Dependence of Residual Rotation Measure (RRM) on Intervening Mg II Absorbers at Cosmic Distances

Ravi Joshi1⋆, Hum Chand1⋆

1 Aryabhatta Research Institute of observational sciencES (ARIES), Manora Peak, Nainital – 263129, India

ABSTRACT

We investigate the dependence of residual rotation measure (RRM) on intervening absorption systems at cosmic distances by using a large sample of 539 SDSS quasars in conjunction with the available rotation measure catalog at around 21cm wavelength. We found an excess extragalactic contribution in standard deviation of observed RRM ($\sigma_{\text{rrm}}$) of about $8.11 \pm 4.83$ rad m$^{-2}$ in our sample with intervening Mg II absorber as compare to the sample without Mg II absorber. Our results suggest that intervening absorbers could contribute to the enhancement of RRM at around 21cm wavelength, as was found earlier for RM measurements at around 6cm wavelength.

Key words: galaxies: distances and redshifts, magnetic fields – polarization, quasars: absorption lines – quasars: objects: general – intergalactic medium – techniques: spectroscopic

1 INTRODUCTION

Magnetic field plays a key role in the structural and dynamical evolution of the Universe (e.g., Mestel & Paris 1984; Rees 1987), but there are no methods for its direct measurement. Faraday Rotation (FR) is one of the powerful probes to measure the strength of magnetic field over the cosmic time scale (e.g., Bernet et al. 2008, 2012; Hammond et al. 2012; You et al. 2003; Welter et al. 1984; Kronberg et al. 2008; Kronberg & Perry 1982; Kronberg et al. 1977; Kronberg & Simard-Normandin 1976). This Rotation Measure (RM) is defined as the change in observed polarization angle ($\Delta \chi_0$) per unit change in observed wavelength square ($\Delta \lambda_0^2$). For a linearly polarized radio source at cosmological redshift ($z_s$) it is given by (Bernet et al. 2012):

$$RM(z_s) = \frac{\Delta \chi_0}{\Delta \lambda_0^2} = 8.1 \times 10^5 \int_{z_s}^{0} n_e(z) B_{||}(z) \frac{dl}{dz} dz,$$

where RM is in units of rad m$^{-2}$, the free electron number density, $n_e$, is in cm$^{-3}$, the magnetic field component along the line-of-sight, $B_{||}$, is in Gauss, and the comoving path increment per unit redshift, $dl/dz$, is in parsec. However, the observed RM has contributions from two components, namely extragalactic radio source and ionized medium of our Galaxy. As a result of this, it is not straightforward to quantify the FR contribution coming from the extragalactic radio source. This extragalactic component also includes the contributions from intervening galaxies and/or their halos, protogalaxies, intergalactic clouds, an intracluster gas consisting of widespread coexpanding diffuse intergalactic medium and intrinsic to the quasar. Therefore, the extragalactic RM can only be studied in terms of the residual rotation measure (RRM), after removing the Galactic component from the observed RM.

Earlier studies of RM on its redshift evolution has shown that the RM dispersion of quasars increases at high redshift (Kronberg et al. 2008; Kronberg & Simard-Normandin 1976; Rees & Reinhardt 1972), in contrast to the $(1+z)^{-2}$ dilution effect on RM (e.g., see Eq. 1). This led to the conclusion that the magnetic field strength as traced by the RM of high redshift galaxies is at least comparable to the current epoch (Kronberg et al. 2008). The possible origin of this high magnetic field at cosmic distances remain ambiguous, however, such high fields could be either intrinsic to the quasars (e.g., arising in its immediate environment) or due to the intervening environments along the lines-of-sight between the polarized source and the observer. Bernet et al. (2008) have probed the latter possibility from the analysis of high resolution optical spectra of 76 quasars. They have shown that the quasars with strong Mg II absorption line systems are unambiguously associated with larger
RM, inferred from their RM observation at around 6cm wavelength. In other words, the major contribution to the extragalactic component of observed RM comes from the intervening galaxies. However, in contrast to the case with Mg II absorption systems having rest frame equivalent width (\(EW_{\text{c}}\)) greater than 0.3A, Bernet et al. (2010) have shown that the weaker systems do not contribute significantly to the observed RM of the background quasars. The above discrepancy is attributed to the higher impact parameters of weak systems compared to strong ones.

