Turbulence Particle Acceleration and UHECR

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Abstract. The standard model to produce non-thermal particles is the particle acceleration at shocks. However, the photon spectra in high-energy objects, such as blazars, frequently show very hard feature, which seems inconsistent with the standard shock acceleration theory. The alternative model is the particle acceleration by turbulence. If we adopt a hard-sphere-like acceleration, in which the acceleration timescale is independent of the particle energy, the electron energy distribution becomes consistent with blazar photon spectra. Adopting this model to the deceleration phase of gamma-ray burst jets, ultra high-energy cosmic-rays can be produced. The resultant spectrum is harder than other models, so that the secondary neutrino production in their propagation is relatively suppressed. As a candidate of the hard-sphere acceleration mechanism, we propose the acceleration by large scale compressible MHD waves, where the transit time damping (TTD) is a key mechanism. We find that the acceleration efficiency is higher than previously considered.

1. Introduction

Long gamma-ray bursts (GRBs) are source candidates of ultra high-energy cosmic-rays (UHECRs), whose energy range is above $10^{18.5}$ eV. However, GRB-UHECR models have the energy budget problem; even if the isotropically-equivalent energy released as UHECRs is ten times larger than the gamma-ray energy $E_{\text{iso}}$ in the prompt phase, which is typically $10^{52}-10^{53}$ erg, the estimated UHECR flux becomes far below at $\sim 10^{19}$ eV [1], as long as UHECRs are injected with a spectral index $p \geq 2$. The ejecta energies estimated from the afterglow modeling are also comparable to the gamma-ray energies in most cases [2].

If UHECRs of the energy $10E_{\text{iso}}$ are injected in the prompt emission phase, the cascade process initiated by photopion production generate secondary photons and the spectrum becomes flat in $\nu F_\nu$-plot [1,3]. Although some spectra of Fermi-LAT GRBs are interpreted as a signature of hadronic cascade [4,5], such a signature is not always seen in bright GRBs. No significant correlation between neutrino events and observed GRBs in IceCube is also unfavorable for a large energy budget of UHECRs [6].

Here, we discuss turbulence acceleration in GRBs to avoid the problems above. In section 2, we introduce the GRB-UHECR model with turbulence acceleration. The hard spectrum realized by the turbulence acceleration alleviates the energy budget problem by concentrating particle in the highest energy region. In section 3, the particle acceleration by MHD waves is discussed. The acceleration by fast mode waves would make the acceleration timescale constant. Such a type of acceleration is favorable to realize the UHECR model shown in section 2.
2. Turbulence Acceleration at the Onset of Afterglow

In this section, we introduce the UHECR production model by Asano & Mészáros [7]. The GRB jets start decelerating at a radius,

$$R = R_{\text{dec}} \equiv \left( \frac{3E_{\text{tot}}}{4\pi n_0 n_p c^2 \Gamma^2} \right)^{1/3} \simeq 8.2 \times 10^{16} n_0 \left( \frac{E_{\text{tot}}}{10^{53.5} \text{ erg}} \right)^{1/3} \left( \frac{\Gamma}{300} \right)^{-2/3} \text{ cm}, \quad (1)$$

where $E_{\text{tot}}$ is the explosion energy, $n = n_0 \text{ cm}^{-3}$ is the number density of the interstellar medium, and $\Gamma$ is the bulk Lorentz factor. Around this radius we can expect the Rayleigh-Taylor instability [8], which induce large scale turbulences. The particle acceleration by turbulence is phenomenologically expressed by the energy diffusion coefficient $D_{EE}$. The detail of the coefficient depends on the property of turbulence. As will be shown in the next section, we can assume a simplest case, $D_{EE} = K E^2$, where $K$ is a constant factor. This case is called the hard-sphere acceleration. The acceleration timescale is independent of particle energy.

