FARADAY ROTATION MEASURE DUE TO THE INTERGALACTIC MAGNETIC FIELD

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ABSTRACT

Studying the nature and origin of the intergalactic magnetic field (IGMF) is an outstanding problem of cosmology. Measuring Faraday rotation would be a promising method to explore the IGMF in the large-scale structure (LSS) of the universe. We investigated the Faraday rotation measure (RM) due to the IGMF in filaments of galaxies using simulations for cosmological structure formation. We employed a model IGMF based on turbulence dynamo in the LSS of the universe, it has an average strength of $\langle B \rangle \sim 10$ nG and a coherence length of several $\times 100$ h$^{-1}$ kpc in filaments. With the coherence length smaller than the path length, the induction of RM would be a random walk process, and we found that the density peak along the line of sight dominantly contributes to the resultant RM. The root mean square of RM through filaments present in the universe was predicted to be $\sim 1$ rad m$^{-2}$. In addition, we predicted that the probability distribution function of RM follows the lognormal distribution, and the power spectrum of RM in the local universe peaks at a scale of $\sim 1$ h$^{-1}$ Mpc. Our prediction of RM could be tested with future instruments.

Key words: intergalactic medium – large-scale structure of universe – magnetic fields – polarization

Online-only material: color figures

1. INTRODUCTION

The intergalactic medium (IGM) contains gas, which was heated mostly by cosmological shocks (Ryu et al. 2003), along with dark matter; the hot gas with $T > 10^7$ K is found inside and around clusters/groups of galaxies and the warm–hot intergalactic medium (WHIM) with $T = 10^5$–$10^7$ K resides mostly in filaments of galaxies, while the lower temperature gas is distributed mostly as sheetlike structures or in voids (Cen & Ostriker 1999; Kang et al. 2005). As the gas in the interstellar medium, the gas in the intracluster medium (ICM) and filaments is expected to be permeated with magnetic fields. Measuring Faraday rotation, the rotation of the plane of linearly polarized light due to the birefringence of the magneto-ionic medium, has been one of a few methods for exploring the intergalactic magnetic field (IGMF).

Observational exploration of the IGMF using Faraday rotation measure (RM) was started with the investigation of the intracluster magnetic field (ICMF; see Carilli & Taylor 2002, for a review). An RM study of the Coma cluster, for instance, revealed the ICMF of the strength of order $\sim \mu$G for the coherent length of order $\sim 10$ kpc (Kim et al. 1990). For Abell clusters, the RM of typically $\sim 100$–$200$ rad m$^{-2}$ was observed, indicating an average strength of the ICMF to be $\sim 5$–$10$ $\mu$G (Clarke et al. 2001; Clarke 2004). RM maps of clusters were analyzed to study the power spectrum of turbulent magnetic fields in the ICM; for instance, a Kolmogorov-like spectrum with a bending at a few kiloparsecs scale was found in the cooled core region of the Hydra cluster (Vogt & Enßlin 2005), and spectra consistent with the Kolmogorov spectrum were reported in the wider ICM for the A2382 cluster (Guidetti et al. 2008) and for the Coma cluster (Bonafede et al. 2010).

The nature of the IGMF in filaments, in contrast, remains largely unknown, because the study of RM outside clusters is still scarce (e.g., Xu et al. 2006); detecting the RM due to the IGMF in filaments is difficult with current facilities, and also removing the galactic foreground is not a trivial task. The next generation radio interferometers including the Square Kilometer Array (SKA), and upcoming SKA pathfinders, the Australian SKA Pathfinder (ASKAP), and the South African Karoo Array Telescope (MeerKAT), as well the Low Frequency Array (LOFAR), however, are expected to be used to study the RM. Particularly, the SKA could measure RM for $\sim 10^8$ polarized extragalactic sources across the sky with an average spacing of $\sim 60$ arcsec between lines of sight (LOSs; see, e.g., Carilli & Rawlings 2004; Krause et al. 2009, and references therein), enabling us to investigate the IGMF in the large-scale structure (LSS) of the universe.