Recently, Hammond et al. (2012) made a catalog of RRM available for 3651 radio sources that were observed at around 21cm. They reported an observed standard deviation in RRM of 23.2 rad m\(^{-2}\) from a mixed sample of quasars and galaxies having a mixture of sightlines with and without Mg II absorber. Further, subtracting the possible errors contributing to this measured standard deviation, such as: (i) the measurement errors of individual RM of 11 rad m\(^{-2}\) as given in the catalog by Taylor et al. (2009); (ii) error associated with the galactic rotation measurement (GRM) calculations of 6 rad m\(^{-2}\) (OPPELMANN et al. 2012); and (iii) 12–17 rad m\(^{-2}\) from the RM fluctuations on smaller angular scales than are being sampled by above GRM (Stil et al. 2011). The remaining contribution from extragalactic component is found to be typically around 10–15 rad m\(^{-2}\), similar to Schnitzeler (2010). Importantly, with this extensive study, they could not reproduce any significant redshift evolution of RRM as seen by other studies (e.g., Kronberg et al. 2008; Welter et al. 1984).

To explain the above discrepancy, Bernet et al. (2012) have proposed a model consisting of partially inhomogeneous rotation measure screen, which causes wavelength dependent depolarization. As a result the depolarization in their model toward longer wavelength such as close to 21cm used in Hammond et al. (2012) data set will be larger than the shorter wavelength close to 6cm used in Bernet et al. (2008), which has been attributed to the above discrepancy. This was supported by their result that the RM distribution with and without Mg II absorber do differ from data set based on 6cm, unlike no such difference seen on their 21cm data set. However, it should be noted that this data set having RM measurements at both the above wavelengths (i.e., 21cm and 6cm) consist of only 54 radio source sightlines. In view of the important consequences of the above results, it is very important to carry out the analysis by using larger sample size to detect and quantify any effect of intervening absorbers on the extra-galactic component of RRM. This forms the main motivation of our present work, by carrying out the analyses for subsample of sightlines with and without Mg II absorber in the parent sample of 567 SDSS quasars and by using the RRM-redshift catalog provided by Hammond et al. (2012).

This paper is organized as follows. Section 2 describe the selection of the samples of RRM data set, while Section 3 gives methodology used in the analysis. In Section 4, we present the results of our analysis, followed by the discussion and conclusions in Section 5.

2 SAMPLE

Our sample is collected from catalog produced by Hammond et al. (2012), which consists of 3651 sources at high galactic latitude, having \(|b| > 20^\circ\). The catalog is constructed by assigning redshift for polarized radio source cataloged by Taylor et al. (2009) using an optical database of, e.g., NED\(^1\) and SIMBAD\(^2\) and optical surveys namely SDSS-DR8\(^3\), 6DFGS\(^4\), 2dFGRS\(^5\) and 2QZ/6QZ\(^6\) (e.g., see their online Table 1). We have applied following criteria to select our sample from the above mentioned catalog.

(i) Firstly, we have restricted ourselves only to those radio sources whose optical association are assigned as quasar using SDSS database due to the advantage of the availability of their spectra from SDSS archive. Of the 3651 source in the catalog of Hammond et al. (2012), this selection filter left us with 860 polarized radio sources having SDSS spectra. Out of them, we only consider the most common designated radio to optical association namely class ‘A’, which represents an unresolved NVSS\(^7\) radio source (observed at 21cm) that align closely with the corresponding optical counterpart (i.e., the NVSS-optical offset < 15 arcsec) and also have a FIRST\(^8\) counterpart, which is used to make the radio-optical association. Further, the class ‘A’ in Hammond et al. (2012) is subdivided into seven subclasses A(i)-A(vii), depending on the radio morphology in FIRST survey. To minimize the uncertainty of radio and optical association, we have included only those subclasses having at the most 3 matches in FIRST image within 30 arcsec of the optical position, leading to the exclusion of sources belonging to A(vi), which have more than 3 such associations. In addition, we have included the class ‘B’ sources, representing a similar situation to class ‘A’ by using only NVSS, either due to the non-detection or the absence of data set in FIRST survey. This left us with a sample of 730 polarized radio sources having SDSS spectra.

