PROPAGATION OF ULTRA-HIGH-ENERGY COSMIC RAYS

HAJIME TAKAMI
Max Planck Institute for Physics, Föhringer Ring 6, 80805 Munich, Germany

The propagation of ultra-high-energy cosmic rays (UHECRs) is an important process to connect sources and observables at the Earth and therefore essential to identify poorly known UHECR sources. UHECRs interact with cosmic background photons, losing their energies and producing their secondaries. Propagating UHECRs are also affected by cosmic magnetic fields and then their arrival directions are not exactly the same as the directions of their sources, which provides difficulty of identifying UHECR sources. Here, we review physics on the propagation of UHECRs with particular emphasis on the importance of determining UHECR composition to understand the origin of UHECRs and its astrophysical nature.

1 Introduction

The origin of ultra-high-energy cosmic rays (UHECRs; $> 10^{19}$ eV) is an intriguing problem in astrophysics. UHECR sources have not been identified yet observationally, while several source candidates have been theoretically proposed, such as gamma-ray bursts (GRBs) [1], active galactic nuclei (AGN) [2], strongly magnetized neutron stars or magnetars [3], and clusters of galaxies [4], all of which are extreme environments in the universe. In general, the possible maximum energy of particles produced in a cosmic accelerator can be estimated by so-called Hillas criterion, that is, the Larmor radius of particles should be smaller than the size of the accelerator [5], which indicates that heavier nuclei can be accelerated easily to higher energies [a]. Heavy nuclei relax physical conditions and enables more objects to produce UHECRs.

UHECRs are detected indirectly through extensive air shower (EAS) induced by themselves to achieve large effective detector volume to overcome their extremely low flux. UHECR experiments use atmosphere as a calorimeter and estimate the energy and arrival directions of primary cosmic rays. Although composition of UHECRs is inferred from several quantities of EAS, the atmospheric depth where the number of shower particles is maximized $X_{\rm max}$ has been mainly adopted in modern UHECR experiments. Since fluctuations of $X_{\rm max}$ is large shower by shower, statistical quantities on $X_{\rm max}$, that is, the averaged $X_{\rm max}$ $\langle X_{\rm max}\rangle$ and the root mean square of $X_{\rm max}$ are often used. While the High Resolution Fly's Eye (HiRes) has reported proton-dominated composition at $E > 10^{19}$ eV based on $\langle X_{\rm max}\rangle$ [6], the Pierre Auger Observatory (PAO) reported a gradual change of composition at $\sim 10^{19}$ eV from light to heavy nuclei based on $\langle X_{\rm max}\rangle$ and the root mean square of $X_{\rm max}$ [7]. The reason of this discrepancy is not clear so far; systematic effects, different methods, and intrinsic difference between the northern and southern sky are possible solutions. However, even if this discrepancy is solved, uncertainty of hadronic interaction models used to interpret observed $\langle X_{\rm max}\rangle$ and the root mean square of $X_{\rm max}$ still remains. Thus, in order to determine UHECR composition, it is necessary to understand hadronic

[a] In fact, whether accelerated particles can escape from sources before significant energy-loss should be checked.

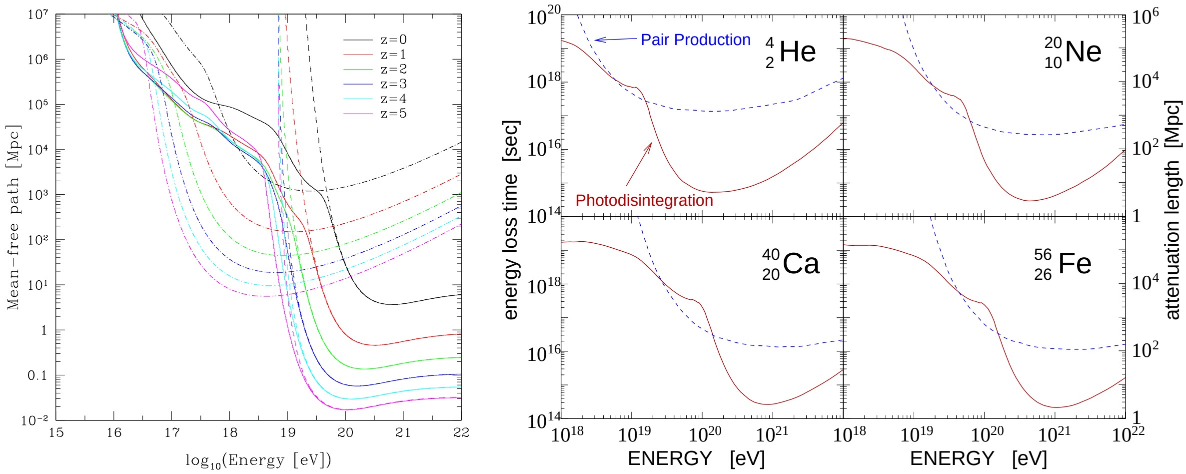

Figure 1: *Left*: Mean free paths of photomeson production and energy-loss lengths of Bethe-Heitler process for protons[20]. *Right*: Energy-loss lengths of photodisintegration and Bethe-Heitler process for several nuclei[21].

interactions better at the highest energies.