Attempts to theoretically predict the RM due to the IGMF have been made: for instance, Ryu et al. (1998) and Dolag et al. (2005) used hydrodynamic simulations for cosmological structure formation to study RM in the LSS, and more recently Dubios & Teyssier (2008) used MHD simulations to study RM for clusters. However, the properties of the IGMF, especially in filaments, such as the strength and coherence length as well as the spatial distribution, are largely unknown, hindering the theoretical study of RM in the LSS of the universe.

Recently, Ryu et al. (2008) proposed a physically motivated model for the IGMF, in which a part of the gravitational energy released during structure formation is transferred to the magnetic field energy as a result of the turbulent dynamo amplification of weak seed fields in the LSS of the universe. In the model, the IGMF largely follows the matter distribution in the cosmic web and the strength is predicted to be $\langle B \rangle \sim 10$ nG in filaments. Cho & Ryu (2009) studied various characteristic length scales of magnetic fields in turbulence with very weak or zero mean magnetic field, and showed that the coherence length defined for RM is $3/4$ times the integral scale in the incompressible limit. They predicted that in filaments, the coherence length for RM would be a few $\times 100$ h$^{-1}$ kpc with the IGMF of Ryu et al. (2008) and the RM due to the magnetic field would be of order $\sim 1$ rad m$^{-2}$.
In this paper, we study RM in the LSS of the universe, focusing on RM through filaments, using simulations for cosmological structure formation along with the model IGMF of Ryu et al. (2008) and Cho & Ryu (2009). Specifically, we present the logical structure formation along with the model IGMF of Ryu focusing on RM through filaments, using simulations for cosmological structure formation, in which weak seed fields were evolved passively, of the passive fields from simulations for cosmological structure formation described above. A functional form for the conversion factor was derived from a separate, cosmological hydrodynamic code (Ryu et al. 1993). A cubic region of comoving volume \((100 \, h^{-1} \text{Mpc})^3\) was reproduced with 512\(^3\) uniform grid zones for gas and gravity and 256 \^3\) particles for dark matter, so the spatial resolution is 195 \(h^{-1}\) kpc. Sixteen simulations with different realizations of the initial condition were used to compensate cosmic variance.

For the IGMF, we employed the model of Ryu et al. (2008); it proposes that turbulent-flow motions are induced via the cascade of the vorticity generated at cosmological shocks during the formation of the LSS of the universe, and the IGMF is produced as a consequence of the amplification of weak seed fields of any origin by the turbulence. Then, the energy density (or the strength) of the IGMF can be estimated with the eddy turnover number and the turbulent energy density as follows:

\[
\epsilon_B = \phi \left( \frac{t}{t_{\text{eddy}}} \right) \epsilon_{\text{turb}}.
\]

Here, the eddy turnover time is defined as the reciprocal of the vorticity at driving scales, \(t_{\text{eddy}} \equiv 1/\omega_{\text{driving}}\) (\(\omega \equiv \nabla \times \mathbf{v}\)), and \(\phi\) is the conversion factor from turbulent to magnetic energy that depends on the eddy turnover number \(t/t_{\text{eddy}}\). The eddy turnover number was estimated as the age of universe times the magnitude of the local vorticity, that is, \(t_{\text{age}} \omega\). The local vorticity and turbulent energy density were calculated from simulations for cosmological structure formation described above. A functional form for the conversion factor was derived from a separate, incompressible, magnetohydrodynamic (MHD) simulation of turbulence dynamo. For the direction of the IGMF, we used that of the vorticity of the resulting IGMF.

