Redshift evolution of extragalactic rotation measures

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ABSTRACT

We have obtained the rotation measures (RMs) of 2642 quasars by using cross-identification of the most updated quasar catalogue and the RM catalogue. After discounting the foreground Galactic Faraday rotation of the Milky Way, we obtain the residual rotation measure (RRM) of these quasars. We have carefully discarded the effects from measurement and systematical uncertainties of RRM as well as large RRM outliers, and we have obtained marginal evidence for the redshift evolution of the real dispersion of RRM which steadily increases to 10 rad m$^{-2}$ about $z \sim 1$ and is saturated at higher redshifts. Ionized clouds in the form of galaxy halos, galaxy clusters or cosmological filaments with different RM dispersion widths could produce the observed RRM evolutions. However, current data sets cannot constrain the contributions from galaxy halos and cosmic webs. Future measurements of RMs for a large sample of quasars with high precision are necessary to disentangle these different contributions.

Key words: ISM: magnetic fields – intergalactic medium – quasars: general – radio continuum: ISM.

1 INTRODUCTION

Faraday rotation is a powerful tool used to probe the extragalactic medium. The observed rotation measure (RM) of a linearly polarized radio source at redshift $z_s$ is determined by the polarization angle rotation ($\psi_1 - \psi_2$) against the wavelength square ($\lambda_1^2 - \lambda_2^2$)

$$RM_{\text{obs}} = \frac{\psi_1 - \psi_2}{\lambda_1^2 - \lambda_2^2} = 0.81 \int_{z_s}^{0} \frac{n_e(z)B(z)}{(1+z)^2} \frac{dl}{dz} dz.$$  \hspace{1cm} (1)

The RM (in units of rad m$^{-2}$) is an integrated quantity of the product of thermal electron density ($n_e$ in units of cm$^{-3}$) and magnetic fields along the line of sight ($B(z)$ in units of $\mu$G) over the path from the source at a redshift $z_s$ to us. Here, the comoving path increment per unit redshift, $dl/dz$, is in parsec. The observed rotation measure $RM_{\text{obs}}$, with an uncertainty $\sigma_{RM}$, is the sum of the RM intrinsic to the source $RM_{\text{in}}$, the RM in intergalactic space $RM_{\text{IGM}}$, and the foreground Galactic RM (GRM) from our Galaxy, the Milky Way, i.e.

$$RM_{\text{obs}} = RM_{\text{in}} + RM_{\text{IGM}} + GRM.$$  \hspace{1cm} (2)

It has been found that the RM distribution of radio sources in the sky is correlated in an angular scale of a few degrees to a few tens of degrees (Simard-Normandin & Kronberg 1980; Oren & Wolfe 1995; Han et al. 1997; Stil, Taylor & Sunstrum 2011), which indicates the smooth GRM foreground. The extragalactic RM is $RM_{\text{in}} + RM_{\text{IGM}} = RM_{\text{obs}} - GRM$, which is often called the residual rotation measure (RRM; i.e. the residual after the foreground GRM is discounted from the observed RM). Because the polarization angle undergoes a random walk in intergalactic space because of the intervening magneto-ionic medium, the RRM from the intergalactic medium should have a zero-mean Gaussian distribution. Radio sources at higher redshift will pass through more intervening medium, so that the variance of RRMs $V_{\text{RRM}}$ of a sample of sources is expected to become larger at higher redshifts. Although the measured RM values from a source could likely be wavelength-dependent because of unresolved multiple components (Farnsworth, Rudnick & Brown 2011; Bernet, Miniati & Lilly 2012; Xu & Han 2012), the RM values intrinsic to a radio source at redshift $z_s$ are reduced by a factor $(1+z_s)^2$ because of a change of $\lambda$ when transformed to the observer’s frame, and for the variance by a factor $(1+z_s)^3$, the RRM are therefore often statistically used to probe magnetic fields in the intervening medium between the source and us, such as galaxies and halos, galaxy clusters or cosmic webs.

