Searches for Cosmic Polarization Rotation

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Introduction

Photons carry almost all the information which we have about the Universe outside the Solar System (a few elusive cosmic rays are the exception). This information essentially consists in (1) the direction of propagation, (2) the wavelength (or energy), and (3) the orientation of the polarization vector. While changes in the direction of propagation and in wavelength have been observed for photons traveling in vacuum, as a result of the expansion of the Universe or of a strong gravitational field, changes in the orientation of the polarization vector have not been measured. We review here the search for these changes, in particular those involving the orientation of linear polarization which are wavelength independent, called **cosmic polarization rotation (CPR)**. Searching for CPR is important both *per se* and as a test of fundamental physical principles which are briefly summarized here. What is necessary for the CPR search is a distant source of polarized radiation for which the polarization angle at the emission can be safely predicted and then compared with the observed one.

Fundamental physical principles tested with CPR

This possibility of CPR arises in a variety of important contexts, like the presence of a cosmological pseudo-scalar condensate, Lorentz invariance violation and CPT violation, neutrino number asymmetry, the Einstein Equivalence Principle (EEP) violation. We refer the reader to Ni (2008, Prog. Theor. Phys. Suppl. 172, 49, and 2010, Rep. Prog. Phys. 73, 3043) and to the talk by Wei-Tou Ni at this Conference.

CPR search with the radio polarization of distant radio sources

The first search for CPR was done using the fact that the extended extragalactic radio sources (radio galaxies and quasars) tend to have their plane of integrated radio polarization, corrected for Faraday rotation, usually perpendicular and occasionally parallel to the radio source axis (Carroll et al. 1990, PRD 41, 1231). The result was negative and the upper limit on CPR was of 6° at 95% confidence for sources at $0.4<z<1.5$. However this method is only statistical and is not based on a precise estimate of the polarization angle at the emission. A significant improvement consists in using, for those sources for which detailed spatially resolved polarimetry is possible, the precise forecast for synchrotron radiation that the polarization should be perpendicular to strong gradients in the surface brightness. This improved method has been used by Leahy (1997, astro-ph/9704285) on 10 radio sources at $\langle z \rangle=0.78$ to obtain a CPR of -0.6°±1.5°, consistent with no rotation.

CPR search with the UV polarization of RG

Soon after the first CPR search, Cimatti et al. (1994, ApJ 422, 562) proposed a new method, using the perpendicularity between the direction of the elongated UV structure of distant powerful radio galaxies and the direction of their linear UV polarization, since they are both the result of scattered anisotropic nuclear radiation, as foreseen by the unification scheme of radio-loud AGN. This method has been used on a sample of 8 radio galaxies at $\langle z \rangle=2.8$ to obtain a CPR of -0.8°±2.2° (di Serego Alighieri et al. 2010, ApJ 715, 33). These data have been used by Kamionkowski et al. (2010, PRD 82, 047382) to set an upper limit to the variance of CPR, in case of of a non-uniform polarization rotation, of $\langle \alpha^2 \rangle \le (3.7°)^2$. For the radio galaxies for which spatially resolved polarization maps can be obtained, the local UV polarization direction must be perpendicular to the vector joining each observed position with the nucleus. This method has been used on 3C265 at z=0.811 to obtain a CPR of -1.4°±1.1° (Wardle et al. 1997, PRL 79, 1801).

CPR search with the CMB polarization

More recently CPR has been searched using the polarization of the CMB, which is particularly suitable, since it is scattered radiation, hence polarized, it is the most distant radiation we can detect directly (z~1100), and the polarization direction at emission is safely predicted, since it must be perpendicular to the intensity (temperature) gradients. Since the first detection of CMB polarization anisotropies by DASI (Kovac et al. 2002, Nature 420, 722), several CMB experiments, both from the ground and from space, have searched for CPR. We summarize in Table 1 the most recent and accurate ones. Since unfortunately the CMB polarization experiments have adopted the opposite convention to the standard one enforced by the IAU for measuring polarization angles, we convert their measurements to the standard system. The systematic errors listed in Table 1 for the CMB experiments are due to the relatively large uncertainties which these experiments still have on the calibration of the polarization angle. Although some have claimed to have detected a rotation (Xia et al. 2010, PLB 687, 129, Kaufman et al. 2014, PRD 89, 062006) the CMB polarization data appear well consistent with a null CPR. Recently di Serego Alighieri et al. (2014, ApJ 792, 35) have raised the possibility of setting constraints on the CPR also using measurements of the B-mode polarization of the CMB, because of the coupling from E-mode to B-mode polarization that any such rotation would produce. This possibility is presently limited by the relatively large systematic errors on the polarization angle still affecting current CMB data. The result is that at the moment it is only possible to set constraints on the fluctuations $\langle \delta\alpha^2 \rangle$ of the CPR, not on its mean value (see Table 1 and Fig.1).

