Evidence for Strong Intracluster Magnetic Fields in the Early Universe

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Abstract

The origin of magnetic fields in clusters of galaxies is still a matter of debate. Observations for intracluster magnetic fields over a wide range of redshifts are crucial to constrain possible scenarios for the origin and evolution of the fields. Differences in Faraday rotation measures (RM) of an embedded double radio source, i.e., a pair of lobes of mostly Fanaroff–Riley type II radio galaxies, are free from the Faraday rotation contributions from the interstellar medium inside the Milky Way and the intergalactic medium between radio galaxies and us, and hence provide a novel way to estimate average magnetic field within galaxy clusters. We have obtained a sample of 627 pairs whose RMs and redshifts are available in the most updated RM catalogs and redshift databases. The RM differences of the pairs are derived. The statistically large RM differences for pairs of redshifts \( z > 0.9 \) indicate that intracluster magnetic fields are as strong as about \( 4 \mu \text{G} \). Such strong magnetic fields in the intracluster medium at the half age of the universe, comparable to the intracluster field strength in nearby galaxy clusters, pose a challenge to the theories of the origin of cosmic magnetic fields.

Unified Astronomy Thesaurus concepts: Extragalactic magnetic fields (507); Intracluster medium (858)

Supporting material: machine-readable tables

1. Introduction

In the past few decades, magnetic fields in galaxy clusters have been observed and studied (see review of Carilli & Taylor 2002; Govoni & Feretti 2004; Ferrari et al. 2008; Feretti et al. 2012; Han 2017). The magnetic fields are crucial for a comprehensive understanding of radio emission from the diffuse intracluster medium (ICM). The presence of diffuse radio halos and relics in galaxy clusters is direct evidence for magnetic fields in the ICM (e.g., Giovannini et al. 2009; van Weeren et al. 2010). Under the minimum energy hypothesis or equipartition approach, magnetic fields permeating the ICM are roughly estimated from the radio emission intensity maps with a strength of a few \( \mu \text{G} \) (e.g., Govoni & Feretti 2004).

The statistical study of Faraday rotation measures (RM) of radio sources within or behind galaxy clusters is an alternative way to investigate magnetic fields in galaxy clusters (e.g., Kim et al. 1991; Clarke et al. 2001; Bonafede et al. 2010, 2013; Govoni et al. 2010; Pratley et al. 2013; Böhinger et al. 2016). When a linearly polarized electromagnetic wave signal travels through a magnetized plasma, the plane of polarization is rotated by an angle \( \Delta \psi \) proportional to the wavelength squared, \( \lambda^2 \), i.e.,

\[
\Delta \psi = \psi - \psi_0 = \text{RM} \cdot \lambda^2,
\]

where \( \psi \) and \( \psi_0 \) are the measured and intrinsic polarization angle, and RM is the rotation measure, which is an integrated quantity of the product of the thermal electron density \( n_e \) and magnetic field strength \( B \) from the source to us, most effectively probing the fields along the line of sight. For a polarized radio source at redshift \( z_s \), RM is expressed by

\[
\text{RM} = 812 \int_{z_s}^{\infty} n_e B \cdot dl = 812 \int_{z_s}^{\infty} n_e(z)B_0(z) \frac{dl}{(1+z)^2} dz. \tag{2}
\]

The electron density \( n_e \) is in \( \text{cm}^{-3} \), the magnetic field is a vector \( B \) (and the magnetic field along the line of sight \( B_0 \) in units of \( \mu \text{G} \)), and \( dl \) is the unit vector along the light path toward us in units of kiloparsecs. The comoving path increment per unit redshift \( \frac{dz}{dz} \) is in kiloparsecs, and \((1+z)^2\) reflects the change of wavelength at redshift \( z \) over the path transformed to the observer’s frame.

The observed rotation measure, \( \text{RM}_{\text{obs}} \), is a sum of the foreground Galactic RM (GRM) from the Milky Way, the RM from the intergalactic medium \( \text{RM}_{\text{IGM}} \), and the RM intrinsic to the source \( \text{RM}_{\text{in}} \), i.e.,

\[
\text{RM}_{\text{obs}} = \text{GRM} + \text{RM}_{\text{IGM}} + \text{RM}_{\text{in}}. \tag{3}
\]

When studying RMs of sources at a cosmological distance, one has to account for RM contributions from all kinds of intervening media along the line of sight. For most extragalactic radio sources, the foreground GRM is the dominant contribution. If the foreground GRM is not assessed properly, it is impossible to get small extragalactic contributions. There have been many efforts to investigate the foreground GRM (e.g., Han et al. 1997; Oppermann et al. 2012; Xu & Han 2014a; Oppermann et al. 2015). The RM values intrinsic to a radio source \( \text{RM}_{\text{in}} \) at a redshift of \( z_s \) are reduced by a factor of \((1+z_s)^2\) due to a change of \( \lambda \) when the values are transformed to the observer’s frame. The typical distribution of source-intrinsic RMs of distant quasar-like sources is only several \( \text{rad} \text{m}^{-2} \) (Banfield et al. 2014). The RMs from the intergalactic medium, \( \text{RM}_{\text{IGM}} \), may have several contributors.
such as RMs from the cosmic webs, intervening galaxy halos, and ICM on the line of sight. The RM from the cosmic webs might be traced by the Lyα forest, and there have been some simulations of their contribution (e.g., Blasi et al. 1999; Akahori & Ryu 2010, 2011; Pshirkov et al. 2016). It is very small (∼1–2 rad m⁻²) and can hardly be detected from the present available data (Xu & Han 2014b; O’Sullivan et al. 2019, 2020). The excess of RM from galaxy halos or protogalactic environments has been studied by intervening absorbers like Mg II absorption lines (e.g., Bernet et al. 2008; Farnes et al. 2014, 2017). Joshi & Chand (2013) and Malik et al. (2020) obtained an increase in the distribution deviation of around 8 rad m⁻² for quasars with Mg II absorption lines. The statistics of the RMs of polarized radio sources located inside or behind galaxy clusters (e.g., Kim et al. 1991; Clarke et al. 2001; Bonafede et al. 2010, 2013; Govoni et al. 2010; Pratley et al. 2013; Böhringer et al. 2016) show the RM excess for the contributions from the ICM with an amplitude from a few to a few tens of rad m⁻² (Clarke et al. 2001; Govoni et al. 2010; Xu & Han 2014b).

It is now well established that the magnetic fields are ubiquitous in the ICM (e.g., Carilli & Taylor 2002). The intracluster magnetic fields are dominated by turbulent fluctuations over a range of scales. The field strength decreases from the central regions to the outskirts. The spatial power spectrum is well represented by a Kolmogorov power spectrum (Bonafede et al. 2010), which can be simulated by fluctuation dynamo (Bhat & Subramanian 2013). Turbulent magnetic fields with a coherence length of a few kiloparsecs are indicated by RM dispersion studies of polarized radio sources (e.g., Kim et al. 1991; Govoni et al. 2010) and found in both relaxed and merging clusters regardless of dynamic state (Clarke et al. 2001; Böhringer et al. 2016; Stasyszyn & de los Ríos 2019). Coherent RMs of radio relics reveal large-scale (>100 kpc) compressed magnetic fields (Owen et al. 2014; Kierdorf et al. 2017). The organized magnetic fields are responsible for the systematic RM gradient over the lobes of radio galaxies (e.g., Taylor & Perley 1993). The ordered net magnetic fields can be considered as the large-scale fluctuations at the outer scale of turbulent magnetic fields where the energy is injected (Vacca et al. 2010). The magnetic fields close to the center of the galaxy clusters are more disturbed and tangled with a strength of a few μG, while those near the outskirts are more representative of the large-scale fluctuation component with a field strength of an order of magnitude smaller (Ryu et al. 2008).