Previously, there have been many efforts to investigate RRM distributions and their possible evolution with redshift. In the early days, without a good assessment of the foreground GRM, the RMs of a small sample of radio sources gave some indications for larger RRM data scatter at higher redshifts, and these were taken as evidence of a magnetic field in the intergalactic medium (Nelson 1973; Vallee 1975; Kronberg & Simard-Normandin 1976; Kronberg, Reinhardt & Simard-Normandin 1977; Thomson & Nelson 1982).
Burman (1974) proposed the steady-state model and found that the variance of RRM approaches a limiting value at $z \sim 1$. Kronberg et al. (1977) suggested $\sigma_{\text{IGM}} < 10 \text{ rad m}^{-2}$, and Vallee (1975) claimed that the upper limit of the intergalactic RM was 10 rad m$^{-2}$. Theoretical models have been proposed for random intergalactic magnetic fields in the Friedmann cosmology (Nelson 1973), in the Einstein–de Sitter cosmology (Burman 1974) and for uniform fields (Vallee 1975). Thomson & Nelson (1982) summarized the Friedmann model (Nelson 1973) and the steady-state model (Burman 1974) and also proposed their own ionized cloud model. In the Friedmann model, particle conservation is assumed and the field is frozen in the evolving Friedmann cosmology. Thomson & Nelson (1982) showed that $V_{\text{RRM}}$ increases with $(1 + z)^{3/2}$ depending on the cosmology density $\Omega_M$. In the steady-state model, contiguous random cells do not vary with time, which induces the intergalactic $V_{\text{RRM}} \propto [1 - (1 + z)z]^{-2}$. In the ionized cloud model, the Faraday-active cells with random fields are in the form of non-evolving discrete gravitationally bound, ionized clouds, so that the final $V_{\text{RRM}} \propto [1 - (1 + z)^{3/2}]$. Thomson & Nelson (1982) applied these three models to fit the increasing RM variance of 134 quasars against redshift, but could not distinguish these models because of large uncertainties. Welter, Perry & Kronberg (1984) studied the statistics of the RMs of 112 quasars and found a systematic increase of $V_{\text{RRM}}$ with redshift, even up to redshift $z > 2$. After considering the possible contributions to the RRM variance from RMs intrinsic to quasars or from RMs due to discrete intervening clouds, Welter et al. (1984) have suggested that the observed RRM variance mainly results from intervening clouds associated with the absorption line.

Because intervening galaxies are most probably clouds for intergalactic RMs at cosmological distances, over many years, there have been efforts to search for evidence of the association between the enlarged RRM variance with the optical absorption lines of quasars. First by Kronberg & Perry (1982), later by Welter et al. (1984), Watson & Perry (1991), Wolfe, Lanzetta & Oren (1992), Oren & Wolfe (1995), Bernet et al. (2008), Kronberg et al. (2008) and Bernet, Miniati & Lilly (2010), and most recently by Bernet et al. (2012) and Joshi & Chand (2013). Small and later larger quasar samples with or without the Mg II absorption lines (e.g. Joshi & Chand 2013), with stronger or weaker Mg II absorption lines (e.g. Bernet et al. 2010), with or without the Ly$\alpha$ absorption lines (e.g. Oren & Wolfe 1995), are compared for RRM distributions. In almost all cases, the RRM or absolute values of the RMs of quasars with absorption lines show a significantly different cumulative RM probability distribution function (PDF) or a different variance value from those without absorption lines, and those of higher-redshift quasars show a marginally significant excess compared to that of lower-redshift objects. Most recently, Joshi & Chand (2013) obtained the excess of RRM deviation of $8.1 \pm 4.8$ rad m$^{-2}$ for quasars with Mg II absorption lines.

Certainly, intervening objects could be large-scale cosmic webs or filaments or superclusters of galaxies, with a coherence length much larger than a galaxy, which might result in a possible excess of RRsMs (Xu et al. 2006). At least the RRM excess due to galaxy clusters has been statistically detected (e.g. Clarke, Kronberg & Böhhringer 2001; Govoni et al. 2010). Computer simulations for large-scale turbulent magnetic fields, together with inhomogeneous density in the cosmic web on a scale of tens of Mpc, have been attempted by, for example, Blasi, Burles & Olinto (1999), Ryu et al. (2008) and Akahori & Ryu (2010, 2011), and have also been compared with real RRM data. The RMs from cosmic webs probably are very small, only about a few rad m$^{-2}$ (Akahori & Ryu 2011). The dispersion of RRsMs caused by the cosmic webs is also small, which increases when $z < 1$ and saturates at a value of a few rad m$^{-2}$ at $z \sim 1$.

