

Limits on Global Cosmic Birefringence Using Radio Sources

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We have made measurements of the difference between the position angle (PA) on the sky and the polarization position angle (PPA) of radio sources using data from a combination of the Radio Fundamental Catalogue (RFC) across a range of frequencies between 2.7 and 15 GHz and Cosmic Lens All-Sky Survey (CLASS) which observes polarization at 8.4 GHz (X-band). For the 2111 sources with jet PAs measured in the X-band and a known redshift, the distribution is peaked at $\approx 0^\circ$ as expected for no birefringence and it can be modeled by two populations: one which is a Gaussian with mean $\mu_\beta = (0.2 \pm 1.0)^\circ$ and standard deviation $\sigma_\beta = (14.7 \pm 1.1)^\circ$ and the other a uniform distribution of sources which are a fraction $f_\beta = 0.72 \pm 0.02$ of the total. Uncertainties in μ_β can be reduced to $\approx 0.6^\circ$ by stacking measurements of the PA from other wavebands. We find that limits of $\approx 0.1^\circ$ might be possible with a sample of $\sim 10^5$ similarly selected sources and that this could provide a confirmation of recent claims of global birefringence made using the cosmic microwave background observations from the *Planck* satellite.

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Introduction—Maxwell’s equations are one of the great triumphs of 19th century physics predicting the existence and detailed properties of electromagnetic (EM) waves [1]. The interpretation of most astrophysical observations is based on their predictions. One important feature which is predicted by Maxwell’s equations is that the plane of polarization of the EM waves is perpendicular to the direction of travel and that the polarization position angle would be unchanged along a trajectory from a distant source to observation here on Earth. This assumption has been tested in a range of laboratory situations [2] but is less well tested on cosmological distance scales over which minute effects can build up into a potentially measurable effect.

Parity violating modifications to Maxwell’s laws have been suggested [3–6] which could be related to the interaction between the electromagnetic sector and a pseudo-Nambu-Goldstone (pNG) field, ϕ , associated with a particle such as an axion. The Lagrangian for the interaction of the pNG field with the EM sector is typically of the form

$$\mathcal{L} = \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - V(\phi) - \frac{1}{4} F^{\mu\nu} F_{\mu\nu} - \frac{1}{4} g \phi F^{\mu\nu} \tilde{F}_{\mu\nu}, \quad (1)$$

where $\tilde{F}_{\mu\nu} = \epsilon_{\mu\nu\rho\sigma} F^{\rho\sigma} / 2$ is the dual of the EM tensor $F_{\mu\nu}$, $V(\phi)$ is the pNG potential and g is the coupling constant. Such models predict a rotation, known as comic birefringence (CB), of the plane of polarization, $\beta(z) = \frac{1}{2} g [\phi(0) - \phi(z)]$ where $\phi(z)$ is the spatially homogeneous value of ϕ at redshift z . If the distribution of the pNG field is spatially inhomogeneous, this can have a nonzero two-point correlation function.

Constraints on the rotation of the plane of polarization can be obtained from observations of the polarization of the cosmic microwave background (CMB). Such observations can be used to estimate the so-called *E*- and *B*-mode power spectra [7–9]. Scalar density waves only create *E* modes and the detection of *B* modes would possibly indicate the existence of primordial gravitational waves, vorticity, or even some kind of anisotropy of the Universe. Even then, the *E*- and *B*-mode spectra would be expected to be uncorrelated, and the cross-power spectrum, C_ℓ^{EB} , can be used to constrain β . Progressively tighter limits on the global component of β have been published [10,11] and the 68% confidence level (CL) range obtained using the data from the *Planck* Satellite is $\beta(z_{\text{LSS}}) = (0.21 \pm 0.05[\text{stat}] \pm 0.28[\text{sys}])^\circ$ with the systematic uncertainty being dominated by the uncertainty in the calibration of the instrumental contribution to the polarization position angle (PPA). Minami and Komatsu [12] have performed a self-calibration analysis of these data claiming a detection $\beta(z_{\text{LSS}}) = (0.35 \pm 0.14)^\circ$ with $|\beta(z_{\text{LSS}})| > 0$ at more than 99% CL.

