The rotation measures of high luminosity sources as seen from the NVSS.

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ABSTRACT

We re-analyse the subset of the Faraday rotation measures data from the NRAO VLA Sky Survey catalogue for which redshift and spectral index information is available, in order to better elucidate the relations between these observables. We split this subset in two according to their radioluminosity, and find that higher power sources have a systematically higher residual rotation measure, once the regular field of the Milky Way is subtracted. This rotation measure stands well above the variances due to the turbulent field of our Galaxy, contrarily to low power sources. The effect is more pronounced as the energy threshold becomes more restrictive. If the two sets are merged one observes an apparent evolution of rotation measure with redshift, but our analysis shows that it can be interpreted as an artifact of the different intrinsic properties of brighter sources that are typically observed at larger distances.

Key words: IGM: magnetic fields

1 INTRODUCTION AND CONCLUSION

Magnetic fields (MFs) seem to be omnipresent in the Universe, from the Earth to the huge intergalactic voids (Kronberg 1994; Han & Wielebinski 2002; Govoni & Feretti 2004; Vallée 2004; Ryu et al. 2012), including stars, galaxies, clusters, and perhaps filaments. They were observed in galaxies at high redshift $z > 1$ when the Universe was only a few billions years old (Kronberg et al. 2008; Bernet et al. 2008).

MFs also permeate the Large Scale Structure (LSS) of the Universe: it is typically believed that they were initially created in the astrophysical sources within the LSS, and only afterwards they polluted the LSS itself. The MFs that are tentatively observed in the voids (Neronov & Vovk 2010; Tavecchio et al. 2010; Dolag et al. 2011; Taylor et al. 2011†) could also be blown away from the LSS; alternatively, they could be of primordial origin—cosmological inflation, early universe phase transitions, etc (Grasso & Rubinstein 2001; Dolgov 2003; Kandus et al. 2011; Durrer & Neronov 2013). Since there are no compelling models for their genesis, it is crucial to better understand their morphology, strength, spectral properties, and distribution in the Universe; the more so for extragalactic fields, for which the very large correlation lengths are theoretically difficult to achieve.

One of the most effective ways to study such extragalactic MFs is through the observations of Faraday rotation measures (RMs). The plane of polarization of a linearly polarized electromagnetic wave of wavelength $\lambda$ that travelled through a magnetized plasma rotates by the angle $\Delta\psi$ proportional to the square of the wavelength, 

$$ \Delta\psi = \frac{812}{\mu G} \int n_e B_\parallel dl, $$

(1)

Thus one needs multi- or at least bi-frequency observations in order to determine the rotation measure $RM$. The value of RM depends on the properties of the medium and the permeating magnetic field as follows,

$$ RM = 812 \int_0^D n_e B_\parallel dl, $$

(2)

where $n_e$ is the density of free electrons measured in $\text{cm}^{-3}$, $B_\parallel$ is the component of the magnetic field parallel to the line-of-sight measured in $\mu\text{G}$ (positive when directed towards the observer), and $D$ is the distance from the observer to the source in kpc. Hence, an independent estimate of the electron density $n_e$ is required to deduce information on the magnetic field proper from Faraday rotation measures.

An indirect evidence of the MF presence in LSS and in...
voids may be obtained by studying the redshift evolution of RM of an ensemble of extragalactic sources. In a recent paper \cite{Neronov:2013} some tentative evidence for a significant redshift evolution in the RMs from the catalogue \cite{Hammond:2012} was reported: the RMs were found to be growing with redshift in a way that could be interpreted as a sign of non-zero nanoGauss-scale MFs in the filaments of the LSS. Such redshift dependence was not observed in the original catalogue \cite{Hammond:2012}; moreover, a recent work \cite{Banfield:2014} while re-examining the same dataset (although retaining a smaller portion of it), did not find indication for a systematic difference in redshift. Finally, most recently another analysis \cite{Xu:2014} reported on a quite weak evolution with redshift, again for a very similar set.

We assess these claims in what follows, where in addition to previous analyses we also search for a possible systematic dependence of the measured RMs on intrinsic properties of sources, in particular their radio luminosity. We perform several tests, from which a coherent interpretation emerges:

- we found no indication of a redshift evolution caused by the intervening medium;
- we do observe a sort of Malmquist bias, i.e., we see brighter sources from larger distances — the further we go, the brighter are the sources that we observe, thus mimicking an apparent redshift evolution by the redshift-dependent selection of sources with intrinsically different properties;
- the RM in low luminosity sources appears to be mostly due to the turbulent random galactic MF (rGMF), and consequently does not change with redshift;
- the residual RM in high luminosity sources instead shows a systematic bias above the contribution from rGMF; however, there is also no clear redshift evolution in this set;
- this bias grows with more selective luminosity cutoffs, that is, there appears to be a positive correlation between the residual RM and the radioluminosity of the source.