Because of the small amplitude of the RM contribution from intergalactic space, in order to study the redshift evolution of extragalactic RMs, we have to enlarge the sample size of high-redshift objects for RMs and reduce the RRM uncertainty. The uncertainty of the RRM is limited not only by the observed accuracy for the RMs of radio sources but also by the accuracy of the estimated foreground GRMs. The GRM uncertainty in most previous studies is large, around 20 rad m$^{-2}$ in general, because of a small covering density of available RMs in the sky. Note that RMs have the smallest random values near the two Galactic poles (Simard-Normandin & Kronberg 1980; Han, Manchester & Qiao 1999; Mao et al. 2010). To reduce the uncertainty of RRsMs, You, Han & Chen (2003) tried to use RMs from only 43 carefully selected extragalactic radio sources towards the Galactic poles, and found only a marginal increase of $V_{\text{RRM}}$ with redshift.

In addition to the previously catalogued RMs (e.g. Simard-Normandin, Kronberg & Button 1981; Broten, MacLeod & Vallee 1988) and published RM data in the literature, Taylor, Stil & Sunstrum (2009) have reprocessed the two-band polarization data of the National Radio Astronomy Observatories (NRAO) Very Large Array (VLA) Sky Survey (NVSS; Condon et al. 1998), and have obtained the two-band RMs for 37 543 sources. Although there is a systematical uncertainty of $10.0 \pm 1.5$ rad m$^{-2}$ (Xu & Han 2014), the NVSS RMs can be used together to derive the foreground GRM (Oppermann et al. 2012; Xu & Han 2014); see Fig. 1. Hammond, Robishaw & Gaensler (2012) obtained the RMs of a sample of 4003 extragalactic objects with known redshifts (including 860 quasars; data not released yet) by cross-identification of the NVSS RM catalogue sources (Taylor et al. 2009) with known optical counterparts (galaxies, active galactic nuclei and quasars) in the literature, and they concluded that the variance for RRsMs does not evolve with redshift. Nevertheless, Neronov, Semikoz & Bannafsheh (2013) used the same data set and found strong evidence for the redshift evolution of the absolute values of RMs. Further investigation is necessary to resolve this controversy.

Recently, Xu & Han (2014) compiled a catalogue of reliable RMs for 4553 extragalactic point radio sources, and used a weighted average method to calculate the foreground GRM based on the compiled RM data together with the NVSS RM data. However, a new version of the Million Quasars (Milliquas) catalogue (Flesch 2014) has been updated and is available online; this is a compilation of about 1 252 004 objects from the literature and archival surveys and data bases. Here, we have cross-identified the two large data sets, and have obtained RMs for 2642 quasars, which can be used to study the redshift evolution of extragalactic RMs. We introduce the data in Section 2, and study their distributions in Section 3. We discuss the results and fit the models in Section 4.

### 2 Rotation Measure Data of Quasars

We have obtained the RM data of quasars from the cross-identification of quasars in the newest version of the Milliquas catalogue with radio sources in the NVSS RM catalogue (Taylor et al. 2009) and the compiled RM catalogue (Xu & Han 2014). The

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1. http://zmtt.bao.ac.cn/RM/
2. http://iquasars.org/milliquas.htm
Milliquas catalogue (version 3.8a) is a compilation of all known type I quasars, active galactic nuclei and BL Lacertae objects in the literature. To avoid a possible influence on RRM from different polarization fractions of galaxies and quasars (Hammond et al. 2012), we take only type I quasars in the catalogue. We adopt 3 arcsec as the upper limit of the position offset for associations between quasars and radio sources with RM data, according to the discussions by Hammond et al. (2012). Finally, we obtain RMs for 2642 associated quasars, as listed in Table 1, which is the largest data set of quasar RMs to date.

To obtain the extragalactic RMs of these quasars, we have to discount the foreground RM from our Milky Way. The foreground GRMs vary with the Galactic longitude (GL) and latitude (GB). In recent similar works (e.g. Hammond et al. 2012; Neronov et al. 2013) the foreground RMs were taken from estimations of Oppermann et al. (2012) using a complicated signal reconstruction algorithm within the framework of information field theory. We have used an improved weighted average method to estimate the foreground GRM by using the cleaned RM data without outliers, which gives more reliable estimations of the GRM with smaller uncertainties (Xu & Han 2014). The extragalactic RMs (i.e. the RRM) are then obtained by \( RRM = RM - GRM \), and their uncertainty by \( \sigma_{RRM} = \sqrt{\sigma_{RM}^2 + \sigma_{GRM}^2} \), as listed in Table 1.