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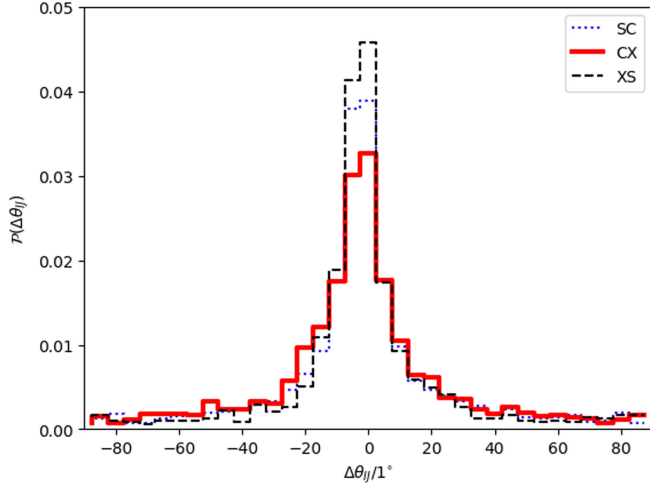


FIG. 1. Probability distribution of $\Delta\Theta_{IJ}$ where $I, J = \{S, C, X\}$. We have not included U because there are relatively few sources.

These conclusions have been supported by a range of other analyses [13–17]. Given the difficulties involved in making these measurements and also the potentially profound implications, it seems reasonable to search for alternative ways of constraining, or measuring CB.

The PPA of a galaxy, $\alpha = \frac{1}{2} \tan^{-1}(U/Q)$ (where Q and U are the Stokes parameters), can be used to provide an estimate of β . This can be done by assuming that some aspect of the measured shape of the source is related to the PPA; something which can be expected on physical grounds for highly polarized sources [3,18]. We measure α and the structural position angle (PA) θ ; then $\beta = \theta - \alpha - 90^\circ$, taking into account that $\beta \in (-90, 90)^\circ$ [19]. Of particular relevance are galaxies with active galactic nuclei (AGN), whose emission is often dominated by highly directional jets and which can be observed in a number of wavebands—a summary of some observations of individual galaxies is presented in Kaufman *et al.* [20] with differences between α and θ being typically $\sim$ a few degrees. However, these sources have been “cherry-picked” to be very well aligned which could be a coincidence and moreover there are limits on how well the angles can be measured. In this Letter we have used a large sample of radio sources to constrain the distribution of β using a statistical approach. The sample is not necessarily selected in an unbiased way, but importantly it has also not been chosen to have low values of β .

Data—As explained in Supplemental Material [21] we have assembled a sample of 6448 radio sources with a measurement of a PA, θ_I for at least one of $I = \{S, C, X\}$, using the Radio Fundamental Catalogue (RFC) [22] and PPA, α , from the Cosmic Lens All-Sky Survey (CLASS) [23]. In addition this includes Refs. [22,24–28]. In Fig. 1 we present a comparison between the measurements of θ_I by plotting the probability distribution $\Delta\Theta_{IJ} = \theta_I - \theta_J$ taking into account wrap-around effects. Although there