The rest of this paper is organised as follows. First, in Sec. 2 we introduce the data and our selection, cleaning, and averaging procedures. Sec. 3 reports all of our results and their interpretation. Finally, we summarise everything in Sec. 4.

2 DATA AND METHODS

The data. The largest set of RMs of extragalactic sources to date was compiled in \cite{Taylor:2009} from re-analyzing the NRAO VLA Sky Survey (NVSS) data. The NVSS is the largest by number survey of polarized radio sources at declinations $|\alpha| < 40^\circ$ \cite{Condon:1998}. The survey was performed in two nearby bands, 1364.9 and 1435.1 MHz; each having a width of 42 MHz. Observations at these close frequencies then give estimations of the RMs of the sources. The total number of observed sources was 37,543. More than 10% of these sources have redshifts assigned \cite{Hammond:2012}.

We selected 4002 NVSS sources with known redshifts from \cite{Hammond:2012}. Also we imposed the following cuts: to lower the influence of the galactic MF we accepted only sources with $|b| > 20^\circ$, and we dismissed all the sources with $|RM| > 300$ rad m$^{-2}$ owing to the fact that RMs obtained in two close frequencies are not fully reliable if their absolute values are too large \cite{Taylor:2009}. That left us with 3647 sources.

Independently, we also cleaned the full NVSS catalogue removing the outliers following the algorithm described in \cite{Pshirkov:2013}. Such algorithm is very simple: a circle of $3^\circ$ radius was circumscribed around every source in the catalogue and both the average RM and its variance were calculated for the selected region. If the RM of the source was more than two r.m.s. values away from the average, the source was marked as “outlier”. In total, 1974 sources were removed after this procedure, leaving 35,569 in the clean set. This set was used to estimate the contribution of the GMF into the RM of a given source, as well as the dispersion of RM due to rGMF and other factors.

Removing the GMF. Each observed $RM_{\text{obs}}$ is the sum of several contributions: the one due to the regular GMF which we denote $RM_{\text{gal}}$, the one due to rGMF, the RM intrinsic to the source, and finally the rotation acquired while travelling through the intergalactic minimum. Due to their random character, the last three contributions cannot be separated on a source-by-source basis; we denote their sum as residual RM ($RRM$). On the contrary, $RM_{\text{gal}}$ can, in principle, be estimated and subtracted for each source. Clearly, any redshift evolution or correlation with luminosity would have a more pronounced effect for the $RRM$ where the piece owing to the galactic field is removed,

$$RRM = RM_{\text{obs}} - RM_{\text{gal}}.$$

The Galactic contribution $RM_{\text{gal}}$ was estimated using observed RMs themselves. For each source with assigned redshift, we averaged the RMs from the cleaned catalogue within the $3^\circ$ circle around the source (typically, about 30 values). We interpreted the average as $RM_{\text{gal}}$ corresponding to that source. Within the same circle, we also calculated the variance $\sigma_{RM_{\text{gal}}}$, which provided us with an error estimate.

Luminosity. In order to assess intrinsic luminosities of the sources, we used information from three additional catalogues: VLS\footnote{VLA Low-Frequency Sky Survey \cite{Cohen:2007}} (74 MHz, dec $> -30^\circ$), WENSS\footnote{The Westerbork Northern Sky Survey \cite{Fregiology:1997}} (352 MHz, dec $> 28.5^\circ$), and SUMSS\footnote{The Sydney University Molonglo Sky Survey \cite{Mauch:2003}} (843 MHz, dec $< -30^\circ$), from which we can calculate the spectral index $\alpha$ of the source. When combined, they nicely cover all the sky. The algorithm to obtain the intrinsic power of each source was as follows:

1. for each item in the catalogue of \cite{Hammond:2012} (with additional cuts at $|b| > 20^\circ$ and $|RM| < 300$ rad m$^{-2}$) we found the counterpart in one or more of the three catalogues mentioned above;
2. wherever possible, that is, where at least two different fluxes are available, we calculated $\alpha$;
3. if $\alpha$ could be calculated from either SUMSS or WENSS we employed these values, because all VLSS entries have larger error;
\begin{figure}[h]
\centering
\includegraphics[width=0.7\textwidth]{figure1.png}
\caption{Redshift-dependence of $|RRM|$.}
\end{figure}

(iv) conversely, if only data from VLSS was available, we used the latter;
(v) only as a last option we calculated $\alpha$ from the (\textit{Véron-Cetty & Véron} 2010) compilation as it is comparatively less reliable.