The RM differences of a pair of lobes from an embedded FR II radio galaxy (Fanaroff & Riley 1974) are the best probes for the magnetic fields in the ICM and their redshift evolution, because both the foreground GRM and the RM contributions on the way to the cluster in all intervening galactic and intergalactic media can be diminished, as depicted in Figure 1. The real physical pair of lobes is the bulk of radio emission from a galaxy on opposite sides, formed when central active galactic nuclei produce two opposite collimated jets that drive relativistic electrons running in magnetic fields into the lobes to generate synchrotron emission (Blandford & Rees 1974). The environs of the host galaxy must be rich in gas. The jets travel through the interstellar medium of the host galaxy and stay supersonic to a great distance to push their way through the external medium where a shock front is formed as shown by hot spots. The ends of the jets move outward much more slowly than material flows along the jets. A backflow of relativistic plasma deflected at the end of the jets forms the lobes. The gaseous environment they inhabit is very important to provide a working surface for the jets to terminate; therefore, the ICM provides an ideal environment for producing FR II radio sources. The observed radio radiation from FR II–type radio sources is often highly linearly polarized (e.g., Bonafede et al. 2010). The Laing–Garrington effect strongly suggests the existence of intracluster magnetonionic material surrounding the radio sources causing asymmetry in the polarization properties of double radio sources with one jet (Garrington et al. 1988; Laing 1988). Many double radio sources have been detected from galaxies at low redshifts (z < 0.3), and a large number of sources have been found in dense cluster-like gaseous environments at higher redshifts (Yates et al. 1989; Hill & Lilly 1991; Wan & Daly 1996; Pentericci et al. 2000; Miley & De Breuck 2008).

It is not known if there is any evolution of intracluster magnetic fields at different cosmological epochs. Statistical studies of the redshift evolution of net RMs contributed by the ICM is the key to the puzzle. Cosmological simulations by Akahori & Ryu (2011) predicted the redshift dependence of extragalactic RMs caused by the intergalactic medium. Contributions by galaxy clusters, however, could not be properly modeled given the cell size in their simulations. There have been a number of works to investigate the redshift evolution of extragalactic RMs (Hammond et al. 2012; Neronov et al. 2013; Xu & Han 2014b; Pshirkov et al. 2015; Lamee et al. 2016; O’Sullivan et al. 2017), which were generally made for the whole contribution on the path from the observer to the sources. A marginal dependence of redshift was found. In the early days, the RM differences were also studied for a small number of double radio galaxies at low Galactic latitudes to investigate the enhanced turbulence in the interstellar medium (Simonetti & Cordes 1986; Pedelt et al. 1989; Lazio et al. 1990; Clegg et al. 1992; Minter & Spangler 1996). Athreya et al. (1998) studied 15 radio galaxies at high redshift z > 2 with large RMs and claimed that their RM contributions were likely to be in the vicinity of the radio sources themselves. Goodlet et al. (2004) and O’Sullivan et al. (2017) concluded that no statistically significant trend was found for the RM difference of two lobes against redshift.
Vernstrom et al. (2019) classified a large sample of close pairs and found a significant difference of ~5–10 rad m⁻² between physical (separate components of a multicomponent radio galaxy or multiple RMVs within one of the components) and random pairs, though the redshift dependence of the physical pairs is not evident. O’Sullivan et al. (2020) used a similar method but high-precision RM data from the LOFAR Two-Meter Sky Survey and found no significant difference between the ΔRM distributions of the physical and nonphysical pairs. In fact, the uncertainty of the RM is a very important factor for the evolution investigation. For example, very small RM differences (1–2 rad m⁻²) between the lobes of large radio galaxies at low redshifts can be ascertained with high-precision observations (Banfield et al. 2019; O’Sullivan et al. 2019; Stuardi et al. 2020). The RM differences for a larger sample of pure double radio sources are necessary to further investigate their correlation with redshift.

A real pair of physically associated lobes shown as double radio sources has a small separation and almost the same flux density, which can be found in the NRAO VLA Sky Survey (NVSS; Condon et al. 1998). Taylor et al. (2009) reprocessed the two-band polarization data of the NVSS and obtained two-band RMVs for 37,543 sources. Xu & Han (2014a) compiled a catalog of reliable RMVs for 4553 extragalactic point radio sources. In addition to the previously cataloged RMVs, many new RM data are published in the literature. In this paper, we have classified RM pairs in the NVSS RM data, the compiled catalog and the literature since 2014, and cross-identified available galaxy redshift data to obtain RMVs and redshifts for 627 pairs. We use these data to study the redshift evolution of RM differences. We introduce the RM data in Section 2 and study the distributions of RM differences of pairs in Section 3. Finally, we discuss our results and present conclusions in Sections 4 and 5, respectively.

Throughout this paper, a standard ΛCDM cosmology is used, taking \( H_0 = 100\ h\ km\ s^{-1}\ Mpc^{-1} \), where \( h = 0.7 \); \( \Omega_m = 0.3 \); and \( \Omega_\Lambda = 0.7 \).

2. RM Data of Pairs

We obtain the RM data for a sample of pairs from the NVSS RM catalog (Taylor et al. 2009) and the literature (Xu & Han 2014a, and afterward). We search for real pairs for the two RM data sets separately, since the observation frequencies and resolutions for RM observations are very different. The NVSS radio images are visually inspected to ensure physical pairs.

2.1. The NVSS RM Pairs

In the NVSS RM catalog, RM data and flux density measurements are available for 37,543 sources. Here a “source” is an independent radio emission component, while a galaxy can produce a few radio components, e.g., two unresolved lobes in addition to a compact core of a radio galaxy. We cross-matched the catalog against itself and found 1513 source pairs with a flux density ratio \( S_{\text{large}}/S_{\text{small}} \) less than 1.5 and an angular separation between 10' and 45' (i.e., the angular resolution of the NVSS survey). Flux densities of real pairs from two lobes of radio galaxies are most likely to be consistent with each other because of a similar radio power ejected from the same central black hole. The ratio limit is therefore used to largely exclude false pairs from two physically unrelated sources. The maximum separation of 10' is set for two reasons. The first is that it would be difficult to identify physically related double sources at a larger separation without a clear connection, such as diffuse emission between two sources. Second, the number of physical pairs at larger separations is small. In the sample of Vernstrom et al. (2019), only a few pairs have angular sizes greater than 10'. The minimum separation was set as being the beam size of 45' of the NVSS survey, so that two very close sources can just be resolved. Vernstrom et al. (2019) adopted twice the beam size, i.e., 15', while we found that the number of physical pairs with separation \( \Delta r < 15' \) is more than twice that for pairs with \( \Delta r > 15' \), which is important to get pairs for high-redshift galaxies.

