Ultra-High Energy Cosmic Rays and Neutrinos

Shigehiro Nagataki
Yukawa Institute for Theoretical Physics, Kyoto University, Oiwake-cho Kitashirakawa
Sakyo-ku, Kyoto 606-8502, Japan
E-mail: nagataki@yukawa.kyoto-u.ac.jp

Abstract. In this paper, simulation of propagation of UHE-protons from nearby galaxies is presented. We found good parameter sets to explain the arrival distribution of UHECRs reported by AGASA and energy spectrum reported by HiRes. Using a good parameter set, we demonstrated how the distribution of arrival direction of UHECRs will be as a function of event numbers. We showed clearly that 1000-10000 events are necessary to see the clear source distribution. We also showed that effects of interactions and trapping of UHE-Nuclei in a galaxy cluster are very important. Especially, when a UHECR source is a bursting source such as GRB/AGN flare, heavy UHE-Nuclei are trapped for a long time in the galaxy cluster, which changes the spectrum and chemical composition of UHECRs coming from the galaxy cluster. We also showed that such effects can be also important when there have been sources of UHE-Nuclei in Milky Way. Since light nuclei escape from Milky Way in a short timescale, the chemical composition of UHECRs observed at the Earth can be heavy at high-energy range. Finally, we showed how much high-energy neutrinos are produced in GRBs. Since GRB neutrinos do not suffer from magnetic field bending, detection of high-energy neutrinos are very important to identify sources of UHECRs. Especially, for the case of GRBs, high-energy neutrinos arrive at the earth with gamma-rays simultaneously, which is very strong feature to identify the sources of UHECRs.

1. Introduction
Many observations on Ultra High-Energy Cosmic Rays (UHECRs) have been done, and there are many interesting information have been reported such as energy spectrum, arrival direction, and chemical composition. However, sources of UHECRs are still unknown. Why is it difficult to hunt the sources of UHECRs? The reason is magnetic fields. The trajectories of UHECRs are not straight by the magnetic field bending effect. This is serious especially for heavy nuclei. Also, the time delay effect due to the magnetic fields is serious. For example, if the source of UHECRs is a Gamma-Ray Burst (GRB), the arrival time difference between GRB and UHECRs can be as large as 1000yrs.

What can we do to identify the sources of UHECRs? More observations for higher statistics are important, of course. This is the matter for observers. From a theoretical point of view, there are two approaches. One is to simulate propagation of UHECRs assuming a lot of source distributions so that we can compare the simulations with observations. This approach will tell us what source distribution is good to explain observations of UHECRs. Another approach is to calculate secondaries (very high energy neutrinos and gamma-rays) from sources of UHECRs. Since the secondary particles are charge-neutral, they do not suffer from magnetic field effects. This is important because VHE neutrinos and VHE gamma-rays (if they do not suffer from
considerable energy-loss during propagation) can arrive at the earth with a bursting source (such as a GRB), which tells us the GRB is the source of VHE-neutrinos/gamma-rays and their parent UHECRs (parent CRs will have about 20 times greater energy than VHE neutrinos/gamma-rays).

In this paper, we would like to show our studies to identify the sources of UHECRs. We show our study on numerical simulation of propagation of UHECRs from nearby galaxies in section 2, propagation of UHE-Nuclei in a galaxy cluster in section 3, propagation of UHE-Nuclei in Milky Way in section 4, and VHE-neutrinos from GRBs in section 5.

2. Numerical Simulations of Propagation of UHECRs

2.1. Formulation

This subsection provides the method of Monte Carlo simulations for propagating protons in intergalactic space. At first, we assume that the composition of UHECRs is proton, and inject an $E^{-2}$ spectrum within the range of $10^{19.5} - 10^{22}$ eV. A total of 10,000 protons are injected in each of 26 energy bins, that is, 10 bins per decade of energy for the cases of $l_c = 40$ Mpc that is the correlation length of the extragalactic magnetic field. For other cases we inject 5000 protons in each of the bins.

Particles below $\sim 8 \times 10^{19}$ eV lose their energies mainly by pair creations and above it by photopion production in collisions with photons of the CMB. The pair production can be treated as a continuous loss process considering its small inelasticity. As for the photopion process, we use the interaction length and the energy distribution of final protons as a function of initial proton energy, which is calculated by simulating the photopion production with the event generator SOPHIA.

