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Pseudoscalar-photon mixing and the large scale alignment of QSO optical polarizations

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Abstract. We review the observation of large scale alignment of QSO optical polarizations. Alignment is seen in patches of distance scale of order 1 Gpc. We argue that the existence of a hypothetical light pseudoscalar can explain these observations.

The optical polarizations from distant QSOs appear to be aligned over very large distance scales [1,2]. It is observed that the polarizations of different QSOs have a tendency to point in the same direction in any three-dimensional local neighbourhood. This alignment is found in patches of distance scales of the order of 1 Gpc [3]. A very striking alignment is found in the region, called A1 in [2], delimited in right ascension by $11^{\rm h}15^{\rm m} \leq \mathrm{RA} \leq 14^{\rm h}29^{\rm m}$ and in redshift by $1.0 \leq z \leq 2.3$. By using several statistical tests the authors in [1,2] rule out the hypothesis of uniform distribution at approximately 0.1% significance level (SL). The SL is defined as the probability that this level of alignment can be obtained in a random sample. The data used in these tests consist of 213 QSO's distributed over the entire celestial sphere. The data were compiled by using all the major surveys available in the literature. In order to eliminate the contribution due to galactic extinction, sources with degree of polarization $p \leq 0.6\%$ and with galactic latitude $|b| \leq 30°$ were eliminated.

The statistical tests performed in [1,2] have the shortcoming that they depend on the coordinate system. The positions of the sources as well as their polarizations are specified with respect to a particular spherical polar coordinate system. The statistical tests depend on the choice of the coordinate system since they require comparison of polarizations at two different points on the sphere. In [3] the authors introduced coordinate invariant statistical tests which use parallel transport to compare polarizations at different points on the celestial sphere. Using these generalized statistical tests, the authors found that the alignment effect is present at approximately 0.2% significance level in the entire data sample. The authors also investigated some cuts on the data. It was found that the low polarization data sample with degree of polarization $p \leq 2\%$ is very strongly correlated with SL of order 0.01% to 0.001%, depending on the test. The number of sources remaining after this cut is 146. The large p sample with $p \geq 1\%$, however, shows no alignment. Here the precise value of the lower limit 1% for p is chosen in order to have approximately the same number of sources as with the cut $p \leq 2\%$. Furthermore, the authors also tried cuts on redshift. It was found that the $z \geq 1$ sample, with 115 sources, is much more strongly aligned in comparison to the low redshift sample with $z \leq 1.3$. Here again the precise cut $z \leq 1.3$ is chosen in order to retain approximately the same number of sources as in the $z \geq 1$ sample. The authors in [3] also found the surprising result that the large redshift sample with $z \geq 1$ shows correlation over the entire celestial sphere.

The physical origin of this alignment effect is so far unknown. One possible cause may be the extinction due to interstellar or intergalactic dust. However, it is difficult to explain the observations in terms of galactic extinction. This is because the contribution due to galactic extinction is considerably reduced due to the cut on degree of polarization and galactic latitude. Furthermore the data show redshift dependent alignment which cannot arise due to galactic extinction. The same argument also eliminates extinction due to local supercluster as a possible explanation. Hence in order to explain the observations in terms of extinction we have to postulate the existence of several regions with magnetic field coherent over the distance scale of a Gpc. The alignment of dust grains due to this magnetic field can lead to the observed alignment in polarizations. However, this phenomenon is unable to explain why the large redshift data show alignment over the entire sky whereas alignment effect is much weaker for the low redshift sample.

We next investigate whether the existence of a hypothetical light pseudoscalar particle can explain these observations. Light pseudoscalars, such as the axion, appear in many extensions of the standard model. The photon can decay into such a particle in the presence of a background magnetic field. Since only the photon polarized parallel to the transverse component of the background magnetic field couples to the pseudoscalar, this effect will lead to polarization perpendicular to the magnetic field. This effect can also give rise to the observed alignment if there exist several regions of magnetic field coherent over distance scale of the order of a Gpc, as postulated above in the case of extinction.

The coupling of photons to axions and other light pseudoscalars is severely limited by astrophysical observations. Here we are interested in a pseudoscalar ϕ with negligible mass, which will be taken to be zero. The most stringent limit on its coupling g with photons is obtained from SN1987A which gives the bound $g < 10^{-11}$ GeV^{-1} [4–6]. For a uniform magnetic field the pseudoscalar-photon conversion probability after propagation through distance L is given by

$$P_{\gamma\to\phi} \approx (gB_{\mathrm{t}}l)^2 \sin^2\left[\frac{L}{2l}\right], \tag{1}$$

where B_{t} is the magnitude of the transverse component of the magnetic field,

$$l = \frac{2\omega}{\overline{\omega}_p^2 - m_\phi^2}. \tag{2}$$

Here $m_\phi \approx 0$ is the pseudoscalar mass, $\overline{\omega}_p^2$ is the mean value of the plasma frequency $\omega_p^2(z)$ and ω is the frequency of the wave. In obtaining this result we have ignored the fluctuations in the plasma density and background magnetic field. The probability is, in general, much larger if these fluctuations are included [7].

In order to estimate pseudoscalar-photon conversion probability we take the Virgo supercluster values of the magnetic field $B \approx 1\ \mu$G and the plasma density $n_e = 10^{-6}$ cm^{-3} [8]. Assuming that $m_\phi \ll \omega_p$, we find that l is given by

$$l \approx \frac{\nu}{10^6\ \text{GHz}}\ 0.04\ \text{Mpc}, \tag{3}$$

where $\nu = \omega/2\pi$. Setting $\sin^2(L/2l)$ in eq. (1) equal to its mean value 1/2, we find that at optical frequencies, $\nu = 10^6$ GHz, the SN87A constraint $g < 10^{-11}$ GeV^{-1} implies

$$P_{\gamma\to\phi} < 0.04\ . \tag{4}$$

The upper bound on the conversion probability is expected to be much larger if we include the fluctuations in plasma density and magnetic field. Hence we find that the conversion probability is large enough so that the alignment can be explained in terms of pseudoscalar-photon mixing.

The explanation in terms of pseudoscalar-photon mixing also requires the existence of large scale magnetic fields in the Universe. The alignment in the A1 region, which lies in the direction of the Virgo supercluster, can be explained in terms of the Virgo cluster magnetic field which has a length scale of order 10 Mpc. The redshift dependence of the alignment can be explained if we postulate the existence of large scale magnetic fields with length scales of the order of 1 Gpc randomly located at different redshifts. However it is not possible to explain alignment over the entire celestial sphere, seen in data with redshifts greater than one, in terms of photon decay into pseudoscalars. In order to explain this global alignment we propose that the large redshift objects emit a significant flux of pseudoscalars [9]. If this flux is larger than the photon flux from these sources then decay of pseudoscalars into photons will give the dominant contribution to alignment. These pseudoscalars decay into photons as they propagate through the magnetic field in the local supercluster, giving rise to alignment over the entire celestial sphere. The small redshift objects do not participate in this global alignment since their pseudoscalar emission rate is assumed to be much smaller.

In summary, we are able to explain all aspects of the observed alignment effect in terms of pseudoscalar-photon mixing. We propose that the large redshift objects emit a significant flux of pseudoscalars at optical frequencies. The decay of pseudoscalars into photons in the local supercluster magnetic field gives rise to the observed global alignment. Furthermore large scale alignment seen in three-dimensional patches can be explained by postulating the existence of magnetic fields of length scale of order 1 Gpc randomly located at different redshifts.

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