In our model, as seed magnetic fields, we took the ones generated through the Biermann battery mechanism (Biermann 1950) at cosmological shocks. There are, on the other hand, a number of mechanisms that have been suggested to create seed fields in the early universe. Besides various inflationary and string theory mechanisms, the followings include a partial list of astrophysical mechanisms. At cosmological shocks, in addition, Weibel instability can operate and produce magnetic fields (Medvedev et al. 2006; Schlickeiser & Shukla 2003) and streaming cosmic rays accelerated by the shocks can amplify weak upstream magnetic fields via non-resonant growing mode (Bell 2004). In addition, for instance, galactic outflows during the starburst phase of galactic evolution (Donnert et al. 2009) and the return current induced by cosmic rays produced by supernovae of first stars (Miniati & Bell 2010) were suggested to deposit seed fields. We point out, however, that in our model the IGMF resulting from turbulent amplification should be insensitive to the origin of seed fields.

The spatial distribution of the strength of the resulting IGMF is shown in Figure 4 of Ryu et al. (2008) and Figure 1 of Ryu et al. (2010). It is very well correlated with the distribution of matter. The average strength of our model IGMF for the WHIM with \(10^5 < T < 10^7\) K in filaments is \(\langle B \rangle \approx 10\) nG, \(\langle B^2 \rangle^{1/2} \sim \text{a few} \times 10\) nG, \(\langle \rho B \rangle/\langle \rho \rangle \approx 0.1\) \(\mu\)G, or \(\langle \rho^2 \rangle^{1/2}/\langle \rho^2 \rangle^{1/2} \sim \text{a few} \times 0.1\) \(\mu\)G.

3. RESULTS

We calculated RM, defined as \(\Delta \chi/\Delta a^2\) (\(\chi\) is the rotation angle of linearly polarized light at wavelength \(\lambda\)), in the local universe with \(z = 0\) along a path length of \(L = 100 \, h^{-1} \text{Mpc}\), which is the box size of structure formation simulations. Figure 1 shows the resulting RM map of \((28 \, h^{-1} \text{Mpc})^2\) area in logarithmic and linear scales. RM traces the large-scale distribution of matter, and we see two clusters and a filamentary structure containing...
tures of positive and negative RM, RM through sheets and voids is much less. The bottom panel of Figure 1 shows the mixture of positive and negative RM, reflecting the randomness of magnetic fields in the LSS.

With the coherence length of magnetic fields for RM (see the Discussion, Section 4) expected to be smaller than the path length which should be a cosmological scale, the inducement of RM is expected to be a random walk process. Figure 2 shows the distributions of RM as well as other quantities along a few LOSs through filaments; it confirms that the inducement of RM is indeed a random walk process. However, we note that the resulting RM is dominated by the contribution from the density along LOSs.

To quantify RM in the LSS of the universe, we calculated the PDF of $|\text{RM}|$ for $512^2 \times 3 \times 16$ (projected grid zones $\times$ directions $\times$ runs) LOSs. Figure 3 shows the resulting PDF through the LOSs of different ranges of the mean temperature weighted with X-ray emissivity, $T_X$. The figure also shows the fitting to the lognormal distribution,

$$\text{PDF}(\log_{10} |\text{RM}|) = \frac{1}{\sqrt{2\pi \sigma^2}} \exp\left[-\frac{(\log_{10} |\text{RM}| - \mu)^2}{2\sigma^2}\right].$$

(2)

finding that the PDF closely follows the lognormal distribution. We also calculated the root mean square (rms) of RM, $\langle |\text{RM}| \rangle_{\text{rms}}$; note that the mean of RM, $\langle \text{RM} \rangle$, is zero for our IGMF. Through the WHIM, which mostly composes filaments, $\langle |\text{RM}| \rangle_{\text{rms}} = 1.41$ rad m$^{-2}$. This agrees well with the value predicted with the mean strength and coherence length of the IGMF in filaments by Cho & Ryu (2009). However, this is an order of magnitude smaller than the values of $|\text{RM}|$ toward the Hercules and Perseus--Pisces superclusters reported in Xu et al. (2006). The difference is mostly due to the mass-weighted path length; the value quoted by Xu et al. (2006) is about two orders of magnitude larger than ours. Through the hot gas with $10^7 \text{K} < T < 10^8 \text{K}$, $\langle |\text{RM}| \rangle_{\text{rms}} = 108$ rad m$^{-2}$, which is in good agreement with RM observations of galaxy clusters (Clarke et al. 2001; Clarke 2004).

