Spontaneous Baryogenesis, CPT Violations and the Observational Imprints

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Abstract

We realize the model of spontaneous baryogenesis in the framework of dynamical dark energy. This will lead to dynamical cosmic CPT violations and leave imprints in the universe. Using the CMB observations of WMAP and Boomerang we get a mild preference of such kind of cosmic CPT violations.

The origin of the baryon number asymmetry in the universe remains a big puzzle in cosmology and particle physics. Sakharov's original proposal for a dynamical generation of the baryon asymmetry requires three ingredients [1]: (1) baryon number violation; (2) C and CP non-conservation; and (3) out of thermal equilibrium. Note that the Sakharov's conditions were originally concerned for models where the CPT is conserved. If the CPT is violated the baryogenesis (or leptogenesis) could happen in thermal equilibrium[2, 3, 4], such as the spontaneous baryogenesis[3].

The current observations show strong evidence that our Universe is in a stage of accelerated expansion. One interesting candidate for the acceleration is the dynamical scalar field dubbed Quintessence[5]. Quintessence is expected to have interactions with the ordinary matter, however for most of cases the couplings are strongly constrained[6]. Nevertheless there could be some exceptions, and here we introduce the following interaction of Quintessence with the matter, which in terms of an effective lagrangian is given by[7]

$$\mathcal{L}_{eff} = \frac{c}{M}\partial_\mu Q \ J^\mu, \tag{1}$$

where M is the cut-off scale, and c is the coupling constant which characterizes the strength of Quintessence interacting with the ordinary matter in the Standard Model. J^μ can be the baryon current J^μ_B or the current of baryon number minus lepton number J^μ_{B-L}.

The term in Eq.(1), when $\dot{Q}$ is non-zero during the evolution of spatial flat Friedmann-Robertson-Walker Universe, violates CPT invariance and generates an effective chemical potential μ_b for baryons[3], $i.e.$, $\frac{c}{M}\partial_\mu Q J^\mu_B \rightarrow \ c \ \frac{\dot{Q}}{M} n_B = \ c \ \frac{\dot{Q}}{M}(n_b - n_{\bar{b}})$, $\mu_b = \ c \ \frac{\dot{Q}}{M} = -\mu_{\bar{b}}$. In thermal equilibrium the baryon number asymmetry is given by (when $T \gg m_b$) $n_B = \frac{g_b T^3}{6}\left(\frac{\mu_b}{T} + \mathcal{O}(\frac{\mu_b}{T})^3\right) \simeq c\frac{g_b \dot{Q} T^2}{6M}$, where g_b counts the internal degree of freedom of the baryon. The final expression for the baryon to entropy ratio would be $n_B/s \simeq \frac{15c}{4\pi^2}\frac{g_b\dot{Q}}{g_\star MT}$, where $\dot{Q}$ can be obtained by solving the equation of motion of Quintessence. Without fine tuning of the parameters, we find there are viable Quintessence models which lead to the observed baryon number asymmetry[7]

$$\frac{n_B}{s}|_{T_D} \sim 0.01 \ c \ \ \frac{T_D}{M} \tag{2}$$

with T_D being the decoupling temperature. In this picture the baryon number asymmetry and the current accelerated expansion of the Universe have been described in a unified way.

In general the scalar field Q in Eq.(1) could be the function of a scalar field as extended models of spontaneous baryogenesis[8, 9]. Meanwhile from naive dimensional analysis for the interaction with the photon sector one would expect to have the Chern-Simons(CS) term:

$$\mathcal{L}_{int} = -\frac{1}{2}\delta \ \partial_\mu Q K^\mu \ , \tag{3}$$

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where $K^\mu = A_\nu \widetilde{F}^{\mu\nu}$, $F_{\mu\nu}$ is the electromagnetic field strength tensor, and $\widetilde{F}^{\mu\nu} \equiv \frac{1}{2}\epsilon^{\mu\nu\rho\sigma}F_{\rho\sigma}$ is its dual. The coefficients between c/M in Eq.(1) and δ could be naturally related when J^μ is anomalous with respect to the electromagnetic interaction[9].