(ii) Secondly, we have excluded all the quasars having emission redshift outside the range of 0.38 \(\leq z_{\text{em}} \leq 2.3\). Here, the lower limit constrain on the quasar emission redshift is to ensure that their SDSS spectra having lowest wavelength about 3800A, which allows to detect at least one Mg II doublet, if present. Similarly, upper \(z_{\text{em}}\) constrain is to ensure that Mg II emission line does not fall above the highest SDSS wavelength, which is 9200A, so that ambiguity of any Mg II absorber falling above the spectral coverage.

\(^{1}\) NED=NASA/IPAC Extragalactic Database http://ned.ipac.caltech.edu
\(^{2}\) SIMBAD=Set of Identifications, Measurements and Bibliography for Astronomical Data; http://simbad.u-strasbg.fr/simbad/
\(^{3}\) SDSS=Sloan Digital Sky Survey DR8; http://skyserv/sds3.org/dr8/en/
\(^{4}\) 6DFGS=Six-degree Field Galaxy Survey; http://www.sdss3.org/dr8/en/
\(^{5}\) 2dFGRS=Two-degree Field Galaxy Redshift Survey; http://www2.aao.gov.au/2dfgrs/
\(^{6}\) 2QZ/6QZ=2df QSO Redshift Survey (2QZ) and 6df QSO Redshift Survey (6QZ); http://www.2dfquasar.org/Spec_Cat/catalogue.html
\(^{7}\) NVSS=NRAO Very Large Array Sky Survey; http://www.cv.nrao.edu/nvss/
\(^{8}\) FIRST=The VLA Faint Images of the Radio Sky at Twenty centimeters survey; http://sundog.stsci.edu/
can be avoided. These filters have reduced the sample to 615 quasars.

(iii) Finally, to minimize the uncertainty in the radio to optical association, we have removed those quasars for which the optical and radio sightlines are separated by more than 7 arcsec (similar to Bernet et al. 2008), resulting in the sample of 567 quasars, for our analysis.

3 ANALYSIS
3.1 Identification of Mg II absorption systems

The identification of the Mg II absorption doublet in the normalized continuum spectrum, was carried out using the procedure discussed in detail by Joshi et al. (2013, under review). Briefly, the procedure initially fits a continuum to the SDSS spectroscopic data, employing a first principal component analysis (PCA) as a guess for the Lyα and C IV emission lines (i.e., from 1000Å–2000Å in the rest-frame). Next, a b-spline algorithm was used to fit the underlying residual continuum, which results roughly in a power-law with broad emission features superposed.

The procedure automatically also searches for absorption features in the normalized spectrum redward of Lyα. The search was carried out for absorption features, fitted with Gaussian profile by taking an initial FWHM of 2.5 pixels, with the additional requirement that the minimum separation between lines of doublet should be about 2 times the FWHM. Out of all such cases, the final selection was made by accepting only the lines which are above 3 times the rms(σ) noise in the spectrum.

The absorption features thus identified for each quasar, were searched for absorption line pairs. For this purpose the procedure first computed redshift of a given absorption feature, assuming it to be Mg II2796. The corresponding positions of the expected Mg II2803 and Fe II2600 lines were then inspected. The criterion for accepting a feature as genuine Mg II absorption system, was that at least two of these three lines must be present at the expected locations above a 3σ threshold. Equivalent widths of all the accepted Mg II absorption lines were then measured by summing the difference from unity of the flux in the normalized observed-frame spectrum, within about 10 pixels wide boxes (~11.5Å in the observed frame) placed at the centroids of the two Mg II lines.

As a further check, we also carried out a visual confirmation of each absorption system identified via the above automated procedure. This step is important since (i) our automated search do not carry out the line profile matching and hence can result in over counting the Mg II doublet, rather than missing out any genuine system, and (ii) any visually noticed uncertainty in the continuum level could have significantly distorted the estimate of EW, rendering the strong/weak classification of absorption systems unreliable. In this process of visual scrutiny, we first looked for the strongest five Fe II lines corresponding to the candidate Mg II doublet. We then made a velocity plot of Mg I, Mg II and the five Fe II lines, so as to match by eye the line profile and strength to that expected on the basis of the line oscillator strengths. Thus, in the spectra of the 567 quasars, we visually inspected all 673 Mg II absorption systems candidates and confirmed 256 of them. Continuum fitting of each confirmed Mg II absorption system was then further checked by plotting the fitted continuum to the spectral segment containing the Mg II doublet. In all cases where the continuum fitting over the relevant spectral segment seemed unsatisfactory, we refined the local continuum fit and recomputed the $EW_{\lambda}(\text{Mg II})$. To test the ‘intervening hypothesis’, we have removed those 28 quasars having associated Mg II absorbers with relative velocity < 5000 km s$^{-1}$ in the spectra. This leads to a final sample of 539 quasars, which is used in rest of our analysis. Among these 539 quasars, 388 are without Mg II absorber, while 119 have one and 32 have more than one Mg II absorber in their spectra.