Through the hot gas, however, we found RM of up to $\gtrsim 1000$ rad m$^{-2}$. This should be an artifact of limited resolution (see Discussion). So the values for the hot gas in our work should not be taken seriously.

Finally, we calculated the two-dimensional power spectrum of RM on $3 \times 16$ (directions $\times$ runs) projected planes; $P_{\text{RM}}(k) \sim |\text{RM}(\hat{k})|^2 \hat{k}$, where $\text{RM}(\hat{k})$ is the Fourier transform of $\text{RM}(\vec{x})$ on planes. Figure 4 shows the resulting power spectrum along with the power spectra of electron density, magnetic fields, and the curl component of flow motions, $\vec{v}_{\text{cut}}$, which satisfies the relation $\vec{\nabla} \times \vec{v}_{\text{cut}} \equiv \vec{\nabla} \times \vec{v}$. The power spectrum of RM peaks at $k \sim 100$, which corresponds to $\sim 1 \text{h}^{-1} \text{Mpc}$. Cosmic variance

![Figure 2](image2.png)

**Figure 2.** Profiles of local RM, LOS magnetic field, $B_\parallel$, electron density, $n_e$, and gas temperature, $T$, along a few LOSs through filaments. The arrows indicate the sign of local RM and $B_\parallel$.

(A color version of this figure is available in the online journal.)

![Figure 3](image3.png)

**Figure 3.** PDF of $|\text{RM}|$ through LOSs of different ranges of the mean temperature weighted with X-ray emissivity, $T_X$. Thin lines, thick lines (red or black), and thick lines (blue or gray) show the PDFs from 16 independent runs, their average, and the best-fit to the lognormal distribution, respectively. The values of fitting parameters and the rms of RM are also shown.

(A color version of this figure is available in the online journal.)

![Figure 4](image4.png)

**Figure 4.** Power spectrum of RM along with the power spectra of electron density, magnetic fields, and the curl component of flow motions, $\vec{v}_{\text{cut}}$, which satisfies the relation $\vec{\nabla} \times \vec{v}_{\text{cut}} \equiv \vec{\nabla} \times \vec{v}$. The power spectrum of RM peaks at $k \sim 100$, which corresponds to $\sim 1 \text{h}^{-1} \text{Mpc}$. Cosmic variance.
is not significant around the peak, although it is larger at smaller $k$, as expected. The power spectrum of RM reflects the spatial distributions of electron density, $n_e$, and LOS magnetic field, $B_\parallel$. The power spectra of projected $n_e$ and projected $B_\parallel$ have peaks at $\sim 3 \, h^{-1} \, \text{Mpc}$ and $\sim 1.5 \, h^{-1} \, \text{Mpc}$, respectively. The shape of the power spectrum of RM follows that of projected $B_\parallel$ rather than that of projected $n_e$, implying that the statistics of RM would primarily carry the statistics of the IGMF.

4. DISCUSSION

Our results of RM depend on the strength and coherence length of the IGMF. We employed a model where the strength of the local IGMF was estimated based on turbulence dynamo, while the direction was gripped from structure formation simulations with passive fields (see Section 2). In principle, if we had performed full MHD simulations, we could have followed the amplification of the IGMF through turbulence dynamo along with its direction. In practice, however, the currently available computational resources do not allow a numerical resolution high enough to reproduce the full development of MHD turbulence. Since the numerical resistivity is larger than the physical resistivity by many orders of magnitude, the growth of magnetic fields is expected to be saturated before dynamo action becomes fully operative (see, e.g., Kulsrud et al. 1997). In such a situation, the state of magnetic fields in full MHD, including, for instance, the power spectrum, is expected to mimic that of passive fields. This is the reason why we adopted the model of Ryu et al. (2008) to estimate the strength of the IGMF, but we still used passive fields from structure formation simulations to model the field direction.