Visual inspection was carried out to identify real physical pairs. We obtain the NVSS image centered on the mean R.A. and decl. of each pair and make a contour map, as shown in Figure 2. For candidates with angular separations \( \Delta r > 3' \), the clear presence of fainter emission connecting the two “sources” is the signature of a real pair, so we get 34 real pairs with \( \Delta r > 3' \). For pairs with a smaller angular separation, we check candidates in the survey coverage area of the VLA Faint Images of the Radio Sky at Twenty centimeters (FIRST; Becker et al. 1995) to verify the true pair. With the experience of classification of real pairs from the NVSS contour maps in the FIRST area, we extrapolate the method to the sources outside the survey area of the FIRST. We notice that physically unrelated pairs are very scarce at much smaller angular separations (Vernstrom et al. 2019; O’Sullivan et al. 2020). We get 1007 real pairs from the NVSS sources in total. Four examples of identified real pairs are shown in Figure 2.
For these 1007 pairs, we search for the redshifts of the host galaxies from several large optical redshift surveys and online databases. First, we cross-match the mean coordinates of RM pairs with the released spectroscopic redshift of 2.8 million galaxies from Data Release 16 of the Sloan Digital Sky Survey (SDSS DR16; Ahumada et al. 2020), and we obtain spectroscopic redshift data for galaxies within 10′′ of the given position for 100 pairs. Second, we get other spectroscopic redshifts from the cross-identification of galaxies in the 6dF Galaxy Survey Redshift Catalogue Data Release 3 (Jones et al. 2009) for 10 pairs. We get photometric redshifts for 227 pairs from the cross-match with the SDSS DR8. For the remaining sources, we cross-identify with the NASA/IPAC Extragalactic Database (NED), and we get redshifts for 64 pairs. In total, we get redshifts and RM for 401 pairs, as listed in Table A2. The reliability of such cross-matches is about 80%, as discussed in Appendix A. This is the largest sample of RM pairs for pairs with redshifts currently available for the NVSS RM data.

2.2. The Compiled RM Pairs

In the compiled RM catalog (Xu & Han 2014a) and more recently published literature, RMfs are available for many pairs, as listed or presented with radio images in the original references. We inspect all of the literature and find 444 double sources as real physical pairs. Among them, 95 pairs have redshifts already listed in the references or from the NED. For the remaining 349 double sources without redshifts and known host galaxies, we adopted the same procedure for redshift searches as for the NVSS RM pairs. The central coordinates of each pair are cross-matched with the SDSS DR16, and we find spectroscopic redshifts for 40 pairs within 10′′. No objects can get the spectroscopic redshift from the 6dF Galaxy Survey data. From the catalog of SDSS DR8, we obtain photometric redshifts for 83 pairs. For the remainder, we found eight redshifts from the NED. In total, we have 226 physical pairs with both RMfs and redshifts, as listed in Table A1. The redshifts for 95 pairs are very reliable, as marked with asterisks in column (10), but for the other 131 pairs, the redshift reliability is about 80%. Notice that the redshifts of pairs of $z > 0.9$ are very reliable, because 34 of the 37 pairs have well-measured redshifts.

2.3. The RM Differences of Pairs

For a physical pair, i.e., the two lobes of a radio galaxy known as double radio sources, their radio waves experience almost the same integration path for the Faraday rotation from their inhabited environment in front of the radio galaxy to us, as shown in Figure 1. The RM difference of a pair indicates mostly the immediate difference of the magnetoeionic medium in their local environment on a scale comparable to the observed source separation on the sky plane, i.e., a scale from tens of kpc to a few Mpc, though we do not know the angle between the line of sight and the pair connection in 3D. All pairs of sources collected in this work are unresolved point sources, so their RMfs are produced by almost the same intervening medium between the source and the observer. The RM difference $\Delta RM = RM_1 - RM_2$ with an uncertainty of $\sigma_{\Delta RM} = \sqrt{\sigma_{RM_1}^2 + \sigma_{RM_2}^2}$ is therefore the cleanest measurement of Faraday rotation in the ICM, avoiding any additional uncertainties caused by not-well-measured foreground GRM and unknown intergalactic contributions, such as from cosmic webs and galaxy halos. These unknown uncertainties caused by the foreground of sources are inherited in all traditional statistics for extragalactic RMfs.

The RM difference can be negative or positive, as we randomly take one to subtract the other, so that statistically, the zero mean is expected for large samples. For our sample, the mean of the RM difference is $-0.21$ and $-0.11$ rad m$^{-2}$ for the NVSS and compiled RM pairs, respectively, which approximate to zero as expected. The distributions of $\Delta RM$ for two samples of pairs are shown in Figure 3. The values of RMfs, RM differences and redshifts of all these 226 and 401 pairs from the compiled and NVSS data are listed in Tables A1 and A2, respectively, together with the angular separation $\Delta r$ and projected linear separation (LS). Only 12 of 401 pairs (3%) of NVSS RM sources have redshifts larger than 0.9, compared with 37 of 226 pairs (16%) in the compiled sources. In the compiled RM data, 34 double sources marked with dashes in columns (11) and (12) have coordinates for the host galaxies but no coordinates for the two radio lobes; thus, the angular and linear separations are not available.

Because the RM uncertainty is a very important factor for the study of the small RM difference of pairs, and because the formal uncertainties of the NVSS RMfs are much larger than those for the compiled data, the two samples should be analyzed separately. The RM data with small uncertainties are more valuable to reveal the possible evolution with redshift; the subsamples with $\sigma_{\Delta RM} < 10$ rad m$^{-2}$ are taken seriously here, and their distribution is shown in the right panel of Figure 3.

3. Large RM Difference at High Redshifts

Based on this largest sample of pairs with both RMfs and redshift data available so far, we study their evolution with redshift and check if the RM difference is related to the separations of two sources.

Figure 4 shows the distribution of the absolute values $|\Delta RM|$ of pairs against the Galactic latitude. Because the RM differences of double sources at low Galactic latitudes may be contaminated by enhanced turbulence in the interstellar medium when the radio waves pass through the Galactic plane (e.g., Simonetti & Cordes 1986; Clegg et al. 1992; Minter & Spangler 1996), we discard nine NVSS pairs and three pairs from the compiled data at low Galactic latitudes of $|b| < 10^°$, though these few pairs may not affect our statistics (see Figure 4). A Spearman rank test demonstrates that the absolute $|\Delta RM|$ of the NVSS data is uncorrelated with Galactic latitude, with a correlation coefficient of $\sim 0.004$ ($p$-value $\sim 0.93$). For the pairs from the compiled data, only a very weak correlation was found from the data, with a correlation coefficient of $-0.22$ ($p$-value $\sim 0.002$). We therefore conclude that the “leakage” to the RM differences from the Galactic interstellar medium can be ignored.

