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

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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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INTRODUCTION

Ultra-high energy cosmic ray (UHECR) physics has gained increasing momentum in recent years. While the present state of observations is still puzzling\textsuperscript{1}, new experiments like the Pierre Auger Observatory (PAO)\textsuperscript{2} or the Telescope Array (TA)\textsuperscript{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\textsuperscript{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 at \( 5 \times 10^{18} \) eV is caused by the cross-over from the steep end of the galactic to the flatter extragalactic flux\textsuperscript{5}. The second one interprets the ankle as dip produced by \( e^+e^- \) pair production of extragalactic protons with CMB photons\textsuperscript{6}. Then the transition between galactic and extragalactic CRs could take place at energies as low as a few \( 10^{17} \) eV\textsuperscript{7}. An extreme but not firmly excluded possibility is that all cosmic rays are galactic as, e.g., in the Zevatron model\textsuperscript{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 \( Q_e \).

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\textsuperscript{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 of galactic anisotropies increases with energy and may range from \( A \sim 10^{-4} \) at \( E \sim \) few \( 10^{14} \) eV to \( A \sim 1 \) at \( E \sim 10^{17} \) eV\textsuperscript{10}. By contrast, in most analyses the extragalactic flux is assumed to be isotropic. However, already Ref.\textsuperscript{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\textsuperscript{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\textsuperscript{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 hori-
zon 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.

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 $u$ 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 distribution of cosmic rays is isotropic will measure
with velocity $v$ relative to the coordinate system in which
the UHECR flux is isotropic, $f(r, p)$. Lorentz invariance
requires $f(r, p) = f(r, p')$. Using $p - p' \simeq p u$ valid for ultra-relativistic particles and for $u \ll 1$
and suppressing from now on the variable $r$, we expand
the phase space distribution function in the frame of the observer,

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

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

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

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

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

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

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 $\lambda_{\text{hor}}$ 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 $\lambda_{\text{hor}}$ is at the Gpc scale at
$E \lesssim 10^{19}$ eV, decreasing to about 600 Mpc at $4 \times 10^{19}$ 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, $\lambda_{\text{hor}}$ abruptly drops below the Gpc scale
only at $E \sim 10^{20}$ eV when photo-dissociation processes
in the microwave and infrared backgrounds are kinemati-
cally allowed. For typical UHECRs source densities of
$n_s = \text{few} \times 10^{-5}$ Mpc$^{-3}$ [12], the number $N_s$ of sources
contributing to the observed flux can be estimated as (we
neglect cosmological effects)

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

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, the dominant intrinsic fluctuation
is due to the number of events $N$ observed at the Earth
and not to $N_s$, even for relatively low $N_s$. A naive calculation of the root-mean-square deflection $\theta_{\text{rms}}$ of a particle
traveling the distance $L$ in a random field with coherence scale $L_c$ and strength $B_{\text{rms}}$ gives

$$\theta_{\text{rms}} = \frac{Q e B_{\text{rms}}}{E} \sqrt{\frac{LL_c}{2}} \simeq 120^\circ Q \frac{10^{19} \text{eV} B_{\text{rms}}}{\text{nG}} \sqrt{\frac{L}{\text{Gpc}} \frac{L_c}{\text{Mpc}}}. \quad (5)$$

In the simulation performed in [14], a significant fraction of all UHECRs suffer deflections comparable or larger
than given by Eq. (5), while the simulation performed in [15] favor considerably smaller values. If the results
of the latter simulation are closer to reality, deflections in extragalactic magnetic fields may be negligible at least for protons even at relatively low energies such as $4 \times 10^{19}$ eV. In any case, one might test observationally
that $E_*$ was chosen low enough by: i) the approximate alignment of the dipole axis of $A_{CCG}$ with the one in the
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that $E_*$ was chosen low enough by: i) the approximate alignment of the dipole axis of $A_{CCG}$ with the one in the
CMB; ii) the absence of higher multipole moments in the
observed maps: While fluctuations in the number of cosmological sources should lead to higher multipole modes $l > 1$ with similar intensity $A^{(l)}$, they are suppressed by powers of $u$ in the case of the CCG effect, $A^{(l)}_{\text{CCG}} \propto u^l$.

In the following, we shall consider the statistics collected by an experiment as the main limiting factor for the detection of the CCG effect. It is clear that the detection of an anisotropy at the 1% level requires also a thorough control of systematic errors and is therefore challenging for UHECR experiments also in this respect.

