An Update on Cosmological Anisotropy in Electromagnetic Propagation

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Abstract. We review evidence for a new phenomenon in the propagation of radio waves across the Universe, an anisotropic rotation of the plane of polarization not accounted for by conventional physics.

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Radio waves propagating on cosmological distances provide an exceedingly sensitive laboratory to explore new phenomena. Recently [1], we reported an indication of anisotropy extracted from polarization measurements taken on distant radio galaxies. Here we review that work, subsequent reactions, and some new studies.

Galaxies monitored in the 100 MHz–GHz range are found to emit linearly polarized radio waves. The emission mechanism is believed to be synchrotron radiation. The observed plane of polarization does not usually align with the symmetry axis of the source (whose orientation angle is denoted $\psi$) [2]. For decades, this has been studied in terms of Faraday rotation in the intervening medium. Faraday rotation can be taken out in a model–independent way, because the Faraday angle of rotation $\theta_i(\lambda)$ for wavelength $\lambda$ goes like $\text{RM}_i\lambda^2$, where RM is a constant depending on the integrated plasma parameters and magnetic field along the line of sight. Consistent linear dependence on $\lambda^2$ is indeed observed. However, the data fit requires more: for each source $(i)$, the fits are given by $\theta_i(\lambda) = \text{RM}_i\lambda^2 + \chi_i$. The de–rotated polarization (whose
orientation angle is $\chi$) does not generally align with the galaxy major axis, nor with the axis at 90 degrees to the major axis; statistics on the offset of angles have puzzled astronomers for 30 years [2].

Analysis of the data is challenging. The data set is small, 160 sources. The angular distribution on the sky is highly non-uniform, as is the distribution in the distances $r(z)$ to the sources. Finally, for decades astronomers have used a particular arbitrary difference, $\chi - \psi$, as a reference variable. There is an underlying conceptual issue, that both the galaxy axis and the polarizations are projective variables that return to themselves after a rotation of $\pi$ (not $2\pi$). Straightforward use of $\chi - \psi$, binned between arbitrary intervals and defined mod $\pi$, will obscure correlations that may depend on the direction of travel of a wave; this is a crucial requirement if one is going to test for anisotropy. It also does not allow an analysis to keep the important distinction between an obtuse angle and the complementary acute one. To keep track of the difference between obtuse and acute angles, and to allow a test for directional dependency, we created [1] the angles $\beta^+$ and $\beta^-$, defined by

\[
\beta^+ = \begin{cases} 
\chi - \psi & \text{if } \chi - \psi \geq 0 \\
\chi - \psi + \pi & \text{if } \chi - \psi < 0
\end{cases}
\]

\[
\beta^- = \begin{cases} 
\chi - \psi - \pi & \text{if } \chi - \psi \geq 0 \\
\chi - \psi & \text{if } \chi - \psi < 0
\end{cases}
\]

(1)

A test for directional dependency is allowed by defining the rotation angle $\beta$ as $\beta = \beta^+$ when $\cos \gamma > 0$ and $\beta = \beta^-$ when $\cos \gamma < 0$, where $\gamma$ is the angle between a spatial direction $\vec{s}$ and the propagating wavevector of the wave. We employed Monte Carlo methods to search for correlations [1]. We made thousands of fake galaxies with random $\chi$ and $\psi$, while keeping their positions on the dome of the sky the same as those of the real galaxies. As we varied $\vec{s}$ systematically across the dome of the sky, we calculated (for each $\vec{s}$) the probabilistic P-value of linear correlations in the observed data relative to the random sets (Procedure 1). In the full data set, we found a correlation described by $\beta = (r/\Lambda_s) \cos \gamma$. This indicates anisotropy. Making a cut on $z > 0.3$, which selects the most distant half of the data set, we found a striking correlation, with probabilistic P-values that the observed correlation would be produced by random angular fluctuations to be less than $10^{-3}$; the effect is $3.7\sigma$.

