Is There Evidence for Cosmic Anisotropy in the Polarization of Distant Radio Sources?

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(Received 20 May 1997)

Measurements of the polarization angle and orientation of cosmological radio sources may be used to search for unusual effects in the propagation of light through the Universe. Recently, Nodland and Ralston [Phys. Rev. Lett. **78**, 3043 (1997)] have claimed to find evidence for a redshift- and direction-dependent rotation effect in existing data. We reexamine these data and argue that there is no statistically significant signal present. We are able to place stringent limits on hypothetical chiral interactions of photons propagating through spacetime. [S0031-9007(97)04321-4]

PACS numbers: 98.80.Es, 14.80.Mz, 41.20.Jb

The polarization of radiation emitted by distant radio galaxies and quasars offers a way to search for chiral effects in the propagation of electromagnetic radiation. Such objects are often elongated in one direction, so that one may define a position angle ψ which describes the orientation of the object in the sky. Synchrotron radiation can lead to a significant linear polarization of the source, and the angle χ of the plane of polarization may also be measured [1]. (The angle of polarization will typically undergo Faraday rotation, but this effect can be removed by using the fact that Faraday rotation is proportional to the square of the wavelength.) One can therefore study the relative angle $\chi - \psi$ between the position and polarization vectors, keeping in mind that this quantity is only defined modulo 180°. It has been found [2] that $\chi - \psi$ is not distributed randomly; there is a large peak at $\chi - \psi \approx 90°$, and a smaller enhancement at $\chi - \psi \approx 0°$. Since many of these sources are at significant redshifts, and therefore very far away, testing whether this relationship is maintained for distant sources provides constraints on possible chiral effects on the propagation of light through the Universe, which could rotate $\chi - \psi$ away from the intrinsic value (that which would be measured at the source).

From a field theory point of view, the simplest such chiral effect arises from a Lagrange density

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \phi F_{\mu\nu} \widetilde{F}^{\mu\nu}. \tag{1}$$

Here, ϕ is a pseudoscalar field which does not need to be fundamental (it can be a function of other fields in the theory). This Lagrangian is the simplest way to couple a neutral pseudoscalar to electromagnetism in a parity-invariant way, and often describes the effective coupling of pseudoscalar particles (such as pions or axions) to photons.

Our interest here is in the case where ϕ varies only very slowly over extremely large distances. In that case an electromagnetic wave traveling through the background ϕ field will undergo a rotation in its polarization state which depends on the change in ϕ; such an effect arises in a variety of contexts [3–8]. In the WKB limit where the length scale for variations in ϕ is much larger than the wavelength of the photon, the polarization angle χ obeys the simple relation $\Delta\chi = \Delta\phi$, where Δ indicates the change between source and observer. [Here, and in Eq. (2), $\Delta\chi$ is measured in radians; elsewhere we measure all angles in degrees; no confusion should arise.] This effect is independent of wavelength, and can therefore be distinguished from ordinary Faraday rotation. Carroll, Field, and Jackiw [5] suggested that observations of polarized radio sources provide a stringent test of such an effect, since they afford an opportunity to constrain $\Delta\phi$ over a large interval in space and time (see also [9,10]).

The specific model investigated in [5] set $\partial_\mu \phi = -(1/2) p_\mu$, where p_μ is a four-vector whose expectation value parametrizes violation of Lorentz invariance (as well as CPT [11]). It was hypothesized that there exists a preferred coordinate frame, close to the background Robertson-Walker frame of our universe, in which $\partial_\mu p_\nu = 0$. This implies that the predicted rotation of the polarization angle for a source at redshift z is given in terms of the timelike component p_0 and the spacelike vector $\vec{p}$ by

$$\Delta\chi = -\frac{1}{2} r (p_0 - p\cos\theta), \tag{2}$$

where $p = |\vec{p}| = (\delta^{ij} p_i p_j)^{1/2}$, θ is the angle between $\vec{p}$ and the direction toward the source, and r is the proper spacelike distance traveled. If we take a flat ($k = 1$) universe as a reasonable approximation, we have

$$r = \frac{2}{3H_0} [1 - (1 + z)^{-3/2}], \tag{3}$$

where H_0 is the Hubble constant today. Regardless of whether or not one is interested in tests of Lorentz invariance, Eq. (2) is a useful parametrization of potentially observable chiral effects.