4 RESULTS

The quasars with strong Mg II absorption systems along their line-of-sight are found to have broad RM distribution from the analysis of 6cm data set (Bernet et al. 2008). However, in a recent study no such signature is observed with the 21cm data set by Bernet et al. (2012), though with the nominal sample size consisting of only 54 radio source sightlines (see their Figure 3). In this work, to test the above discrepancy, in Figure 1 (left panel), we have shown the cumulative distribution of RM for sightlines with Mg II (with number $n_{\text{MgII}} > 0$, dashed-dotted line; $n_{\text{MgII}} > 1$, dashed line) and without Mg II ($n_{\text{MgII}} = 0$, thick line) absorbers using our large data set of 539 sightlines having RM measurement at around 21cm wavelength. The K–S test rules out the null hypothesis for the quasar subsets, (i) without and with at least one Mg II absorber and (ii) without and with at least two Mg II absorbers, at a confidence level of 48% and 66% respectively, which is statistically nonsignificant using our this modest sample size. We also notice here that the major difference in RM distribution can be seen at around 30 rad m$^{-2}$, which is similar to the average contribution of 20 rad m$^{-2}$ from the foreground galactic RM (GRM) component (Bernet et al. 2008). To see any such effect of GRM, we have plotted the cumulative distribution of RM (i.e., GRM subtracted RM), shown in the right panel of Figure 1. The two distribution without and with at least one Mg II absorber are found to be different with the K–S test giving $P_{\text{null}} = 0.21$. Similarly, a $P_{\text{null}} = 0.32$, is seen between the quasar subsets having at least two Mg II absorber and no absorber, implying that the hypothesis of quasars with and without Mg II absorber have a similar distribution is ruled out at a confidence level of 79%.

To elucidate the effect of intervening absorber on RRM, in Figure 2, we have plotted the histogram of RRM for the quasars with absorber (shaded region) and without absorber (thick line), after normalizing with total quasar count within respective subsets. At first look, it appears that the RRM distribution for the sightlines that passes through the Mg II systems is significantly broader than that for which absorption is absent. This reflects in the standard deviation of RRM for the quasars with and without Mg II absorber being 18.93±1.05 rad m$^{-2}$ and 17.11±0.69 rad m$^{-2}$, respectively. Here, the error on standard deviation of RRM is computed by propagation of errors in individual RRM value by assuming their Gaussian nature, as follows:
Figure 1. Left panel: Cumulative distribution of the Rotation Measure (RM), for the quasar with no absorber (thick line), with at least one absorber (dashed-dotted line) and with at least two absorber (dashed line). Right panel: same as left, for the Residual Rotation Measure (RRM) measurements, the inset displays the zoom-in on the maximum distance between the distribution functions.

Figure 2. Histogram of Residual Rotation Measure (RRM), normalized by the total quasars counts in the subsets of quasar with \((\text{EW}_r(2796) \geq 0.3\text{Å})\) Mg \(\text{II}\) absorber (shaded region) and without absorber (thick line).

\[
\delta \sigma = \frac{1}{\sigma (N-1)} \left( \sum_{i=1}^{N} (x_i - \bar{x})^2 \delta x_i^2 + \left( \sum_{i=1}^{N} x_i - \bar{x} \right)^2 \delta \bar{x}^2 \right)^{1/2},
\]

(2)

Where, \(\sigma\) is the standard deviation of RRM, \(x_i\)’s are the observed RRM values, \(\bar{x}\) is mean RRM value and \(\delta x_i\)’s, \(\delta \bar{x}\) are their respective errors.