Extra Galactic Magnetic Fields (EGMFs) are little known theoretically and observationally. So we studied propagation of UHECRs for various magnetic field models. The mean values of EGMFs are chosen to be 1nG, 10nG, 100nG. The coherent length of magnetic fields are set to be 1Mpc, 10Mpc, 40Mpc. We assume that the magnetic field is represented as the Gaussian random field with zero mean and a power-law (Kolmogorov) spectrum.

![Figure 1. Distribution of galaxies in our ORS sample within 8000 km s$^{-1}$.](image)

In this study, we assume that the source distribution of UHECRs is proportional to that of the galaxies. We use realistic data from the ORS galaxy catalog, which is a nearly full-sky survey. Compared with IRAS PSCz Survey data, Local Super Cluster members are more included (such as Virgo Cluster). The distribution of galaxies in ORS data is shown in Figure 1.

2.2. Results

By doing a lot of simulations, we found some good parameter sets to explain the observations of UHECRs. We show the results below.
In Figure 2, two-point correlation function predicted by a specific source scenario in the case that the number fraction (NF) $\sim 10^{-1.7}$ of the ORS galaxies more luminous than $M_{\text{lim}} = -20.5$ is selected as UHECR sources. The number of simulated events is set to be 57 with energies of $10^{19.6} - 10^{20.3}$ eV. The histograms represent the AGASA data in this energy range.

In Figure 3, energy spectra predicted by sources selected from the ORS galaxies more luminous than $M_{\text{lim}} = -20.5$ in the case of $(B, l_c, \text{NF}) = (1, -20.5, 10^{-1.7})$. They are fitted to the data of HiRes I detector (squares and error bars). The shaded regions represent $1\sigma$ error due to the source selection from our ORS sample.

Using the most favorite parameter sample, we demonstrate arrival directions of UHECRs above $4 \times 10^{19}$ eV for various event number. Distribution of selected sources within 200Mpc is also shown as circles of radius inversely proportional to their distances. Only the sources within 100Mpc are shown with bold circles. The upper right panel shows the case that event number is 100 that is similar to the event number of PAO in 2010. As the event number increases (1500, 5000, 15000), we can see clear correlation between source distribution and arrival direction of UHECRs. Thus we conclude that about more than 10 times more events than PAO in 2010 are necessary to see the source distribution. South/North Auger, TA, and JEM-EUSO should provide us with such important data in the future. Please see [1, 2] for details.

**Figure 2.** Two-point correlation function predicted by a specific source scenario in the case that the number fraction (NF) $\sim 10^{-1.7}$ of the ORS galaxies more luminous than $M_{\text{lim}} = -20.5$ is selected as UHECR sources. The number of simulated events is set to be 57 with energies of $10^{19.6} - 10^{20.3}$ eV. The histograms represent the AGASA data in this energy range.

**Figure 3.** Energy spectra predicted by sources selected from the ORS galaxies more luminous than $M_{\text{lim}} = -20.5$ in the case of $(B, l_c, \text{NF}) = (1, -20.5, 10^{-1.7})$. They are fitted to the data of HiRes I detector (squares and error bars). The shaded regions represent $1\sigma$ error due to the source selection from our ORS sample.
3. Propagation of UHECRs in Galaxy Clusters

3.1. Formulation

In this section, we present our modeling of cluster of galaxies for UHECR propagation. This comprises a three-dimensional modeling of the magnetic field and infrared photon background, a consistent baryonic background profile and an adequate choice of sources for injection. We model our cluster magnetic field using the three dimensional outputs of MHD simulations run by Dubois and Teyssier (2008)[3]. The simulations were run including dark matter, gas, ultraviolet heating, hydrogen and helium cooling, star formation, and magnetic fields with the Adaptive Mesh Refinement code RAMSES.

At the center of a cooled core born in their simulation, we injected UHECRs assuming that the source is AGN. We assumed that the lifetime of $t_{\text{AGN}}=10\text{My s}$ and the chemical composition of UHECRs is same with solar abundances. The transport scheme in the magnetic field was adapted from Kotera and Lemoine (2008)[4]. The interactions of protons and nuclei with CMB, infrared, optical and ultraviolet photon backgrounds were mostly modeled according to the Monte Carlo methods of Allard et al. (2005)[5].

In Figure 5, we show evolution of the cosmic-ray spectrum in time for the case of a cool core cluster of central magnetic field $B_c = 10\mu\text{G}$. Each panel presents the spectrum at the time indicated at the top right-hand corner. The injection from the source (AGN) is assumed to begin at $t = 0$. The contribution of the different chemical components are shown. The thick black line is the total spectrum and the thin black line indicates the total flux obtained for an infinite AGN lifetime and an an integration of the flux over a Hubble time (stationary regime). The spectra are normalized to the value of the stationary flux obtained at $E = 10^{19}\text{eV}$.