In [5] it was shown that the radio galaxies at redshift greater than 0.4, with maximum polarizations greater than 5%, were strongly clustered around $\chi - \psi \approx 90°$, using

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a sample of galaxies and redshifts obtained from the literature [2,12]. Assuming that the timelike component p_0 would be significantly larger than the spacelike part $\vec{p}$, the limit $p_0 \leq 0.80 H_0$ was obtained. Recently, Nodland and Ralston [13], using the same set of data [14], searched for anisotropic effects such as those that would arise from a nonzero spacelike part $\vec{p}$ in Eq. (2). Surprisingly, they claimed to find a significant signal in the data. Given the fundamental importance of such a result, we have undertaken a reexamination of the data, and present our results in this paper. We conclude that the data are most consistent with no effect, contrary to [13]. Our disagreement stems primarily from the method used to disentangle the 180° ambiguity in the quantity $\chi - \psi$, and the use of randomly generated data for comparison purposes, as will be shown below [15].

The data set used in [5] includes 160 sources, with redshifts as high as 2.012. In the present paper we shall make use only of the 71 sources with redshifts $z \geq 0.3$; this choice is consistent with [13], allowing for direct comparison of our results. In Fig. 1, we have plotted a histogram of $\chi - \psi$ for these sources, defining $\chi - \psi$ so that it lies between 0° and 180°, and grouping the data into bins which are 10° wide. It is clear that there is a peak at $\chi - \psi \approx 90°$, but none at 0°; this is consistent with models of the sources [2].

This peak represents the crux of our disagreement with [13]. If the claim of [13] is true, it is necessary to believe that the peak at 90° is an accident, and these data are actually drawn from a distribution which is intrinsically centered at 0°, with position- and redshift-dependent contributions of order 180°. We will argue that this is not the simplest interpretation of these data.

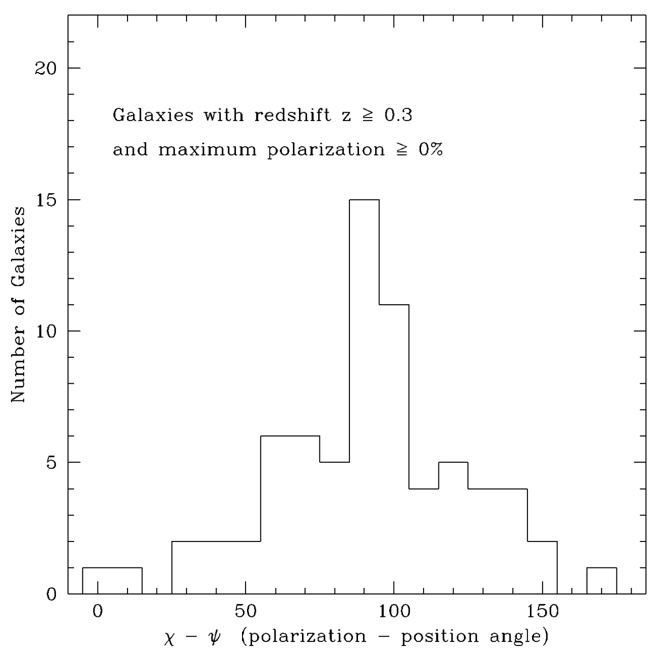

FIG. 1. Histogram of number of galaxies vs $\chi - \psi$, for galaxies with $z \geq 0.3$.

