Ultra High Energy Comic Rays in the Cosmic Microwave Background

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(July 24, 2011)

Abstract

We consider the propagation of ultra high energy cosmic rays (UHECR), for energies greater than $E > 10^{14}\, eV$ but less than $E < 10^{26}\, eV$, in the cosmic medium of the Cosmic Microwave Background (CMB). We find that the CMB plays a pivot role in this energy range. As example, the observed "knee(s)" and the "ankle" could be understood in reasonable terms. What we may observe at energy near $10^{25}\, eV$ ($W^{\pm}$ bursts or Z^0 bursts) is also briefly discussed.

1 Introduction

The Comic Rays spectrum at high energies[1, 2] become quite elaborated these days. In particular, the so-called "knee", slightly above $10^{15}eV$, and the "ankle", slightly above $10^{18.5}eV$, appear rather convincingly. To develop the field further, it is important to understand how these phenomena occur, especially in our Universe.

In this note, we are interested in cosmic rays in the energy range greater than $10^{14}eV$ but less than $10^{26}eV$, including those greater than $10^{20}eV$ (those unexplored regimes), the so-called "ultra high energy cosmic rays (UHECR's)". In particular, we examine the interaction of UHECR with the 3° cosmic microwave background (CMB), one cosmic media in our Universe. As seen below, the center of mass (CM) energy squared would be $1.3 \times 10^{19}eV^2$ for an UHECR of energy $10^{22}\, eV$ intersecting or interacting a CMB photon. So, the CM energy would be $1.15 \times 10^{11}\, eV$, or 115 GeV, if an UHECR of energy $10^{25}\, eV$ intersects a CMB photon. It is slightly above the mass of the Z^0 weak boson. So, the energy range which we talk about coincides the range which the Standard Model[1] is well tested - so, we shouldn't anticipate any new physics but only a replay of the Standard Model physics in a very peculiar kinematic setup. Isn't it?

What is an UHECR particle? The possibility may include the protons, neutrons (time-dilated), deuterons, alphas, the heavy nuclei, neutrinos, and others. For some reason they could be produced or accelerated to these energies. In the bottom-up scenario, heavy nuclei from astronomical events, maybe severer than supernovae explosions and happening (approaching) in our direction with high relative velocities, may provide UHECR's of greater than $10^{20}\, eV$; chunks of nuclei or protons would be the origins of those extremely high energy particles (say, $\geq 10^{22}\, eV$).

The muon, if produced at $10^{22}\, eV$, would have a time-dilation factor $10^{22}/10^8$, or 10^{14}; the lifetime would be $2 \times 10^{-6} \times 10^{14} sec$, or $2 \times 10^8 sec$ (about 7 years). So, 7 light years

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(a muon produced and captured 7 light years away) are still too short in our astronomical environments. Others such as pions, kaons, etc. have lifetimes even much shorter and do not play a role here[1]. On the other hand, a neutron of $10^{22}\,eV$, of which the lifetime at rest is $15\,min$, would have a dilated lifetime $1,000\,sec \times 10^{22}/10^9$ or $10^{16}\,sec$ or 3.17×10^8 years. So, neutrons of $10^{22} eV$ would be fairly stable and could come from 317 Mega light years away or 100 Mpc away.

In this context, we know that the electrons, positrons, photons, etc., could not survive beyond certain (high) energies, because of the electromagnetic interactions. For example, $e^\pm + \gamma_{CMB} \to e^\pm + \gamma$, $\gamma + \gamma_{CMB} \to e^- + e^+$, etc.

In our Universe, there are plenty of $3^\circ K$ cosmic microwave background (CMB) and $1.9^\circ K$ cosmic neutrino background (CνB). Even though the energies of these particles sound extremely low, the ultra high energy cosmic rays (UHECR), including protons, in fact can see them if energy is high enough. In particular, the following reactions don't have the thresholds:

$$e^\pm + \gamma_{CMB} \to e^\pm + \gamma, \qquad \mu^\pm + \gamma_{CMB} \to \mu^\pm + \gamma, \tag{1}$$

$$p + \gamma_{CMB} \to p + \gamma, \tag{2}$$

$$\gamma + \gamma_{CMB} \to \gamma + \gamma, \tag{3}$$

$$\alpha + \gamma_{CMB} \to \alpha + \gamma, ... \tag{4}$$

On the other hand, the reactions listed below have some thresholds and would start to play some important roles, when UHECR's energy reaches at the threshold:

