Cosmic polarization rotation: A general relativity test using astrophysical measurements

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The cosmic polarization rotation is introduced as a test of the Einstein equivalence principle, on which general relativity is based. The astrophysical tests of cosmic polarization rotation, which have been made in the past 25 years using the polarization of radio galaxies and of the cosmic microwave background, are briefly reviewed. Current problems and future prospects for cosmic polarization rotation measurements are described.

Keywords: Polarization; Einstein equivalence principle; radio galaxies; cosmic microwave background.

1. Why search for cosmic polarization rotation?

Almost all the information we have about the universe outside the solar system is carried to us by photons; a few cosmic rays and several elusive neutrinos are so far the only exceptions, at least until gravitational waves will be discovered. Photons carry information about their direction, their energy (or wavelength/frequency) and their polarization. The latter consists essentially in the position angle (PA) of the polarization ellipse, i.e. photons carry throughout the universe an important geometrical information, although our eyes cannot see it. In order to make the best use of this information, it is important to know if and how it is changed while photons travel to us. We know that the direction of photons can be modified by a strong gravitational field, and that their energy is modified by the expansion of the universe. Is the polarization PA also modified while photons travel large distances in vacuum?[a] The searches for cosmic polarization rotation (CPR) deal with this important question.

Clearly, if there is any CPR, i.e. if the CPR angle α is not zero, it should be either positive for a counter-clockwise rotation, or negative for a clockwise rotation.[b] Therefore symmetry must be broken at some level, leading to the violation of fundamental physical principles (see ref. 24 for a recent review of the violations of physical principles leading to CPR). Indeed CPR is linked also to a possible violation of the Einstein equivalence principle (EEP), which is the foundation of any metric theory of gravity, including general relativity (GR), for which we celebrate

[a]We know that the polarization PA is modified while photons travel in a plasma with a magnetic field, the so called Faraday rotation, which is proportional to the wavelength squared. However we deal here with possible modifications in vacuum.

[b]We adopt the IAU convention for PA: it increases counter-clockwise facing the source, from North through East.[13]

the centennial at this conference. The reasons for the link are due to the unique counterexample to Schiff's conjecture[27] that any consistent Lorentz-invariant theory of gravity which obeys the weak equivalence principle (WEP) would also obey the EEP, which involves a pseudoscalar field, producing CPR.[22,23] Therefore, if we could show that the CPR angle is zero, the EEP would be tested with the same high accuracy of the WEP, greatly increasing our confidence in the EEP and then in GR.

In the following I will briefly review the tests on CPR carried out with different methods in the past 25 years, and discuss current problems and future prospects for these tests. A more extensive recent review of CPR tests can be found in Ref. 10.

2. Searches for cosmic polarization rotation

CPR tests are simple in principle: they require a distant source of polarized radiation for which the polarization orientation at the emission PA_{em} can be established. By measuring the observed orientation PA_{obs}, the CPR angle can be calculated:

$$\alpha = PA_{obs} - PA_{em}.$$

The problem is the estimate of PA_{em}. Fortunately it can be solved using the fact that scattered radiation is polarized perpendicularly to the plane containing the incident and scattered rays. This simple physical law has been applied to CPR tests, using both the ultraviolet (UV) radiation of radio galaxies (RG) and the tiny disuniformities of the cosmic microwave background (CMB). The first CPR tests 25 years ago used instead a stastical analysis of the radio polarization in RG.[5] The most accurate CPR tests obtained with the various methods are summarized in Fig. 1, which is derived from the data of Ref. 10.

In summary, the results so far are consistent with a null CPR with upper limits of the order of one degree.

3. Current problems in searches for cosmic polarization rotation

Searches for CPR using the UV polarization of RG have reached the limits allowed by current instrumentation, for the lack of suitable RG, where the test can be performed and which are bright enough so that their polarization can be measured with the available instruments.

The most accurate results are now obtained with the CMB polarization, averaging over large sky areas, i.e. assuming uniform CPR over these areas. A current problem with CPR searches using the CMB is the calibration of the polarization PA for the lack of sources with precisely known PA at CMB frequencies. This introduces a systematic error, which is similar to the statistical measurement error, of the order of 1 degree (see the red error bars in Fig. 1). Recently the polarization PA of the Crab Nebula (Tau A) has been measured with an accuracy of 0.2 deg. at 89.2 GHz. However most CMB polarization measurements are made at higher frequencies (100–150 GHz) and the Crab Nebula is not visible from the South pole, the