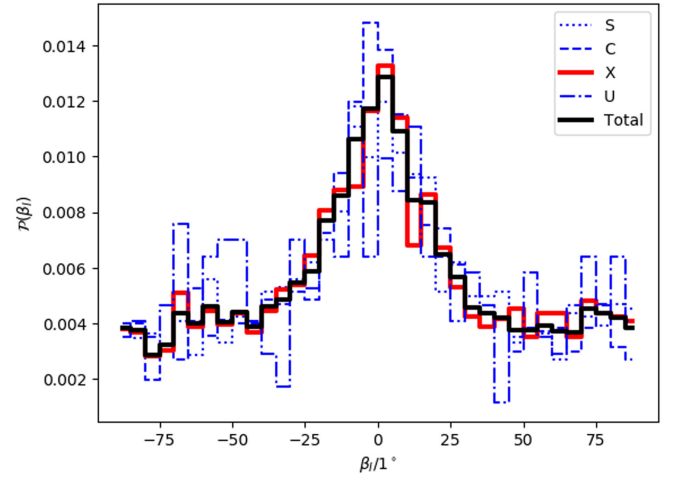


FIG. 2. Probability distribution $\mathcal{P}(\beta_I)$ for $I = \{S, C, X, U\}$ and total for the subset defined in column 3 of Table I, that is, with $\text{SNR} > 3$ and where there is a known redshift. The cases of the X-band and “Total” are highlighted since they are emphasized in the discussion.

is some dispersion between the different frequencies, probably due to them probing different parts of the source, this clearly indicates that the PAs are consistently measured. We have also compared the position angles to those measured in Ref. [29] which were computed by visual inspection of individual images and there is very good agreement. Focusing specifically on $\Delta\theta_{CX}$ we find that the distribution is compatible with a dispersion of $\approx 10^\circ$ and a failure fraction, modeled by a uniform distribution, of ≈ 0.25 . The polarization signal-to-noise ratio is defined by $\text{SNR} = (Q^2 + U^2) / \sqrt{Q^2 \sigma_Q^2 + U^2 \sigma_U^2}$ where σ_I for $I = \{Q, U\}$ is the measured noise, typically ≈ 0.3 mJy, for each source. If the $\text{SNR} > 3$ then the rms uncertainty in the PPA $\langle \Delta\alpha^2 \rangle^{1/2} \approx 10^\circ$ and hence we expect an overall dispersion in β , ignoring possible calibration uncertainties, by adding the two uncertainties in quadrature to give $\sim 14^\circ$. We are unable to quantify possible biases in the estimates of β derived from this procedure, but we do not claim a detection using this sample. Future work will be necessary to develop unbiased estimators and precisely quantify the uncertainties in the calibration, before this technique can be applied to larger samples—see the later discussion. We note that we do not expect the effects of Galactic Faraday rotation (FR) to be significant at X-band since typical Galactic RMs $\sim 10 \text{ rad m}^{-2}$ and they will not be coherent across the sky; the effects of FR internal to the sources could add some dispersion to the measurement. Again this is unlikely to be coherent. We have investigated the effects of made corrections to the PPAs using a Galactic Faraday rotation map [30] and found that correction to the inferred limits on β were $< 0.1^\circ$ backing up our assertion above.

We have used the data to estimate the probability distribution $\mathcal{P}(\beta)$ —calculated by creating a histogram with

TABLE I. Constraints on $\mu_\beta/1^\circ$. Uncertainties are defined at the 68% CL. z denotes that the catalogue contains a known redshift. The row “All” refers to all sources in the catalogue and “Total” to adding together all wavebands. The column NR means no restriction. From the left the subsets include all constraints from the previous column. The number of sources in each subset is shown in Supplemental Material [21].

Selection	All	SNR > 3	z	$ \Delta\theta_{CX} < 20^\circ$
θ_S	0.7 ± 1.5	1.0 ± 1.4	0.7 ± 1.5	0.2 ± 2.1
θ_C	1.1 ± 1.2	1.3 ± 1.0	0.9 ± 1.0	0.1 ± 1.1
θ_X	1.3 ± 1.3	0.3 ± 1.0	0.2 ± 1.0	-0.4 ± 1.1
θ_U	1.5 ± 4.6	2.0 ± 4.0	1.8 ± 3.9	-5.2 ± 4.6
Total	1.1 ± 0.7	0.9 ± 0.6	0.6 ± 0.6	-0.3 ± 0.7

36 bins and normalizing such that $\int \mathcal{P}(\beta) d\beta = 1$ —and these results are presented in Fig. 2. We see that all the distributions are peaked around $\beta \approx 0^\circ$, but that they do not fall-off to zero at $\pm 90^\circ$. The U-band is the most noisy due to the relatively small number of sources, but all the bands look consistent with each other. In what follows we will concentrate on the X-band, which has the largest number of sources and has both θ and α measured at the same frequency, and “total” which includes measurements at all frequencies [31].