$$\gamma + \gamma_{CMB} \to e^- + e^+, \tag{5}$$

$$p + \gamma_{CMB} \to p + \{e^- e^+\}, \tag{6}$$

$$d + \gamma_{CMB} \to p + n, \tag{7}$$

$$^3He + \gamma_{CMB} \to d + p, \tag{8}$$

$$\alpha + \gamma_{CMB} \to ^3 H + p, ...etc., \tag{9}$$

plus some others. Hereafter we assume that cosmic rays, depending on the energy, would be composition of all "stable" particles, including protons, deuterons, $e^\pm$, $\mu^\pm$, γ, ν, etc. As said earlier, $\mu^\pm$ may be the borderline of "stable particles" when we consider the effects due to time dilation; the neutrons, with the lifetime (≈ 15 min) much longer, could be "stable" if the energy is greater than, e.g. $10^{22} eV$. High energy ν (those higher than tens of GeV) are presumably there but, in view of the feeble nature of weak interactions, cannot be seen so far. These are well-known particles; thus, in this note we don't speculate on those unknown particles, such as super-symmetric particles.

Here we assume that in the UHECR there contain γ, p, d, etc., with certain probabilities - our definition of UHECR[2]. The UHECR's interact with the CMB photons via the above reactions and etc. This note emphasizes the interactions of UHECR's with CMB, and emphasizes CMB's visibility by UHECR's.

In a related context[3], we discussed the interplay of the cosmic neutrino background (CνB) and UHECR's, assuming some clustering of CνB. The significant clustering of CνB would lead to the *first* detection of the CνB. So far, the detection of CνB is still in the air. In this note, we try to provide some semi-quantitative treatments of the interplay of CMB and UHECR.

2 Initial Thinking

Let us quote the Compton-scattering formula[4]:

$$\sigma(p+\gamma \to p+\gamma) \to \frac{2\pi\alpha^2}{s} ln(\frac{s}{m^2}), \quad as \quad t \to \infty. \tag{10}$$

Now the initial photon is the CMB photon. Suppose that the energy of the UHECR proton is 10^{22} eV and so the CM energy is $s \approx 2\times 10^{22}eV \cdot 6.5\times 10^{-4}eV \approx 1.3\times 10^{19}eV^2$. So, we obtain

$$\sigma \approx 10^{-23}eV^{-2} \approx 4pb \to \lambda_p \approx 2\times 10^5\, Mpc, \tag{11}$$

which already exceeds the size of the present Universe (about 4500 Mpc).

On the other hand, $E_p = 10^{20}eV$ would imply the mean free path $\lambda \approx 2000\, Mpc$ and $E_p = 10^{18}eV$ implies $\lambda_p \approx 20Mpc$.

Now we turn our attention to the similar formula if the UHECR is the electron (positron). For the electron energy $E_e = 10^{15}\, eV$, we have $s \approx 2\times 10^{15}eV \cdot 6.5\times 10^{-4}\, eV \approx 1.3\times 10^{12}eV^2$ so that $\sigma \approx 3.35\times 10^{-4}\cdot s^{-1}ln(s/m_e^2) \approx 4.14\times 10^{-16}\, eV^{-2}$, the cross section corresponding to $0.17\, barns$, or to $\lambda_e \approx 50kpc$. If nothing else happens, then the electron would be deflected in $50\, kpc$.

For the muon of energy $10^{19}\, eV$ or $1.3\times 10^{16}eV^2$, we have $\sigma \approx 3.35\times 10^{-4}\cdot s^{-1}ln(s/m_\mu^2)$ or $\sigma \approx 0.7176\times 10^{-23}\, eV^{-2}$. For such muon, the (dilated) lifetime becomes $2\times 10^{-6}\times 10^{19-8}sec$ or $2\times 10^5 sec$. Combining the two, a muon of energy $10^{24}eV$ would last $2\times 10^{10}sec$ and gets negligible effect from bremsstrahlung.

For the reaction $\gamma + \gamma_{CMB} \to \gamma + \gamma$, it comes from the box diagrams and is of higher order, $O((\alpha/2\pi)^4)$ (and so is small). Thus, we needn't consider it for the moment. For $\alpha + \gamma_{CMB} \to \alpha + \gamma$ or off other nuclei, the situation is similar to that for $p + \gamma_{CMB} \to p + \gamma$, as described as above.

3 UHECR physics near $10^{20}\, eV$

Next, we consider those inelastic reactions which might leave their marks on the UHECR physics, say, Reactions (5)-(9), etc. Reliable estimates can be obtained by working out the peculiar kinematics and using the well-known cross sections.