A separate study (Procedure 2) eliminated possible bias in Procedure 1’s determination of $\vec{s}$. Procedure 2 determined the $\vec{s}$-direction that yielded the highest correlation for a specific random data set; the resulting “best” correlations were then accumulated for over a thousand different random sets. We then calculated the probabilistic P-value of finding the correlation of the observed data set relative to the best correlated random sets so constructed. This gave a P-value less than 0.006, corresponding to $2.7\sigma$. The fits to the parameters $\Lambda_s$ and $\vec{s}$ are $\Lambda_s = (1.1 \pm 0.08)10^{25} h_0 £m$ and $\vec{s} = (\text{Decl.}, R.A.)^*_s = (0^\circ \pm 20^\circ, 21\text{hrs} \pm 2\text{hrs})$, where $h_0 = \frac{2}{3}10^{-10}$(years)$^{-1}$ and $h$ is the Hubble constant. We do not find a significant correlation for
$z < 0.3$; in our full data set we also do not find a significant correlation of $\beta = (\text{const})r$.

Other searches have been conducted looking for systematic rotation depending only on distance $r(z)$. For example, Carroll, Field and Jackiw (CFJ) [3] looked at the same data set as we did. However, CFJ used $\chi - \psi$, which mixes up obtuse and acute angles, and doesn’t allow for straightforward correlation analysis to be done. Moreover, one could easily question any systematic correlation with distance as possibly due to the evolution of a population: there was a “two–population” hypothesis 30 years ago [2], surmising that nearby sources emitted waves of polarization parallel to the sources’ major axes, and that distant sources emitted waves of polarization perpendicular to the sources’ major axes. We looked for an anisotropic correlation on the sky firstly because we had a theory that predicted it [1], and secondly because no population hypothesis could reasonably explain a signal if seen.

We have concentrated mainly on data analysis, because establishing that the effect is statistically significant is the first step. As for theoretical questions, in Ref. [1] we noted a gauge invariant modification of electrodynamics which has the same number of parameters as needed to explain the data, and is compatible with precision measurements of the Standard Model. Another possible explanation might be a domain wall from an axion–like particle condensate. A third explanation might be the twisting of polarization predicted by Brans [4], and Matzner and Tolman [5], from parallel transport in ordinary general relativity in an anisotropic cosmology. Several alternate cosmologies or theories of gravity [5] have also come to our attention, with claims that the anisotropic effect we saw would (or, in some cases, was) predicted.

Not unexpectedly, after publication of Ref. [1] there has been considerable controversy. Early charges that the data was “old and incomplete” were found to be spurious, as we have been vigorously reassured that the data set we used is the most complete one available [6]. The statistics have come under attack, but we have seen nothing valid to alter our conclusions. Eisenstein and Bunn (EB) [7] quickly criticized the work on the basis of a single scatter plot of $\beta$ versus $r \cos \gamma$ included in Ref. [1]. EB observed that the data for $z > 0.3$ was not uniformly distributed along the $\beta$–axis. Without making any calculations, but “estimating by eye” as EB put it, the observed data set for $z > 0.3$ was claimed not to be better correlated than data with $\beta$–values randomly distributed about 90 degrees. EB conjectured that the anisotropic correlation would go away if one compared the observed data to data with random shufflings of the observed $\beta$–values, rather than comparing (as we did, and in fact, only in Procedure 1) the observed data to data with $\beta$–values obtained from uniform random distributions of $\chi$ and $\psi$. (The distributions of the observed $\chi$ and $\psi$ are, in fact, uniform in the full data set).

There are several problems with EB’s criticism, explained in more detail in our response to EB in Ref. [7]: (1) Procedure 2, the more demanding, was ignored; (2) The scatterplot showed data after a cut; this, combined with the
fact that the data was linearly correlated, predicts the distribution in $\beta$ to be as observed; (3) Since shuffled data from such a limited, cut region is pre–correlated, comparison of this data with the observed data may underestimate the statistical significance of a real correlation in the observed data; (4) Since eyeball estimates can be deceiving, we actually did the “EB calculation” we found that our correlation survived, both in identifying the same anisotropy axis as found in Ref. [1], and in being statistically significant, with a P-value less than $2 \times 10^{-2}$. This was also independently confirmed numerically by P. Jain, who also reproduced our original numerical results in Ref. [1]. [We note that a more appropriate way to do shuffling is to shuffle the observed pairs $(\psi, \chi)$, not the $\beta$’s; this resulted in an even stronger signal. Furthermore, we shuffled only the $\beta$’s and $(\psi, \chi)$ pairs from the $z \geq 0.3$ set, although it is more reasonable to use the total set for this purpose].