Figure 5 shows the absolute RM difference as a function of the angular separation and projected linear separation of two lobes on the sky plane. For the purpose of exploring the magnetic fields in the ICM, we discard four pairs with LS $\geq 1$ Mpc from the NVSS data and 25 pairs from the compiled data because these pairs probably impact much less ICM, and their differences may stand more for the RM contribution from the intergalactic medium, given the typical size of galaxy clusters being about 1 Mpc. In addition, one pair from a very distant radio galaxy in the compiled RM data and one pair from the NVSS data have a host galaxy with a redshift of $z > 3$. They are also discarded for the following statistics.
All of these discarded pairs are marked with “†” in column (13) of Tables A1 and A2. We finally have a very clean 387 NVSS pairs and 197 compiled pairs with a separation of $\text{LS} < 1\text{ Mpc}$, $|b| > 10^\circ$, and $z < 3$ for further analysis.

3.1. The RM Difference versus Redshift

In order to reveal the possible redshift evolution of the small RM difference caused by the ICM, the $\Delta\text{RM}$ data have to be carefully analyzed.

Figure 3. In the left panel, the RM differences $\Delta\text{RM}$ for 401 pairs from the NVSS data (top) and for 226 pairs from the compiled data (middle) and their histograms (bottom) against redshift are shown together with the histograms for uncertainties $\sigma_{\Delta\text{RM}}$. There are two and nine pairs with $\Delta\text{RM}$ values outside the value range of the subpanels for the NVSS and compiled data, respectively. The distributions for the same data but $\sigma_{\Delta\text{RM}} \leq 10\text{ rad m}^{-2}$ are shown in the right panel.

Figure 4. Absolute values of the RM difference $|\Delta\text{RM}|$ of pairs from the NVSS (top panel) and compiled (bottom panel) data against the Galactic latitudes $|b|$. No apparent dependence implies no significant contribution from the Galactic interstellar medium. The uncertainties of the NVSS RM data are not shown for clarity.

Figure 5. Absolute values of RM difference $|\Delta\text{RM}|$ of pairs for the NVSS (top panels) and compiled (bottom panels) data against the angular separation ($\Delta r$) and the projected LS. The uncertainties of the NVSS data are not shown for clarity. A few pairs without the separation values or having an RM difference out of the plotted ranges are not shown.

From Figure 3 and Tables A1 and A2, we see that the uncertainties $\sigma_{\Delta\text{RM}}$ from the NVSS RM measurements have a value between 0 and 25 rad m$^{-2}$, and those for the compiled RM data are mostly less than 10 rad m$^{-2}$ and more than half less than 1 rad m$^{-2}$. Xu & Han (2014b) showed that large uncertainties would leak to the $\Delta\text{RM}$ distribution. Therefore, we have to study the two samples of pairs with very different $\Delta\text{RM}$ uncertainties separately. We examine two cases, one for the $\Delta\text{RM}$s from the whole samples without a threshold of uncertainty and the other with a threshold of $\sigma_{\Delta\text{RM}} \leq 10\text{ rad m}^{-2}$.
According to the number distribution in Figure 3, we divide the samples of pairs into five redshift ranges, 
\[ z = (0.0, 0.3), (0.3, 0.6), (0.6, 0.9), (0.9, 1.5), \text{ and } (2.0, 3.0) \], and examine the data dispersion in these ranges as shown in Figure 6, assuming an insignificant evolution of RM differences in a given redshift range. The RM differences of a pair of lobes can be negative or positive and, for an ideal case of a large sample of \( \Delta RM \) values, should follow a Gaussian distribution with the zero mean. The dispersion, i.e., the width of a Gaussian function \( \Delta W_{RMrms} \), can be fitted from the real data distribution of \( \Delta RM \) through calculating the rms for the \( \Delta RMs \),

\[
\Delta W_{RMrms} = \sqrt{\frac{\sum_{i=1}^{N}(RM1 - RM2)^2}{N}}.
\]

where \( N \) is the total number of pairs. Alternatively, a more robust approach is to get the median absolute deviation \( W_{ARMmad} \), which is good for small data samples and robust in the presence of outliers (see Malik et al. 2020). For our \( \Delta RM \) data, the zero mean is expected. Therefore, we consider the median of the absolute values of the RM difference, i.e.,

\[
W_{\Delta ARMmad} = \text{Median}(|RM1 - RM2|_{i=1,N}).
\] (5)

For normally distributed data, this can be linked to \( W_{\Delta ARMrms} \) by

\[
W_{\Delta ARMrms} = 1.4826 \times W_{\Delta ARMmad} \approx W_{\Delta ARMrms} \quad \text{(Leys et al. 2013)}.
\]

In the redshift ranges with more than five pairs, we calculate the dispersion of RM differences, \( W_{\Delta ARMrms} \) and \( W_{\Delta ARMmad} \); see Table 1 and Figure 6. Though a large \( \Delta RM \) is possible for embedded double sources contributed by the ICM, with a value of maybe up to a few hundred rad m\(^{-2} \) (e.g., Clarke et al. 2001), a few outliers are cleaned in our statistics, since they affect the calculation of the dispersion of the main stream of data. For the rms calculation, data points scattered away from the main distribution by more than three times the standard deviation are marked as outliers and removed iteratively until no outliers are marked. The trimmed rms of \( \Delta RM \) is taken as \( W_{\Delta ARMrms} \) for a subsample in a redshift bin. The uncertainty of \( W_{\Delta ARMrms} \) is taken as the standard error for the zero mean, as done by Vernstrom et al. (2019). For the median calculation, the outliers are also cleaned first, and the median is found from the

![Figure 6. Distribution of absolute values of RM difference |\( \Delta RM \)| and the data dispersions as a function of redshift for 387 NVSS pairs and 197 pairs of compiled data with a projected separation of LS < 1 Mpc, |\( b | > 10^\circ\), and \( z < 3 \) (left panel). Sources with |\( \Delta RM \)| > 100 rad m\(^{-2} \) are plotted at the top boundary of the subpanels. The vertical dotted lines in the top two rows indicate the redshift at \( z = 0.3, 0.6, 0.9, \) and 1.5. The dispersions of the \( \Delta RM \) distribution are calculated with a Gaussian fitting with a characteristic width \( W_{\Delta ARM} \) or simply taken as the median absolute values, as shown in the third and fourth rows, respectively. The open circles represent the values from the NVSS RM data, and the filled circles stand for values from the compiled data, plotted at the median redshift for each redshift range. The same plots but for 152 NVSS pairs and 186 compiled pairs with a formal \( \Delta RM \) uncertainty \( \sigma_{\Delta RM} \leq 10 \) rad m\(^{-2} \) are shown in the right panels.](image-url)
remaining $|\Delta \text{RM}|$, which is taken as $W_{\text{RM}}^{\text{min}}$ and then converted to $W_{\text{RM\ max}}$ with a factor of 1.4826. Its uncertainty is taken as being $\sigma_{|\Delta \text{RM}|}$, the error of the estimated mean value of $|\Delta \text{RM}|$, also with a factor of 1.4826.