Searching for a signal in the polarization data is complicated by the fact that $\chi - \psi$ is only defined modulo 180°. In testing any specific hypothesis, it is necessary to choose some reasonable procedure for resolving this ambiguity. The method chosen by the authors of [13] was the following: for any choice of direction for the vector $\vec{p}$, define an angle $\beta = \chi - \psi \pm 180°$ which is between 0° and 180° if $\cos\theta \geq 0$ and between $-180°$ and 0° if $\cos\theta < 0$, where θ (which they called γ) is the angle between $\vec{p}$ and the direction toward the source. It was noted in [13] that this procedure necessarily introduces correlations between β and $r\cos\theta$. It would be illegitimate, therefore, to take a statistical correlation between these two quantities as itself evidence of a signal in the data. However, if the degree of correlation were much higher than that which would be expected if there were no signal in the data, we might conclude that there was a measurable effect.

It is at this point in the analysis that we find two important flaws in the procedure followed in [13]. First, one must reliably determine the zero point for $\chi - \psi$, which would be observed in the absence of any chiral effects. In [13], the authors searched for a best fit to the data of the form $\beta = (1/2)\Lambda_s^{-1} r\cos\theta + \delta$, where in the notation of Eq. (2), $\Lambda_s = p^{-1}$. They found that the favored value for the zero point was $\delta \approx 0°$. This seems to be inconsistent with the evidence of Fig. 1, which exhibits a peak at 90°. The resolution is simply the fact that the definition of β, as described above, separates the data into two groups, one with $-180° < \beta < 0°$ and one with $0° < \beta < 180°$. With this procedure the favored value for δ will always be near 0°; it arises essentially from taking the average of a group of points clustered around 90° and another clustered around $-90°$. This method of resolving the 180° ambiguity is therefore inappropriate for data which lie naturally in the vicinity of 90°.

Nevertheless, [13] argues that the correlation found is statistically significant, as it was only very rarely reproduced in artificially generated sets of data. The procedure for generating these sets is the second important flaw that we find. Figure 1 provides evidence that, regardless of the position of the source in the sky, $\chi - \psi$ is distributed approximately in a Gaussian distribution centered on 90°; a best fit to the Gaussian yields a dispersion of $\sigma = 33°$. Therefore, in searching for position-dependent effects, it is appropriate to compare the actual data to data which are generated by drawing from a similar distribution. In [13], on the other hand, artificial realizations were generated completely randomly, i.e., from a flat probability distribution for $\chi - \psi$. This has a dramatic effect on the claimed significance of the result. We performed an independent analysis, using two different methods of generating the artificial data sets: first by drawing from a flat distribution, and then from a Gaussian with the appropriate width. The numbers generated were values of $\chi - \psi$ for the positions and redshifts of the 71 sources in the sample with $z \geq 0.3$. In 1000 realizations of the data drawn from a flat distribution, in only 7 trials was the significance of the correlation greater than that in the actual data; this is comparable to the 6 out of 1000 reported in [13], and if reliable would be evidence of the existence of a signal. On the other hand, in 1000 realizations of the data drawn from the appropriate Gaussian distribution, the artificial data were more strongly correlated with the hypothesized test function in 911 out of 1000 trials. Even if there were no signal at all in the data, we would expect the artificial realizations to have a stronger correlation approximately 50% of the time; the fact that our trials had better correlations over 90% of the time is due to the fact that the Gaussian slightly underestimates the number of data points near 0°. This result, however, vividly demonstrates our main point: the existence of a real enhancement of $\chi - \psi$ near 90° leads to a spuriously large correlation coefficient if one uses the procedure described in [13]. When this enhancement, which is consistent with conventional models of the sources, is taken into account, there is no sign of an additional effect such as that in Eq. (2).