The RRM distributions of the 2642 quasars are shown in Fig. 2, including the distribution against redshift and amplitude, together with the histograms for RRM amplitude and uncertainty. Most RM data taken from Taylor et al. (2009) have a large formal uncertainty and also a previously unknown systematic uncertainty (Mao et al. 2010; Xu & Han 2014). Because the uncertainty is a very important factor for deriving the redshift evolution of the RRM (see below), the best RRM data set for the redshift evolution study should consist of those with a very small uncertainty (e.g. \( \sigma_{RRM} \leq 5 \) rad m\(^{-2}\)). We obtain a RRM data set of 684 quasars with such a formal accuracy, without considering the systematic uncertainty, and their RRM distribution is shown in the top-right panel of Fig. 2. To clarify the sources of RM data, we present the RRM distribution for 2202 quasars that have RM values obtained only from the NVSS RM catalogue (Taylor et al. 2009), and also for 440 quasars whose RM values are obtained from the compiled RM catalogue of Xu & Han (2014).

### 3 RRM DISTRIBUTIONS AND THEIR REDSHIFT EVOLUTION

The RRM data shown in Fig. 2 should be carefully analysed to reveal the possible redshift evolution of the RRM distribution.

First, looking at Fig. 2, we see that most of the 2642 RRM have values less than 50 rad m\(^{-2}\), with a peak around 0 rad m\(^{-2}\). Only a small sample of quasars have \( |RRM| > 50 \) rad m\(^{-2}\), which might result from the intrinsic RMs of sources or the RM contribution from galaxy clusters. The RM dispersion due to foreground galaxy clusters is about 100 rad m\(^{-2}\) (see Govoni et al. 2010; Clarke et al. 2001). In this paper, do not investigate the RMs from galaxy clusters, and therefore we exclude 91 objects (3.44 per cent) with \( |RRM| > 50 \) rad m\(^{-2}\). Thus, 2551 quasars are left in our sample for further analysis. Secondly, most of these quasars have a redshift \( z < 3 \). Because the sample size for high-redshift quasars is too small to obtain meaningful RRM statistics, we have excluded 62 quasars (2.43 per cent) with \( z > 3 \) from further analysis of redshift evolution.

Finally, we have the RRM of 2489 quasars with \( |RRM| \leq 50 \) rad m\(^{-2}\) and \( z < 3 \).

Note, in Table 1, that the RRM of these quasars have formal uncertainties \( \sigma_{RRM} \) between 0 and 20 rad m\(^{-2}\), which would undoubtedly broaden the real RRM distribution and probably bury the possible small excess RRM with redshift. Therefore, we study four subsamples of these quasars with different RRM uncertainty thresholds, \( \sigma_{RRM} \leq 20, 15, 10 \) and 5 rad m\(^{-2}\). Because the NVSS RMs have an implicit systematic uncertainty of 10.0 ± 1.5 rad m\(^{-2}\) (Xu & Han 2014), different from that of the compiled RMs, which is less than 3 rad m\(^{-2}\), we study the RRM distribution for two samples of quasars separately: one with RMs taken from the NVSS RM catalogue, and the other with RMs from the compiled RM catalogue. We divide the quasar samples into five subsamples in five redshift bins, \( z = (0.0, 0.5), (0.5, 1.0), (1.0, 1.5), (1.5, 2.0) \) and (2.0, 3.0), to check the redshift evolution of the real dispersion of RRM distributions.

How do we obtain the real dispersion of RRM distributions, given various uncertainties of RRM values? Here, we have used the bootstrap method. It is clear that the probability of a real RRM
value follows a Gaussian function centred at the observed RRM value with a width of the uncertainty value, i.e.,

\[
p(RRM) = \frac{1}{\sqrt{2\pi}\sigma_{RRM}} \exp\left(-\frac{(RRM - RRM_i)^2}{2\sigma_{RRM}^2}\right),
\]

where \(RRM_i\) is the \(i\)th data in the sample and \(\sigma_{RRM}\) is its uncertainty. Then, we sum the PDF calculated in this way for \(N\) observed RRM values for a subsample of quasars in a redshift range, assuming that there is insignificant evolution in such a small redshift range,

\[
P(RRM) = \sum_{i=0}^{N} p(RRM_i).
\]

This contains the contributions not only from the real RRM distribution width but also from the effect of observed RRM uncertainties.