With this procedure, we obtained the final set of 3190 sources (out of the original 3647) for which $\alpha$ was assigned.

Once the spectral index was assigned to as many sources as possible, we calculated the luminosity with the help of the relation

$$L_{1.4\text{GHz}} = \frac{4\pi D_L^2 S_{1.4\text{GHz}}}{(1 + z)^{\alpha + 1}}, \quad (3)$$

where $D_L$ is the luminosity distance and $S_{1.4\text{GHz}}$ the flux density at 1.4 GHz (Hogg, 1999).

\section{RESULTS}

With the final set at hand, we binned all sources in redshift. The criteria with which we chose the bins are explained below. Figure 1 shows that there might exist an apparent redshift evolution of $|RRM|$; in fact, our results are in a very good qualitative agreement with the results of (Neronov et al. 2013). The small quantitative difference could arise due to the different procedures of foreground (i.e., GMF) subtraction. Notice that here, as well as everywhere else in the paper, the errors are estimated as the actual variance of the value in the bin (in this case a redshift bin, but we will also use galactic latitude bins) divided by the square root of the number of sources.

However, this agreement disappears after we further split the set of sources into two subsets according to their intrinsic radioluminosity. Each of the 3190 sources in the total set is assigned to either of two subsets with varying size according to where the threshold is chosen. In order to have reasonable statistics, we chose to cut at $L = 10^{27.8}\text{WHz}^{-1}$ so that we could work with 6 bins at high redshift and high radioluminosity, for each of which we had approximately 80 sources (see Fig. 2 below). We also checked that our results are not very sensitive to the choice of binning — moreover, the picture which we arrive at is corroborated by a coherent set of observations, so it does not rely solely on this cut and the associated binning choice. Overall, the larger, low-power $(lp)$ group consisted of 2721 sources, while there are 469 sources in the high-power $(hp)$ group.

The binning procedure was as follows.

- We first looked at the high power set. Going from the highest $z$, we chose the bins such that there are about 80 $(hp)$ sources in each bin. This gave us 6 bins starting at redshift $z = 0.7$ and upward.
- At redshifts below 0.7 there are only 5 sources in the $(hp)$ sample. For this reason, at low redshifts the binning was set according to the $(lp)$ sample. We decided to keep three additional low-redshift bins and again chose the bin boundaries so as to have about the same number of events in each bin.

The resulting bin boundaries $z_k$—starting from $z = 0$, as well as the numbers of $(lp)$ and $(hp)$ sources in each bin are summarised in Table 1.

\begin{table}[h]
\centering
\begin{tabular}{lcccccccc}
\hline
$z_k$ & 0.15 & 0.35 & 0.70 & 1.30 & 1.65 & 1.95 & 2.25 & 2.60 & 5.0 \\
\hline
\( (lp) \) & 474 & 450 & 528 & 683 & 289 & 135 & 74 & 51 & 27 \\
\( (hp) \) & 0 & 0 & 5 & 74 & 81 & 76 & 77 & 78 & 78 \\
\hline
\end{tabular}
\caption{Number of sources in the $(lp)$ and $(hp)$ sets in each redshift bin.}
\end{table}

\begin{figure}[h]
\centering
\includegraphics[width=0.7\textwidth]{figure2.png}
\caption{Mean RM in $z$-bins for $(lp)$ and $(hp)$ sets separately.}
\end{figure}

Figure 2 shows the impact of the separation into the $(lp)$ and $(hp)$ sets. There seems to be a systematic shift in $|RRM|$ between the two sets; the shift is not very large (of order of $5\text{ rad m}^{-2}$) but is coherent throughout all the bins. At the same time, neither $(lp)$ nor $(hp)$ separately show a systematic dependence of $|RRM|$ with $z$.

The most straightforward interpretation of this first result is that: (a) there is no significant evolution with redshift, and (b) higher $|RRM|$ correlate with higher power.

Motivated by this initial result, we have performed several complementary tests in order to assess the validity of this conclusion. Before delving into this analysis, we show the distribution of $|RRM|$ itself in Fig. 3 where we observe the (slight) predominance of high residual RM in the $(hp)$ set — notice that this is a probability distribution, and does not mean that in the entire set there are more high
power sources at very large $|\text{RRM}|$, but that their distribution prefers them.

As already discussed, the measured RMIs include the contributions of regular (coherent) fields from our Galaxy and possibly from intervening media, and random ones (the turbulent random field of our Galaxy, intergalactic fields, as well as instrumental errors). Now, clearly our procedure for the subtraction of the Milky Way field allows to remove only the contribution from the large-scale regular field, leaving any possible contribution from the random fields intact.

