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The Compton–Getting effect on ultra-high energy cosmic rays of cosmological origin

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Abstract

Deviations from isotropy have been a key tool to identify the origin and the primary type of cosmic rays at low energies. We suggest that the Compton–Getting effect can play a similar role at ultra-high energies: If at these energies the cosmic ray flux is dominated by sources at cosmological distances, then the movement of the Sun relative to the cosmic microwave background frame induces a dipole anisotropy at the 0.6% level. The energy dependence and the orientation of this anisotropy provide important information about the transition between galactic and extragalactic cosmic rays, the charge of the cosmic ray primaries, the galactic magnetic field and, at the highest energies, the energy-loss horizon of cosmic rays. A 3σ detection of this effect requires around 10^6 events in the considered energy range and is thus challenging but not impossible with present detectors. As a corollary we note that the Compton–Getting effect allows one also to constrain the fraction of the diffuse γ-ray background emitted by sources at cosmological distance, with promising detection possibilities for the GLAST satellite.

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1. Introduction

Ultra-high energy cosmic ray (UHECR) physics has gained increasing momentum in recent years. While the present state of observations is still puzzling [1], new experiments like the Pierre Auger Observatory (PAO) [2] or the Telescope Array (TA) [3] are expected to shed light on many unresolved issues with their improved detection techniques and increased statistics.

Among the most important open questions are the origin and the composition of UHECRs. Cosmic rays with energy below $E \sim 10^{16}$ eV are generally believed to be accelerated in galactic supernova remnants, but at higher energies their sources are unknown. Given the strength of the galactic magnetic field (GMF), one would expect a significant excess of events towards the galactic plane at least at energies above 10^{19} eV if these CRs have a galactic origin. Since up to the highest energies the arrival directions of CRs show no correlation with the galactic plane, the UHE part of the spectrum is generally thought to be extragalactic. Moreover, Hillas' argument [4] that the Larmor radius of an accelerated particle should fit inside the accelerator favors extragalactic sources as origin of the cosmic rays with the highest energies.

At present, two main models exist for the transition between galactic and extragalactic sources: the first one argues that the ankle in the cosmic ray spectrum 5×10^{18} eV is caused by the cross-over from the steep end of the galactic to the flatter extragalactic flux [5]. The second one interprets the ankle as dip produced by e^+e^- pair production of extragalactic protons with CMB photons [6]. Then the transition between galactic and extragalactic CRs could take place at energies as low as a few $\times 10^{17}$ eV [7]. An extreme but not firmly excluded possibility is that all cosmic rays are galactic as, e.g., in the Zevatron

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model [8]. In this case, the UHECR primaries should be heavy nuclei because the GMF can isotropize them only sufficiently—if at all—for a large electric charge Qe.

Extensive air shower experiments can in principle measure the chemical composition of the UHECR flux and thus determine the transition from a galactic, iron-dominated component to extragalactic protons. However, the uncertainties in the hadronic interaction models become so large above $E \sim 10^{17}$ eV that a reliable differentiation between proton and nuclei primaries is at present impossible [9]. Moreover this method fails if the extragalactic component is also dominated by heavy nuclei.

Anisotropies in the CR flux are another important tool to distinguish between different origin and primary models. Theoretical predictions of anisotropies for galactic sources depends on the GMF and the exact source distribution. The amplitude A of galactic anisotropies increases with energy and may range from $A \sim 10^{-4}$ at $E \sim$ few $\times 10^{14}$ eV to $A \sim 10^{-2}$ at $E \sim$ few $\times 10^{17}$ eV [10]. By contrast, in most analyses the extragalactic flux is assumed to be isotropic. However, already Ref. [11, p. 160] noticed that the movement of the Sun relative to the cosmic microwave background frame induces a dipole anisotropy at the 0.6% level. The experimental data at that time indicated a larger anisotropy at $E \sim 10^{17}$ eV. Furthermore, it was believed that extragalactic protons dominate the CR flux only at $E \gtrsim 10^{19}$ eV. As a result, this idea was not followed up.

A similar effect connected with the rotation of the Milky Way was proposed already 70 years ago by Compton and Getting, and was recognized as a diagnostic tool for low-energy cosmic rays [12]. More recently, the importance of the cosmological Compton–Getting (CCG) effect has been stressed as a signature for the cosmological origin of gamma ray bursts [13]. An analysis of its potential as a diagnostic tool in UHECR physics is however, to the best of our knowledge, still missing. In the following, we shall perform such an analysis. We shall argue that the CCG provides information about the transition between galactic and extragalactic cosmic rays, their charge, the GMF, and, at the highest energies, the energy-loss horizon of cosmic rays. We also briefly discuss the CCG effect on the diffuse γ-ray background, and comment on the chances for a detection of the two signatures in forthcoming experiments.