With the presence of the CS term the equations of motion for the electromagnetic field are now

$$\nabla_\mu F^{\mu\nu} = \delta\ \partial_\mu Q \widetilde{F}^{\mu\nu}\ , \nabla_\mu \widetilde{F}^{\mu\nu} = 0\ . \tag{4}$$

In a FRW cosmology we can write the electromagnetic field strength tensor in terms of **E** and **B**:

$$F^{\mu\nu} = a^{-2}\begin{bmatrix} 0 & -E_x & -E_y & -E_z \\ E_x & 0 & -B_z & B_y \\ E_y & B_z & 0 & -B_x \\ E_z & -B_y & B_x & 0 \end{bmatrix}\ . \tag{5}$$

The dual tensor $\widetilde{F}^{\mu\nu}$ can be obtained from $F^{\mu\nu}$ by replacing **E** and **B** with **B** and $-$**E** respectively. In terms of the notations given by Ref.[10]:

$$\begin{aligned} &\mathbf{B}(\vec{\mathbf{x}}, \eta) = \mathrm{e}^{-\mathbf{ik\cdot x}}\mathbf{B}(\eta)\ , \\ &F_\pm = a^2 B_\pm(\eta) = a^2(B_y \pm iB_z)\ , \end{aligned} \tag{6}$$

we have the equation of motion for a given mode **k**,

$$F''_\pm + (k^2 \pm \delta k Q')F_\pm = 0\ , \tag{7}$$

where the prime represents the derivative with respect to the conformal time η and k is the modulus of **k**. In the equation above, we have assumed the wave vector **k** is along the x axis, and $+$ and $-$ denote right- and left-handed circular polarization modes respectively. The non-vanishing Q' induces a difference between the dispersion relations for the modes with different handedness. This will rotate the direction of the polarization of light from distant sources. For a source at a redshift z, the rotation angle is

$$\Delta\alpha = \frac{1}{2}\delta\ \Delta Q\ , \tag{8}$$

where ΔQ is the change in Q between the redshift z and today, i.e., $\Delta Q = Q|_z - Q|_{z=0}$.

The CMB polarization can be described with two Stokes parameters of Q and U, which can be spherically expanded to get a gradient (G) and a curl (C) component [11]. If the temperature/polarization distribution does not violate parity, one gets vanished CMB TC and GC due to the intrinsic properties of the tensor spherical harmonics. The interaction in Eq.(3) violates P, CP and also CPT. In our case the polarization vector of each photon is rotated by a same angle $\Delta\alpha$ everywhere and one would get nonzero TC and GC correlations with[12, 9]

$$C_l'^{TC} = C_l^{TG}\sin 2\Delta\alpha\ , \tag{9}$$

$$C_l'^{GC} = \frac{1}{2}(C_l^{GG} - C_l^{CC})\sin 4\Delta\alpha. \tag{10}$$

The rotated quantities have been denoted with primes. Meanwhile the original TG,GG and CC are also modified as[13]

$$C_l'^{TG} = C_l^{TG}\cos 2\Delta\alpha\ , \tag{11}$$

$$C_l'^{GG} = C_l^{GG}\cos^2 2\Delta\alpha + C_l^{CC}\sin^2 2\Delta\alpha\ , \tag{12}$$

$$C_l'^{CC} = C_l^{CC}\cos^2 2\Delta\alpha + C_l^{GG}\sin^2 2\Delta\alpha\ \ . \tag{13}$$

As implied above, the rotation angel $\Delta\alpha$ can be used as a model independent parameter for the cosmological probe of the CPT violations, namely independent of the form of the scalar in Eq.(3). We use the WMAP observations and the data from the January 2003 Antarctic flight of BOOMERANG[19] (Hereafter B03) for the measurement of this rotation angel[13]. To break possible degeneracy between this term and the variation of other parameters, we make a global fit to the CMB data with the publicly