Let us consider, for example, Reaction (6), i.e. $p + \gamma_{CMB} \to p + (e^- e^+)$, with $(e^- e^+)$ characterized a composite mass $\bar{m}$. The four momentum conservation reads

$$p'_\mu + k'_\mu = p_\mu + k_\mu. \tag{12}$$

Or, we have

$$p'_\| + k'_\| = p - k, p'_\perp + k'_\perp = 0, p' + m_p^2/(2p') + k' + \bar{m}^2/(2k') = p + m_p^2/(2p) + k. \tag{13}$$

We find

$$p' = (4k + m_p^2/p)^{-1}\{2p \cdot k + m_p^2 - \bar{m}^2/2 \pm [(2p \cdot k)^2 - \bar{m}^2 2p \cdot k + \bar{m}^4/4 - \bar{m}^2 m_p^2]^{\frac{1}{2}}\}. \tag{14}$$

$$k' = (4k + m_p^2/p)^{-1}\{2p \cdot k + m_p^2 - \bar{m}^2/2 \mp [(2p \cdot k)^2 - \bar{m}^2 2p \cdot k + \bar{m}^4/4 - \bar{m}^2 m_p^2]^{\frac{1}{2}}\}. \tag{15}$$

To get some ideas, we have $\sigma(p + \gamma_{CMB} \to p + \gamma) \to \frac{2\pi\alpha^2}{S} ln(\frac{S}{m^2})$ as $S \to \infty$. As quoted earlier (as our benchmark), at $E \approx 10^{22} eV$, one has $\sigma \approx 10^{-23} eV^{-2} \approx 4pb$ and, with the density of CMB photons, we find a mean free path $\lambda \approx 2 \times 10^5 Mpc$, bigger than the Universe size of 4,000 Mpc.

However, the $\frac{1}{S}$ behavior indicates that at $E \approx 10^{18} eV$ we have $\sigma \approx 0.4nb$ or $\lambda \approx 20 Mpc$, a noticeable result. Comparing the process $p + \gamma_{CMB} \to p + (e^- e^+)$ to $p + \gamma_{CMB} \to p + \gamma$, we lose a factor of α. This means that at $10^{18} eV$ this effect is barely visible. *This would be a marginal explanation of the ankle effect!!*

Fortunately, there are other reactions, such as $d + \gamma_{CMB} \to p + n$ (Reaction (7)) or similar, with the thresholds in the range of a couple of MeV. The deuteron component in the UHECR flux might be small but the cross section is much bigger - it serves as an additional reason for the "ankle".

Our explanation of the "ankle" makes some sense. In general, the electromagnetic effects out of CMB photons, or of higher order, would make marks in the UHECR physics. On the other hand, the weak reactions, of cross section $10^{-42} cm^2$ $(= 10^{-6} pb)$, are mostly invisible.

Now let us return to Reaction (5), i.e. $\gamma + \gamma_{CMB} \to e^- + e^+$. We have

$$S \approx 4E \cdot E_{CMB} \geq 4m_e^2; \quad or \quad E_\gamma \geq 4.1 \times 10^{14} eV. \tag{16}$$

This means that the high energy photons, those greater than $4.1 \times 10^{14} eV$, would be depleted from UHECR. After all, the electromagnetic reactions proceed fast enough. The depletion of the photons from UHECR would explain the happening of the "knee".

Channel (6) or (7) or others, as described as above in a simplified manner, would not occur until UHECR reaches a certain threshold. This happens for UHECR at $10^{18.5} eV$, the place for the "ankle". In fact, the cross section for the channel $p + \gamma_{CMB} \to p + (e^- e^+)$ would be down by a factor of α/π (as compared to, for example, Reaction (5) or (7)), but the logarithmic plot for the UHECR could show that - the effect of $10^{-2.5}$ if protons are majority of UHECR.

Let come back to Reaction (7), i.e. $d + \gamma_{CMB} \to p + n$. At the threshold, we find, UHECR identified as deuterons,

$$4k(p+\frac{m_d^2}{2p})+m_d^2=2m_n^2+2m_p^2, \quad 4kp=8349.34MeV^2, \quad p=8.8785\times 10^{18}eV. \qquad (17)$$

These numbers indicate the threshold of $(2m_e)$, or sightly above, to occur at $10^{18.5}eV$, as explained earlier.

How about reactions (8), (9), etc.? In fact, heavy nuclei ($A \geq 3$), as seen by the Auger Collaboration[2, 1], could be of some importance. As indicated earlier, this may be so if parts of UHECR's come from the inward collapse of Supernova explosion.

We see that a lot of nuclear reactions with effective energies less than 10 MeV may become relevant at $10^{19}eV$, until we hit another threshold of the famous GZK[5]:

$$p+\gamma_{CMB}\rightarrow \pi+N, \quad E\approx\frac{2m_N m_\pi+m_\pi^2}{2E_{CMB}}=1.10\times 10^{20}eV. \qquad (18)$$

This is another order of magnitude - but very close in our logarithmic plot. Clearly, interesting physics occurs for UHECR of energy $10^{18.5-20.5}eV$.

