Large-Scale Alignments of Quasar Polarization Vectors: Evidence at Cosmological Scales for Very Light Pseudoscalar Particles Mixing with Photons?

D. Hutsemékers (1*), A. Payez (1†), R. Cabanac (2), H. Lamy (3), D. Sluse (4), B. Borguet (1), and J.-R. Cudell (1)

(1) University of Liège, Belgium, (2) Observatoire Midi-Pyrénées, France, (3) BIRA-IASB, Belgium, (4) EPFL, Switzerland

Abstract. Based on a sample of 355 quasars with significant optical polarization, we found that quasar polarization vectors are not randomly oriented over the sky as naturally expected. The probability that the observed distribution of polarization angles is due to chance is lower than 0.1%. The polarization vectors of the light from quasars are aligned although the sources span huge regions of the sky (∼1 Gpc). Groups of quasars located along similar lines of sight but at different redshifts (typically z ∼ 0.5 and z ∼ 1.5) are characterized by different preferred directions of polarization. These characteristics make the observed alignment effect difficult to explain in terms of a local contamination by interstellar polarization in our Galaxy. Interpreted in terms of a cosmological-size effect, we show that the dichroism and birefringence predicted by a mixing between photons and very light pseudoscalar particles within a magnetic field can qualitatively reproduce the observations. We find that circular polarization measurements could help constrain this mechanism.

1. Introduction

Large-scale alignments of quasar polarization vectors were first uncovered looking at a sample of 170 quasars selected from the literature (Hutsemékers 1998, hereafter Paper I). The presence of such alignments was confirmed later on a larger sample (Hutsemékers & Lamy 2001, hereafter Paper II). The departure from random orientations was found at significance levels small enough to merit further investigation. Moreover, these alignments seemed to come from high redshift regions, implying that the underlying mechanism might cover physical distances of gigaparsecs. A large survey of linear polarization was then started, with the goal to characterize better the polarization properties of quasars and to investigate the reality of the alignments. A final sample of 355 quasars with reliable polarization measurements was then built on the basis of the new polarization measurements and of a comprehensive compilation from the literature. A detailed analysis of this sample was carried out by Hutsemékers et al. (2005, hereafter Paper III). The main results are reviewed here and a possible interpretation based on photon-pseudoscalar mixing is presented.

*Senior Research Associate FNRS, †IISN Research Fellow
2. Large-scale coherent orientations of quasar polarization vectors

The sample under study contains 355 polarized quasars up to redshifts $z \sim 2.5$ and with optical polarization position angles ($\theta$) reasonably well determined ($\sigma_{\theta} \leq 14^\circ$). It contains various types of bright quasars: radio-quiet and radio-loud, with or without broad absorption lines, etc. As far as possible, blazars were excluded due to their variable polarizations and unsecure redshifts. To minimize contamination by interstellar polarization, only objects with polarization degrees $p \geq 0.6\%$ and located at high ($\geq 30^\circ$) galactic latitudes were considered.

Alignments of quasar polarization vectors are illustrated in Fig. 1 which shows maps of polarization vectors at low ($z < 1$) and high ($z > 1$) redshifts. We immediately see that the polarization vectors are not randomly oriented as one would expect. Circular statistics indicates that the departures from a uniform distribution are statistically significant, and that the polarization angles of low- and high-redshift objects cluster around significantly different directions. The sources cover a huge region of the sky, typically 1 Gpc at $z \sim 1$.

Statistical tests based on the nearest-neighbour analysis were applied to the full sample of 355 quasars. They indicate that the quasar polarization vectors are not randomly distributed over the sky with a probability in excess of 99.9\% (Paper III; Jain et al. 2004). Coherent orientations are best detected in groups of 30-40 objects which correspond to the regions of alignments seen in Fig. 1.

Possible contamination of the data by intrumental and interstellar polarization was carefully inspected. Instrumental polarization was measured to be very small. Furthermore, quasar polarization data obtained at different observatories with different instruments do agree within the uncertainties. At high galactic latitudes the interstellar polarization is typically $\leq 0.2 - 0.3\%$ but can occasionally be higher. Although we adopt the cutoff $p \geq 0.6\%$ on the polarization degree to make sure that most of the measured polarization is intrinsic to the quasars, the polarization of the objects in our sample is usually lower than 2\% (Fig. 1) so that at least some data might be affected by interstellar polarization. Several tests and simulations were then performed in Paper III, as well as in Shuse et al. (2005) and Cabanac et al. (2005), leading to the conclusion that it is very unlikely that interstellar polarization can be at the origin of the observed alignments. This is basically what we can also conclude from Fig. 1: should interstellar polarization (or any local contamination) be responsible for the observed alignments, one would expect the same effect at all redshifts and no significant difference between mean polarization angles at low and high redshifts.