The dispersion calculated above in fact includes a “noise” term coming from various uncertainties of RM values. In principle, the noise term should be discounted from the $\Delta \text{RM}$ dispersion to get real astrophysical contributions. For each pair, the noise term can be expressed from the quadrature sum of the uncertainty of RMS of two lobes, e.g., for the $i$th pair, the noise $\sigma_{\Delta \text{RM}}^2 = (\sigma_{\text{RM}1}^2 + \sigma_{\text{RM}2}^2)^i$. The procedure of noise subtraction for the dispersion width $\sqrt{W_{\text{RM\ max}}^2 - \langle \Delta \text{RM} \rangle^2}$ should be carried out under the assumption that the uncertainties in the observed RMS provide a realistic estimate of the measurement error. However, the RM uncertainties of the NVSS data are underestimated for most sources (Stil et al. 2011) or probably overestimated for physical pairs (Vernstrom et al. 2019), probably caused by a previously unknown systematic uncertainty (Mao et al. 2010; Xu & Han 2014a). For the compiled RM data, different estimation methods were used for measurement errors, or observations with uncorrected ionospheric RM will introduce an extra RM uncertainty about 3 rad m$^{-2}$. It is hard to get a realistic uniform estimate of the measurement error for the pair sample in this paper. Fortunately for this work, the RM difference $\Delta \text{RM}$ is investigated, which can largely diminish any systematical uncertainties that contribute the same amount to the RMS of two closely located sources, though a small unknown amount of noise leakage may still occur. We found that even $W_{\text{RM\ max}}$ is much smaller than the average noise power $\langle \sigma_{\text{RM}}^2 \rangle$; thus, no correction of the noise term is made to dispersion quantities $W_{\text{RM\ max}}$ and $W_{\text{RM\ min}}$ in Table 1.

With these careful considerations, it is time to look at the dispersion of RM differences of pairs as a function of redshift $z$, with or without a threshold of $\Delta \text{RM}$ uncertainty for the NVSS and compiled RM pairs, respectively. First of all, the amplitudes of dispersion represented by $W_{\text{RM\ min}}$ and $W_{\text{RM\ max}}$ are consistent with each other within the error bars, as shown in Table 1 and Figure 6. Second, for the NVSS RM pairs, no significant variation of the dispersion with redshift is seen in both the whole sample and the high-precision sample with $\sigma_{\Delta \text{RM}} \leq 10$ rad m$^{-2}$, which is consistent with the results for physical pairs obtained by Vernstrom et al. (2019). However, a systematically larger dispersion is obtained from the whole sample than from the high-precision sample, which implies that the large uncertainty of the NVSS RM values (a noise term around 10.4 rad m$^{-2}$ given by Schnitzeler 2010) significantly affects the dispersion of $\Delta \text{RM}$ and probably buries the small amplitude evolution at low redshifts. This is a sign of some noise leakage that cannot be cleaned. Third, for pairs from the compiled RM data that have very small noise, a much larger dispersion appears for pairs of $z > 0.9$ in both samples with/without a $\sigma_{\Delta \text{RM}}$ threshold setting, compared to a small dispersion for pairs of $z < 0.9$. The amplitude of dispersion for pairs of $z < 0.9$ is mostly less than 2 rad m$^{-2}$, but for pairs of $z > 0.9$, the dispersion is about 30–40 rad m$^{-2}$. Even the measurement noise which is about 5.6/4.7 rad m$^{-2}$ at $z > 0.9$ without/with $\sigma_{\Delta \text{RM}} \leq 10$ rad m$^{-2}$ threshold is discounted, the result on larger dispersion is not changed. Since the dispersion values for two redshift ranges of $z > 0.9$ are similar, the data of all pairs in the redshift range of $0.9 < z < 3.0$ are therefore jointly analyzed, and the uncertainty becomes smaller. The large dispersion for the high-redshift pairs of $z > 0.9$ is therefore a good detection at about a $5\sigma$ level.

We note that the pairs with a low redshift in the compiled data are mainly measured at low frequencies by LOFAR (144 MHz; e.g., O’Sullivan et al. 2020) and MWA (200 MHz; e.g., Riseley et al. 2020). Low-frequency data may probe the outer part of galaxy clusters or poor clusters; hence, the dispersion amplitude around 2 rad m$^{-2}$ calculated from pairs of $z < 0.9$ should read as a lower limit of Faraday rotation from the ICM. The dispersion of about 7–9 rad m$^{-2}$ estimated from the NVSS RM data with $\sigma_{\Delta \text{RM}} \leq 10$ rad m$^{-2}$ should be taken as an upper limit. Such “intrinsic” dispersions of the NVSS RM data in three low-redshift bins at $z < 0.9$ are verified by the mock method introduced by Xu & Han (2014b); see Appendix B.

### Table 1

Table 1. Statistics of the $\Delta \text{RM}$ Distribution for Pairs in Redshift Bins

| Redshift Range | No. of Pairs | $z_{\text{median}}$ | $W_{\text{RM\ max}}$ (rad m$^{-2}$) | $W_{\text{RM\ min}}$ (rad m$^{-2}$) | $W_{\text{RM\ max}}$ (rad m$^{-2}$) |
|---------------|-------------|---------------------|----------------------------------|----------------------------------|----------------------------------|
| 0.0–0.3       | 116         | 0.171               | 13.3 ± 1.3                       | 9.9 ± 1.2                        | 10.2 ± 3.1                       |
| 0.3–0.6       | 174         | 0.455               | 11.5 ± 0.9                       | 11.0 ± 0.8                       | 10.2 ± 1.6                       |
| 0.6–0.9       | 86          | 0.668               | 12.3 ± 1.3                       | 13.9 ± 1.2                       | 10.7 ± 2.1                       |
| 0.9–1.5       | 9           | 1.148               | 18.7 ± 6.6                       | 17.5 ± 6.1                       | ...                              |
| 2.0–3.0       | 2           | ...                 | ...                              | ...                              | ...                              |
| 0.9–3.0       | 11          | 1.198               | 17.3 ± 5.5                       | 17.0 ± 5.1                       | ...                              |

584 pairs with no uncertainty constraint: 387 NVSS RM pairs and 197 compiled RM pairs

| Redshift Range | No. of Pairs | $z_{\text{median}}$ | $W_{\text{RM\ max}}$ (rad m$^{-2}$) | $W_{\text{RM\ min}}$ (rad m$^{-2}$) |
|---------------|-------------|---------------------|----------------------------------|----------------------------------|
| 0.0–0.3       | 54          | 0.150               | 8.6 ± 1.2                        | 7.1 ± 1.2                        | 7.4 ± 1.4                        |
| 0.3–0.6       | 60          | 0.454               | 9.0 ± 1.2                        | 7.9 ± 1.1                        | 8.2 ± 0.8                        |
| 0.6–0.9       | 33          | 0.647               | 9.7 ± 1.7                        | 8.5 ± 1.6                        | 8.4 ± 1.9                        |
| 0.9–1.5       | 4           | ...                 | ...                              | ...                              | ...                              |
| 2.0–3.0       | 1           | ...                 | ...                              | ...                              | ...                              |
| 0.9–3.0       | 5           | ...                 | ...                              | ...                              | ...                              |

338 pairs of $\sigma_{\Delta \text{RM}} \leq 10$ rad m$^{-2}$: 152 NVSS RM pairs and 186 compiled RM pairs

Note. Here $W_{\text{RM\ max}}$ denotes the “intrinsic” dispersions of the NVSS data derived by the mock method in Appendix B.
Based on the above results, we conclude that the dispersion of RM differences for pairs of $z < 0.9$ should be a value in the range of $2-8$ rad m$^{-2}$, much smaller than the value of $30-40$ rad m$^{-2}$ for high-redshift pairs of $z > 0.9$.