Table 1: A summary of CPR searches

Experiment	CPR angle ±stat (±syst)	Frequency or λ	Distance	Direction	Reference
Resolved RG radio pol.	α=-0.6°±1.5°	3.6 cm	$\langle z \rangle$=0.78	All-sky (uniformity ass.)	Leahy 1997
RG UV pol.	α=-0.8°±2.2°	~1300Å	$\langle z \rangle$=2.80	All-sky (uniformity ass.)	di Serego A. et al. 2010
Resolved RG UV pol.	α=-1.4°±1.1°	~3000Å	z=0.811	RA=176.4°, Dec = 31.6°	Wardle et al. 1997
RG UV pol.	$\langle \alpha^2 \rangle \le (3.7°)^2$	~1300Å	$\langle z \rangle$=2.80	All-sky (stoch. var.)	Kamionkowski 2010
CMB pol. BOOMERanG	α=4.3°±4.1°	145 GHz	z~1100	RA~82°, Dec~-45°	Pagano et al. 2009
CMB pol. QUAD	α=-0.64°±0.50°(±0.50°)	100-150 GHz	z~1100	RA~82°, Dec~-50°	Brown et al. 2009
CMB pol. BICEP1	α=2.77°±0.86°(±1.3°)	100-150 GHz	z~1100	-50°$<$RA$<$50°,-70°$<$Dec$<$-45	Kaufman et al. 2014
CMB pol. WMAP9	α=0.36°±1.24°(±1.5°)	23-94 GHz	z~1100	All-sky (uniformity ass.)	Hinshaw et al. 2013
CMB pol. B-mode	$\langle \delta\alpha^2 \rangle \le (1.56°)^2$	95-150 GHz	z~1100	Various regions	di Serego A. et al. 2014

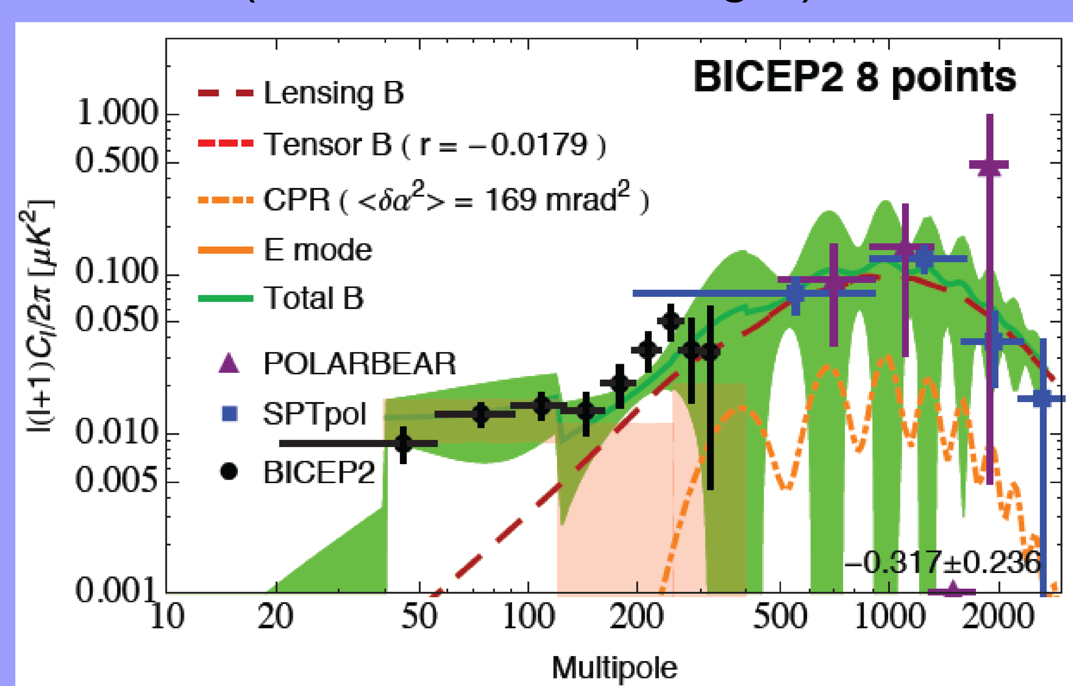

Fig.1: The CMB B-Mode power spectrum comparing the data points and the models, including the lensing, the CPR and the dust contributions (Pan et al. in prep.).

Conclusions and outlook

The current combined evidence so far is consistent with a null CPR and upper limits are of the order of 1 degree. CPR searches have benefited from the variety of methods which have provided a useful complementarity, examining sources at different wavelengths, different distances and different positions in the sky. Recently Galaverni et al. (2014, arXiv:1411.6287) have examined the dependence of CPR on energy (or wavelength/frequency) and distance, and found none, which is not surprising for a null CPR. Improvements on the CPR search can come from an improvement in the polarization angle measurement accuracy. This can be expected in the near future for all methods. The coming generation of giant optical/IR telescopes on the ground and in space will provide more accurate polarization measurements for a large number of RG; improvements can also be expected for the method using the spatially resolved radio polarization on distant radio sources; improvements for the CMB polarization experiments are expected both on the measurement accuracy and hopefully also on the calibration of the polarization angle which at the moment constitutes the “bottle neck”. We also hope that the CMB polarization experiments will soon adopt the standard convention for the polarization angle, to avoid confusion and improve the complementarity between the different methods for CPR search.