IMPLICATIONS OF ULTRA-HIGH-ENERGY COSMIC RAYS FOR TRANSIENT SOURCES IN THE AUGER ERA

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Abstract

We study ultra–high-energy cosmic rays (UHECRs) from transient sources, propagating in the Galactic and intergalactic space. Based on recent observational results, we also estimate upper and lower bounds on the rate of transient UHECR sources and the required isotropic cosmic-ray energy input per burst as 0.1 Gpc−3 yr−1 ≲ ρ0 ≲ 10−3.5 Gpc−3 yr−1 and 1049.5 erg ≲ Eiso ≲ 1054 erg by constraining the apparent burst duration, i.e., dispersion in arrival times of UHECRs. Based on these bounds, we discuss implications for proposed candidates such as gamma-ray bursts and active galactic nuclei.

Key words: cosmic rays – galaxies: active – gamma rays: bursts

1. INTRODUCTION

The origin of ultra–high-energy cosmic rays (UHECRs) is one of the biggest mysteries in astroparticle physics. So far, a number of possibilities have been proposed, and several acceleration mechanisms have been theoretically developed (see, e.g., Kachelrieß 2008, and references therein). However, physical conditions in these potential sources are uncertain, and observational progress in source identification has been limited by the scarcity of experimental data at the highest energies (see, e.g., Nagano & Watson 2000).

The recent observational results of large area detectors such as the Akeno Giant Air Shower Array (AGASA), High Resolution Fly’s Eye (HiRes), and especially the Pierre Auger Southern Observatory (PAO), have started to give us crucial clues to the association of UHECRs with AGN sources. Indeed, the first results of the PAO reported a significant correlation between the arrival directions of the highest-energy cosmic rays and the 12th Veron-Cetty & Veron catalog of active galactic nuclei (AGNs) closer than 75 Mpc (Abraham et al. 2007; Abraham et al. 2008). Although this result has not been confirmed by the HiRes (Abbasi et al. 2008) and has been criticized by several authors (Gorbunov et al. 2007), it has received some confirmations, and it would be an important step toward solving the UHECR mystery (see, e.g., Stanek 2008).

However, one should not overinterpret the significance of these results. Although several authors also reported correlations of UHECRs with AGNs (George et al. 2008; Moskalenko et al. 2008; Zaw et al. 2008), one cannot exclude the possibility of other objects associated with the large-scale structure of the universe, which is inhomogeneous up to dozens of Mpc. Significant correlations of UHECRs with galaxies can also be found (Kashit & Waxman 2008; Ghisellini et al. 2008; H. Takami et al. 2008, in preparation), so that gamma-ray bursts (GRBs; Vietri 1995; Waxman 1995a; Murase et al. 2006) and magnetars (Arons 2003) can be sources.

Even if the association of UHECRs with AGNs is real, the report by the PAO raised several new questions on the nature of AGNs generating UHECRs. Surprisingly, the large majority of the correlating AGNs seems radio-quiet, a class of objects not showing any nonthermal high-energy emission in their photon spectrum (George et al. 2008). Radio-loud AGNs, showing high-energy nonthermal emission, are more plausible candidates in the conventional jet paradigm (e.g., Rachen & Biermann 1993; Norman et al. 1995). Although the association with them is argued (Moskalenko et al. 2008), it seems that the power of the correlating AGNs is insufficient to produce UHECRs (Zaw et al. 2008). The above problem may be solved if UHECRs are produced during intense but short-duration flares (Farrar & Gruzinov 2008). The magnetic fields in the universe deflect UHECRs, so that UHECRs are significantly delayed compared to photons and neutrinos generated during the bursts (Miralda-Escude & Waxman 1996). A transient hypothesis might also help to reproduce the isotropy of the arrival distribution of UHECRs at ~1019 eV (Takami & Sato 2008b).

In this Letter, we focus on the possibility that UHECR sources are transient, and evaluate the deflection angles and arrival times of UHECRs through numerical calculations, considering both the Galactic magnetic field (GMF) and the intergalactic magnetic field (IGMF). The required cosmic-ray energy input and rate of the sources are estimated. In this work, UHECRs are also assumed to consist of protons.