The validity of our model IGMF was checked as follows.

1. In MHD turbulence, the distribution of magnetic fields, including the direction, is expected to correlate with that of vorticity, since magnetic fields and vorticity are described by similar equations except for the baroclinity term in the equation for vorticity (if dissipative processes are ignored; see, e.g., Kulsrud et al. 1997). Such a correlation can be clearly seen in Figure 5, which depicts the distributions of our IGMF and vorticity in two-dimensional slices.

2. Full MHD turbulence simulations suggest that the peak of the magnetic field spectrum occurs at $\sim 1/2$ of the energy injection scale, or the peak scale of velocity power spectrum, at saturation; in the linear growth stage, the peak scale of magnetic field spectrum grows as $\sim t^{1.5}$ or so (Cho & Ryu 2009). With our model IGMF, the peak scale of magnetic field spectrum is $\sim 1 \, h^{-1} \, \text{Mpc}$ (the third panel of Figure 4); on the other hand, the curl component of flow motions has the peak of the power spectrum at $\sim 4 \, h^{-1} \, \text{Mpc}$ (the bottom panel of Figure 4). That is, the peak scale of the magnetic field spectrum is $\sim 1/4$ of the energy injection scale in our model IGMF. By considering the fact that the turbulence in the LSS of the universe has not yet reached the fully saturated stage (see, e.g., Ryu et al. 2008), the ratio of the two scales seems to be feasible.

These suggest that our model IGMF would produce reasonable results, although eventually it needs to be replaced with those from full MHD simulations for cosmological structure formation when computational resources allow such simulations in future.

Apart from our model for the IGMF, the finite numerical resolution of simulations could affect our results. The average strength of our model IGMF is $\langle B \rangle \sim \mu \text{G}$ in clusters/groups, $\sim 0.1 \mu \text{G}$ around clusters/groups, and $\sim 10 \, \text{nG}$ in filaments. Ryu et al. (2008) tested the numerical convergence of the estimation. With simulations of different numerical resolutions for cosmological structure formation, it was shown that $\langle B \rangle$ of our model IGMF for the WHIM with $10^5 \, \text{K} < T < 10^6 \, \text{K}$ would approach the convergence value within a factor $\sim 2-3$ at the resolution of $512^3$ grids (see Figure S5 of SOM of Ryu et al. 2008).

It is, on the other hand, rather tricky to assess the effect of finite resolution on the coherence length of our model IGMF, because the definition of coherence length for RM is not completely clear and the estimation of coherence length, for instance, for

![Figure 4. Two-dimensional power spectra of RM, projected electron density ($n_e$), projected LOS IGMF strength ($B_\parallel$), and projected curl component of flow motions ($\vec{v}_{\text{curl}}$) from top to bottom panels, respectively. Thin solid lines show the power spectra for $3 \times 16$ two-dimensional maps, and thick solid lines show their average. The three-dimensional power spectra of $n_e$, $B_\parallel$, and $\vec{v}_{\text{curl}}$ are also shown with thick dashed lines.](A color version of this figure is available in the online journal.)
the filament IGMF alone is not trivial. We tried to quantify coherence length in the following three ways. (1) We directly calculated the coherence length of $B_\parallel$, that is, the length with the same sign of $B_\parallel$ along LOS’s. Figure 6 shows the PDF of the resulting coherence length through the WHIM, which composes mostly filaments. It peaks at the length of three zones corresponding to $586$ $h^{-1}$ kpc. (2) We calculated $3/4$ times the integral scale:

$$\frac{3}{4} \times 2\pi \int \frac{P_{B}^{3D}(k) / k}{\int P_{B}^{3D}(k) / k} \, dk,$$

which is the coherence length defined for RM in the incompressible limit (see the Introduction, Section 1), for the IGMF inside the whole computational box of $(100 \, h^{-1} \text{Mpc})^3$ volume. Here, $P_{B}^{3D}(k)$ is the three-dimensional power spectrum of magnetic fields (the third panel of Figure 4). We found the value to be $\sim 800$ $h^{-1}$ kpc for our model IGMF. (3) We also calculated the largest energy containing scale in the whole computational box, which is the peak scale of $k P_{B}^{3D}(k)$ (not shown). It is $\sim 900$ $h^{-1}$ kpc for our model IGMF. Note that the latter two values include contributions from the IGMF in filaments as well as in clusters, sheets, and voids. All the three scales are comparable. These length scales are $\sim 3$–5 times larger than the grid resolution of our simulations, $195$ $h^{-1}$ kpc.