The absence of redshift evolution in the $(lp)$ group indicates that the observed residual RM is produced close to us, which is tempting to interpret as most likely coming from the turbulent magnetic field of the Milky Way itself. As we said, in principle there are also errors associated with each RM measurement.

The variance of $RM_{\text{gal}}$, $\sigma_{RM_{\text{gal}}}$, encodes both these terms in itself. In what follows we test how much of our calculated $RM$ could be due to these random fluctuations. Figure 3 shows again $|\text{RRM}|$ now together with $\sigma_{RM_{\text{gal}}}$ for the $(lp)$ and $(hp)$ sets, in the same redshift bins as before. We can note three facts. First of all, as it should be, there is nearly no difference in the $\sigma_{RM_{\text{gal}}}$ for the two sets, as these are calculated using the entire catalogue and contain events at all redshifts and luminosities. Second, there is no obvious trend with redshift for the variances, which is compatible with our interpretation that the dominant contribution arises in our Galaxy. Third, and most importantly, we see how for the $(lp)$ data, the RM never clearly stands out from the $\sigma_{RM_{\text{gal}}}$ points, whereas the $(hp)$ set seems to be incompatible with the hypothesis that all of the RMs come from the variance $\sigma_{RM_{\text{gal}}}$.

The featureless binning in $z$ for the $(lp)$ set seems also to be at odds with the model proposed in (Beck et al. 2013). The final result of the galactic dynamics outlined in that work is that it is not uncommon for host galaxies to possess extended and strongly magnetised halos, which result in a (truly) intrinsic RM around 1000 rad m$^{-2}$ already at $2 < z < 4$; if this type of galaxies represented a significant part of our sample, we would observe a prominent rise of $|\text{RRM}|$ with redshift: this is not the case in our analysis. Moreover, since we rejected all RM above 300 rad m$^{-2}$, if the distribution of $RRM$ had a much larger variance due to the predominance of very large $|\text{RRM}|$, after the cut we would obtain a flat profile in Fig. 3.

To understand the significance of the shift we observe, the panels of Figure 5, where we bin the data in latitude $b$, are even more telling. We notice two relevant facts which corroborate our interpretation. Firstly, $\sigma_{RM_{\text{gal}}}$ shows a very clear $b$-dependence, which is exactly what we expect if the main contribution is to come from the turbulent field of the Galaxy; indeed, at lower latitudes the random MF in the Milky Way is significantly stronger than towards the north and south poles — this contribution is well described by a geometry-dependent component, dropping with $b$, on top of an overall constant value of about 13 rad m$^{-2}$ (Pshirkov et al. 2013). Secondly, as before, we notice how, while the $(lp)$ points track the features of $\sigma_{RM_{\text{gal}}}$ in $b$ very well, and are thus completely ascribable to this variance, the $(hp)$ sources once again do present a systematic coherent shift of about 5 rad m$^{-2}$.

In principle a possible explanation for the different behaviour of the $(hp)$ group could be that the sources in this group are distributed differently, i.e. closer to the galactic plane, and that would lead to the observed excess. In fact, there is a slight preference for low-$b$ in the $(hp)$ set, as evidenced in the histogram in Figure 6, however, we have just seen how it is impossible to attribute all our excess to this
small “bias” when we binned with latitude itself. This explanation is therefore ruled out. That means that the positive correlation between the $|RRM|$ and radioluminosity is real, and seemingly compatible with its arising close to the source.

We now turn our attention to the effect of the luminosity cutoff, to check for a possible dependence on the particular value we have chosen. We begin with Figure 6 we show here the average $|RRM|$ of all sources in the $(hp)$ set, as a function of the radioluminosity where we split the entire set in two. The trend towards a more pronounced $|RRM|$ with more severe threshold is very clear. This adds another piece of evidence to our global interpretation, since it shows how the threshold itself is not important, and that in fact if we were to choose higher luminosity, were we not limited by statistics, the results would be even more significant.

Above and below the data points we also report the number of $(hp)$ and $(ip)$ sources which result for a given cut in $L_{1.4\ GHz}$, respectively. It becomes clear now why in order to have about 80 to 100 points in each of some 5 or 6 high power bins, our cut has to be taken around the log $L_{1.4\ GHz} = 27.8$ threshold value.