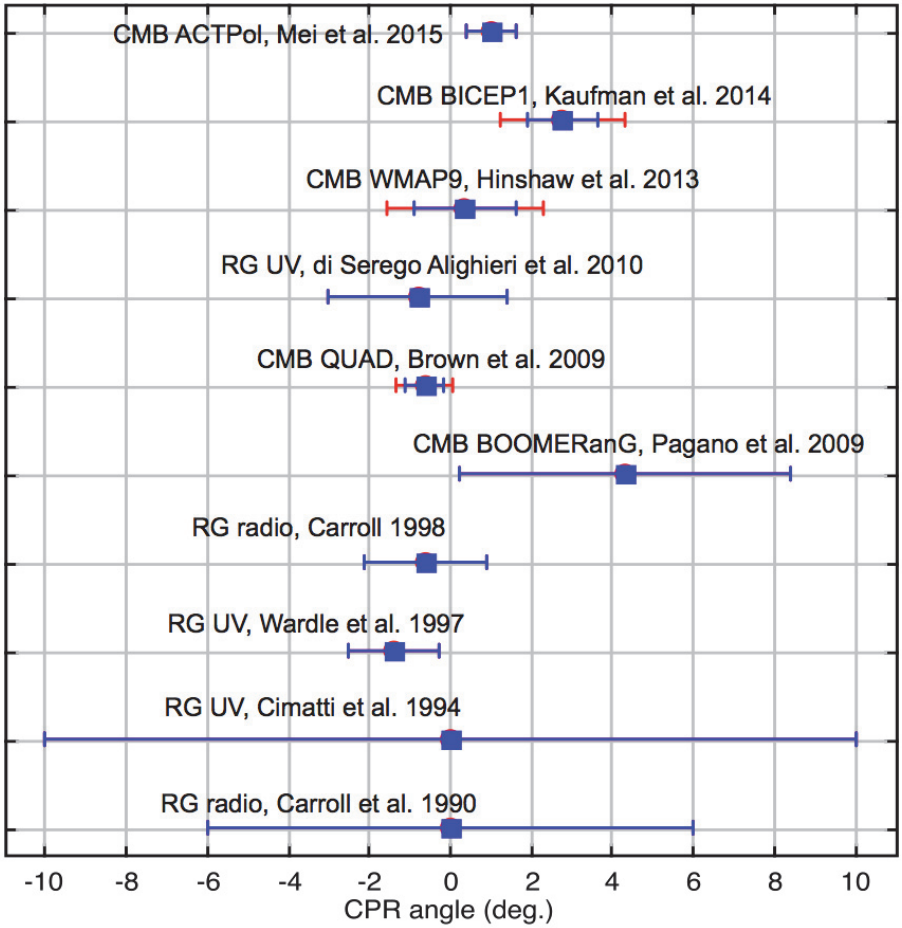

Fig. 1. CPR angle measurements by the various experiments, displyed in chronological order. Blue error bars are for the statistical error, while red ones include also the systematic one, if present. A systematic error should be added to the ATCPol measurement, equal to the unknown difference of the Crab Nebula polarization PA between 146 GHz and 89 GHz.

site of several CMB experiments. In order to overcome the PA calibration problem, some CMB polarization experiments have used a TB and EB nulling procedure.[17] However this procedure would eliminate together the PA systematic error and any CPR angle α, so it cannot be used for CPR tests.

A second problem with CMB tests is that unfortunately the CMB polarimetrists have adopted the convention that the polarization PA increases clockwise (looking at the source), which is opposite to the standard convention adopted by all other polarimetrists for centuries and enforced by the IAU (PA increases counter-clockwise).[13] This is obviously producing problems when comparing measurements with different methods, like for CPR tests, also because the "CMB convention" has not been well documented in the CMB polarization papers. For example, a recent preprint reviewing the CPR tests obtained with different methods has mixed in the same figure results obtained with the opposite conventions without taking that into proper account.[15] This error has negligible effects on the results of the paper, since CPR is consistent with zero, but the figure shows a tendency for α to be negative, which is not justified. In fact it has disappeared in the corrected version of the figure.[16] It would clearly be desirable that we all use the same convention and avoid parochialism in science. The "CMB convention" has been adopted following a sofware for pixelization on a sphere[11] (*sic*!!). However pixelization software using the IAU convention exists[30] and should be used by CMB polarimetrists.

4. Summary and future prospects

All results are so far consistent with a null CPR. All CPR test methods have reached so an accuracy of the order of 1 deg. and upper limits to any rotation of the same order.

The different methods are complementary in many ways. They cover different wavelength ranges and the methods at shorter wavelength have an advantage, if CPR effects grow with photon energy, as foreseen in some cases.[18,19] They also reach different distances, and the CMB method obviously reaches furthest. However the relative difference in light travel time between z = 3 and z = 1100 is only 16%.

Improvements can be expected by better targeted high resolution radio polarization measurements of RGs and quasars, by more accurate UV polarization measurements of RGs with the coming generation of giant optical telescopes,[3,8,26] and by future CMB polarization measurements such as those from Planck[1] and BICEP3.[2] Indeed the Planck satellite is expected to have a very low statistical error ($\sim$ 0.06 deg.) for CPR measurements. Unfortunately, although Planck has completed its observations in October 2013, its results on CPR have not yet been released. In any case, in order to exploit its great accuracy, Planck will have to reduce accordingly also the systematic error in the calibration of the polarization angle, which at the moment is of the order of 1 deg. for the CMB polarization experiments. The best prospects to achieve this improvement are likely to be more precise measurements of the polarization angle of celestial sources at CMB frequencies with ATCA[20] and with ALMA,[28] and a calibration source on a satellite.[16]

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