2. PROPAGATION AND CHARACTERISTICS OF UHECRs FROM TRANSIENT SOURCES

We briefly describe the method of calculation and characteristics of UHECRs from transient sources. UHECRs ejected from their sources are deflected by the GMF and IGMF during their propagation. Only if the deflection angle θd(E, D) is small, where E is the energy of UHECRs at the Earth and D is the source distance, could we see a positional correlation of the highest-energy events with the sources at observationally suggested small-angle separations. The deflection also causes the time delay τd(E, D) between arriving times of a UHECR and light emitted at the same time. UHECRs with the same energy have different arrival times, not only because of different particle trajectories but also stochastic photomeson production (Miralda-Escude & Waxman 1996). Therefore, the time delay has a certain distribution with an averaged delayed time τd(E, D) and standard deviation in arrival times σd(E, D). The arrival time spread σd can be regarded as the apparent duration of an UHECR burst.

Clearly, the magnetic fields play an essential role in both θd and σd. For intergalactic propagation, one can typically expect σd ≈ τd ≈ 105 yr E−2 D−1 00 Mpc B−3 G−3 = 0.1 Mpc (Miralda-Escude & Waxman 1996), which is also confirmed by our
Numerical calculations. Due to limited statistics of the highest-energy events, it is convenient to use quantities weighted by the observed cosmic-ray spectrum. The apparent burst duration of UHECRs above the threshold energy $E_{th}$ is

$$
\tau_d (> E_{th}) = \frac{1}{N_0} \int_{E_{th}}^{\infty} dE \frac{dN_0}{dE} \frac{dD^2 \sigma_d(E, D)}{f_{\text{max}}(E) D DD^2} ,
$$

where $dN_0 / dE$ is the UHECR spectrum observed at the Earth, $N_0 = \int_{E_{th}}^{\infty} dE dE dE (E)$ is the normalization factor, and $D_{\text{max}}(E)$ is the maximum distance of UHECRs that can reach the Earth at the energy $E$. In this work, we adopt $E_{th} = 10^{19.75}$ eV as the threshold energy, according to the PAO results.

Through $\tau_d$, we can relate the local rate of transient sources $\rho_0$ with the apparent source density $n_s$. We have

$$
n_s(> E_{th}) = \frac{1}{N_0} \int_{E_{th}}^{\infty} dE \frac{dN_0}{dE} n_0(E) ,
$$

where

$$
n_0(E) \approx \frac{f_{\text{max}}(E) D DD^2 \sigma_d(E, D)}{\int f_{\text{max}}(E) D DD^2} .
$$

Note that $n_s$ can be estimated from the observed small-scale anisotropy in the arrival distribution of the highest-energy cosmic rays with energies above $E_{th}$. For example, the small-scale anisotropy observed by the AGASA implied $n_s \sim 10^{-6} - 10^{-4}$ Mpc$^{-3}$ (e.g., Yoshiguchi et al. 2003; Kachelriess & Semikoz 2005; Takami & Sato 2007). The more recent PAO data imply $n_s \sim 10^{-4}$ Mpc$^{-3}$ (Takami & Sato 2008b), and we hereafter adopt this value. Then, the local burst rate is estimated via $\rho_0 \approx n_s / \tau_d$.

Assuming that the sources are uniform, we can also estimate typical values of the isotropic cosmic-ray energy input per burst at the energy $E$ as $\dot{E}_{\text{CR}}(E) \approx E^2 dE_{\text{CR}}(E) / \rho_0$. Here, $E^2 dE_{\text{CR}}(E) / \rho_0$ is the UHECR energy budget per volume per year at the energy $E$. Through our numerical calculations, we obtain $E^2 dE_{\text{CR}}(10^{19} \text{ eV}) \approx (0.5–2) \times 10^{44}$ erg Mpc$^{-3}$ yr$^{-1}$ (depending on the source spectral index $s$) from the PAO data (see also, e.g., Waxman 1995b; Berezhnsky et al. 2006).