If there is an ideal RRM data set without any measurement uncertainty, the RRM values follow a Gaussian distribution with the zero mean and a standard deviation of \(W_{RRM}\), which is the real dispersion of RRM data as a result of the medium between the sources and us. We generate such a mock sample of RRM data with a sample size 30 times the original RRM data but with a RRM uncertainty randomly taken from the observed RRsMs. We sum the RRM PDF for the mock data, as done for the real data. Finally, we can compare the two PDFs, \(P(RRM)\) and \(P_{mock}(RRM)\), by using the \(\chi^2\) test as for two binned data sets (see section 14.2 of Press et al. 1992). For each input \(W_{RRM}\), the comparison gives an integrated residual

\[
[P(RRM) - P_{mock}(RRM)]^2,
\]

which mimics \(\chi^2\). For a set of input values of \(W_{RRM}\), we obtain the residual curve. Figs 3 and 4 show example plots for the subsamples of quasars with the NVSS RMs and \(\sigma_{RRM} \leq 20\) rad m\(^{-2}\) and with compiled RMs and \(\sigma_{RRM} \leq 5\) rad m\(^{-2}\), respectively. Obviously, the best match between \(P(RRM)\) and \(P_{mock}(RRM)\) with an input \(W_{RRM}\) should give the smallest residual, and thus we take this best \(W_{RRM}\) as the real RRM dispersion.

The residual curve, if normalized with the uncertainty of the two PDFs which is unknown and difficult, should give \(\chi^2 = 1\) for the best fit, and \(\Delta \chi^2 = 1\) in the range of the doubled residual for the 68 per cent confidence level. Therefore, the uncertainty of \(W_{RRM}\) is simply taken for the range with less than two times the minimum residual in the residual curve.

Finally, note that there is an implicit systematic uncertainty of \(\sigma_{sys} = 10.0 \pm 1.5\) rad m\(^{-2}\) in the NVSS RMs and a maximum of about \(\sigma_{sys} < 3\) rad m\(^{-2}\) in the compiled RMs (Xu & Han 2014), which are inherent in the observed RRM values. The above mock calculations have not considered this contribution, and therefore the real dispersion of RRM distributions should be \(W_{RRM} = \sqrt{W_{RRM}^2 + \sigma_{sys}^2}\). We have listed all calculated results of \(W_{RRM}\) and \(W_{RRMB}\) for all subsamples of quasars in Table 2. Because almost all \(W_{RRM}\) and \(W_{RRMB}\) have values larger than 10 rad m\(^{-2}\), the small uncertainty of the systematic uncertainty of less than 2 or 3 rad m\(^{-2}\) does not greatly change these results in Table 2.

Fig. 5 plots different \(W_{RRMB}\) values as a function of redshift \((1 + z)\) for five subsamples of quasars, calculated for quasar subsamples...
Figure 2. Redshift and RRM distributions for 2642 quasars together with histograms for RRM uncertainty (top-left) and 684 quasars with formal RM uncertainty $\sigma_{\text{RRM}} \leq 5 \text{ rad m}^{-2}$ (top-right). Similar plots for 2202 quasars with only the NVSS RMs of Taylor et al. (2009) (bottom-left) or for 440 quasars with RMs from the compiled RM catalogue of Xu & Han (2014) (bottom-right).

