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Study of Radio and Optical Polarization Anisotropies in the Electromagnetic Waves from Extragalactic Sources

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Abstract. Polarizations of electromagnetic radiation from active galactic nuclei (AGN) show some interesting effects such as the existence of a global anisotropy in the orientations of the radio wave polarizations from distant radio galaxies and quasars and a very large scale alignment of optical polarizations of quasars. We studied in detail whether the observational bias in the data would have led to these effects. We propose that the existence of a hypothetical pseudoscalar explains these effects.

1. Anisotropy in the Radio wave Polarizations

In 1982 Birch claimed the existence of a global anisotropy in the orientations of the radio wave polarizations from distant radio galaxies and quasars. This effect, which we refer to as the Birch effect, was later confirmed by Jain and Ralston (1999) using a larger data set with a more reliable statistical procedure. The observable of interest in the Birch effect is the offset angle $\beta = \chi - \psi$, where ψ is the orientation angle of the axis of the radio galaxy and χ is the observed polarization angle after the effect of Faraday rotation is taken out of the data. It was found that β was not isotropically distributed on the dome of the sky but instead showed a dipole anisotropy such that the offset angle for a source is given by

$$2\beta - \pi = \boldsymbol{\lambda} \cdot \boldsymbol{X} \tag{1}$$

where $\boldsymbol{X}$ is a unit vector in the direction of the source. The axial (or pseudo) vector $\boldsymbol{\lambda}$ represents the three parameters of this fit. The effect was found to be independent of redshift. So far there is no physical explanation for such an anisotropic behaviour of radio wave propagation. In order to explain the Birch effect the traditional and conservative scientific approach will be to test for a systematic bias in the estimation of both the parameters χ and ψ. We therefore isolated 15 sources which gave the dominant contribution to the statistic and tried to find if the determination of ψ and/or χ may be biased for these sources. No such bias was found.

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We next examined whether the standard statistical procedure used to estimate the polarization position angle, χ, can itself introduce some bias in its estimation. This is possible since the Faraday Rotation Measure has conventionally been extracted from the radio polarization data by using the stantard χ^2 procedure. The relationship between the polarization and the wavelength of the wave can be given as

$$\theta(\lambda^2) = \chi + (RM)\,\lambda^2$$

where θ is the polarization angle, RM is the slope, called Faraday Rotation Measure, and χ is the intercept, also called the intrinsic position angle of polarization, IPA. However, since the linear polarization angle θ is a circular variable, this can introduce bias in the estimate of χ. We developed an alternate methodology based on the maximum likelihood analysis to estimate these parameters (Sarala and Jain, 2001). The distribution function of the linear polarization angle was obtained by assuming that the two components of the electric field vector follow a normal distribution. The resultant distribution, obtained by MacDonald (1949) and Bunimovitch (1949), which we refer as MacDonald-Bunimovitch (MB) distribution is given by

$$p_{MB}(\theta) = \frac{(1-\xi^2)}{\pi(1-\mu^2)^{3/2}}\left[\mu \sin^{-1}\mu + \frac{\pi}{2}\mu + (1-\mu^2)^{1/2}\right] \qquad (2)$$

where $\mu = \xi\cos(2\theta - 2\bar{\theta})$. Here $\xi^2 = 1 - |R_{12}|^2/R_{11}R_{22}$ $(0 \le \xi \le 1)$ and $\bar{\theta}$ are the parameters of the distribution which measure the concentration and mean value of the population respectively. In Fig. 1 we compare the χ^2/dof obtained using the linear method with the analogous measure of the goodness of fit for the MB distribution, $2(\Delta \ln \mathcal{L}/dof)$ for all the sources. For small values of $\chi^2/dof < 1$ we find that $2(\Delta \ln \mathcal{L}/dof) \approx \chi^2/dof$. As χ^2/dof becomes much larger than one we find that $2(\Delta \ln \mathcal{L}/dof)$ is considerably smaller than χ^2/dof. This happens since the MB distribution has a large tail and allows larger fluctuations, which seem to be inherent in the polarization data (Sarala and Jain, 2002). We conclude that the MB distribution provides an unbiased and efficient method to extract RM from polarization data. However we did not observe any bias in the extraction of RM or χ if we use the linear χ^2 procedure. The data continues to show the anisotropy observed by Birch and Jain & Ralston, if the parameter χ is estimated using our likelihood method.