2. The cosmological Compton–Getting effect

Let us recall briefly the derivation of the Compton–Getting effect (see, e.g., [11, p. 30]). An observer in motion with velocity $\mathbf{u}$ relative to the coordinate system in which the distribution of cosmic rays is isotropic will measure an anisotropic cosmic ray flux. If UHECR sources are on average at rest with respect to the cosmological frame, the magnitude and direction of the velocity $\mathbf{u}$ of the solar system can be deduced from the detection of the dipole anisotropy in the CMB, $u = 368 \pm 2\ \mathrm{km\,s^{-1}}$ in the direction $(l, b) = (263.85°, 48.25°)$ [14]. Since $u \equiv |\mathbf{u}| \ll 1$, the anisotropy induced by the CCG effect is dominated by the lowest moment, i.e., its dipole moment.

To derive the amplitude of this anisotropy, we compare the phase space distribution function f in the frame of the observer, denoted by $f'(\mathbf{r}', \mathbf{p}')$, with the one in the frame in which the UHECR flux is isotropic, $f(\mathbf{r}, \mathbf{p})$. Lorentz invariance requires $f(\mathbf{r}, \mathbf{p}) = f'(\mathbf{r}', \mathbf{p}')$. Using $\mathbf{p} - \mathbf{p}' \simeq p\,\mathbf{u}$ valid for ultra-relativistic particles and for $u \ll 1$ and suppressing from now on the variable $\mathbf{r}$, we expand the phase space distribution function in the frame of the observer,

$$f'(\mathbf{p}') \simeq f(\mathbf{p}') + p\mathbf{u} \cdot \frac{\partial f(\mathbf{p}')}{\partial \mathbf{p}'} = f(\mathbf{p}')\left(1 + \frac{\mathbf{u}\cdot\mathbf{p}}{p}\frac{\mathrm{d}\ln f}{\mathrm{d}\ln p'}\right). \tag{1}$$

Cosmic ray experiments present their measured energy spectrum normally as differential intensity $I(E)$, i.e., the number of particles per unit solid angle and unit energy that pass per unit of time through an area perpendicular to the direction of observation. With $I(E) \simeq I(p) = p^2 f(p)$, one obtains

$$I'(E') \simeq I(E)\left[1 - \left(2 - \frac{\mathrm{d}\ln I}{\mathrm{d}\ln E'}\right)\frac{\mathbf{u}\cdot\mathbf{p}}{p}\right]. \tag{2}$$

Thus the dipole anisotropy due to the CCG effect has the amplitude

$$A_{\mathrm{CCG}} \equiv \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} = \left(2 - \frac{\mathrm{d}\ln I}{\mathrm{d}\ln E}\right)u. \tag{3}$$

Taking into account the observed spectrum $I(E) \propto E^{-2.7}$ of cosmic rays above the ankle, $A_{\mathrm{CCG}} = (2 + 2.7)u \simeq 0.6\%$. Note that the Earth motion with respect to the solar system barycenter only induces a subleading (8%) modulation in the vector $\mathbf{u}$.

3. CCG effect and UHECRs

The flux of extragalactic UHECRs is isotropic in the cosmic microwave background frame at energies $E \lesssim E_*$ for which the energy-loss horizon λ_{hor} of CRs is large compared to the scale of inhomogeneities in their source distribution. In the same energy range, peculiar velocities average out on cosmological scales and the UHECR flux is thus isotropic at leading order. The exact value of E_* depends both on the density of the CR sources and on the primary type, but $E_* \lesssim 4 \times 10^{19}$ eV is a conservative estimate. Indeed, for protons λ_{hor} is at the Gpc scale at $E \lesssim 10^{19}$ eV, decreasing to about 600 Mpc at 4×10^{19} eV due to the onset of the pion production on the CMB, and rapidly dropping to few tens of Mpc at larger energies. For iron nuclei, λ_{hor} abruptly drops below the Gpc scale only at $E \sim 10^{20}$ eV when photo-dissociation processes on the microwave and infrared backgrounds are kinematically allowed. For typical UHECRs source densities of $n_s =$ few $\times 10^{-5}\ \mathrm{Mpc}^{-3}$ [15], the number N_s of sources contributing to the observed flux can be estimated as (we neglect cosmological effects)

$$N_s \simeq \frac{4\pi}{3}\lambda_{\mathrm{hor}}^3 n_s \simeq 4.2 \times 10^4 \frac{n_s}{10^{-5}\ \mathrm{Mpc}^{-3}}\left(\frac{\lambda_{\mathrm{hor}}}{\mathrm{Gpc}}\right)^3. \tag{4}$$

Since Poisson fluctuations in N_s are roughly at the 0.5% level, one might wonder if the CCG effect could be mimicked by a fluctuation in the number of source per hemisphere. However, as long as extragalactic magnetic fields wash-out anisotropies,