Figure 3. PDF of measured RRM values, $P(\text{RRM})$ (solid line), compared with that of the mock RRM sample with the best $W_{\text{RRM}}$, $P_{\text{mock}}(\text{RRM})$ (dotted line), for the subsamples of quasars with the NVSS RMs and $\sigma_{\text{RRM}} \leq 20 \text{ rad m}^{-2}$ in different redshift ranges. The fitting residues, which mimic $\chi^2$, against various $W_{\text{RRM}}$ are plotted in the lower panels, which define the best $W_{\text{RRM}}$ and its uncertainty at 68 per cent probability.
with different thresholds of RRM uncertainties and also separately for quasars with the NVSS RMs and with the compiled RMs. We note that the $W_{\text{RRM}}$ values obtained from the NVSS RMs and the compiled RMs are roughly consistent within error bars, and that the $W_{\text{RRM}}$ values obtained from RMs with different RRM thresholds are also consistent within error bars. In all four cases of different $\sigma_{\text{RRM}}$ thresholds, we cannot see any redshift evolution of $W_{\text{RRM}}$ of quasars with only the NVSS RMs, which is consistent with the conclusions obtained by Hammond et al. (2012) and Bernet et al. (2012). However, the $W_{\text{RRM}}$ values systematically increase (from $\sim 10$ to $\sim 15$ rad m$^{-2}$) with the $\sigma_{\text{RRM}}$ thresholds (from 5 to 20 rad m$^{-2}$), which implies the leakage of $\sigma_{\text{RRM}}$ to $W_{\text{RRM}}$ even after the simple discounting systematical uncertainty. There is a clear tendency seen for the change of $W_{\text{RRM}}$ for quasars with the compiled RMs, increasing steeply when $z < 1$ and flattening after $z > 1$, which is best seen from the samples of $\sigma_{\text{RRM}} \leq 5$ rad m$^{-2}$. This indicates the marginal redshift evolution, which is consistent with the conclusion given by, for example, Kronberg et al. (2008).

Figure 4. Same as Fig. 3 but for subsamples of quasars with the compiled RMs and $\sigma_{\text{RRM}} \leq 5$ rad m$^{-2}$. The PDF is not smooth because of the small sample size and the small RRM uncertainties.

Table 2. Statistics for the real RRM distribution of subsamples in redshift bins.

| Redshift range | Subsamples from the NVSS RM catalogue | Subsamples from the compiled RM catalogue |
|---------------|--------------------------------------|-----------------------------------------|
|               | No. of quasars | $z_{\text{median}}$ | $W_{\text{RRM}}$ (rad m$^{-2}$) | No. of quasars | $z_{\text{median}}$ | $W_{\text{RRM}}$ (rad m$^{-2}$) |
| 0.0–0.5       | 152 | 0.400 | 17.7 ± 2.9 | 38 | 0.356 | 11.2 ± 4.5 |
| 0.5–1.0       | 455 | 0.772 | 17.5 ± 1.8 | 109 | 0.768 | 13.2 ± 5.6 |
| 1.0–1.5       | 587 | 1.286 | 17.4 ± 1.8 | 82 | 1.276 | 15.0 ± 3.1 |
| 1.5–2.0       | 441 | 1.756 | 18.2 ± 1.8 | 47 | 1.685 | 14.5 ± 8.6 |
| 2.0–3.0       | 383 | 2.300 | 17.5 ± 1.9 | 44 | 2.396 | 14.3 ± 6.9 |
| 0.0–0.5       | 136 | 0.400 | 16.9 ± 3.4 | 37 | 0.360 | 10.7 ± 4.4 |
| 0.5–1.0       | 386 | 0.768 | 17.1 ± 2.0 | 106 | 0.775 | 13.1 ± 5.6 |
| 1.0–1.5       | 510 | 1.286 | 17.0 ± 1.8 | 81 | 1.271 | 15.2 ± 3.1 |
| 1.5–2.0       | 365 | 1.741 | 18.0 ± 2.0 | 46 | 1.690 | 14.7 ± 9.1 |
| 2.0–3.0       | 306 | 2.300 | 17.4 ± 2.5 | 42 | 2.371 | 14.4 ± 7.2 |
| 0.0–0.5       | 88  | 0.400 | 15.4 ± 3.4 | 36 | 0.362 | 10.8 ± 4.4 |
| 0.5–1.0       | 272 | 0.752 | 16.4 ± 2.1 | 99  | 0.799 | 13.3 ± 6.2 |
| 1.0–1.5       | 336 | 1.283 | 15.7 ± 2.0 | 76  | 1.270 | 14.8 ± 3.0 |
| 1.5–2.0       | 232 | 1.724 | 17.5 ± 2.1 | 43  | 1.700 | 13.9 ± 9.9 |
| 2.0–3.0       | 201 | 2.300 | 16.6 ± 2.6 | 42  | 2.371 | 14.4 ± 7.2 |
| 0.0–0.5       | 40  | 0.394 | 13.7 ± 4.2 | 27  | 0.364 | 8.4 ± 2.7 |
| 0.5–1.0       | 93  | 0.720 | 15.1 ± 4.7 | 77  | 0.751 | 12.7 ± 6.1 |
| 1.0–1.5       | 119 | 1.270 | 13.6 ± 3.1 | 56  | 1.268 | 13.6 ± 3.0 |
| 1.5–2.0       | 76  | 1.732 | 15.1 ± 4.4 | 34  | 1.704 | 14.4 ± 12.4 |
| 2.0–3.0       | 78  | 2.316 | 13.4 ± 3.6 | 26  | 2.396 | 13.9 ± 14.8 |
Figure 5. Real dispersion $W_{\text{RRM}}$ of RRM distributions as a function of redshift in five redshift ranges for five subsamples of quasars, calculated for different RRM uncertainty thresholds and separately for the NVSS RMs (open circles) and the compiled RMs (filled circles). The median redshift of the subsample is adopted for each redshift bin. The two dot-dashed lines are the scaled ‘ALL’ and ‘CLS’ models from Akahori & Ryu (2011), the dotted line is the evolving Friedmann model (the EF model by Nelson 1973) and the dashed line is the ionized cloud model (the IC model by Thomson & Nelson 1982), which are scaled and fitted to the filled circles.