We next investigated whether the hypothetical pseudoscalar particles, which arise in certain extensions of the standard model of elementary particles, can explain the Birch effect. The photons emitted by the source can decay into pseudoscalars as they propagate through the background magnetic field. Since only the photons polarized parallel to the transverse component of the background magnetic field ($\vec{B}_t$) decay, this effect can lead to a change in polarization of the electromagnetic wave. Moreover the magnetic field due to our galaxy and the local supercluster is known to be anisotropic and hence can in principle explain the anisotropy. Another effect that can also contribute is the mixing of photons with off-shell pseudoscalars. This process changes the dispersion equation for the photon polarized parallel to $\vec{B}_t$ and hence can lead to changes in polarization. For the electromagnetic wave propagating through interstellar medium the probability to produce pseudoscalars, taking into consideration the electron density fluctuations (Carlson

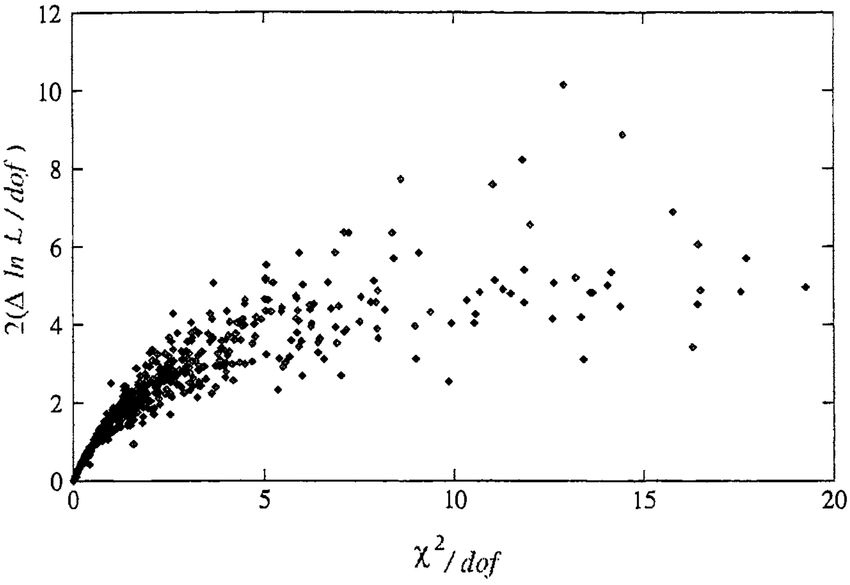

Figure 1. Comparison of the goodness of fit of linear and circular method with MB distribution.

and Garretson, 1994), $P_{\gamma\to\phi}$, is given by,

$$\begin{aligned} P_{\gamma\to\phi} &\approx 2.7\times10^{-5}\left[\frac{g}{10^{-10}\,\mathrm{GeV}^{-1}}\right]^2\left(\frac{\overline{B}_t}{\mu\mathrm{G}}\right)^2\left(\frac{0.03\mathrm{cm}^{-3}}{\overline{n}_e}\right)^{11/3} \\ &\times \left(\frac{C_N^2}{3\times10^{-4}\,\mathrm{m}^{-20/3}}\right)\left(\frac{L}{\mathrm{kpc}}\right)\left(\frac{\nu}{10^6\,\mathrm{GHz}}\right)^{5/3}\left|1-\frac{m_a}{\overline{\omega}_p^2}\right|^{-11/3} \end{aligned} \tag{3}$$

By calculating the pseudoscalar-photon conversion probability, it was found that the mixing is too small to produce any observable consequences at the radio frequencies (≈ 1 GHz) (Jain *et al.*, 2002). This conclusion holds even if the mass of the pseudoscalar is taken to be arbitrarily small. An alternate possibility is that the AGNs are emitting a very large flux of pseudoscalar particles at radio frequencies (Jain *et al.*, 2002). In that case small mixing probability can be compensated by the large flux. This explanation requires that the pseudoscalar flux is about one order of magnitude larger than the bolometric luminosity of a typical quasar.