The thing left to do is to calculate the distribution of deflection angles of arrival times. Our method of calculation, taking into account the GMF as well as the IGMF, is described below. The IGMF strength $B_{\text{IGM}}$ is very uncertain, but we can estimate upper bounds on $B_{\text{IGM}}$ and the resulting $\tau_d$ by comparing the calculated distribution of deflection angles to the typical angular separation of observed UHECRs. In this work, we adopt $\psi \sim 5^\circ$ as the angular separation, according to the PAO results (Abraham et al. 2008; H. Takami et al. 2008, in preparation). As the energy distribution of cosmic rays at a source, we assume power-law spectra $dN / dE \propto E^{-s}$.

\subsection{2.1. Propagation in the Galactic Space}

Propagation in the Galactic space is important for the deflection of UHECRs. The corresponding delay time would typically be smaller than that in the IGMF, but it is not zero and is unavoidable. Under a given separation angle, the coherent component of the GMF leads to the minimum delay time, and the lower bound on $\tau_d$ is also obtained. Following the method used in Takami & Sato (2008a), we pursue cosmic-ray trajectories with proton mass and charge of $-1$ from the Earth, and calculate their delay times for given GMF models. We define a sphere with radius 40 kpc, centered at the Galactic center, as the boundary of Galactic space. As a GMF model (for reviews see Vallé 2004; Han 2007), a bisymmetric spiral field with even parity is adopted. This leads to a conservative estimate of $\tau_d$, although other models such as axisymmetric spiral field may be possible due to uncertainty in the GMF (Vallé 2005). Note that all the energy-loss processes can be neglected for propagation in the Galactic space.

The delay time and arrival time spread in the GMF depend on the arrival directions of UHECRs, where the averaged standard deviation of observed $k$ events is $\sigma_d = (1/k) \sum \sigma_{d,i}$. In this work, we instead use $\sigma_d(E) = [1 / \tau_d] \int d\Omega \frac{d\Omega}{d\Omega} \sigma_{d,\Omega}$ (E). Through our numerical calculations, we found that this gives us a reasonable estimate of $\sigma_d$, even though the GMF leads to a hole in the arrival directions of UHECRs (Takami & Sato 2008a). In Table 1, we show the resulting lower bounds on $\tau_d$. Here $p(\leq 0)$ is the pitch angle of the spiral component of the GMF at the vicinity of the solar system, and smaller values of $-p$ lead to smaller deflection angles of UHECRs.

The vertical magnetic field near the solar system and many gaseous filaments perpendicular to the Galactic plane are observed, indicating another regular component (Han 2007). Also, a dipole field with odd parity is predicted by the dynamo theory. Hence, we also consider cases of the GMF with a dipole magnetic field whose strength is normalized to 0.3 $\mu$G at the vicinity of the solar system. In Table 2, the resulting lower bounds on $\tau_d$ are shown. However, note that there is no direct observational evidence of such a dipole field.

\subsection{2.2. Propagation in the Extragalactic Space}

Propagation in the extragalactic space is expected to play an essential role in both the deflection and time delay of UHECRs. We numerically calculate the distribution of $\theta_d$ and $\tau_d$ for given GMFs. Our method of calculation is similar to that used in Yoshiguchi et al. (2003), where proton propagation is treated as Monte Carlo simulations. We set 10 logarithmic bins per logarithmic energy interval, and isotropically inject 5000 protons for every energy bin. Particle trajectories are pursued at every 1 Mpc for $D < 100$ Mpc, and at every 10 Mpc for $D > 100$ Mpc. As relevant energy-loss processes, we consider photomeson production and Bethe–Heitler processes with the cosmic microwave background photons, and the adiabatic energy loss due to the expanding universe. The resulting
distribution of $\theta_d$ or $t_d$ is
\[
   f_d(E, D) = \int_{E_{\text{min}}(E_g, D)}^{\infty} dE_g f_d(E, D; E_g),
\]
where $E_{\text{min}}(E_g, D)$ is the minimum energy, at a source at distance $D$, of protons observed with $E_g$ at the Earth. $f_d(E, D; E_g)$ is the more basic distribution of $\theta_d$ or $t_d$, generated by cosmic rays with $E_g$ at a source.

