

Observational Evidence against Birefringence over Cosmological Distances

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We show that recent radio and optical observations of polarized radiation from well-resolved high redshift quasars and radio galaxies rule out the cosmological rotation of the plane of polarization claimed recently by Nodland and Ralston [Phys. Rev. Lett. **78**, 3043 (1997)]. A least squares fit to the radio data has a slope only 2% of their claimed effect. [S0031-9007(97)04016-7]

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In a recent paper, Nodland and Ralston [1] claim to find a systematic rotation of the plane of polarization of electromagnetic waves propagating over cosmological distances. Their claimed effect is large, requiring the plane of polarization from high redshift objects to be rotated by as much as 3.0 rad—an easily detectable signature. Here we report new optical data taken with the Keck telescope, and radio observations made with the Very Large Array (VLA) which show that any such rotation is less than 3° out to redshifts in excess of 2.

The data used by Nodland and Ralston consisted of radio measurements of the *integrated* polarization of extragalactic radio sources. After correcting for Faraday rotation, they compare the intrinsic angle of polarization, χ , to the major axis of the radio source, ψ . They suggest that “On symmetry grounds χ would be expected to align with the major axis angle ψ of the galaxy.” High resolution observations of extragalactic radio sources [2,3] show that such an expectation is optimistic. The integrated polarization of a radio source is the vector sum of the polarized radiation from several different emission regions, which have different angles of polarization. The resulting degree of polarization is generally low, with a net angle only weakly related to the major axis of the radio source.

Nodland and Ralston [1] fit the misalignment angle $\beta = \chi - \psi$ to a dipole anisotropy of the form $\beta = \frac{1}{2} \Lambda_s^{-1} r \cos(\gamma)$. Here, r is a distance which they define as $r = 6.17 \times 10^{25} [1 - (1+z)^{-\frac{3}{2}}]$ m for a Hubble constant of (100 km/sec)/Mpc, and Λ_s is a scale length which they find to be about 0.9×10^{25} m, or nearly one billion light years. γ is the angle between the direction to the radio source and a pole direction \vec{s} , whose coordinates are 20 ± 2 h in right ascension, and $-10^\circ \pm 20^\circ$ in declination. Thus, the Nodland and Ralston relation states that the plane of polarization of emission from cosmological objects should be seen to be rotated by

$\beta = 31.8r \cos(\gamma)$ degrees. Note that in their paper, Nodland and Ralston arbitrarily add $\pm\pi$ to the measured β values such that β is constrained to be positive for positive $\cos \gamma$, and negative for negative $\cos \gamma$. It is this procedure which leads at first sight to the apparently strong correlation in their Fig. 1(d). In fact, judgments of the significance must be based on the data within each quadrant separately, as is pointed out by Nodland and Ralston.

We shall not discuss the statistical or theoretical arguments of their paper. Problems with their statistical methods have been discussed by Carroll and Field [4], Eisenstein and Bunn [5], and Loredo, Flanagan, and Wasserman [6]. Here we will appeal directly to recent high resolution polarization observations of distant objects with well-defined structural axes against which we can test the claimed rotation. A cosmological rotation of this type has already been rejected by Cimatti *et al.* [7] based on polarized UV light from the distant radio galaxy MRC 2025-218 ($z = 2.63$). The polarized light is due to electron or dust scattering of light emanating from the galaxy nucleus, and the observed electric vectors are nearly exactly perpendicular to the axis of extended UV and Ly α emission, as is often found in high redshift radio galaxies [7–9]. Cimatti *et al.* [7] show that the angle $\chi - \psi = 87^\circ \pm 10^\circ$, and state that “the plane of polarization is not rotated by more than 10° when the radiation travels from $z = 2.63$ to us.” The rotation predicted from the relation of Nodland and Ralston [1] for this object is 163°—close to a π ambiguity, however. The presence of such an ambiguity can be confidently ruled out by the results of optical polarimetry for lower redshift radio galaxies [8,9], which show a strong tendency for the misalignment angles to cluster near 90°.

With a large optical telescope, a polarization image of a faint, distant radio galaxy can be made, and this gives directly the polarization distribution of the radiation

from the extended emission regions. When this is done, the polarization vectors typically show a centrosymmetric pattern, with the E vectors perpendicular to the radius to the nucleus. This is the signature of scattering (whether by dust or from electrons) of radiation from a point source. A circularly symmetric pattern in such an image is clear evidence of an absence of rotation of the plane of polarization (provided there is not an $n\pi$ rotation of the plane of polarization to that particular object).