Figure 5. shows that light nuclei such as proton and helium can escape from the cool core first, then heavy nuclei such as iron follow. Especially, the upper right panel shows that the UHECRs are composed of iron mainly. This may be interesting possibility to explain the observations of chemical composition of UHECRs reported by PAO. Please see [6] for details.

4. Propagation of UHECRs in Milky Way

In this section, we consider the possibility that UHECR (but lower than GZK cutoff) spectrum and composition may be explained due to the past GRBs in Milky Way. Stellar explosions in our own Galaxy can accelerate both protons and nuclei, but, while the protons leave the Galaxy promptly, the heavier and less mobile nuclei get trapped in the turbulent magnetic field and
Figure 5. Evolution of the cosmic-ray spectrum in time, assuming a lifetime of $t_{\text{AGN}} = 10\text{Myr}$ for the central AGN, for the case of a cool core cluster of central magnetic field $B_c = 10\mu\text{G}$. Each panel presents the spectrum at the time indicated at the top right-hand corner. The injection from the source (AGN) is assumed to begin at $t = 0$. The contribution of the different chemical components are shown.

linger longer than protons. As a result, the local density of nuclei is increased, and they bombard Earth in greater numbers, as seen by the Pierre Auger Observatory.

The ultrahigh-energy nuclei observed today have been trapped in the web of Galactic magnetic fields for millions of years, and their arrival directions have been completely randomized by the numerous twists and turns in the tangled field. However, we predict, the protons escaping from other galaxies should still be seen at the highest energies and should point back to their sources.

We did one-dimensional Monte Carlo simulations for the propagation of UHE-protons and Nuclei, assuming that the sources produce 90% protons and 10% iron, with identical spectra $\propto E^{-2.3}$, and that the source distribution traces the distribution of stars in the Galaxy. We used samples of $10^3$ GRBs at random locations with time intervals of $10^5$ years. The magnetic field was assumed to be $4\mu\text{G}$, coherent over $l_0 = 0.2$ kpc domains. The overall power and the iron fraction were adjusted to fit the PAO data points. For each random sample, the fit parameters differ slightly, depending on the location of the latest or closest burst. The result is shown in Figure 6. As for the anisotropy of UHECRs, the result is shown in Figure 7. Please see [7] for details.

5. Ultra-High Energy Neutrinos from Gamma-Ray Bursts

In this section, high energy neutrino emission from GRBs is discussed. In this section, by using GEANT4, we calculate proton cooling efficiency including pion-multiplicity and proton-inelasticity in photomeson production. First, we estimate the maximum energy of accelerated protons in GRBs. Using the obtained results, neutrino flux from diffuse neutrino background is evaluated quantitatively. We also take account of cooling process of pion and muon, which are crucial for resulting neutrino spectra. We introduced the nonthermal baryon-loading factor $\epsilon_{\text{acc}}$. We found that the obtained background can be comparable with the prediction of Waxman and Bahcall limit. Detection of high-energy neutrinos from GRBs will be one of the strong evidences that protons are accelerated to very high energy in GRBs. We also considered neutrino flux from X-ray flares and optical flares found by Swift satellite.

In figure 8, we show diffuse neutrino background from GRBs for $z_{\text{max}} = 20$ on several SFR models. R-R means the case using Rowan-Robinson SFR. SF1-SF3 correspond to the models of
Figure 6. Predicted UHECR spectra, assuming that the sources produce 90% protons and 10% iron, with identical spectra \( \propto E^{-2.3} \), and that the source distribution traces the distribution of stars in the Galaxy. We used samples of \( 10^3 \) GRBs at random locations with time intervals of \( 10^5 \) years. The magnetic field was assumed to be \( 4 \mu G \), coherent over \( l_0 = 0.2 \) kpc domains. The overall power and the iron fraction were adjusted to fit the PAO data points. For each random sample, the fit parameters differ slightly, depending on the location of the latest or closest burst. To model the spectrum at \( E > 3 \times 10^{19} \) eV, one has to account for energy losses and (proton) contribution of extragalactic sources, which we leave for future work.