In this work, we consider a uniform turbulent IGMF with the Kolmogorov turbulence spectrum as the extragalactic magnetic field. Although the IGMF is highly uncertain, we can constrain it by comparing the calculated $\theta_d$ distribution to $\psi$. As a result, we found $B_{IG} \gtrsim nG Mpc^{1/2}$ is required for the averaged deflection angle $\theta_d$ not to exceed the typical angular separation $\psi \sim 5^\circ$. It is consistent with the result from Faraday rotation measurements (Kronberg 1994), but independently obtained. Hence, the $\tau_d$ obtained for $B_{IG} \gtrsim nG Mpc^{1/2}$ can be regarded as upper bounds. Our results for $B_{IG} = (0.1-1)nG$ and $\lambda_{coh} = 1$ Mpc are shown in Table 3.

### 3. IMPLICATIONS FOR TRANSIENT UHECR SOURCES

We have estimated lower and upper bounds on $\tau_d$ using $\psi \sim 5^\circ$, which allows us to estimate the allowed range of $\rho_0$ and $E_{\text{iso}}$ by using $n_s \sim 10^{-4}$ Mpc$^{-3}$. For the local rate, we obtain
\[
   0.1 \text{ Gpc}^{-3} \text{ yr}^{-1} \lesssim \rho_0 \lesssim (60-300) \text{ Gpc}^{-3} \text{ yr}^{-1}.
\]
Note that stronger upper bounds can be obtained for the GMF with a dipole magnetic field. However, since the existence of a dipole field is very tentative, we hereafter consider the GMF without a dipole field for conservative discussions.

The required cosmic-ray energy input at $10^{19}$ eV, $E_{\text{iso}}$ by $\xi_{\text{iso}}(10^{19}$ eV), is estimated as
\[
   (0.3-20) \times 10^{50} \text{ erg} \lesssim \xi_{\text{iso}} \lesssim 10^{54} \text{ erg}.
\]
Note that Equations (5) and (6) are valid as long as UHECR sources are regarded as transient, i.e., $\delta T < \tau_d < \Delta T$, where $\delta T$ is the true burst duration during which particle acceleration occurs and $\Delta T$ is the time interval between bursts. $\delta T$ depends on the nature of potential sources. For example, classical high-luminosity (HL) GRBs have $\delta T \sim 10^{-2}$ s, which is much shorter than $\tau_d$. For bounds to be meaningful, $\tau_d < \Delta T$ should be satisfied. Otherwise, more than one UHECR burst occurs in $\tau_d$ within $\psi$, and we would see these bursts as a single but more energetic burst. When $\psi \sim 5^\circ$, the time interval is estimated as $\Delta T \sim (3/\pi)\rho_0^{-1}\psi^{-2}D_{\text{coh}}^{-1}(E_{\text{th}}) \sim 3\tau_d n_s^{-1/4}$. Since $\Delta T > \tau_d$, we may expect that the obtained bounds would make sense, although we should be careful of the possibility not to see each UHECR burst as a distinctive one for larger $n_s$.

### Table 3

| $s$  | $\tau_d^{-1}$ (yr$^{-1}$) for 0.1 nG Mpc$^{-1/2}$ | $\tau_d^{-1}$ (yr$^{-1}$) for 1.0 nG Mpc$^{-1/2}$ |
|------|-----------------------------------------------|-----------------------------------------------|
| 2.0  | $9.7 \times 10^{-3}$                         | $8.9 \times 10^{-7}$                         |
| 2.2  | $9.5 \times 10^{-3}$                         | $8.6 \times 10^{-7}$                         |
| 2.4  | $9.3 \times 10^{-3}$                         | $8.4 \times 10^{-7}$                         |
| 2.6  | $9.1 \times 10^{-3}$                         | $8.3 \times 10^{-7}$                         |