Modeling the distribution of β for radio sources—One can attempt to model the measured distribution of β from the average and standard deviation of the distributions presented in Fig. 2, but this is fraught with dangers of bias since it can become dominated by large asymmetric fluctuations in the uniform background. We have derived limits by modeling the probability distribution $\mathcal{P}(\beta)$ comprising two components: one is a truncated Gaussian distribution with mean μ_β and standard deviation σ_β and the other is a uniform background that makes up a fraction f_β of the sources. We then estimate the likelihood of the model parameters $(\mu_\beta, \sigma_\beta, f_\beta)$ with respect to the data and marginalize over the other two to create a probability distribution for each of the parameters to allow conclusions to be drawn. We have tested our analysis pipeline by including offsets in Q and U , added to each of the sources, that might come from calibration uncertainties and also a spurious constant offset in the values of α , which was easily detected when larger than the statistic uncertainties found using the real data.

For completeness, in Table I we present the estimates of μ_β for various subsets; all are compatible with zero. The uncertainties vary very little, with decreases in the number of sources as one goes left to right in the table being offset by a cleaner sample—lower values of f_β and σ_β . We will concentrate on the case in column 3, which has SNR > 3 and a known redshift, leading to the lowest uncertainty. The marginalized posterior distributions are presented in Fig. 3. The values of $\sigma_\beta \approx 15^\circ$, which is compatible with the