To quantify the excess standard deviation \((\sigma^{ex})\) seen along the sightlines with intervening absorbers, we have subtracted the standard deviation of RRM for the quasar subsample with and without Mg \(\text{II}\) absorber in the quadrature i.e.

\[
\sigma^{ex} = \sqrt{\sigma^2_{\text{(MgII)}} - \sigma^2_{\text{(noMgII)}}},
\]

(3)

The excess in the standard deviation is found to be \(8.11 \pm 2.85\ \text{rad m}^{-2}\), i.e., at 2.8\(\sigma\) level, where the associated error is computed with error propagation as.
RRM and intervening Mg II absorbers

\begin{equation}
\delta \sigma^{\text{ex}} = \frac{1}{\sigma^{\text{ex}}} \sqrt{\frac{\delta \sigma^2_{(\text{MgII})}}{\sigma_{(\text{MgII})}} + \frac{\delta \sigma^2_{(\text{noMgII})}}{\sigma_{(\text{noMgII})}}}.
\end{equation}

This high significance excess at 2.8σ level in standard deviation is much higher than the above discussed 79% confidence level implied by the K–S test for the subsample of quasar with and without Mg II absorber. One possibility could be that the error bars in RRM measurements may be underestimated. To quantify it, we have computed the reduced χ² value for our subsample without Mg II absorber, by assuming the expected value of RRM measurements to be (i) the mean value of RRM measurements, and (ii) as zero value. In both the cases, the reduced χ² values are found to be around 2.87. Now, assuming that for true error bars in RRM measurements for subsample without Mg II absorber should result this reduced χ² to be around unity, suggests us to scale up all the error bars on our RRM measurements by square root of 2.87. Repeating the above analysis with these scaled error bars on RRM, our revised standard deviation for quasars with and without Mg II absorber becomes 18.93±1.78 rad m⁻² and 17.11±1.16 rad m⁻² respectively. Similarly, the excess standard deviation (using Eq 3) now becomes 8.11±4.83 rad m⁻², i.e., at 1.7σ level. Given that our K–S test also give the similar confidence level (i.e., 79%) it appear that our earlier result with higher significance of 2.8σ level perhaps may be due to this underestimation of error bars in RRM measurements. Therefore, henceforth throughout the analysis, we have derived our results using the scaled error bars in RRM measurements.

We also note that our result is in good agreement with Hammond et al. (2012) and Schnitzeler (2010), where they have shown the standard deviation of RRM by its extragalactic component in the order of 10–15 rad m⁻² and ~6 rad m⁻², respectively. In this 10–15 rad m⁻² standard deviation of RRM by Hammond et al. (2012), they have also taken into account the possible contribution caused by errors associated with GRM and RM measurements, by their quadrature subtraction from the observed σ(RRM) value (e.g., see Section 1). Recall that in their study they have used a mixture of sightlines consisting of both with and without Mg II absorber. However in our study, as we do have separate subsample of sightlines with and without Mg II absorber, it allows us to quantify the contribution in σ² due to intervening absorbers by subtracting the σ(RRM) of later from the former in quadrature (e.g see Eq. 3). This being the difference of two standard deviations in quadrature, makes our result of 8.11±4.83 rad m⁻², free from any error contribution to σ(RRM) that are common for both the subsamples of with and without Mg II absorbers, such as associated with the GRM and RM measurements considered in Hammond et al. (2012).

Now, it is also worth to see the RRM distribution with EWr, as the quasars having absorber with larger EWr are expected to have larger observed RRM dispersion. In Figure 3, we have plotted the RRM distribution with EWr, where the open circle represents the EWr corresponding to an absorber over a sightline, while the star (red) corresponds to the sum of EWr values for the sightlines having more than one Mg II absorber. In the absence of obvious trend of RRM with EWr, we have computed the standard deviation in RRM for the absorber having EWr < 1Å and EWr ≥ 1Å, which are 18.65±2.42 and 19.23±3.23 rad m⁻², respectively, with error bars computed using Eq 2. Though there is a very mild excess in the value of standard deviation of RRM for larger EWr subsample but it is consistent within 1σ error bars.

