information criterion (BIC), and best-fitting values and 1σ confidence regions for model parameters in the QU-fit.

| Model          | RCS  | BIC   | φ   | Amp.  | χ₀  | Width |
|----------------|------|-------|-----|-------|-----|-------|
| Delta function | 21.2 | 645.2 | −41.55 ±0.745 | 0.42 ±0.008 | −0.55 ±0.012 | 1.05 ±0.005 |
| Gaussian       | 21.2 | 648.6 | −41.53 ±0.736 | 0.42 ±0.008 | −0.55 ±0.012 | 1.05 ±0.005 |
| Two deltas     | 3.0  | 110.2 | −40.87 ±0.626 | 21.23 ±1.118 | 0.12 ±0.003 | 0.04 ±0.003 |
| Two Gaussian   | 2.2  | 93.3  | −40.36 ±0.649 | 21.17 ±1.118 | −0.55 ±0.012 | 0.04 ±0.003 |
| Delta + Gaussian| 2.6 | 100.9 | −50.35 ±0.322 | 12.11 ±1.270 | 0.55 ±0.069 | 0.16 ±0.045 |

6 Conclusions

We reported on new polarimetry results of Abell 2256 with JVLA at the S band (2051–3947 MHz) and X band (8051–9947 MHz) in the C array configuration. We made images of the Stokes I, Q, and U, with 47″ and 15″ resolution. At the S band, we detected the significant polarized emission from the radio relic, Source A, and Source B. At the X band, we detected the significant polarized emission only from Source A.

The total 2051 MHz flux of the radio relic is 286 mJy which includes the flux from the tail of Source C. The total flux is substantially smaller than ~330 mJy, an expectation from previous L band observations under an assumption of the spectral index α = −0.81. The estimated upper limit of the total 2051 MHz flux of the radio halo is ~49 mJy assuming that the radius of the radio halo emission is ~63 kpc and the upper limit of the flux density is 606 μJy beam⁻¹. The estimated flux is also smaller than ~66 mJy, an expectation from previous L band observations with an assumption of the spectral index α = −1.1.

We examined the missing flux caused by the LAS of our observations. Actually, the scales of the major axis of the radio relic and halo are 1014″ and 732″ (Clarke & Ensslin 2006) on the sky, respectively, while the LAS is 970″ at 1.5 GHz or 490″ at 3.0 GHz in the JVLA C array configuration.

We obtained RMs of the radio relic, Source B, and Source A. The mean and standard deviation of RM are ⟨RM⟩ = −3.45 rad m⁻² and σRM = 6.2 rad m⁻² in the radio relic, ⟨RM⟩ = −24.9 rad m⁻² and σRM = 65.5 rad m⁻² in Source A, and ⟨RM⟩ = −34.1 rad m⁻² and σRM = 10.5 rad m⁻² in Source B.

We calculated the magnetic-field strengths in the radio relic and the intracluster space in Abell 2256. For the radio relic, we calculated the magnetic-field strength using the revised equipartition formula, and the fractional polarization. The total magnetic-field strength is ~5.0 μG with l = 25 kpc and ~1.8 μG with l = 1125 kpc, the uniform magnetic-field strength is ~3.7 μG with l = 25 kpc and ~1.3 μG with l = 1125 kpc, and the random magnetic-field strength is ~3.4 μG with l = 25 kpc and ~1.2 μG with l = 1125 kpc. For the intracluster space, we calculated the magnetic-field strengths using σRM. The magnetic-field strength along the line of sight toward Source A is B ~ 1.26 μG with ΛA = 5 kpc and B ~ 0.63 μG with ΛB = 20 kpc. The magnetic-field strength along the line of sight toward Source B is B ~ 0.21 μG with ΛA = 5 kpc and B ~ 0.11 μG with ΛB = 20 kpc.

We inferred that the shift of the mean of the RM from 0 rad m⁻² to about ~30 rad m⁻² toward the Abell 2256 field is due to the Galactic contribution since the averaged RM values of 28 polarized sources within 6° around...
Abell 2256 is broadly consistent with the means of RM for the radio relic, Source A, and Source B.

We found that the fractional polarization of the radio relic remains about 20% between 1.3–3 GHz and increases above 3 GHz. The Burn’s law with a single depolarization component cannot reproduce the observed steplike fractional polarization spectrum of the radio relic. This may be due to the missing flux and/or depolarization.

Our simulations of depolarization, which allow us to know three-dimensional position information of the magneto-ionic plasma from the fractional polarization, indicated that two-component depolarization models can explain the steplike variations of the fractional polarization. Furthermore, we found that the standard deviation of RM for the foreside component viewed from the observer should be smaller than that for the backside component. The existence of two components was also suggested from Faraday tomography.

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