There is another way of quantifying our claim that a random distribution centered around 90° is a better fit to the data than the correlation proposed in [13]. Figure 2 is a plot of $\chi - \psi$ as a function of $r \cos\theta$, where θ is defined using the best-fit direction quoted in [13] and $\chi - \psi$ is defined to be between 0° and 180°. We may think of this graph as being defined on a cylinder, where 0° is to be identified with 180°. With this in mind, we have plotted two possible relationships, a solid horizontal line at 90° and a dashed line at $(1/2)\Lambda_s^{-1} r\cos\theta + \delta$, where we have measured the parameters Λ_s and δ from Fig. 1(d) of [13]. If the relationship claimed in [13] is correct, the dashed line wrapping around the cylinder should be a better fit to the data than the solid horizontal line. This can be measured by calculating

$$\chi^2 = \sum_i \left(\frac{\Delta_i}{\sigma}\right)^2, \tag{4}$$

where we take the average error to be $\sigma = 33°$, although the precise value is irrelevant for purposes of comparison. The quantity Δ_i, which represents the difference between the predicted and measured value of $\chi - \psi$, is of course subject to the 180° ambiguity; however, we can resolve this ambiguity optimistically for each point, by defining $-90° < \Delta_i < 90°$. Using this procedure, we calculate that the best fit proposed in [13] yields $\chi^2 = 161$, while the hypothesis of no effect yields $\chi^2 = 69$. Thus, the horizontal solid line in Fig. 2 is a much better fit than the diagonal dashed lines.

Given that there is ample evidence that the intrinsic zero point is centered on $\chi - \psi = 90°$, we may ask how good a limit we can place on an effect such as that

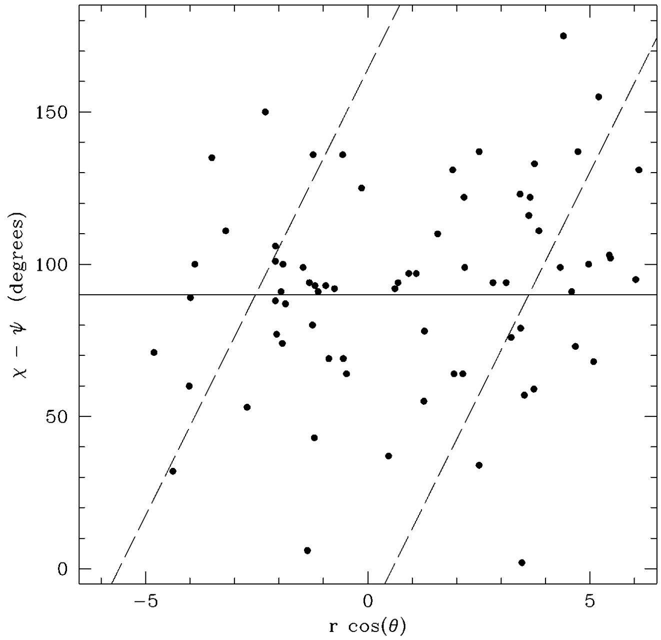

FIG. 2. The difference between polarization and position angles as a function of $r\cos\theta$ for the best-fit direction of anisotropy proposed in [13]. Angles of 180° are to be identified with 0°; the data thus live on a cylinder. The solid line represents the predicted relationship in the absence of any signal, while the diagonal dashed line wrapping around the cylinder represents the model suggested in [13].

in Eq. (2). One approach to this problem is to define $\chi - \psi$ to be between 0° and 180°, and to assume that the deviation from the intrinsic value is given by $\Delta\chi = \chi - \psi - 90°$. It is then possible to do a straightforward least-squares fit to Eq. (2), with the four components of p_μ as free parameters. Using the data at redshifts $z \geq 0.3$, the best-fit parameters obtained in this way are

$$\begin{aligned} p_0 &= (0.59 \pm 0.80)H_0\,, \\ |\vec{p}| &= (1.13 \pm 1.40)H_0\,. \end{aligned} \tag{5}$$

(This procedure yields separate values for each of the three spacelike components p_i; since each value is consistent with no preferred direction, it is more appropriate to quote the limit on the magnitude $|\vec{p}|$.) These values are consistent with $p_\mu = 0$, and similar to the limit on p_0 from [5] quoted above.

After analyzing the data in a variety of ways, we are able to conclude with confidence that there is no evidence for a chiral effect on the propagation of photons from distant radio sources. Despite this negative result, there are still good reasons to further pursue observations such as those examined in this paper.