**SIGNATURES AND DIAGNOSTIC POTENTIAL FOR UHECRS**

In the following, we discuss the signatures and the potential of the CCG effect in resolving some long-standing puzzles in UHECR physics.

(i) The amplitude $A_{\text{CCG}}$ of the anisotropy is charge- and energy-independent, as long as the UHECR flux in the energy range studied is dominated by sources at cosmological distance.

(ii) Since the CCG effect is a dipole anisotropy, the magnitude of its amplitude should be robust against deflections of UHECRs in the GMF, and only the dipole axis is displaced. The expected deviation of the dipole vector of the CCG anisotropy from the one in the CMB is around $20^\circ \times 10^{19} \text{eV}(Q/E)$ [18]. Thus at energies $2\text{-}3\times 10^{19} \text{eV}$ and for proton primaries, the dipole position should be aligned to the one observed in the CMB within about $10^\circ$. As a technical point that does not affect qualitatively our estimate we note that the GMF is fixed with respect to the galactic frame, not to the solar system one. Thus, the CCG dipole is deflected by the GMF “boosted” by our relative motion in the Galaxy. Similar considerations would apply to the effect of possible diffuse fields in the local group of galaxies, which is moving with respect to the CMB with $v_{\text{LG}} \simeq 630 \text{km s}^{-1}$ [14].

(iii) Observing the CCG feature at only one energy provides combined information on the intervening GMF and the charge of the cosmic ray primaries. However, observations at two or more energies break this degeneracy. For example, the determination of the primary charge is straightforward as long as the cosmic rays propagate in the quasi-ballistic regime and a single primary species dominates the flux. Denoting by $\delta_{\text{CMB}}$ the location of the dipole in the CMB, and by $\delta_{1,\text{CCG}}$ and $\delta_{2,\text{CCG}}$ the dipole location measured via the CCG effect at two energies with $E_1 < E_2$, the primary charge $Q$ is

$$Q = \frac{\theta(\delta_{\text{CMB}},\delta_{1,\text{CCG}})}{\theta(\delta_{\text{CMB}},\delta_{2,\text{CCG}})},$$

where $\theta$ is the angular distance.

(iv) Moving to lower energies, the anisotropy due to the CCG effect should disappear as soon as galactic UHECRs start to dominate. Relatively large anisotropies connected to an increased source density in the disc or towards the galactic center are expected to turn on somewhere between $10^{17} \text{eV}$ and the ankle [10]. The disappearance of the CCG anisotropy and its replacement by galactic anisotropies is therefore an indicator for the transition between galactic and extragalactic cosmic rays.

(v) Moving to sufficiently high energies, $\lambda_{\text{hor}}$ decreases and anisotropies due to local inhomogeneities in the distribution of sources are expected to dominate. For protons, local anisotropies should become important around $4\text{-}5\times 10^{19} \text{eV}$ [19]. Thus the decrease of the CCG anisotropy with increasing energy is connected both to the amount of inhomogeneity in the source distribution of UHECRs and to the energy-loss horizon of the UHECR primary. This is also the energy range where local motions, like the one towards the “Great Attractor”, might play an important role (for a review on motions on large scales, see [20]).

**DETECTABILITY**

Is it possible for present experiments to detect a 0.6% dipolar anisotropy in the UHECR flux? In a sample of $N$ events, typical fluctuations are of the order of $\sqrt{N}$. Thus a 0.6% level sensitivity is only reached for $\sqrt{N}/N \simeq 0.006$ or $N \simeq 3 \times 10^4$ events. Reference [21] gave an empirical fit for the expected error $\sigma_A$ in the determination of the amplitude of a dipole anisotropy as function of the event number $N$ and the declination $\delta$ of the dipole vector,