Cho & Ryu (2009) studied characteristic lengths in incompressible simulations of MHD turbulence (see the Introduction); based on it, they predicted that the coherence length for RM would be a few $\times 100$ $h^{-1}$ kpc in filaments, while a few $\times 10$ $h^{-1}$ kpc in clusters. With our grid resolution of $195$ $h^{-1}$ kpc, the coherence length of the IGMF in clusters should not be resolved and so our estimation of RM for clusters should not be resolved and so our estimation of RM for clusters should be affected by resolution, as pointed in Section 3. On the other hand, while the predicted coherence length for the IGMF in filaments is still larger than the grid resolution, the estimated coherence length of $B_\parallel$ for the WHIM is a couple of times larger than the prediction for filaments. It could be partly due to
the limited resolution in our simulations. However, as noted in Section 3, the density peak along LOSs dominantly contributes to RM (Figure 2).

The above statements indicate that our estimate of the RM through filaments is expected to have an uncertainty, especially due to the limited resolution of our simulations; it could be up to a factor of several.

5. SUMMARY AND CONCLUSION

We studied RM in the LSS of the universe, focusing on RM through filaments; simulations for cosmological structure formation were used and the model IGMF of Ryu et al. (2008) and Cho & Ryu (2009) based on turbulence dynamo was employed. Our findings are summarized as follows: (1) with our model IGMF, the rms of RM through filaments at the present universe is \( \sim 1 \) rad m\(^{-2}\), (2) the PDF of [RM] through filaments follows the lognormal distribution, (3) the power spectrum of the RM due to the IGMF in the local universe peaks at a scale of \( \sim 1 \) h\(^{-1}\) Mpc, and (4) within the frame of our model IGMF, we expect that the uncertainty in our estimation for the rms of RM through filaments, due to the finite numerical resolution of simulations, would be a factor of a few.

We note that our model does not include other possible contributions to the IGMF, for instance, that from galactic black holes (Active galactic nucleus feedbacks; see, e.g., Kronberg et al. 2001). So our model may be regarded as a minimal model, providing a baseline for the IGMF. With such contributions, the real IGMF might be somewhat stronger, resulting in somewhat larger RM.

It has been suggested that future radio observatories such as LOFAR, ASKAP, MeerKAT, and SKA could detect the extragalactic RM of \( \sim 1 \) rad m\(^{-2}\) that we predict (see, e.g., Beck 2009). However, it is known that the typical galactic foreground of RM is a few tens and of order 10 rad m\(^{-2}\) in the low and high galactic latitudes, respectively (see, e.g., Simard-Normandin & Kronberg 1980), so the detection of the extragalactic RM of \( \sim 1 \) rad m\(^{-2}\) or so could be possible only after the galactic foreground is removed. We note, however, that with filaments at cosmological distance, the peak of the power spectrum of the RM due to the IGMF in filaments would occur at small angular scales; for instance, for a filament at a distance of 100 h\(^{-1}\) Mpc, the peak would occur at \( \sim 0.5 \) or so. This is much smaller than the expected angular scale of the peak of the galactic foreground, which would be around \( 10^\circ \) (see, e.g., Frick et al. 2001). Then, it would be plausible to extract the signature of the RM of \( \sim 1 \) rad m\(^{-2}\) due to the IGMF in filaments. We leave this issue and the connection of our theoretical prediction of RM in the LSS of the universe to observations for future studies.

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