Hammond et al. (2012) found an anti-correlation between RRM and fractional polarization (p). One possible physical bias suggested by them was the presence of intervening absorbers; which need to be tested by plotting the RRM with ‘p’ for a subclass of sample with and without Mg II absorber. In this possible scenario, to explain anti-correlation of RRM versus p, one would expect that the fractional polarization observed for a sample with Mg II absorber (having larger RRM) should be smaller than the sample without Mg II absorber. To test this hypothesis in Figure 4, we have plotted the histogram of fractional polarization (p) for the quasars with Mg II absorber (shaded region) and without (thick line) Mg II absorber. The median (weighted mean) values of p, for sample with and without Mg II absorber, are found to be 3.50(4.57) and 3.57(5.16), respectively. The K–S test shows that the null hypothesis is ruled out with a low confidence level of 63.13%. This very mild difference with present sample size does not allow us to conclude much on above hypothesis, but a larger sample will be helpful to say firmly about it.

5 DISCUSSION AND CONCLUSIONS

The excess extragalactic FR due to the presence of a strong intervening absorber in the optical spectrum of quasars is noticed in many recent studies (Kronberg & Perry 1982; Welter et al. 1984; You et al. 2003; Bernet et al. 2008). Commonly accepted view is that the major contributor could be the intervening galaxies along the sightline of polarized radio sources. For instance, Bernet et al. (2008) have used a sample of total 76 sightlines with RM observations at around 6cm, and found a statis-
tically higher RM for their 7 sources showing more than one Mg II absorber. Many other studies have also shown the increase of RRM with redshift (e.g., Kronberg et al. 2008; Kronberg & Simard-Normandin 1976; Rees & Reinhardt 1972), albeit by using only a nominal sample size till now. Recently, with a large data set of 3651 quasars with RRM observation at 21cm, Hammond et al. (2012) have not found any such signature of RRM evolution with redshift. Similarly, the role of intervening absorber in RRM at 21cm was also studied till now by using a small sample size of only 54 quasars (Bernet et al. 2012). Here, we have addressed these questions by using a larger sample size of the 539 SDSS quasars having RM data set at wavelength at around 21cm, rather than at around 6cm.

Our analysis has shown that RRM distribution for the quasars with and without Mg II absorber do differ at confidence level of 79%. This show that there is contribution of intervening absorber to enhance the RRM, even at wavelength of 21cm. Its non-detection in the analysis of Bernet et al. (2012), could be due to their smaller sample size, where they have used just a sample of 54 sightlines having RRM measurement at 21cm. However, we also note that at 6cm measurement of RM, the two distribution with and without Mg II absorber do differ with much more confidence levels (e.g, Bernet et al. 2008) than what we have found for our sample of RRM measurement at 21cm. This may be due to the recent mechanism proposed by Bernet et al. (2012), where the intervening absorbers acts as a RM screens and causes more depolarization at longer wavelength.

We also found that the standard deviation of RRM for sample with Mg II absorber do have excess of about $8.11 \pm 4.83$ rad m$^{-2}$ as compared to the sample without Mg II absorber. This is consistent with Hammond et al. (2012) and Schnitzeler (2010) studies, where in their independent analysis they have found the value of extragalactic component in RRM standard deviation to be around 10–15 rad m$^{-2}$ and 6 rad m$^{-2}$ respectively.

Further, we have also computed the standard deviation of RRM for subsets having Mg II absorber with $EW_{\alpha} < 1A$ and $EW_{\alpha} \geq 1A$, as another check to the hypothesis of contribution by intervening absorber, where for stronger absorber RRM dispersion is expected to be higher than weaker absorber. The values for $EW_{\alpha} < 1A$ and $EW_{\alpha} \geq 1A$ are found to be $18.65 \pm 2.42$ and $19.23 \pm 3.23$ rad m$^{-2}$, respectively (see Figure 3), which is tentatively consistent with above expectation.

We also notice that the factional polarization ($p$) of the quasars with and without Mg II absorber show nominal difference, with median (weighted mean) values of $p$, to be $3.50(4.57)$ and $3.57(5.16)$ respectively. This very nominal excess for sightlines without Mg II absorbers, could be due to the less depolarization in the absence of intervening absorbers (e.g., see also Hammond et al. 2012; Bernet et al. 2012). However, a larger data set would require to reduce the statistical error bar.