### 3.2. The RM Difference and Projected Separation

Is the significant change of $\Delta$RM dispersion for pairs at $z > 0.9$ biased by the linear sizes of double radio sources or their separation? Figure 7 shows the projected separation of pairs versus the redshift for both the NVSS and compiled RM samples. The majority of high-redshift pairs ($z > 0.9$) in the compiled data have a separation less than 500 kpc.

As seen in Figure 5, the absolute values of the RM differences decline to small values when a projected separation is larger than 1 Mpc, the typical size of a galaxy cluster. The pairs with a projected separation greater than 1 Mpc probably lie at a large angle to the line of sight, and their light paths pass through much less content of the ICM.

To examine if the larger RM dispersion of high-redshift pairs is caused by different separation, in the following, we split the NVSS and compiled data samples into two cases, i.e., subsamples with a separation larger or smaller than 500 kpc. In the compiled sample, 34 pairs (14 sources of $z > 0.9$) are omitted, since the angular separation and hence the LS are not available, though they are probably smaller than 1 Mpc.

**Figure 7.** Projected separation of pairs at various redshifts from the NVSS sample (top) and the compiled data (bottom). Note that 34 pairs (14 pairs at $z > 0.9$) in the compiled data are not included, since their angular separation and hence LS are not available.

4. Discussion

If the larger RM differences of high-redshift pairs were caused by the intergalactic medium between the pair and us, the larger the separation between a pair of lobes, the more likely they experience different foreground cosmic filaments and intervening medium along the lines of sight. That is to say, the larger the separation of lobe positions, the greater the likelihood of a larger RM difference (e.g., O’Sullivan et al. 2019). However, for the compiled RM samples in Figures 5 and 8, this is not the case, and the results are just the opposite, which means that the main RM differences are caused by the local ICM environment surrounding the double radio sources, instead of the intervening intergalactic medium in the foreground of a pair of lobes. Therefore, the RM differences of pairs are excellent probes for the ICM.

#### 4.1. Strong Magnetic Fields in the ICM in the Early Universe

Evidence for larger RM differences for higher-redshift pairs, having wisely excluded any obvious influence by the Galactic and intergalactic contributions and also a possible dependence on the LS of pairs, demonstrates the strong magnetic fields in the ICM in the early universe. We can estimate the field strengths in the ICM from the dispersion of RM differences at the present epoch and high redshift.

As mentioned in Section 1, pairs of lobes are believed to mainly reside in dense environments of galaxy clusters/groups. Such dense ambient gas plays a key role in forming Faraday screens, which contribute to the difference between the RM values of the lobes. The RM asymmetry of a pair of lobes indicates that there probably exists a large-scale ordered net magnetic field in the foreground ICM with a scale of pair separation. Because of the turbulent nature of intracluster magnetic fields, large-scale fluctuations (>100 kpc) should be responsible for the RM differences of pairs, and a very large outer scale for turbulent intracluster magnetic fields of ~450 kpc could be used for modeling of magnetic fields for a giant radio halo (Vacca et al. 2010). The small-scale field fluctuations at a few kpc could be averaged out over a path length comparable to the projected separation.

A pair of radio sources in our sample could have any separation and arbitrary orientation in space. The path difference along the line of sight of the two lobes may vary from zero to the largest linear size. Assuming a unidirectional large-scale magnetic field geometry and a constant electron
density in the ambient environs, we get an RM difference of

$$\Delta RM = 812 \ n_e \ B L_\parallel \cos \theta,$$

(6)

where $L_\parallel$ is the separation of the pair (in kpc) projected onto the line of sight, and $\theta$ is the angle between the magnetic field direction and the line of sight. For a sample of pairs with the same separation but random directions of magnetic fields, the mean of $\Delta RM$ is

$$\langle \Delta RM \rangle = 812 \ n_e \ B L_\parallel \int_0^\pi \cos \theta \sin \theta \, d\theta / \int_0^\pi \sin \theta \, d\theta = 0,$$

(7)

and the variance is given by

$$\langle (\Delta RM)^2 \rangle = (812 \ n_e \ B L_\parallel)^2 \int_0^\pi \cos^2 \theta \sin \theta \, d\theta / \int_0^\pi \sin \theta \, d\theta$$

$$= \frac{1}{3} (812 \ n_e \ B L_\parallel)^2.$$

(8)

Furthermore, we consider a pair of sources with a random separation $L$ along a random orientation $\phi$, i.e., $L_\parallel = L \cos \phi$, where $L$ is the size and $\phi$ is the angle between the orientation

Table 2

Statistics of the $\Delta RM$ Distribution for Pairs with a Separation Larger or Smaller than 500 kpc

| Redshift Range | No. of Pairs | $z_{\text{median}}$ | $W_{\Delta RM_{\text{rms}}}$ (rad m$^{-2}$) | $W_{\Delta RM_{\text{mad}}}$ (rad m$^{-2}$) |
|---------------|-------------|---------------------|---------------------------------|---------------------------------|
| Pairs with a separation larger than 500 kpc: 76 NVSS pairs and 54 compiled pairs | | | | |
| 0.0–0.3 | 7 | 0.218 | 10.9 ± 4.5 | 15.7 ± 3.4 |
| 0.3–0.6 | 37 | 0.467 | 13.7 ± 2.3 | 8.5 ± 2.4 |
| 0.6–0.9 | 27 | 0.704 | 9.7 ± 1.9 | 7.1 ± 1.8 |
| 0.9–1.5 | 5 | 1.247 | 23.2 ± 11.6 | 29.8 ± 9.6 |
| Pairs with a separation smaller than 500 kpc: 309 NVSS pairs and 109 compiled pairs | | | | |
| 0.0–0.3 | 109 | 0.167 | 13.4 ± 1.3 | 9.7 ± 1.3 |
| 0.3–0.6 | 137 | 0.453 | 13.1 ± 1.0 | 11.2 ± 0.9 |
| 0.6–0.9 | 59 | 0.653 | 13.3 ± 1.8 | 15.3 ± 1.6 |
| 0.9–1.5 | 4 | ... | ... | ... |
| 0.0–0.3 | 15 | 0.199 | 2.6 ± 0.7 | 2.1 ± 0.7 |
| 0.3–0.6 | 19 | 0.467 | 1.1 ± 0.2 | 1.1 ± 0.2 |
| 0.6–0.9 | 18 | 0.754 | 4.0 ± 1.0 | 2.1 ± 1.0 |
| 0.9–1.5 | 2 | ... | ... | ... |

Figure 8. Absolute RM difference ($|\Delta RM|$) distributions and their dispersion ($W_{\Delta RM_{\text{rms}}}$ and $W_{\Delta RM_{\text{mad}}}$) against redshift for pairs with a separation larger and smaller than 500 kpc for the NVSS RM (left) and compiled data (right) samples.
and the line of sight. Hence, we expect

$$\langle (\Delta R M)^2 \rangle = \frac{1}{3} (812 \ n_e B^2) \langle L^2 \rangle \langle \cos^2 \phi \rangle$$

$$= \frac{1}{9} (812 \ n_e B^2) \langle L^2 \rangle. \quad (9)$$

Here $\langle L^2 \rangle$ denotes the mean square of the separation of pairs.