We also propose an explanation of the Birch effect within conventional physics. It is well known that due to the turbulent nature of the interstellar medium the density and magnetic field correlations are described by the Kolmogorov power spectrum. This also leads to fluctuations in the RM which are known to be as large as 100 rad/m^2 for an angular separation of 100 arc seconds. If in a particular patch these fluctuations are anisotropic we find that they can explain the Birch effect. The basic idea can be explained as follows. Radiation emerging from different regions of the source show different RMs. Moreover it is well known that emission at different wavelengths is dominated by different regions of the source. Hence if we consider the mean polarization vector over the entire source it can no longer be described by a single RM. Therefore if we extract a single RM then the resulting estimate of χ will be biased. This phenomenon can explain the Birch effect if we assume that the fluctuations in the magnetic field and/or plasma density in our astrophysical neighbourhood show quadrupole anisotropy. We propose further observational tests which can verify if this is indeed the correct explanation.

2. Anisotropy in the Optical wave Polarizations

Another interesting polarization effect was observed by Hutsemékers in 1998. It was found that optical polarizations from distant quasars are aligned on very large scales. The alignment effect in the optical polarizations from quasars was observed only in patches without any indication of a large scale anisotropy. The effect also showed redshift dependence, i.e. alignment was found in patches delimited by angular as well as radial coordinates. A very striking alignment was found in the region, which is called the A1 region, delimited in Right Ascension by $11^h15^m \leq \mathrm{RA} \leq 14^h29^m$ and in redshift by $1.0 \leq z \leq 2.3$.

One of the problems associated with the statistical analysis performed by Hutsemékers is that it is not invariant under coordinate transformations. This is because the procedure requires the comparison of polarization vectors at two different positions on the surface of a sphere. The vectors at the respective locations are measured in terms of a local coordinate basis and hence cannot be compared directly. It is therefore important to introduce a coordinate independent procedure in order to properly assess the significance of the effect.

We propose a statistical procedure in which the polarization vectors at two different locations are compared after parallel transporting one of the vectors to the location of the second vector (Jain *et al.*, 2003). The results obtained by this procedure are found to be similar to those obtained by the procedure used by Hutsemékers and we find that the alignment effect is present in the data at the level of about 3 standard deviations. We also examined several cuts on the data sample in order to determine whether the alignment arises from large or small degrees of polarization and redshifts. We find that low polarizations $p \leq 2\%$ show a very significant redshift dependent alignment, as seen in Fig. 2, over a very large distance scale of a Gpc.

We also found that the large redshift points show alignment over the entire sample. Hence we find that besides the redshift dependent alignment, which happens primarily for the objects with low polarization, the entire set of large redshift objects are aligned with one another. This effect is different from the redshift dependent alignment and was not noticed by Hutsemékers (1998). This is shown more clearly in Fig. 3, which shows the $\log(S.L.)$ for very large values of n_v. The results for $p \leq 2\%$ cut are also shown for comparison.

Several explanations of this alignment effect in terms of propagation of electromagnetic waves were considered by Hutsemékers & Lamy (2001). They argued that extinction due to

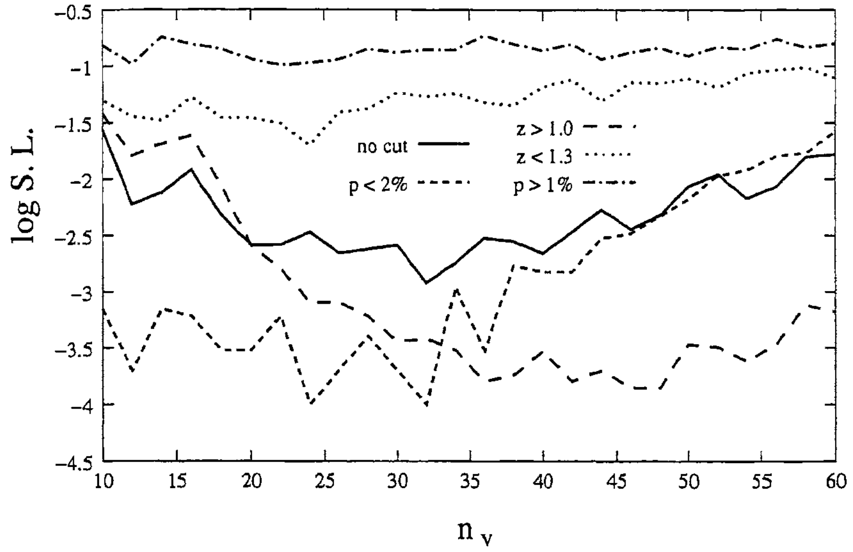

Figure 2. The logarithmic significance level, log($S.L.$), as a function of the number of nearest neighbours n_ν using the statistic S_D^p. The nearest neighbours are obtained by taking into account the radial distance of the source and hence this tests for redshift dependent alignment. The black curve corresponds to the entire data set. The short dashed, dash-dotted, long dashed and dotted curves correspond to the cuts $p \leq 2\%$, $p \geq 1\%$, $z \geq 1.0$ and $z \leq 1.3$ respectively.