Figure 7. Galactocentric anisotropy for a source distribution that traces the stellar counts in the Milky Way, modeled by random generation of \( 10^3 \) bursts separated by time intervals of \( 10^5 \) yr. The model parameters are the same as in Fig.6. Although the anisotropy in protons is large at high energies, their contribution to the total flux is small, so the total anisotropy < 10%, consistent with the observations. The latest GRBs do not introduce a large degree of anisotropy, as it would be in the case of UHE protons, but they can create ‘hot spots’ and clusters of events.

Porciani and Madau. The left lines are for set A, while the right is for set B. For comparison, we show WB bounds (three dashed lines). The upper WB bound is for \( z \)-evolution of QSOs. The lower is for no \( z \)-evolution. \( \epsilon_{\text{acc}}=10 \) and \( \epsilon_B=1 \) are assumed. In figure 9, we show diffuse neutrino background from GRBs for \( z_{\text{max}} = 20 \) with \( \epsilon_{\text{acc}}=100 \). \( \epsilon_B \) is set to be 0.1, 1, 10. All lines use the SF3 model. In figure 10, we show diffuse neutrino background from flares. X-ray flare (the upper dashed line), FUV-ray flare (the dotted line), and GRB are shown respectively. WB is Waxman-Bahcall bounds. Please see [8, 9] for details.

6. Summary and Conclusion
In this paper, simulation of propagation of UHE-protons from nearby galaxies is presented. We found good parameter sets to explain the arrival distribution of UHECRs reported by AGASA and energy spectrum reported by HiRes. Using a good parameter set, we demonstrated how the distribution of arrival direction of UHECRs will be as a function of event numbers. We showed clearly that \( 1000-10000 \) events are necessary to see the clear source distribution. We also showed that effects of interactions and trapping of UHE-Nuclei in a galaxy cluster are very important. Especially, when a UHECR source is a bursting source such as GRB/AGN flare, heavy UHE-Nuclei are trapped for a long time in the galaxy cluster, which changes the spectrum and chemical composition of UHECRs coming from the galaxy cluster. We also showed that such effects can be also important when there have been sources of UHE-Nuclei in Milky Way.
Figure 8. Diffuse neutrino background from GRBs for $z_{\text{max}} = 20$ on several SFR models. R-R means the case using Rowan-Robinson SFR. SF1-SF3 correspond to the models of Porciani and Madau. The left lines are for set A, while the right is for set B. For comparison, we show WB bounds (three dashed lines). The upper WB bound is for z-evolution of QSOs. The lower is for no z-evolution. $\epsilon_{\text{acc}}=10$ and $\epsilon_B=1$ are assumed.

Figure 9. Diffuse neutrino background from GRBs for $z_{\text{max}} = 20$ with $\epsilon_{\text{acc}}=100$. $\epsilon_B$ is set to be 0.1, 1, 10. All lines use the SF3 model.

Figure 10. The diffuse neutrino background from flares. X-ray flare (the upper dashed line), FUV-ray flare (the dotted line), and GRB are shown respectively. WB is Waxman-Bahcall bounds.

Since light nuclei escape from Milky Way in a short timescale, the chemical composition of UHECRs observed at the Earth can be heavy at high-energy range. Finally, we showed how much high-energy neutrinos are produced in GRBs. Since GRB neutrinos do not suffer from magnetic field bending, detection of high-energy neutrinos are very important to identify sources of UHECRs. Especially, for the case of GRBs, high-energy neutrinos arrive at the earth with gamma-rays simultaneously, which is very strong feature to identify the sources of UHECRs.

References
[1] H. Yoshiguchi, S. Nagataki, S. Tsubaki, K. Sato, Astrophys. J. 586 (2003a) 1211.
[2] H. Yoshiguchi, S. Nagataki, K. Sato, Astrophys. J. 592 (2003b) 311.
[3] Y. Dubois, R. Teyssier, Astron. Astrophys. 482 (2008) L13.
[4] K. Kotera, M. Lemoine, Physical Review D 77 (2008) 023005.
[5] D. Allard, E. Parizot, A.V. Olinto, E. Khan, S. Goriely, Astron. Astrophys. 443 (2005) L29.
[6] K. Kotera, D. Allard, K. Murase, J. Aoi, Y. Dubois, T. Pierog, S. Nagataki, Astrophys. J. 707 (2009) 370.
[7] A. Calvez, A. Kusenko, S. Nagataki, Physical Review Letters 105 (2010) 091101.
[8] K. Murase, S. Nagataki, Physical D 73 (2006a) 063002.
[9] K. Murase, S. Nagataki, Physical Review Letters 97 (2006b) 051101.