$$\sigma_A = \sqrt{\frac{3}{N}} (1 + 0.6 \sin^3 \delta),$$

where a detector located at the PAO site and a maximum zenith angle of $60^\circ$ were assumed. Equation (7) implies that a $3\sigma$ detection of a 0.6% anisotropy requires of the order of $10^6$ events. Working from January 2004 to June 2005, the PAO has reached a cumulative exposure of 1750 km$^2$ sr yr, observing 1216 events in a 0.1 dex energy bin around $10^{18.55} \text{eV}$ [22]. Once completed, the total area covered will be around 3000 km$^2$, so that around 2000 events per year should be collected close to the ankle. At this energy, one can expect only a $1\sigma$ hint in a decade of working time. However, systematic errors are still quite large, and a shift in the energy scale could significantly modify the flux estimate. More importantly, since the UHECR spectrum is steep, better detection possibilities are at lower energies, say between $10^{17}$ and $10^{18} \text{eV}$, which will be explored in the near future by the PAO and especially the TA thanks to the lower energy threshold. For comparison, the 4% anisotropy pattern found by the AGASA collaboration around $10^{18} \text{eV}$ was based on about 284,000 events collected after standard cuts at energies above $10^{17} \text{eV}$ [23]. While a clear detection of
the CCG effect above the ankle will probably require future UHECR observatories (see e.g. [2]), the PAO and TA have the realistic chance to disprove scenarios where the transition to extragalactic cosmic rays happens below 10^{18}\,\text{eV}.

THE CCG EFFECT AND THE DIFFUSE $\gamma$-RAY BACKGROUND

The CCG effect should be present in any cosmological diffuse background. Thus one might wonder if the previous considerations apply to other diffuse fluxes of interest in high energy astroparticle physics. Such a case is the diffuse $\gamma$-ray background, that may offer interesting detection perspectives of the CCG effect, too. This background is a superposition of all unresolved sources emitting $\gamma$-rays in the Universe and provides thus an interesting signature of energetic phenomena over cosmological time-scales. While a clear detection of this background has been reported by the EGRET mission [25], its origin is still uncertain. The original analysis of the EGRET data derived an intensity spectrum of the unresolved flux in the GeV region $I_\gamma \simeq 1.4 \times 10^{-6} (E/\text{GeV})^{-2.1}\,\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}\text{GeV}^{-1}$ [26]. From this flux and the specifics of the GLAST satellite experiment (a roughly energy independent effective area $A_{\text{eff}} = 10^4\,\text{cm}^2$ and a field of view of $\Omega_{\text{fov}} = 2.4\,\text{sr}$ [20]) we can estimate the number of events $N_\gamma$ above the energy $E_\gamma$ to be collected in the time $t$ as

$$N_\gamma = A_{\text{eff}} \Omega_{\text{fov}} t \int_{E_\gamma}^{\infty} dE \, I_\gamma \simeq 9 \times 10^5 \left( \frac{t}{\text{yr}} \right) \left( \frac{E_\gamma}{\text{GeV}} \right)^{-1.1}.$$  

Such a relatively large statistics would allow one to detect the signal at GeV energies at $3\,\sigma$ confidence level in about 1 year. The predicted amplitude of $(2+2.1)\,u \simeq 0.5\%$ (see Eq. [3]) and the alignment of the dipole with the CMB provide a smoking gun for the detection of the CCG effect. Note that this signature would be useful to assess in a robust way the cosmological (as opposed to the galactic) fraction of the diffuse $\gamma$-ray background. Since the $\gamma$-ray flux after extracting pointlike sources still contains a sizeable galactic contamination, it is at present necessary to model the galactic foreground. This foreground subtraction is however a delicate issue as shown e.g. in the recent reanalysis of the EGRET data in [27]. Using a revised model for the galactic propagation of cosmic rays, the deduced extragalactic spectrum was estimated to be lower and with a different spectral shape than the one reported in [27]. Obviously, the CCG effect provides a powerful, complementary tool in these analyses that are for instance crucial in the detection of the putative diffuse $\gamma$-ray signal from dark matter annihilations.

CONCLUSIONS

We have argued that the cosmological Compton-Getting effect is a powerful diagnostic tool for the study of UHECR physics, in particular as a probe of the transition from galactic to extragalactic cosmic rays and of the charge of the UHECR primaries. Although challenging, the detection of the CCG effect appears within reach with present detectors at least at energies below the ankle. If UHECRs are of cosmological origin (i.e., they come from within an energy-loss horizon of Gpc scale), the CCG effect should be the most prominent large-scale anisotropy, similar to the case of the CMB. The detection of a significantly larger dipole or of higher moments with comparable size at energies around or above $10^{19}\,\text{eV}$ would be difficult to explain, unless peculiar local sources are important for UHECRs. The information encoded in the CCG effect motivates serious experimental efforts towards its detection. A similar effect is expected in the diffuse $\gamma$-ray background, with excellent perspectives for its detection by GLAST. This signature might be very useful in the difficult task to assess the cosmological fraction of the measured $\gamma$-ray background, which in turn might indirectly affect the constraints on UHECRs physics as well.

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