and Joshi & Chand (2013). Therefore, we understand that the small amplitude dispersion of RRMs is buried by the large uncertainty of RRMs, and such real RRM evolution can only be detected through high-precision RM measurements of a large sample of quasars in future.

4 DISCUSSION AND CONCLUSIONS

Using the largest sample of quasar RMs and the most recently updated foreground GRMs, and after carefully excluding the influence of RRM uncertainties and large RRM outliers, we have obtained Fig. 5 where we show the redshift evolution of the dispersion of extragalactic RMs. Now, we try to compare our results with the previously available models mentioned in Section 1.

Nowadays, the ΛCDM cosmology is widely accepted. The non-evolving steady-state Universe is no longer supported by many modern observations and we do not discuss it. The old coexpanding evolving Friedmann model (Nelson 1973) is also ruled out by our RRM data (see Fig. 5), because the electron density and magnetic field in the model are scaled with redshift via $n_e = n_0(1 + z)^3$ and $B = B_0(1 + z)^2$ and the variance of RRMs ($\propto W_{\text{RRM}}^2$) should increase with $z$. Among the three old models, the IC model given by Thomson & Nelson (1982) can fit to the data. The ionized clouds along the line of sight can be the gravitationally bounded and ionized objects, which might be associated with protogalaxies, galactic haloes, galaxy clusters or even widely distributed intergalactic medium in cosmic webs. The dashed lines in Fig. 5 are the fitting to the $W_{\text{RRM}}$ data by the IC model. In ΛCDM cosmology, it has the form of

$$V_{\text{RRM}} = V_0 \int_0^{z_s} \frac{1}{(1 + z)^3 \Omega_m(1 + z)^3 + \Omega_\Lambda} \, dz$$

with a fitting parameter

$$V_0 = (0.81 n_c B_{\|} L_c f_0 H_0^2) \approx 441 \pm 150 \, \text{rad}^2 \, \text{m}^{-2},$$

where $n_c$, $B_{\|}$ and $L_c$ are the electron density, magnetic field and the coherence size of a random field size, $f_0$ is the filling factor, $H_0$ is the Hubble parameter and $c$ is the light velocity. Current ΛCDM cosmology takes $H_0 = 70 \, \text{km} \, \text{s}^{-1} \, \text{Mpc}^{-1}$, $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$. The RRM variance ($V_{\text{RRM}} \propto W_{\text{RRM}}^2$) in the IC model has a steep increase at low redshift and flattens at high redshift, which fits the $W_{\text{RRM}}$ data very well (see Fig. 5). The simulations given by Akahori & Ryu (2011) verified the shape of the RM dispersion curves. We scaled the ‘ALL’ model of Akahori & Ryu (2011) to fit the data, and also scaled their ‘CLS’ model to show the relatively small amplitude from cosmic webs.