In Fig. 3 we have plotted the position in the sky of the sources with $z \geq 0.3$, indicated by symbols related to the deviation of $\chi - \psi$ from 90°. The □'s represent sources with $\chi - \psi < 90°$, while the ×'s are sources with $\chi - \psi > 90°$. The size of the symbol is related linearly to the

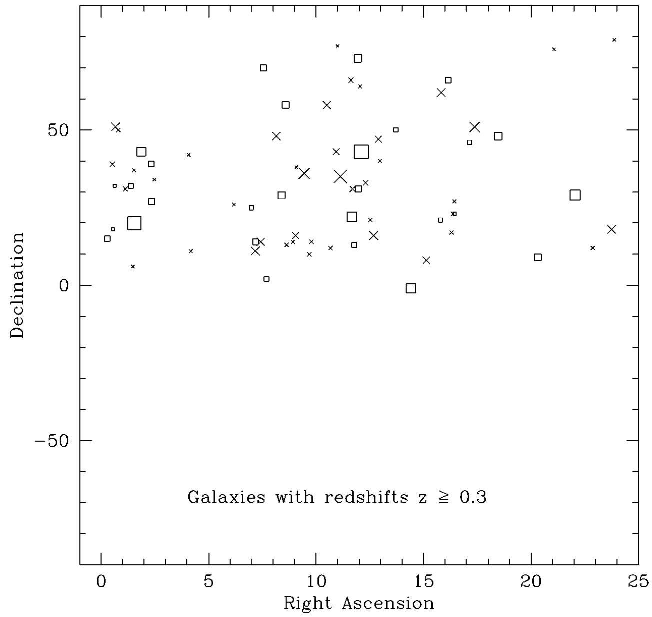

FIG. 3. Positions of radio sources in the sky, including only galaxies with $z \geq 0.3$. The symbols indicate deviations from $\chi - \psi = 90°$; $\square$'s are sources with $\chi - \psi < 90°$, and $\times$'s are sources with $\chi - \psi > 90°$. The size of the symbol indicates the amount of deviation from 90°.

deviation from 90°, although for clarity there is an offset so that points with $\chi - \psi$ very close to 90° still have a nonzero size. One conclusion to be drawn immediately from this graph is that there is a need for additional data to be collected in the southern celestial hemisphere, especially at high redshifts. In the future, observations of polarization of the cosmic microwave background may be the best source of data for constraining phenomena such as these [7,17].

In characterizing the limits one can place on chiral effects, for convenience we hypothesized a fixed four-vector p_μ which would represent a violation of Lorentz invariance. If an effect were to be found, however, it is by no means necessary that such a profound conclusion would have to be drawn. A more plausible hypothesis would be that of a very slowly varying scalar field ϕ with a coupling as in (1); the application of the data discussed in this paper to this possibility was examined in [6]. Such a field could arise as an ultralight axion, with mass of order the Hubble constant today (or less). Interestingly, such axions may appear naturally in the strongly coupled limit of heterotic string theory [18]. Another possibility is the detection of axionlike cosmic strings; in the vicinity of such a string, the polarization angle of two light rays passing on either side will undergo rotations in opposite directions [4]. Although there is no obvious sign of such a signal in Fig. 3, the importance of such a finding encourages us to continue the search.

We thank Ilana Harrus, Jack Hughes, Arthur Kosowsky, and Uros Seljak for helpful conversations, and Borge Nodland for assistance with the data. This work was supported in part by the National Science Foundation under Grant No. PHY/94-07195 and NASA under Grant No. NAGW-931.

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[14] As mentioned in [13], there were a handful of transcription errors in the table published in [5]. The corrected values are entry 9, coordinates 0106 + 72; entry 35, coordinates 0459 + 25; entry 84, $\psi = 39°$; entry 124, coordinates 1626 + 27; entry 144, $z = 0.054$; and entry 153, $z = 0.0244$. We are grateful to Borge Nodland for informing us of these corrections.
[15] As this paper was being completed we received a preprint by Eisenstein and Bunn [16], who come to conclusions similar to those expressed in this paper.
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