If the coefficient $K$ and the particle injection rate $\dot{N}$ is constant during the dynamical timescale $R/c\Gamma$, we can analytically calculate the cosmic-ray spectrum [7]. Here, averaging over the luminosity function of GRBs, we show two extreme cases: (A) the UHECR luminosity is commonly assumed to be ten times the prompt gamma-ray luminosity $L_{\gamma}$, and $\Gamma = 300$, (B) an optimistic model, where the total luminosity of GRBs is commonly assumed as $10^{53.5} \text{ erg s}^{-1}$. In model B, GRBs with $L_{\gamma} < 10^{53.5} \text{ erg s}^{-1}$ can load a large UHECR luminosity, while bright luminosity GRBs do not accelerate UHECRs very much. The bulk Lorentz factor in model B is assumed as $\Gamma = 72.1 \left( L_{\gamma}/10^{52} \text{ erg s}^{-1} \right)^{0.49} [9]$. The coefficient is set as $K/c = 3 \Gamma/R$, which will be discussed in the next section, so that the UHECR spectrum at the dynamical time $K t_{\text{dyn}}$ does not depend on radius $R$. In Figure 1, we plot average UHECR spectra per burst. The turbulence acceleration model produces a hard spectrum so that the UHECR energy is concentrated in the high-energy region. Compared to the power-law injection model with $p = 2$ (dashed line), the energy fraction of the lower energy particles is negligible, which alleviates the energy budget problem.

![Figure 1. Average UHECR spectra for models A and B. The dashed line is the shock acceleration model in Asano & Mészáros [1].](image)

Adopting the local GRB rate $R_{\text{GRB}}(0) = 1.3 \text{ Gpc}^{-3} \text{ yr}^{-1}$ and its redshift evolution given by Wanderman and Piran [10], we calculate the UHECR flux at earth as shown in Figure 2. The two models can reproduce the observed flux above $10^{19} \text{ eV}$.
Figure 2. The diffuse UHECR spectra for models A and B (thick solid lines). The thick dashed lines are spectra neglecting the effects of photomeson production and Bethe-Heitler pair production during propagation. The thin lines show the all-flavor cosmogenic neutrino intensities. We also plot the prompt plus cosmogenic neutrinos in Asano & Mészáros (denoted as AM14) [1].

Since we consider the acceleration site at the deceleration radius, the neutrino production efficiency is too low to be detected with IceCube. In the hard-sphere model, the acceleration timescale for low-energy electrons is too long compared to the cooling effect. So electrons are not accelerated, and a leptonic signature of UHECR acceleration is hard to be found.

3. Hard-Sphere Acceleration by Fast Waves

In the model in the previous section, the diffusion coefficient was assumed as $D_{EE} = 3c\Gamma E^2/R$, which is derived from a very simplified model with assumptions of the turbulence velocity $c/\sqrt{3}$ and injection scale $1R/\Gamma$ in the comoving frame. However, the injected turbulence at a large scale cascades into smaller scales as magnetohydrodynamical (MHD) waves. In this section, we review the particle acceleration by large-scale MHD waves, especially fast mode waves.

Teraki & Asano [11] investigate the energy-diffusion efficiency in a temporally evolving wave ensemble that consists of a single mode (Alfven, fast or slow) of linear MHD waves. Given the wave number $k = (k_\parallel, k_\perp)$ and frequency $\omega$, the resonance condition is written as

$$\omega - k_\parallel v_\parallel = n\Omega,$$

where $v_\parallel$ is the particle velocity component along the magnetic field, and $\Omega$ is the gyro frequency. The gyroresonance condition, which is frequently discussed, corresponds to $n = \pm 1$. The gyroresonance leads to $D_{EE} \propto E^{5/3}$ in the Kolmogorov turbulence irrespectively of the wave mode. This is confirmed by the simulations by Teraki & Asano [11].