dust or decay of photons into pseudoscalars in the presence of background magnetic field can polarize the radiation. This polarization is correlated to the background magnetic field and hence can give rise to alignment of the polarization vectors of different quasars. However this fails due to the following reason. One finds that in general the distribution of the degree of polarization for the radio quiet (RQ) along with optically selected non-broad absorption line quasars (O) differs from the distribution of the broad absorption line (BAL) quasars. Precisely the same difference between these different types of quasars is also seen in the A1 region. If the supercluster magnetic field causes the alignment in polarization due to decay of photons then this difference would not be preserved in the A1 region.

We argue that the alignment effect can be explained in terms of pseudoscalar-photon mixing if the quasars emit sufficiently large flux of pseudoscalars along with photons at optical frequencies (Jain *et al.*, 2002). We further assume that the pseudoscalar flux from (RQ+O) quasars is negligible. With these assumptions we find that with the currently allowed value of the pseudoscalar-photon coupling it is possible to explain the Hutsemékers effect.

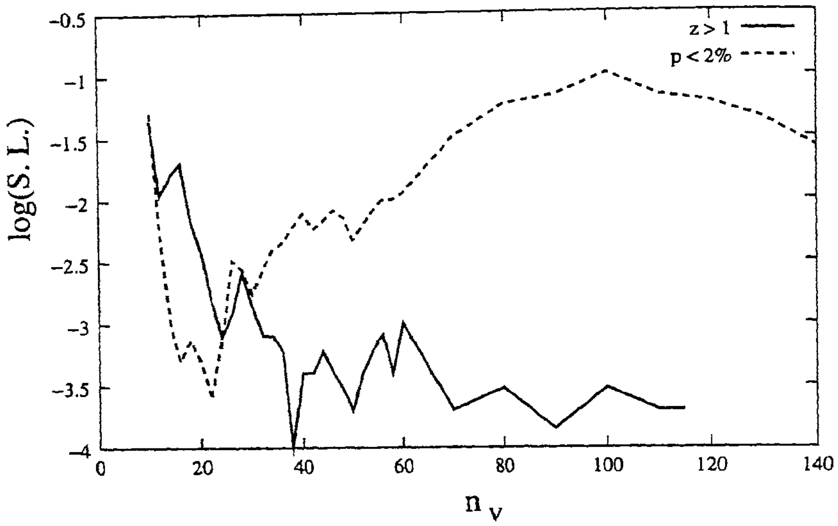

Figure 3. The logarithmic significance level, log($S.L.$), as a function of the number of nearest neighbours n_v using the statistic S_D^p for the cuts $z \geq 1$ (solid curve) and $p \leq 2\%$ (dashed curve). The nearest neighbours are obtained without taking into account the radial distance of the source and hence this tests for redshift independent alignment. Results are shown for very large values of n_v and this tests for alignment over very large distances. The total number of points in the sets $z \geq 1$ and $p \leq 2\%$ are 115 and 146 respectively.

3. Conclusion

To summarize, we have proposed a new method for the computation of rotation measures and IPA from spectral polarization data. We also found that the significance level of the correlation found by Jain & Ralston remains approximately unchanged if the likelihood analysis based on MB distribution is used to estimate the RM and IPA. We have analyzed whether the existence of hypothetical pseudoscalar can explain this effect. We find that the Birch effect may also be explained if we assume that radio galaxies and quasars emit a very large flux of pseudoscalars at radio frequencies. We also find that it is possible to explain the Birch effect in terms of quadrupole fluctuations in the background magnetic field and/or plasma density.

We have developed coordinate invariant statistical procedures in order to test for the large scale alignment of optical polarizations. We find that the alignment is redshift dependent and is seen dominantly for the data sample with low polarizations ($p \leq 2\%$). We also find that the large redshift, $z \geq 1$, sample shows a very large scale alignment. Infact the polarizations contained in almost the entire data sample at $z \geq 1$ seem to be correlated with one another. We find that galactic or supercluster extinction is unlikely to provide an explanation for these observations. The Hutsemékers effect can be explained if we assume the existence of a very light pseudoscalar particle.

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