### Table 4

| Source          | Typical Rate $\rho_0$ (Gpc$^{-3}$ yr$^{-1}$) | Reference |
|-----------------|---------------------------------------------|-----------|
| HL GRB          | $\sim 0.1$                                  | e.g., GP07|
| LL GRB          | $\sim 400$                                  | e.g., L+07|
| Hypernovae      | $\sim 2000$                                 | e.g., GD07|
| Magnetar        | $\sim 12000$                                | e.g., G+05|
| Giant Magnetar Flare | $\sim 10000$                              | e.g., O07   |
| Giant AGN Flare | $\sim 10000$                                | FG08      |
| SNe Ibc         | $\sim 20000$                                | e.g., GD07|
| Core Collapse SNe | 1200000                                    | e.g., M+98 |

The total cosmic-ray energy input $E_{CR}^\text{iso}$ is generally larger than $E_{\text{HECR}}^\text{iso}$ by $R(10^{19} \text{ eV}) \equiv \langle \int dE \psi(E) dN(E, \psi)/\int dE dN(E) \rangle_{E_{\text{iso}}=10^{19} \text{ eV}}$ (Murase et al. 2008). $R$ depends on the cosmic-ray spectrum at a source, and we expect $R \sim 20–500$ for $s \sim 2.0–2.2$ expected in the ankle scenario while $R \gtrsim 100$ for $s \sim 2.4–2.6$ expected in the proton-dip scenario; the latter scenario generally requires the break energy below the second knee (Berezinsky et al. 2006). In both scenarios, we expect that the transient hypothesis requires the relatively large cosmic-ray energy input per burst $E_{CR}^\text{iso} \gtrsim 10^{50.5} \text{ erg}$, which would be a strong requirement on potential sources.

So far, several potential sources have been proposed as transient accelerators, and HL GRB is one of them. The isotropic radiation energy is $E_{\text{iso}}^\text{iso} \sim 10^{55} \text{ erg}$, and HL GRBs are the most energetic transient phenomena in the universe. The local rate is uncertain, but recently suggested rates in the Swift era, $\rho_0 \sim (0.05–0.27) \text{ Gpc}^{-3} \text{ yr}^{-1}$, are smaller than previous ones (Le & Dermer 2007; Guetta & Piran 2007). If $\rho_0 \lesssim 0.1 \text{ Gpc}^{-3} \text{ yr}^{-1}$ is real, HL GRBs would be difficult as UHECR sources, since they require rather strong IGMFs with $B_{IG} \gtrsim nG$ and large isotropic energy input of $E_{CR}^\text{iso} \gtrsim 2 \times 10^{50}/(R/20) \text{ erg}$. Low-luminosity (LL) gamma-ray bursts may overcome the problem that the local rate of HL GRBs seems too small (Murase et al. 2006; Murase et al. 2008), because their local rate is likely to be much higher, $\rho_0 \sim 10^{-2} \text{ Gpc}^{-3} \text{ yr}^{-1}$ (Liang et al. 2007; Guetta & Della Valle 2007). Some GRBs are associated with energetic supernovae (SNe) called hypernovae, which may also be high-energy cosmic-ray accelerators. Although they are sufficient as the energy budget, it seems difficult to accelerate protons up to $\gtrsim 10^{19} \text{ eV}$ (Wang et al. 2007).

About 10% of core collapse SNe may form magnetars (e.g., Gaensler et al. 2005), which may be UHECR sources (Arons 2003). However, our results would suggest that all the magnetars (and SNe) do not produce UHECRs uniformly and only a fraction of magnetars is the main origin, which is also consistent with the theoretical expectation (Arons 2003). For example, only newly born magnetars associated with SNe Ibc could be major UHECR accelerators, which leads to $\rho_0 \sim 3000 \text{ Gpc}^{-3} \text{ yr}^{-1}$ and $E_{CR}^\text{iso} \sim 3 \times 10^{50}/(R/10) \text{ erg}$. Giant magnetar flares could not explain UHECRs, since their radiation energy, $E_{\nu}^\text{iso} \sim 10^{50} \text{ erg}$, is much smaller than $E_{CR}^\text{iso}$.
The typical source rates are summarized in Table 4, but one should keep in mind that they are very uncertain at present.