The rest-frame RM dispersion of a Faraday screen at redshift $z$ is expected to be decreased to the observed values by a factor of $(1 + z)^2$. Then we can derive an analytical formulation by assuming the field strength and electron density to be constant in the environs around the double radio sources at redshift $z$, i.e.,

$$\langle (\Delta R M)^2 \rangle = \frac{1}{9} (812)^2 \langle L(z)^2 \rangle \left[ \frac{n_e(z) B(z)}{(1 + z)^2} \right]^2, \quad (10)$$

and finally, we get

$$W_{\text{ARM}} = \langle (\Delta R M)^2 \rangle^{1/2} = 271 n_e(z) B(z) \langle L(z)^2 \rangle^{1/2} (1 + z)^{-2}. \quad (11)$$

From Equation (11), we can derive the magnetic fields in the ICM if the dispersion of the RM difference, the electron density $n_e$, and the variance of the pair separations $\langle L(z)^2 \rangle$ at redshift $z$ are known.

Based on the results shown in Figure 6, the dispersion of the RM difference of the pairs remains nearly flat at $z < 0.9$, with an amplitude of about $2$–$8$ rad m$^{-2}$. We take a typical value of $3.5$ rad m$^{-2}$ to represent the dispersion at the present time. For pairs of $z > 0.9$, the dispersion increases to $30$–$40$ rad m$^{-2}$ at a median redshift of $z = 1.1$. We take a typical value of $35$ rad m$^{-2}$ at $z = 1.1$. For the variance of the pair separations $\langle L(z)^2 \rangle$ at redshift $z$, we take the same typical value of $350$ kpc for pairs at low and high redshifts. At low redshifts, the mean electron density $n_e$ in the ICM is taken to be $4 \times 10^{-4}$ cm$^{-3}$, which is obtained by integrating the $\beta$-model profile of electron density over a sphere with a radius of $1$ Mpc for $12$ galaxy clusters (Govoni et al. 2010). According to Equation (11), from $W_{\text{ARM}} = 3.5$ rad m$^{-2}$, $n_e = 4 \times 10^{-4}$ cm$^{-3}$, and $\langle L(z)^2 \rangle = 350$ kpc at $z = 0$, we can obtain a simple estimation of the magnetic field strength over this scale as being $B = 0.1 \mu G$ at the present epoch. At high redshift, $z > 0.9$, we do not know the exact properties of the ICM. If we assume the mean electron density $n_e(z)$ at $z > 0.9$ is the same as the density at the present epoch, along with $W_{\text{ARM}} = 35$ rad m$^{-2}$, $\langle L^2 \rangle = 350$ kpc as well as at $z = 1.1$, the magnetic field would be $B(z) = 4 \mu G$. To get this value, any field reversals smaller than $350$ kpc are ignored. If field reversals at a scale of $30$ kpc are considered, the field strength would be boosted by a factor of $\sqrt{350/30}$, reaching a field strength of $14 \mu G$.

4.2. Implication of Strong Magnetic Fields in the ICM

The field strength estimated above for the ICM from the pairs at $z < 0.9$, if in the form of a uniform large-scale field geometry, is $0.1 \mu G$, close to the minimum intracluster magnetic field obtained by Pratley et al. (2013). More tangled fields would have a strength that is a few times stronger. The estimated field strength is smaller than that of some targeted clusters, such as a few $\mu G$ on scales of tens of kpc in merging clusters and a few $10 \mu G$ in cool core clusters (see, e.g., Carilli & Taylor 2002; van Weeren et al. 2019). There are two possible reasons. The first, the well-measured RM differences at low redshifts, are predominantly from the RM data with very small uncertainties, which were mainly measured at low frequencies by LOFAR (e.g., O’Sullivan et al. 2020) and MWA (e.g., Riseley et al. 2020). Those observations at such low frequencies may probe the medium in the outer part of galaxy clusters or poor clusters, so that the estimated field strength is close to the large-scale intergalactic magnetic fields around galaxy clusters, as illuminated by simulations (Ryu et al. 2008). In contrast, the small number of RM data with larger uncertainties and more scatter in the distribution were mostly observed at $1.4$ GHz or higher frequencies, which are more likely to probe the inner part of galaxy clusters. Second, at low redshifts, most powerful radio sources reside in comparatively sparse environments, with few exceptions, e.g., Cygnus A (Dreher et al. 1987) and other sources of large RM differences in the compiled data, as pointed out by Pentericci et al. (2000), so that the dispersion of RM differences is small. This is supported by the NVSS sample with a similar small dispersion of RM differences, i.e., upper limits of $7$–$9$ rad m$^{-2}$ derived by this work and $4.6 \pm 1.1$ rad m$^{-2}$ by Vernstrom et al. (2019).

The value of a uniform intracluster magnetic field strength of $4 \mu G$ (or $\sim 14 \mu G$ for tangled fields) at $z > 0.9$ derived from the RM difference of pairs is intriguing, as it is comparable to the field strength of galaxy clusters at low redshifts (see a review by Han 2017), for example, a central field strength of $4.7 \mu G$ in the Coma cluster (Bonafede et al. 2010) and a few $\mu G$ in a sample of X-ray-selected clusters (Clarke et al. 2001; Böhringer et al. 2016). This is evidence for strong organized magnetic fields in galaxy clusters in the early universe. If this scenario is correct, it poses a considerable challenge to theories on the origin of intracluster magnetic fields, because the time available at $z > 0.9$ is not sufficient to generate and align strong magnetic fields on such large scales. The building up of large-scale coherent magnetic fields via the inverse cascade of the $\alpha - \Omega$ dynamo fields that often works in normal spiral galaxies cannot operate in galaxy clusters because they do not have an observed organized rotation. Even if they do, only one or two rotations at this age of the universe under slow cluster rotation ($\nu \lesssim 100 \text{ km s}^{-1}$) is insufficient for generation of such a strong mean field (Carilli & Taylor 2002).

The origin and growth of magnetic fields in galaxy clusters are an enigma. The widely accepted hypothesis is that they are amplified from much weaker seed fields (either primordial or injected by galactic outflows) through a variety of processes (see review in Donnert et al. 2018). Simulations show evidence of significant magnetic field amplification with a small-scale dynamo driven by turbulence and compression during structure formation (Vazza et al. 2018; Domínguez-Fernández et al. 2019; Steinwandel et al. 2021). Assuming the dynamo growth can start soon after the cluster forms, it often takes a time span of several Gyr to amplify magnetic fields to a few $\mu G$ (e.g., Domínguez-Fernández et al. 2019). Increasing the Reynolds number can reduce the timescale for magnetic amplification, but the number is limited by the efficiency of the transfer of

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4 The average projected LS is $281$ and $234$ kpc for samples of $z < 0.9$ and $>0.9$ with a separation smaller than $500$ kpc, based on the fact that a majority of pairs at $z > 0.9$ have small separations, and their dispersions are consistent with those from the whole sample. Considering a random projection effect, we estimate the real pair separations should be larger by a factor of $\sqrt{2} = 1.4$, i.e., $396$ or $329$ kpc, respectively.
kinetic energy into magnetic energy. Merger-induced shocks that sweep through the ICM or motions induced by sloshing cool cores may play additional roles in the fast amplification of the intracluster magnetic field at high redshifts (Donnert et al. 2018), but not up to such a large scale. The recent observations of diffuse radio emission in distant galaxy clusters (Di Gennaro et al. 2021) have put a strong limit on the timescale of the magnetic growth by discovering field strengths of $\mu$G at $z \sim 0.7$. The time available for the amplification in their case is about 3.7 Gyr. Our results are strong evidence for strong magnetic field strengths at such a large scale at $z > 0.9$ and even up to $z \sim 2$, comparable to those in nearby clusters, which is a more stringent constraint for magnetic field generation and evolution.