At present, with our large data set of 539 sightlines, we could only found a statistical excess of $8.11 \pm 4.83$ rad m$^{-2}$ in standard deviation of RRM for the sample with Mg II absorber as compared to the sample without Mg II absorber, by using RRM observation at around 21cm wavelength. This has allowed us to conclude that the intervening Mg II absorber also makes contribution for the excess in standard deviation of RRM observed even at around 21cm wavelength, though perhaps with smaller magnitude than at 6cm (e.g, Bernet et al. 2008); the theoretical implication of which needs further explorations.

ACKNOWLEDGMENTS

We thank the anonymous referee for the constructive and helpful suggestions. We also thank R. Srianand for useful discussion.

Funding for the SDSS and SDSS-II has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, the U.S. Department of Energy, the National Aeronautics and Space Administration, the Japanese Monbukagakusho, the Max Planck Society, and the Higher Education Funding Council for England. The SDSS Web Site is http://www.sdss.org/. The SDSS is managed by the Astrophysical Research Consortium for the Participating Institutions. The Participating Institutions are the American Museum of Natural History, Astrophysical Institute Potsdam, University of Basel, University of Cambridge, Case Western Reserve University, University of Chicago, Drexel University, Fermilab, the Institute for Advanced Study, the Japan Participation Group, Johns Hopkins University, the Joint Institute for Nuclear Astrophysics, the Kavli Institute for Particle Astrophysics and Cosmology, the Korean Scientist Group, the Chinese Academy of Sciences (LAMOST), Los Alamos National Laboratory, the Max-Planck-Institute for Astronomy (MPA), the Max-Planck-Institute for Astrophysics (MPA), New Mexico State University, Ohio State University, University of Pittsburgh, University of Portsmouth, Princeton University, the United States Naval Observatory, and the University of Washington.

REFERENCES

Bernet M. L., Miniati F., Lilly S. J., 2010, ApJ, 711, 380
Bernet M. L., Miniati F., Lilly S. J., 2012, ApJ, 761, 144
Bernet M. L., Miniati F., Lilly S. J., Kronberg P. P., Dessauges-Zavadsky M., 2008, Nature, 454, 302
Hammond A. M., Robishaw T., Gaensler B. M., 2012, arXiv: 1209.1438
Joshi R., Chand H., Gopal-Krishna, 2013, under review
Kronberg P. P., Bernet M. L., Miniati F., Lilly S. J., Short M. B., Higdon D. M., 2008, ApJ, 676, 70
Kronberg P. P., Perry J. J., 1982, ApJ, 263, 518
Kronberg P. P., Reinhardt M., Simard-Normandin M., 1977, A&A, 61, 771
Kronberg P. P., Simard-Normandin M., 1976, Nature, 263, 653
Mestel L., Paris R. B., 1984, A&A, 136, 98
Oppermann N. et al., 2012, A&A, 542, A93
Rees M. J., 1987, QJRAS, 28, 197
Rees M. J., Reinhardt M., 1972, A&A, 19, 189
Schnitzeler D. H. F. M., 2010, MNRAS, 409, L99
Still J. M., Taylor A. R., Sunstrum C., 2011, ApJ, 726, 4
Taylor A. R., Still J. M., Sunstrum C., 2009, ApJ, 702, 1230
Welser G. L., Perry J. J., Kronberg P. P., 1984, ApJ, 279, 19

Funding for the SDSS and SDSS-II has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, the U.S. Department of Energy, the National Aeronautics and Space Administration, the Japanese Monbukagakusho, the Max Planck Society, and the Higher Education Funding Council for England. The SDSS Web Site is http://www.sdss.org/. The SDSS is managed by the Astrophysical Research Consortium for the Participating Institutions. The Participating Institutions are the American Museum of Natural History, Astrophysical Institute Potsdam, University of Basel, University of Cambridge, Case Western Reserve University, University of Chicago, Drexel University, Fermilab, the Institute for Advanced Study, the Japan Participation Group, Johns Hopkins University, the Joint Institute for Nuclear Astrophysics, the Kavli Institute for Particle Astrophysics and Cosmology, the Korean Scientist Group, the Chinese Academy of Sciences (LAMOST), Los Alamos National Laboratory, the Max-Planck-Institute for Astronomy (MPA), the Max-Planck-Institute for Astrophysics (MPA), New Mexico State University, Ohio State University, University of Pittsburgh, University of Portsmouth, Princeton University, the United States Naval Observatory, and the University of Washington.
You X. P., Han J. L., Chen Y., 2003, Acta Astronomica Sinica, 44, 155