For a sample of quasars, the lines of sight for some of them pass through galaxy haloes indicated by Mg II absorption lines, which probably have a RRM dispersion of several rad m$^{-2}$ (Joshi & Chand 2013); some quasars behind galaxy clusters might have large RRM dispersion of a few tens of rad m$^{-2}$ (Clarke et al. 2001; Govoni et al. 2010); some quasars just through the intergalactic medium without such intervening objects should have a RRM dispersion of 2–3 rad m$^{-2}$ from cosmic webs (see the cluster subtracted model of Akahori & Ryu 2011). These different clouds give different $V_0$. However, we note that the redshift evolution of the RRM dispersions
of each kind of cloud depends only on cosmology (see equation 5), not the $V_0$.

In principle, we can model the RRM dispersion with a combination of ionized clouds with different fractions (i.e. $V_0 = V_{\text{gala}} f_{\text{gala}} + V_{\text{cluster}} f_{\text{cluster}} + V_{\text{IGM}} f_{\text{IGM}}$). We checked our quasar samples in the Sloan digital Sky Survey (SDSS) area, and about 10–15 per cent of the quasars (for different samples in Table 2) are behind the known galaxy clusters of $z \leq 0.5$ in the largest cluster catalogue (Wen, Han & Liu 2012). Quasars behind galaxy clusters have a large scatter in RRM data in Fig. 2, most probably extended to beyond 50 rad m$^{-2}$, which gives a wide Gaussian distribution of real RRM dispersions. The fraction for the cluster contribution is at least $f_{\text{cluster}} \sim 0.1–0.15$, because of unknown clusters at higher redshifts. The fraction for galaxy halo contribution shown by Mg II absorption lines $f_{\text{gala}}$ is about 28 per cent (Joshi & Chand 2013). If we assume that the coherence size of magnetic fields in these three clouds is 1, 10 and 1000 kpc, that the mean electron density is $10^{-3}$, $10^{-4}$ and $10^{-5}$ cm$^{-3}$, that the mean magnetic field is 2, 1 and 0.02 µG (e.g. Akahori & Ryu 2011) and that the filling factor is 0.00001, 0.001 and 0.1 (Thomson & Nelson 1982) for galaxy halos, galaxy clusters and the intergalactic medium in cosmic webs, respectively, then we can estimate the dispersions of these clouds, which at $z = 1$ are 7, 11 and 2 rad m$^{-2}$, respectively. Whatever values for the different ionized clouds, they have to sum together with various fractions to fit the dispersions of RRM data.

Having realized that the real RRM dispersion of quasars at $z > 1$ does not change with redshift for each kind of ionized cloud, we now model the PDF of the absolute values of RRM data for all 146 quasars with $z \geq 1$ from the compiled RM catalogue, without discarding any objects limited by redshift and RRM values but with a formal RM uncertainty $\sigma_{\text{RM}} \leq 5$ rad m$^{-2}$ (see Fig. 6). We found that such a PDF can be fitted with two components, one for a small $W_{\text{RRM}}$, which stands for the contributions from galactic haloes and cosmic webs, and one for a wide $W_{\text{RRM}}$, which comes from galaxy clusters. Two such mock samples with optimal fractions are searched for the best match with the PDF. We obtain $W_{\text{RRM}1} = 11.4_{-2.4}^{+2.6}$ rad m$^{-2}$ with a fraction of $f_1 = 0.65$ and $W_{\text{RRM}2} = 51_{-20}^{+35}$ rad m$^{-2}$ with a fraction of $f_2 = 0.35$ for clusters. However, we cannot separate the contributions from galaxy haloes and cosmic webs, which are tangled together in $W_{\text{RRM}}$.

Therefore, we conclude that the dispersion of RRM data steadily increases from $z = 0$ to $z \sim 1$ and saturated at about 10 rad m$^{-2}$ when $z \geq 1$. However, the current RM data sets, even the largest sample of quasars, are not yet good enough to separate the RM contributions from galaxy haloes and cosmic webs, because of large RRM uncertainties. A larger sample of quasars with better precision in RM measurements is necessary to make clarifications.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Table 1. 2642 quasars with RM data available in literature (http://mnras.oxfordjournals.org/lookup/suppl/doi:10.1093/mnras/stu1018/-/DC1).

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