Another type of resonance is called the transit-time damping (TTD), which corresponds to $n = 0$ in equation (2). This resonance acceleration occurs only for fast and slow modes. In turbulence in a weakly magnetized plasma, the kinetic energy would be dominant rather than the magnetic field. Then, fast mode waves would be the dominant accelerator. The cascade process stops at a significantly large scale by the TTD effect. If the Larmor radius is shorter than this minimum wave length, the diffusion coefficient behaves as $D_{EE} \propto E^2$ as assumed in the previous section. Actually, blazar spectra are successfully reproduced by the hard-sphere acceleration model [12].
However, to resonate with the TTD mode, \( v_\parallel = \omega / k_\parallel \ll c \). For relativistic particles, the fraction in such a condition would be very small. The resonance broadening by the mirror force will resolve this problem. As shown in Figure 3, about 50% of particles are diffused in the energy space. In the parameter set in Figure 3, the simple estimate gives us only a fraction 0.03 in the TTD resonance. The mirror force induced by fast waves frequently change the pitch angle of particles. As a result a significant fraction of particles are accelerated as shown in Figure 3.

\[
\frac{dN}{d\gamma} = \frac{\pi}{6} E^2 \left( \frac{V}{c} \right)^2 c k_{\text{max}} \left( \frac{k_{\text{max}}}{k_{\text{min}}} \right)^{2/3},
\]

where \( V \) is the turbulence velocity at the injected scale. As long as \( k_{\text{min}} \geq \Gamma / R \), some sets of combination of \( k_{\text{max}} \) and \( k_{\text{min}} \) provides the required value in the previous section. Note that the Larmor radius of the highest energy particles should be smaller than \( k_{\text{min}}^{-1} \) to realize the hard-sphere acceleration. When this condition is broken, the UHECR spectrum above this energy region becomes harder.

**Figure 3.** Energy distribution of particles at \( t = 10^6 mc/(eB_0) \) in the pure fast mode waves [11]. The initial Lorentz factor is 10. The blue dashed line and green dotted lines are the Gaussian curves with particle numbers 0.5\( N_{\text{all}} \) and 0.3\( N_{\text{all}} \), respectively (the total particle number \( N_{\text{all}} = 12,800 \)).

In the Kolmogorov case, our simulations show a larger diffusion coefficient by a factor of 5.6 than the analytical formula

\[
D_{EE} = \frac{\pi}{6} E^2 \left( \frac{V}{c} \right)^2 c k_{\text{max}} \left( \frac{k_{\text{max}}}{k_{\text{min}}} \right)^{2/3},
\]

where \( V \) is the turbulence velocity at the injected scale. As long as \( k_{\text{min}} \geq \Gamma / R \), some sets of combination of \( k_{\text{max}} \) and \( k_{\text{min}} \) provides the required value in the previous section. Note that the Larmor radius of the highest energy particles should be smaller than \( k_{\text{min}}^{-1} \) to realize the hard-sphere acceleration. When this condition is broken, the UHECR spectrum above this energy region becomes harder.

**References**

[1] Asano K and Mészáros P 2014 *ApJ* 785 54
[2] Lloyd-Ronning N M and Zhang B 2004 *ApJ* 613 477
[3] Asano K Inoue S and Mészáros P 2009 *ApJ* 699 953
[4] Asano K Guiriec S and Mészáros P 2009 *ApJL* 705 L191
[5] Asano K Inoue S and Mészáros P 2010 *ApJL* 725 L121
[6] Aartsen M. G et al. 2017 *ApJ* 843 112
[7] Asano K and Mészáros P 2016 *PRD* 94 023005
[8] Duffell P C and MacFadyen A I 2013 *ApJ* 775 87
[9] He H-N et al. 2012 *ApJ* 752 29
[10] Wanderman D and Piran T 2010 *MNRAS* 406 1944
[11] Teraki Y and Asano K 2019 *ApJ* 877 71
[12] Asano K and Hayashida M 2018 *ApJ* 861 31