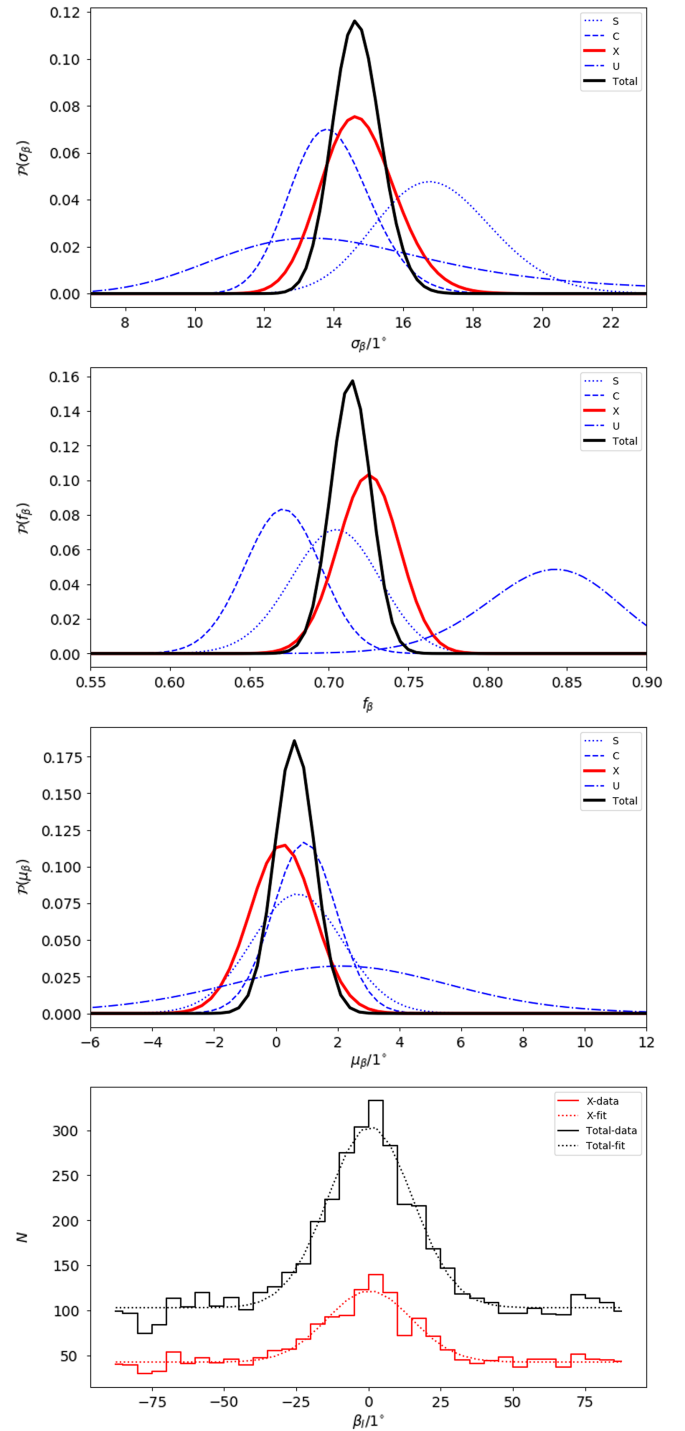


FIG. 3. The marginalized likelihoods for the fitting parameters for the probability distributions in column 3 of Table I for θ_X and “Total.” The top left is μ_β , top right σ_β , and bottom left f_β . The bottom right shows the maximum likelihood model compared to the data presented in Fig. 2.

measurement error of $\approx 10^\circ$ in both PA and PPA, and $f_\beta \approx 0.7$, 0.25 of which one might attribute to the imperfections in measuring PA (see Fig. 1) and the rest to sources where, probably for a variety of reasons, there is no

correlation between PA and PPA. We note that if we make an “opposite” assumption, that is, there is no known redshift, then we get an almost flat distribution for β indicating that there could be two populations in the sample. When we combine all measurements of β , assuming as we have argued earlier that these are independent, we find the best possible uncertainty of $\beta = (0.6 \pm 0.6)^\circ$. We caveat our conclusions with the possibility that a global mismatch of the PPA calibration could mask a nonzero cosmological signal which we consider to be very unlikely.

Discussion—Our current best uncertainty in β is a factor of ~ 4 – 6 greater uncertainty than the current CMB constraints dependent on which result one compares to, but is better than published constraints from individual sources [4,32,33]. Here, we present the study of radio sources as a way of confirming, or refuting, the claimed detection from the CMB. We note that measurements from radio sources and the CMB are not directly comparable and when comparing to a specific model for $\beta(z)$ one would need to convolve that model with the redshift distribution of the sources. It is clear that the approach could be extended to much larger samples than the present one. Such approaches would need to be accompanied by more careful calibration of polarization systematics than were possible using the CLASS observations that were not originally designed for this purpose. In particular, contemporaneous calibration of the absolute position angle of polarized calibration sources [34] is needed in order to reduce the systematic error in the absolute position angle. In addition, higher signal-to-noise observations of calibrators used to correct instrumental polarization would also be important in reducing errors of similar size in the derived polarization angles.

There are $\sim 10^6$ jet-dominated sources in the Universe with flux densities $\gtrsim 1$ mJy and it might be expected that, at some point in the future, these sources will be mapped to a similar level of noise as the RFC using the Square Kilometre Array (SKA). Modeling the distribution of N such sources as a *mixture* of two populations with a fraction f_β having $\beta \sim U(-a, a)$ and $1 - f_\beta$ being $\sim N(0, \sigma_\beta^2)$ truncated at $-a$ and a where $a = 90^\circ$, we can deduce that the variance of the mixture is