5. Conclusions

Faraday rotation measure differences between the two lobes of a sample of radio galaxies, which is completely free from the Faraday rotation effect contributed from the interstellar medium inside the Milky Way and the intergalactic medium between radio galaxies and us, is significantly large at $z > 0.9$, indicating the average intracluster magnetic fields about $4\mu$G (or $14\mu$G for tangled fields), in contrast to the weaker intracluster fields at the present epoch about $0.1\mu$G (or $0.3\mu$G for tangled fields). Such a strong magnetic fields in the early universe makes a big challenge on the generation of cosmic magnetic fields.

More RM data for pairs at high redshift are desired to reach a firm conclusion. Polarization observations for the RMs of a larger sample of double radio sources with better precision, which are necessary to further constrain the evolution of magnetic fields in the ICM, should be available soon.

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Appendix A

Comparison of Redshift Data of Pairs with Those in Vernstrom et al. (2019)

Vernstrom et al. (2019) obtained 317 physical pairs of polarized sources at Galactic latitudes $|b| \geq 20^\circ$ with a polarization fraction of $\geq 2\%$ and an angular separation between 1/5 and 20′ from the NVSS RM catalog (Taylor et al. 2009). These pairs include not only pairs of lobes but also separated components of some multicomponent radio galaxies or even multiple RMs within one of the components (e.g., two RMs within one active galactic nucleus jet or lobe). Of these 317 pairs, 208 have been found to have spectroscopic or photometric redshifts by performing a redshift search from the catalogs of Hammond et al. (2012) and Kimball & Ivezić (2008, 2014), as well as their own compiled ERG catalog of extended radio galaxies.

Appendix B

Application of Mock Method to the Redshift Bins at $z < 0.9$ for the NVSS Data

We tried to use the mock method introduced by Xu & Han (2014b) to derive the intrinsic dispersion of a data sample by carefully discarding the effects from measurement uncertainties. As done in Xu & Han (2014b), we use the bootstrap method to obtain the intrinsic dispersion of the RM difference ($\Delta RM = RM1 - RM2$) distribution given a variety of uncertainties of $\sigma_{\Delta RM} = \sqrt{\sigma_{RM1}^2 + \sigma_{RM2}^2}$. It is clear that the probability of a $\Delta RM$ value follows a Gaussian function centered at the $\Delta RM$ value with a width of the uncertainty.
For an ideal data set without any measurement uncertainty, the distribution width but also the effect of the $\Delta$ RM uncertainties.

Note. Columns (1) and (2): equatorial coordinates of source 1. Columns (3) and (4): RM values and errors of source 1. Columns (5) and (6): equatorial coordinates of source 2. Columns (7) and (8): RM values and errors of source 2. Column (9): reference. Column (10): redshift of double radio sources. Columns (11) and (12): angular separation ($\Delta r$) and projected LS of double radio sources. Columns (13) and (14): RM differences and uncertainties of double radio sources. In column (10), values marked with an asterisk signify reliable redshift information from the original references. In columns (11) and (12), a dash means that values are not available. In column (13), values marked with "r" signify source removed from the final sample used for the analysis. The references are: akm+98, Adriyana et al. (1998); bbh+07, Broderick et al. (2007); bowe19, Banfield et al. (2019); ccsk92, Clegg et al. (1992); gkb+04, Goodlet et al. (2004); hbb98, Han et al. (1998); hbe09, Heald et al. (2009); m09, Minter & Spangler (1996); obv+20, O’Sullivan et al. (2020); ovn+19, O’Sullivan et al. (2019); opa+17, O’Sullivan et al. (2017); prm+89, Pedelty et al. (1989); rgs+20, Riseley et al. (2020); sc86, Simonetti & Cordes (1986); sob+20, Stuardi et al. (2020); tss09, Taylor et al. (2009). This table is available in its entirety in machine-readable form.

Note. Columns are the same as Table A1. This table is available in its entirety in machine-readable form.

$$p(\Delta RM) = \frac{1}{\sqrt{2\pi} \sigma_{\Delta RM}} \exp \left[ -\frac{(\Delta RM - \Delta RM_0)^2}{2\sigma_{\Delta RM}^2} \right],$$

where $\Delta RM_0 = (RM_1 - RM_2)$, is the RM difference of the $i$th pair in the sample, and $\sigma_{\Delta RM}$ is its uncertainty. Then, we sum the probability distribution function (PDF) for all $\Delta RM$ of a subsample of pairs in a redshift range:

$$P(\Delta RM) = \sum_{i=1}^{N} p(\Delta RM_i).$$

Such a method should work well for a larger sample but does not work well in the case of a small sample number (e.g., $n < 30$) or mostly a very small uncertainty (e.g., $\sigma < 0.1$ rad m$^{-2}$). For the NVSS pairs in three redshift bins at $z < 0.9$, we got good results.

Following the method introduced by Xu & Han (2014b), we generate a mock sample of $\Delta RM$ with a sample size of 50 times the original $\Delta RM$ data with a $\Delta RM$ uncertainty randomly taken from the measured $\Delta RM$s. We then sum the PDF of $\Delta RM$ for the mock data, as done for the real data. Finally, by comparing the two PDFs, $P(\Delta RM)$ and $P_{mock}(\Delta RM)$, as shown in Figures B1 and B2, we get the dispersions at $z = (0.0, 0.3), (0.3, 0.6),$ and (0.6, 0.9) as being $10.2 \pm 3.1, 10.2 \pm 1.6,$ and $10.7 \pm 2.1$ for the whole sample and $7.4 \pm 1.4, 8.2 \pm 0.8,$ and $8.4 \pm 1.9$ for the sample with $\sigma_{\Delta RM} \leq 10$ rad m$^{-2}$, also listed in Table 1. The decrease of the derived dispersions of the whole sample to that of the sample with $\sigma_{\Delta RM} \leq 10$ rad m$^{-2}$ indicates the leakage of measurement uncertainties to the dispersions. Therefore, we conclude that the dispersions at $z < 0.9$ being $7-9$ rad m$^{-2}$ from the NVSS sample with $\sigma_{\Delta RM} \leq 10$ rad m$^{-2}$ is the only upper limit of intrinsic dispersion.
Figure B1. The PDF of ΔRM values (solid line), compared with that of the mock ΔRM sample with the best distribution dispersion $W_{\Delta RM}$ (dotted line), for the whole NVSS sample in three redshift bins at $z < 0.9$. The fitting residuals against various dispersions are plotted in the lower panels, which define the best dispersion and its uncertainty at 68% probability.

Figure B2. Same as Figure B1 but for the NVSS sample with $\sigma_{\Delta RM} \leq 10 \text{ rad m}^{-2}$.

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