Carroll and Field (CF) recently released a preprint [8], based on the “two–population hypothesis.” Restricting themselves to $z > 0.3$, CF confirmed some of our calculations, and also restated their previous calculations (in Ref. [3]) using the variable $\chi - \psi$. With this variable, they found no indication of a correlation nor anisotropy. As explained above, the variable is unsuitable (as also pointed out in our response to Leahy in Ref. [9]), and the procedure used by CF will generally miss an anisotropic signal even in perfectly correlated data sets. Unfortunately, CF have not made a clear distinction between $\beta$ and $\chi - \psi$ in their presentation, leading some readers to think that their calculation applies to our work, which used the direction-of-travel-dependent $\beta$. The same problem of not using $\beta$ occurs in Leahy, Ref. [9].

Other reactions [9,10] have come from radio astronomers, who so far have not addressed the anisotropic correlations on the sky, which was the basic nature of our result in Ref. [1]. Instead, these studies use high resolution VLBI data examining special internal structures of selected objects, such as jets in the detailed radio maps of certain nice–looking quasars. There are some problems with the claims: (1) their data seems to be highly selected, with much smaller sets than we used, and ignoring parts of the quasars which are not “pretty;” (2) some of the logic appears to be circular, depending strongly on theoretical ideas engineered to understand the same data before birefringence was considered; (3) the methodology lacks statistical criteria. If these problems are ignored, the claims state that no polarization rotation of the size we found is seen in the VLBI data. One actually goes beyond the scope of Ref. [1] when one compares the VLBI data and our data in this way: we reported an anisotropic correlation in our data, along with a thorough statistical characterization of its likelihood, and also pointed out the possibility that it was caused by systematic bias in our data.

Naturally, we believe that the VLBI data contains great potential for information, and should be studied systematically on its own basis. By this, we mean that the VLBI data should be subjected to the same kind of statistical Monte Carlo tests for anisotropy as the tests we applied to our data. One
FIGURE 1. Plot of $\beta \cos \gamma$ versus $r \cos^2 \gamma$, for the data of Fig. 1(d) in Ref. [1]. This plot is equivalent to that of Ref. [1], but places all data points in the first quadrant. A definite correlation can be seen.

cannot deduce much from any particular polarization rotation found in one or a few galaxies. Much more relevant would be statistical significance of a possible anisotropic signal, as quantified by the P–values obtained from analyses like ours.

It is also interesting to note that the frequency of the VLBI data is much higher than the frequency of the data we studied, so perhaps the studies in Refs. [9,10] really are looking at different phenomena. For example, we would think that the Brans mechanism [4] (if it exists) is independent of frequency. Regarding other hypotheses, there will be other predictions. For example, what is known generally about the frequency dependence of domain walls? It would seem to be model dependent to compare the different types of data in Refs. [9,10] and Ref. [1] prematurely.

Several recent articles report interesting progress. Obhukov et al. [11] claim that the correlation we observed could be caused by global rotation. Kühne [12], and Bracewell and Eshleman [13] have independently observed that the anisotropy axis extracted in Ref. [1] coincides tolerably well with the direction of the cosmic microwave background (CMB) dipole axis. This seems to be a strong clue, although our calculations on kinematic Doppler effects on Faraday rotation do not yield any mechanism to suggest a connection. It thus seems possible that some non–kinematic, grand medium effect may be at work, but we don’t know what.

Finally, some critics seemed to be uncomfortable with the fact that our data for $\beta$ versus $r \cos \gamma$ occupied both the first and third quadrants. We have taken this to heart by plotting $\beta \cos \gamma$ versus $r \cos^2 \gamma$ instead, which brings all the data into the first quadrant. The Jacobian of this transformation is a power of $\cos \gamma$, scaling both of the variables of interest by the same function. The plot is shown in Fig. 1, for the data of Fig. 1(d) in Ref. [1]. It must be noted that “eyeballing” scatter plots is dangerous; the plot in these variables happen to look nice, but one should rely on quantitative statistical measures.
Yet the figure may make it more clear to the eye that there is a definite signal of anisotropy. The next question, yet unanswered, is: why?

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