Numerical Study of Propagation of UHECRs: Spectrum, Arrival Direction, Composition


Abstract: In this paper, simulations of propagation of UHE-protons from nearby galaxies are presented. We found good parameter sets to explain the arrival distribution of UHECRs reported by AGASA and the energy spectrum reported by HiRes. Using a good parameter set, we demonstrated what distribution of arrival direction of UHECRs will be as a function of event numbers. We show that 1000-10000 events are necessary to clearly see the 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 a 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 important when there have been sources of UHE-Nuclei in the Milky Way. Since light nuclei escape from the Milky Way in a short timescale, the chemical composition of UHECRs observed at the Earth can be heavy at the high-energy range as suggested by Auger.

Keywords: UHECRs, Spectrum, Arrival Direction, Composition

1 Introduction

Many observations on Ultra-High-Energy Cosmic Rays (UHECRs) have been done, and a lot of interesting information has 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 significant especially for heavy nuclei. Also, the time delay effect due to the magnetic fields is significant. 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? From a theoretical point of view, it is important 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.

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, and propagation of UHE-Nuclei in the Milky Way in section 4.

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 case that $l_c = 40$ Mpc 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 energy mainly by pair creation 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 1 nG, 10 nG, 100 nG. The coherent length of magnetic fields are set to be 1 Mpc, 10 Mpc, 40 Mpc. 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$^{-1}$.

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, the two-point correlation function predicted by a specific source scenario is shown 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 shows energy spectra predicted by sources selected from the ORS galaxies more luminous than $M_{\text{lim}} = -20.5$ in the case of $(B, l_c, NF) = (1, -20.5, 10^{-1.7})$. 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 favorable parameter sample, we demonstrate arrival directions of UHECRs above $4 \times 10^{19}$ eV for various event number. Distribution of selected sources within 200 Mpc is also shown as circles of radius inversely proportional to their distances. Only the sources within 100 Mpc are shown with bold circles. The upper right panel shows the case where the 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, 3, 4] for details.
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)[5]. 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 an AGN. We assumed that the lifetime of $t_{\text{AGN}}=10\text{Myrs}$ and the chemical composition of UHECRs is the same with solar abundances. The transport scheme in the magnetic field was adapted from Kotera and Lemoine (2008)[6]. 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)[7].

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 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 an interesting possibility to explain the observations of chemical composition of UHECRs reported by PAO. Please see [8] for details.

4 Propagation of UHECRs in Milky Way

In this section, we consider the possibility that UHECR (but lower than the GZK cutoff) spectrum and composition may be explained due to past GRBs in the 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 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 ultra-high-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 that 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$\mu$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 [9] for details.

4.1 About References

References