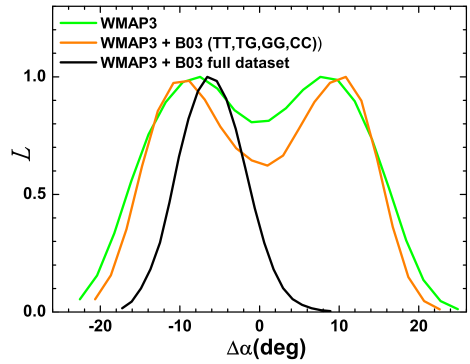

Figure 1: One dimensional constraints on the rotation angle $\Delta\alpha$ from WMAP data alone (Green or light gray line), WMAP and the 2003 flight of BOOMERANG B03 TT, TG, GG and CC(Orange or gray line), and from WMAP and the full B03 observations (TT, TG, GG, CC, TC, GC) (Black line)[13].

available Markov Chain Monte Carlo package `cosmomc`[14, 15], which has been modified to allow the rotation of the power spectra discussed above, with a new free parameter $\Delta\alpha$.

In Fig. 1 we plot our one dimensional constraints on $\Delta\alpha$ from the WMAP data alone, and from the combined WMAP and B03 data. "WMAP3" here denotes the three year WMAP observations[16] and previously we have also performed our analysis on the first year WMAP(WMAP1)[17, 18] combined with B03. We have assumed that the cosmic rotation is not too large and imposed a flat prior $-\pi/2 \leq \Delta\alpha \leq \pi/2$. Using the data from WMAP alone, for both the first and three year data set, we obtain a null detection within the error limits. For WMAP3 the 1, 2 σ constraints are $\Delta\alpha = 0.0^{+11.6}_{-11.7}\,^{+5.9}_{-5.9}$ deg and for WMAP1 $\Delta\alpha = -0.1^{+11.6}_{-11.6}\,^{+7.5}_{-7.4}$ deg. In the likelihood of Fig. 1 we have gained double peaks, which can be easily understood from Eqs.(11,12,13) due to the symmetry around $\Delta\alpha = 0$. For the first year WMAP while only TT and TG data were available, an indirect measurement on $\Delta\alpha$ could still be worked out with Eq.(11). WMAP3 constraints are a bit more stringent than WMAP1 results.

With the inclusion of the B03 data, the measurement could be improved dramatically. In a first step we also consider the indirect measurements only by including the B03 TT, TG, GG and CC data. We find the constraint on $\Delta\alpha$ becomes a bit more stringent compared with WMAP only, a nonzero $\Delta\alpha$ is slightly favored and the double peaks are still present. When the B03 TC and GC data are also included the degeneracy around $\Delta\alpha = 0$ is broken. We get the 1, 2 σ constraints to be $\Delta\alpha = -6.0^{+4.0}_{-4.0}\,^{+3.9}_{-3.7}$ deg with WMAP3 and the B03 full data set. And for the first year WMAP combined with B03 the constraint is $\Delta\alpha = -5.3^{+3.9}_{-4.0}\,^{+4.1}_{-3.5}$ deg. The mild preference on the nonzero rotation angel lies on the fact that for B03 there are several GC bands where the center values are below zero[19]. Future CMB polarization experiments like Planck and CMBpole will help significantly to detect such kind of effects[9].

In summary the current CMB polarization experiments have opened a new window to search the signature of cosmic P and CPT violations mentioned above and this can help to understand the nature of the dark energy which gives rise to the accelerated expansion of our Universe. Yet we need to understand better the inherited possible systematics and the degeneracy among the various cosmological parameters and difference physical processes, which are necessary to be explored in more details in the coming precision cosmology.

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