To say it explicitly, $10^{20}eV$ *is where the GZK effect occurs and* $10^{18.5}eV$ *is where the "knee" appears (and where nuclear physics dominates). So, what is above* $10^{21-25}\,eV$*? Particle physics is probed by CMB - that would be our answer.*

The high energy cosmic rays measured in the atmosphere are what we are interested most. We are already in the vicinity of $10^{20}\,eV$, maybe marching toward higher and the higher. Those UHECR's may come from the outside solar system, or from the distant galaxies, and these would be most interesting. As we have said earlier, these UHECR's are presumably there for a while and thus stable, composed of "stable" particles, such as $e^\pm$, γ, ν, p, $\bar{p}$, d, ..., n, $\mu^\pm$, etc. We don't take into account $e^\pm$ because of their zigzag paths. we so far don't take into account ν's or $\bar{\nu}$'s mainly due to their (weak) no-interacting features. As indicated before, too high energy photons (greater than $4.1\times 10^{14}eV$) could become elusive also. How to reproduce the UHECR curve[2] should be one of the most urgent questions.

4 UHECR Physics near $10^{25}\,eV$

An UHECR particle of energy $10^{25}\,eV$ encountering the 3° CMB photon would have the CM energy squared of $1.3\times 10^{22}\,eV^2$ or the CM energy $115\,GeV$, just above the $W^\pm$ or Z^0 mass. This is where Weiler called it the Z^0-bursts[6]. Clearly, both $W^\pm$ and Z^0 show up at these energies.

If the UHECR particle would be a proton, an alpha particle, or one of those familiar particles in the Standard Model, it would be a replay of the Standard Model[1], except the very odd kinematics.

What if the UHECR particle is something else, such as some supersymmetric particle? But it interacts with the 3° CMB photon, or with the electromagnetic interactions; it means that it carries the electric charge. We infer that this supersymmetric particle cannot be the lowest-mass neutral supersymmetric particle. The open-up of new channel would be very interesting.

In other words, the initial UHECR's do not have to be the ordinary particles and may not interact with the 3° CMB - we should partition these UHECR's accordingly. It could be the supersymmetric particle to begin with - the primary supersymmetric particle decays eventually the most stable neutral supersymmetric particle plus a bunch of more familiar particles. Our Universe might be full of surprises foe us.

The other aspect is well-known - the occurrence of the $W^{\pm}$ or Z^0 bursts when we crosses the thresholds, as we know the CM energy exceeding $100\,GeV$. This ought to be rather familiar, except that things are happening with the very odd kinematics.

5 Outlook

Ultra High Energy Cosmic Rays, for the energy greater than $10^{14}eV$ but less than $10^{26}eV$, via interactions with the Cosmic Microwave Background, sort of map out nuclear physics in the lower end (less than $10^{20}\,eV$) and particle physics in the higher end (near $10^{26}\,eV$). Why is this interesting? CMB serves as as the medium, becoming the obstacle when the comic rays are energetic enough. CMB and UHECR are both exotic and deserve our attention.

Acknowledgments

The Taiwan CosPA project is funded by the Ministry of Education (89-N-FA01-1-0 up to 89-N-FA01-1-5). W-Y. P. Hwang's research is also supported by National Science Council (NSC99-2112-M-002-009-MY3). B.-Q. Ma's research is supported in part by China's National Science Foundation.

References

[1] Particle Data Group, "Review of Particle Physics", J. Phys. G: Nucl. Part. Phys. **37**, 1 (2010).

[2] T.K. Gaisser and T. Stanev, see Figure 24.9, p.250, in particular of *Review of Particle Physics*, Particle Data Group, J. Phys. G: Nucl. Part. Phys. **33**, 1 (2006); see also **37**, 269 (2010).

[3] W-Y. P. Hwang and Bo-Qiang Ma, New J. Phys. **7**, 41 (2005).

[4] Ta-You Wu and W-Y. Pauchy Hwang, "Relativistic Quantum Mechanics and Quantum Fields" (World Scientific, Singapore, 1991); F. Halzen and A.D. Martin, "Quarks & Leptons: an Introductory Course in Modern Particle Physics" (John Wiley & Sons, 1984).

[5] K. Greisen, Phys. Rev. Lett. **16**, 748 (1966); G.T. Zatsepin and V.A. Kuz'min, Sov. Phys. JETP lett. **4**, 78 (1966).

[6] T. Weiler, Phys. Rev. Lett. **49**, 234 (1982); Astrophys. J. **285**, 495 (1984); Astropart. Phys. **11**, 303 (1999).