The last Figure 8 shows the difference between $|RRM|$ and $\sigma_{RM_{gal}}$ for the $(ip)$ and $(hp)$ sets taken at each latitude bin (that is, from Fig. 5) and averaged across the bins. This was done for varying luminosity cutoff, like in the previous figure Fig. 7. We notice how in the $(ip)$ set, even when accounting for the known behaviour of $\sigma_{RM_{gal}}$ with latitude $b$, as was obvious from Fig. 5, at any power cut everything is consistent with all of this signal to come from the random Galactic field. Once more, on the other hand, there is a systematic, albeit weak as it is limited by the statistics of the dataset, increase for this differential in the $(hp)$ sources as we move towards higher thresholds. This test shows how the shift observed in Fig. 5 is real, and tends to increase with more restrictive cutoffs, as we naively expected from Fig. 7 where there is no apparent direct information about $b$.

Having established that there seems to be a positive correlation between $RRM$ and luminosity, a legitimate question is whether a relatively small group of sources with perhaps extreme properties is driving this result. We then studied the effect of the few highest $RRM$ sources (the high power set distribution is slightly more heavy-tailed) by cutting off all sources whose RM was beyond a given threshold $RM_{th}$, for instance 80 rad m$^{-2}$ or 60 rad m$^{-2}$, and binned the remaining points with $|RRM| < RM_{th}$ in the same redshift bins as before. This test turned out to be quite inconclusive, since the offset still persists, although not so pronounced as before, but it is no longer clear whether the $(hp)$ signal is completely compatible with variance or not: we are reaching the statistical limits of the sample.
Another possibility is that the total set made of two (or more) different populations of sources with different intrinsic properties; if one population is predominant at high (or low) luminosity or at high or low $RRM$, it will bias the set and artificially generate the $|RRM, L_{1.4\,\text{GHz}}|$ correlation that we observe. However, employing the spectral index $\alpha$ as discriminant, we were not able to clearly discern between two (or more) populations. In any case, while performing these additional tests, which require a further split of the data into smaller sets, we have noticed that, due to the paucity of data points, it becomes difficult to tell anything apart from just statistical variance: we will have to wait for a larger statistical sample.

4 SUMMARY

To conclude, we briefly recapitulate the salient features of our searches. We set out with the purpose of investigating the possibility of a redshift dependence in the observed Faraday sky, search which we based on the set of all NVSS catalogue sources for which redshift information is known—this is the largest available set in the literature at the moment. The catalogue was cleaned removing outliers with potentially unreliable RMs; we then used the data itself to separate the RM due to the regular MF of the Milky Way: all our statistical results are based on the residual $|RRM|$.

We specifically looked for the effect of the radioluminosity $L_{1.4\,\text{GHz}}$ of the sources (calculated independently for most sources through their flux densities); this effect and our interpretation of our results can be summarised in these seven points below.

- The residual $|RRM|$ positively correlates with $L_{1.4\,\text{GHz}}$, that is, the higher luminosity sources have higher residual RMs (Fig. 7).
- The $|RRM|$ of low luminosity sources can be all explained by the variance due to the rGMF (Figs. 4 and 6, top). This is consistently decreasing with latitude as we move away from the Galactic plane as expected.
- The $|RRM|$ of high power sources, on the other hand, stands out coherently above the expected $\sigma_{\text{RMgal}}$ variance; this is true in both redshift and latitude bins, where in the latter it is also easy to single out the Galactic contribution (Figs. 4 and 7, bottom).
- Therefore, there is an overall shift in $|RRM|$ between the two sets. This shift appears in redshift bins (Figs. 2 and 4) as well as in latitude bins (again Fig. 5), and amounts to the same value of approximately 5 rad m$^{-2}$ for a split at log $L_{1.4\,\text{GHz}} = 27.8$.
- The systematic shift is not an artifact of the luminosity cutoff, as it actually grows with more constraining choices (Figs. 7 and 8).
- The systematic shift is also not an artifact of some redshift evolution, as we do not observe any trend in the $z$ behaviour of either set (Figs. 2 and 4).
- If we ignore the luminosity and analyse the full catalogue we do observe a weak redshift dependence (Fig. 4), which we can hence impute to a Malmquist bias, i.e., from larger distances brighter sources are more easily detected. Again, what does appear to correlate are $|RRM|$ and luminosity, not redshift.

These results are promising, and it would be extremely useful to understand if this correlation is physical and isolate its origin: we performed a few tests in this sense but the statistical size of the sample was too limiting a factor. In particular it would be very interesting to see whether the correlation and/or the systematic shift are driven by a particular set of sources, for instance a small set belonging to a particular type of objects. With a larger dataset these questions could be easily addressed; a larger set would also allow a much better estimation of the Galactic contribution, and would finally shed light on possible features as for any redshift development of $|RRM|$. We leave all these updates for future investigations.

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