$$\sigma^2 = \frac{1}{3} f_\beta a^2 + (1 - f_\beta) \sigma_\beta^2 \frac{I_2(\frac{a}{\sigma_\beta})}{I_0(\frac{a}{\sigma_\beta})}, \quad (2)$$

where $I_n(y) = \int_{-y}^y x^n e^{-\frac{1}{2}x^2} dx$ and hence $I_2(y) = I_0(y) - 2ye^{-\frac{1}{2}y^2}$. In our case $a/\sigma_\beta \approx 7$ and hence it is a good approximation that $I_2/I_0 \approx 1$. For $f_\beta \approx 0.7$ this implies that $\sigma \approx 90^\circ \sqrt{f_\beta/3} \approx 45^\circ$ and the measurement error on μ_β will be $45^\circ/\sqrt{N}$. Therefore, we find that uncertainties of 0.1° might be possible with $N \sim 10^5$ sources. We note that this is the variance of the distribution, not what one would get from the marginalization of the likelihood. We have tested

this argument with simulations and, for the relevant values of f_β and σ_β , it is a good approximation.

A clear issue in the above analysis is the relatively large value of $f_\beta \approx 0.7$ that we found; that is, increasing N is used to mitigate the effects by reducing the impact of the uniform background rather than random errors on the measurement of μ_β . The value of f_β may be intrinsic to any such observations, but could be related to our choice of data and measurement methods. The CLASS data—which are chosen since the data already exist—might not be optimal for these purposes and a more bespoke polarization survey might lead to a reduction in f_β . However, ultimately, the uniform distribution will dominate the uncertainties. Ideally, one would have some additional observations which would allow one to select objects *ab initio* to have an alignment. If this could be done for $\sim 10^4$ objects, uncertainties $\sim 0.1^\circ$ would be possible. We have spent some time looking at the sample and, at this stage, we have not found any obvious way to reject the sources that form the uniform distribution. Obviously to reduce the uncertainties to $\sim 0.1^\circ$ would require very accurate calibration of the absolute PPAs to a similar level of accuracy which might be achieved using further observations of Mars [35]. By only including sources with polarized fraction $\sqrt{Q^2 + U^2}/I > 0.02$, for which we expect a stronger correlation, we found that $f_\beta \approx 0.5$, but this reduces the number of sources such that the overall uncertainty on μ_β is slightly increased. This remains a challenge for the future, but the benefits would be very significant.

We should comment that there are two other approaches that have been suggested to perform similar analyses using radio sources selected in other ways. The first [36] makes the assumption that the isocontours of flux density in large radio sources are statistically correlated with the direction of the position angle of polarized flux measured in the same direction. This technique, which was shown to lead to a constraint of $\beta = (-2.03 \pm 0.75)^\circ$ using data from ~ 30 sources, builds on earlier ideas put forward by Kronberg *et al.* [37,38]. The number of sources to which this technique can be applied is limited by the number of suitable large radio sources. We have not done a detailed estimate, but numbers $\sim 10^5$ – 10^6 might be possible with the SKA dependent on resolution.

An alternative is to use ordinary star-forming galaxies [39,40] together with a simple extension of ideas that have been proposed to correct radio weak lensing surveys for the effects of intrinsic alignment [41–43] relying on a different correlation between the shape of the galaxy and the polarization position angle [44]. Large scale surveys using the SKA phase I [45] might find $\sim 10^8$ such galaxies. Depending on how many can be resolved, in order to calculate the shape of the galaxy, this could become a powerful technique.

Finally, we note that Naokawa [46] has recently shown that a particular class of slowly rolling scalar field coupled

to EM using the type of coupling discussed earlier could lead to a very specific functional dependence as a function of redshift. This strongly motivates a similar study to ours with bins of $\beta(z)$. It seems clear that measuring birefringence using radio sources will continue to be an active area of research for some time to come.

Data availability—The data are not publicly available. The data are available from the authors upon reasonable request.

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