Recent optical observations with the Keck telescope by Cohen and collaborators [10] have produced polarization images with low noise and tight upper limits on any rotation. In Fig. 1 we show the results for 3C 265—a radio galaxy with a redshift of $z = 0.811$ for which the expected rotation from Nodland and Ralston is -57° . Our analysis of the data gives a $3 - \sigma$ upper limit for any anomalous rotation of $<4^\circ$. The same result comes from observations of 3C 405 (= Cygnus A), where the “expected” rotation is 11° , but the limit is observed to

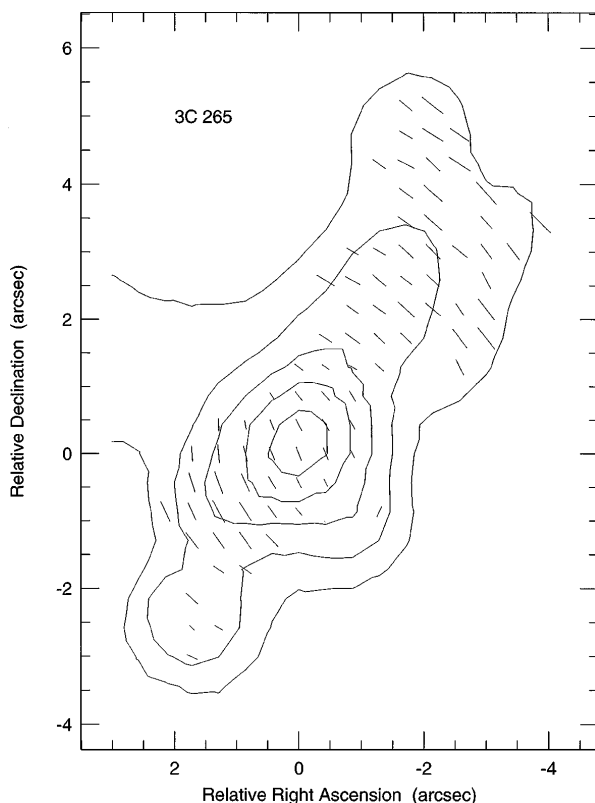


FIG. 1. Optical V band imaging polarimetry of 3C 265, a radio galaxy with $z = 0.811$ for which the relation of Nodland and Ralston [1] predicts a rotation of -57° . Contours are plotted at 4%, 8%, 16%, 32%, and 64% of the peak brightness. The position angle and degree of polarization of the polarized light are given by the orientation and length of the plotted vectors, with the rightmost vector representing 22.3%. Only vectors with an error less than 7° are shown. The centrosymmetric pattern of vectors is caused by scattering of light from a hidden central source. The mean deviation of the 53 plotted vectors from the perpendicular to a line joining each to the nucleus is $-1.4^\circ \pm 1.1^\circ$.

be 5° . Several other radio galaxies with redshifts near 0.1 also show no rotation to a limit of about 3° (Cohen, private communication)

An equally stringent test of cosmological birefringence at radio wavelengths comes from VLA observations of the jets in powerful radio quasars. It is well established [11,12] that in high luminosity radio jets, the magnetic field is closely aligned with the local jet direction, so that the plane of polarization of the radio waves (emitted by the synchrotron process) is perpendicular to the jet. Such jets therefore provide well-defined reference directions, ψ , against which we can measure any cosmological rotation in the plane of polarization. Note that this is not the only well-defined structural axis with which an accurate local measure of the misalignment angle can be made. Leahy [13] uses the well-known alignment of polarization with the sharp intensity boundaries seen in the lobes of radio galaxies and quasars in his response to [1].

In Fig. 2 we show an image of the radio quasar PKS 2209 + 152 ($z = 1.502$) made with the VLA at $\lambda 3.6$ cm. The contours are total intensity, showing the compact central core of the quasar to the southwest (lower right) and a thin jet curving to the northeast, ending in a bright compact “hotspot.” The degree of polarization is between 20% and 50% throughout the jet and hotspot. The tick marks show the plane of polarization of the radio waves, χ , and it is seen that the polarization vectors are closely orthogonal to the jet direction over most of its path. (It is also easily seen that the *integrated* polarization of this quasar will bear no particular relationship to the major axis of the source.) The relation published by Nodland and Ralston [1] predicts a rotation of the plane of

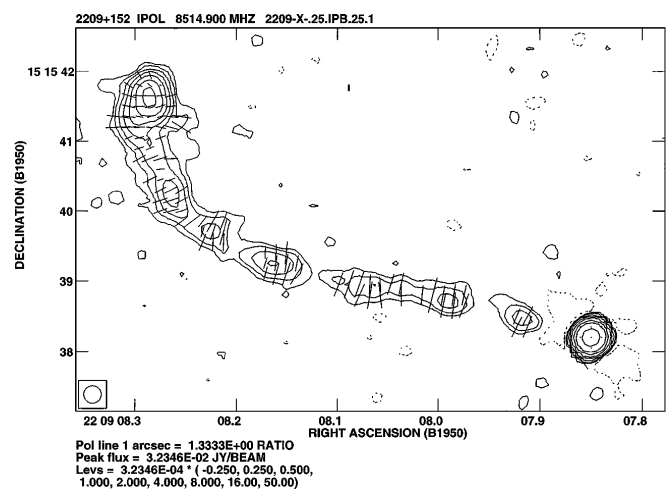


FIG. 2. A map made with the VLA at a wavelength of 3.6 cm of the jet in the radio-loud quasar PKS 2209 + 152 ($z = 1.502$) with a resolution of $0.25''$. The relation of Nodland and Ralston [1] predicts a rotation of the plane of polarization of 113° . The curved structure and high degree of polarization is typical for objects of this type. There is a negligible rotation of the position angle of the polarized radiation from that expected on the basis of observations of nearby objects of the same class.

polarization of about 115° —but it is clear from this figure that such a rotation is not present. We emphasize that the relation seen in this figure is faithfully reproduced in all radio observations of radio quasars known to us that have been made to date.