4. SUMMARY AND DISCUSSIONS

We have constrained $t_\sigma$ through our numerical calculations of proton propagation, taking into account not only the IGMF but also the GMF. The recent PAO results, the positional correlation with $\psi \sim \sigma$ degrees, and small-scale anisotropy have brought us implications for the sources, as well as indicating $B_{\text{IGM}} \chi_{\text{coh}}^2 \lesssim n \text{ Gpc}^{1/2}$. The results are important in the sense that they are implications of UHECR observations and also useful for the detectability of secondary emission. They suggest that HL GRBs may be marginally disfavored as UHECR sources if the recently suggested local rate is real. LL GRBs, newly born magnetars associated with LL GRBs or SNe Ibc, and giant AGN flares seem possible, unless there exists a strong dipole magnetic field in our Galaxy.

Although these implications may be interesting, because of current poor statistics we should be cautious in drawing definite conclusions about the sources. The suggested positional correlation is confirmed only at $2 \sigma$–$3 \sigma$ levels. Also, the estimate of $n_\text{e}$ has large errors at present due not only to poor statistics but also our lack of knowledge of the precise positions of UHECR sources, and it is not so easy to exclude the possibility that UHECR sources contain many dim accelerators, i.e., large $n_\text{e}$. But statistics will be better in the near future, and the order of $n_\text{e}$ will be accurately determined by 5 yr observations by the PAO (Takami & Sato 2007). However, statistical analyses become more complicated when the sources are transient and/or their luminosity function is taken into account (and note that we have assumed that the sources are uniform). More detailed and careful studies will be presented in our forthcoming paper.

We have discussed implications for the transient UHECR sources, but it is also important to know whether the sources are transient or not. The signature of transient sources may be found from the observed UHECR spectrum, e.g., from the average number of multiplets (Harari et al. 2004). For identification of sources, multimessenger astronomy will be particularly important. High-energy neutrinos are useful as a probe of cosmic-ray acceleration, and associated gamma rays are often expected for transient sources such as GRBs (see, e.g., Murase 2007; Murase et al. 2008, and references therein).

In addition, electrons are also accelerated in the shock acceleration theory, which allows us to expect photon counterparts. In fact, we may also expect the high electron luminosity $L_e \gtrsim (e_e/0.1e_p)10^{15} (10^5 s/\delta T)$ erg s$^{-1}$, as well as the high magnetic luminosity $L_B \gtrsim 10^{45}$ erg s$^{-1}$ which will be required for UHECR acceleration (Waxman 1995a). For example, approximately 30 events from giant AGN flares may be detected by Fermi (Farrar & Gruzinov 2008). Note that, once we know that the UHECR sources are transient, we can obtain precious information on the effective IGMF (Miralda-Escude & Waxman 1996). If LL GRBs are the UHECR sources, for example, the effective IGMF can be estimated as $\sim 0.03$ nG Mpc$^{-1/2}$. UHECRs would also be useful as a probe of the GMF (Takami & Sato 2008a), and several GMF models may be tested as the number of detected events increases. This will help to reduce uncertainties in the estimate of bounds on $t_\sigma$ and resulting $\rho_0$.

We have assumed a uniform IGMF, but this is not realistic. If the sources are inside clusters or filaments, UHECRs are affected by the magnetic field in the structured region. When a uniform IGMF is weak enough, the structured magnetic field is more important. In such cases, HL GRBs are more disfavored as UHECR sources because they require a rather strong IGMF, as shown in this work. The structured magnetic field may also play a role as an unavoidable field. Some AGNs are inside clusters, so that UHECRs from them should be delayed due to that field. The local rate will be more constrained as $\rho_0 \lesssim 10^{1−2}$ Gpc$^{-3}$ yr$^{-1}$, and the necessary cosmic-ray energy input will also be increased.

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