3. Towards an interpretation

To summarize, current observations show that quasar polarization vectors appear coherently oriented or aligned over huge (1 Gpc) regions of the sky located at both low ($z \sim 0.5$) and high ($z \sim 1.5$) redshifts and characterized by different preferred directions of the quasar polarization. Looking in more details, there seems to exist a regular alternance along the line of sight of regions of randomly oriented and aligned polarization vectors, the mean polarization angle apparently rotating with the redshift (Paper III). Interestingly enough, the alignment effect seems to be prominent along an axis not far from preferred
Figure 1. Maps of quasar polarization vectors towards the North Galactic Pole region, together with the corresponding distributions of polarization angle (in °) and polarization degree (in %). The regions illustrated are delimited in right ascension and declination by $168^\circ \leq \alpha \leq 218^\circ$ and $\delta \leq 50^\circ$, and in redshift by $0.0 \leq z < 1.0$ (top, 43 objects) and $1.0 \leq z \leq 2.3$ (bottom, 56 objects). At low (resp. high) redshifts the probability that the distribution of polarization angles is drawn from an uniform distribution is 0.3% (resp. 0.2%) with a mean value of the polarization angles around 79° (resp. 8°).
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Figure 2. **Top:** Evolution of the degree of linear polarization, $p$, and of the normalized Stokes parameters $q$, $u$ and $v$ as a function of the distance to the quasar (which corresponds to the extent of the external magnetic field). The external magnetic field is taken parallel to polarization vectors with $q > 0$ and $u = 0$. Among the Stokes parameters, only $u$ has been chosen initially different from zero, $u(0) = 0.001$. The other parameters are: the mass of the pseudoscalar or axion-like particle $m = 3.70025 \times 10^{-14}$ eV, the photon plasma frequency $\omega_p = 3.7 \times 10^{-14}$ eV, the observation wavelength $\lambda = 500$ nm, the coupling constant $g \simeq 7 \times 10^{-12}$ GeV$^{-1}$ and the strength of the external magnetic field $B \simeq 4 \times 10^{-11}$ G (only the product $gB$ is relevant). **Bottom:** Same as previous figure but for $u(0) = 0.01$. 
directions tentatively identified in the Cosmic Microwave Background (Ralston & Jain 2004).

Alignments can be simulated for a group of quasars polarized at \( p \sim 2\% \) by adding a small systematic polarization (\( \sim 0.5\% \)) to their intrinsic polarization vectors, assumed to be initially randomly oriented. This systematic polarization, which can be generated along the line of sight, cannot be too high since existing correlations between polarization and other morphological or spectral properties of quasars (e.g. Lamy & Hutsemékers 2004, Borguet et al. 2008, and references therein) cannot be washed out.

Although various interpretations might be possible (Paper I–III; see also Morales & Sáez 2007, Demiański & Doroshkevich 2007, Campanelli et al. 2007), the dichroism and birefringence due to photon-pseudoscalar mixing within a magnetic field can modify the polarization of quasar light during its propagation in a way that qualitatively reproduces the observations (Jain et al. 2002, Das et al. 2005, Gnedin et al. 2007, Piotrovich et al. 2008, Payez et al. 2008).

Fig. 2 illustrates the effect of photon-pseudoscalar mixing, within an external magnetic field, on the light from a distant quasar (cf. Payez et al. 2008 for details). A small additional polarization which oscillates with the distance is created, such that an alternance of regions of random and aligned polarization vectors can be reproduced. The wavelength dependence of the effect (e.g. Payez et al. 2008) could explain why such alignments are not detected at radio-wavelengths (Joshi et al. 2007). While the adopted magnetic field strength is lower than current upper limits for a cosmological magnetic field, a huge coherence scale is needed. Also, fine tuning is necessary to produce an oscillation with the observed periodicity. While an interpretation in terms of photon-pseudoscalar mixing seems promising, more realistic simulations are needed, such as a study of the cumulative effect of a succession of smaller regions with randomly oriented magnetic fields. Interestingly, an apparently generic effect of photon-pseudoscalar mixing is the creation of circular polarization with \( \vec{v} \approx \vec{u} \) (Fig. 2).

References

Borguet, B., Hutsemékers, D., Letawe, G. et al. 2008, A&A, 478, 321
Cabanac, R., Hutsemékers, D., Sluse, D., Lamy, H. 2005, ASPC, 343, 498
Campanelli, L., Cea, P., Tedesco, L. 2007, Phys. Rev. D, 76, 063007
Das, S., Jain, P., Ralston, J.P., Saha, R. 2005, JCAP, 06, 002
Demiański, M., Doroshkevich, A.G., 2007, Phys. Rev. D, 75, 123517
Gnedin, Y.N., Piotrovich, M.Y., Natsvlishvili, T.M. 2007, MNRAS 374, 276
Hutsemékers, D. 1998, A&A, 332, 410 (Paper I)
Hutsemékers, D., Lamy, H. 2001, A&A, 367, 381 (Paper II)
Hutsemékers, D., Cabanac, R., Lamy, H., Sluse, D. 2005, A&A, 441, 915 (Paper III)
Jain, P., Panda, S., Sarala, S. 2002, Phys. Rev. D, 66, 085007
Jain, P., Narain, G., Sarala, S. 2004, MNRAS, 347, 394
Joshi, S.A., Battye, R.A., Browne, I.W.A., et al. 2007, MNRAS 380, 162
Lamy, H., Hutsemékers, D. 2004, A&A, 427, 107
Morales, J.A., Sáez, D. 2007, Phys. Rev. D, 75, 043011
Payez, A., Cudell, J.-R., Hutsemékers, D. 2008, arXiv:0805.3946
Piotrovich, M.Y., Gnedin, Y.N., Natsvlishvili, T.M., 2008, arXiv:0805.3649
Ralston, J.P., Jain, P. 2004, Int. J. Mod. Phys., 13, 1857
Sluse, D., Hutsemékers, D., Lamy, H., Cabanac, R., Quintana, H. 2005, A&A, 433, 757