To demonstrate quantitatively the absence of any cosmological rotation of the plane of polarization, we use two samples of quasars for which deep VLA images at high resolution are available. Both samples were selected on the basis of the strength and large angular extent of their radio structure—ideal criteria for testing for any cosmological rotation of the plane of polarization. The first is from Bridle *et al.* [3], and contains 13 bright quasars of large angular size from the 3CR catalog [14], observed at λ 6 cm. We omit from our analysis 3C 215 and 3C 249.1, whose jets are short and distorted, and 3C 432, whose jet is unpolarized. The second sample consists of ongoing observations of 19 high redshift quasars with bright jets made by Kronberg, Perley, Röser, and Dyer (unpublished) at λ 3.6 cm. The λ 6 cm data were corrected for Faraday rotation, using published rotation measures [15]. The λ 3.6 cm data were not corrected, as only 12 of the objects have a published rotation measure [15,16]. However, for these 12 objects, the mean correction at this wavelength is less than 4° , and there is no indication that the corrections for the others will be any larger. These corrections are far smaller than the effect we are searching for. For each quasar, we measure the misalignment angle, defined as $\chi - \psi$, using only the integrated polarization of a straight, well-resolved portion of each jet. Following Carroll and Field [4], we constrain this difference to lie between 0° and 180° . We note that 7 of the 10 Bridle *et al.* [3] quasars, and 3 of the 19 Kronberg *et al.* quasars are in the sample used by [1], and that all of our sample quasars have $z > 0.3$.

The results for the 29 quasars are shown in Fig. 3, where we plot $\chi - \psi$ against $r \cos \gamma$. We also show the relation proposed by Nodland and Ralston [1]. It is obvious that the radio and optical data directly refute such a relation. A regression line fitted to our data has a slope of $0.54^\circ \pm 0.74^\circ$ per 10^{25} m, less than 2% of Nodland and Ralston's slope of about 32° per 10^{25} m. Our 3σ upper limit is 14 times smaller than their slope. The scatter in the radio data can be attributed entirely to noise and to small deviations in the local path of the jets.

The zero intercept for our fit is $89.6^\circ \pm 1.7^\circ$, as expected for synchrotron emission where the magnetic field is oriented along the emitting structure—the jet. Note that this offset from the relation proposed by Nodland and Ralston is arbitrary—we could have equally well defined our misalignment angle with respect to the normal to the observed E vector, in which case the intercept would have been -0.4° . The physical significance lies in the slope of the relation.

In summary, the observational data taken with modern high resolution instruments of high redshift galaxies and

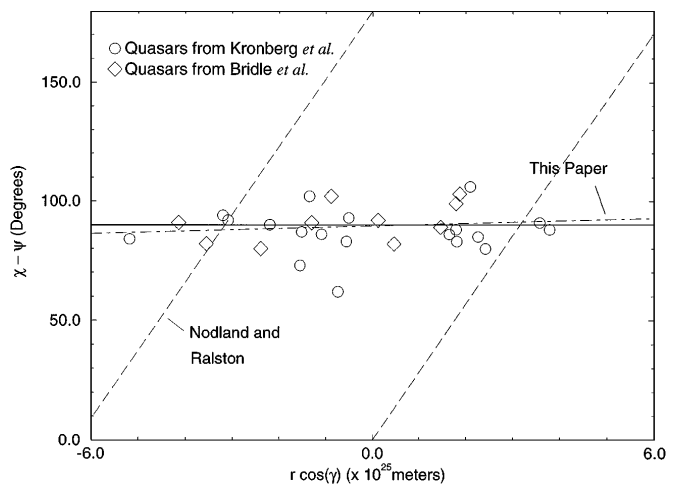


FIG. 3. A plot of the measured deviation between the local jet direction and the position angle of polarized emission for 29 high-redshift quasars from two different surveys. Superposed is the relation claimed by Nodland and Ralston [1]. The detailed data do not support their claim of a cosmological rotation in the plane of polarization of high redshift objects.

quasars at both optical and radio wavelengths show that any rotation of the plane of polarization (circular birefringence) over cosmological distances is at least a factor of 50 smaller than that claimed by Nodland and Ralston, and is statistically indistinguishable from zero.

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