UHECR composition not only provides information on their sources but also allows us to estimate the possibility of "cosmic-ray astronomy," in which we can identify UHECR sources and understand their nature by UHECRs. Here, the propagation of UHECRs is essential to research because it connects physics at sources with observables. We review the propagation of UHECRs with particular emphasis on the importance of determining UHECR composition.

2 Interactions with Cosmic Background Photons

2.1 Interactions

The universe is filled by radiation from cosmic microwave background (CMB) and stellar emission (infrared to ultraviolet; extragalactic background light [EBL]). UHECRs interact with these photons inelastically and produce e^+e^- pairs ($N\gamma \rightarrow Ne^+e^-$; Bethe-Heitler process). The threshold energy of this reaction is 6×10^{16} eV for protons in the CMB. At higher energies ($> 6 \times 10^{19}$ eV in the CMB) UHE protons can produce mesons, while UHE nuclei lose their constituent nucleons via giant dipole resonance and/or quasi-deuteron process (photodisintegration). The mesons decay into and generate high-energy electromagnetic particles and neutrinos. These secondary particles also have information on UHECR sources. The energy-loss of UHECRs by these processes dominates that by the Bethe-Heitler process above the threshold energies.

Figure 1 shows mean free paths / energy-loss lengths (attenuation lengths) of these processes. The energy-loss lengths of Bethe-Heitler process are $\sim$ Gpc because inelasticity is the order of $m_e/m_N \sim 10^{-3}$. For protons the mean free path of photomeson production is a few Mpc above 10^{20} eV in local universe ($z = 0$). Since the inelasticity of photomeson production is roughly 20%, observed UHE protons above 10^{20} eV arrive only from nearby universe, typically within 100 Mpc, and therefore the suppression of flux is predicted at $\sim 10^{20}$ eV (Greisen-Zatsepin-Kuz'min [GZK] effect)[8]. A similar effect is expected even for nuclei, but energies where it appears are generally different among nuclear species.

2.2 UHECR Spectrum

The left panel of figure 2 shows a UHECR spectrum observed by the PAO, which has two characteristic features; one is spectral steepening at $\sim 6 \times 10^{19}$ eV and the other is spectral hardening at $10^{18.5}$ - 10^{19} eV, so-called *dip* or *ankle*. In the case of pure proton composition the spectral steepening is well explained by the GZK suppression. This composition scenario can also reproduce the dip structure on the assumption of a steep spectrum and the dominance of extragalactic cosmic rays down to 10^{18} eV by Bethe-Heitler process with CMB photons; the minimum of its energy-loss length in the local universe corresponds to the energy of the dip [12]. The energy scale of UHECR energies has systematic uncertainty in each experiment. The dip position, which well determined by the CMB spectrum and cross-section of Bethe-Heitler process, can be applied for an absolute calibrator of the energy scale. After this dip calibration UHECR spectra of different experiments become consistent within statistical uncertainty. The observed spectral steepening can also reproduced by heavy nuclei dominated composition[b]. Here, a result in the case of pure irons is shown. For more realistic composition scenarios in nuclei dominated composition scenarios, see Ref. 25 for example. Since the steepening energy depends on nuclear species, the dominance of light nuclei in UHECRs is not favored from the observed spectrum. Thus, in ion-dominated scenarios much larger deflections by cosmic magnetic fields are inevitably predicted. Note that the dip generally does not reproduced by Bethe-Heitler process (see the figure), and therefore another component should be responsible for cosmic rays up to $10^{18.5}$ - 10^{19} eV, e.g., Galactic cosmic rays. Thus, the determination of UHECR composition also provides information on transition from Galactic to extragalactic cosmic rays.

Whether the spectral steepening is the GZK suppression (even in nuclear cases) is not clear at present. Another possibility is the maximum acceleration energy of UHECRs by sources. A spectral re-hardening (GZK recovery) above $10^{20.5}$ eV provides a clue of the GZK suppression.

2.3 Secondary Particles

Since the universe is almost transparent for neutrinos, secondary neutrinos (called cosmogenic neutrinos [14]) are expected to provide us with information on the cosmological evolution of UHECR sources. Cosmogenic neutrinos also give information on transition from Galactic to extragalactic cosmic rays [9] and composition of UHECRs [15].

The right panel of figure 2 shows the flux of cosmogenic neutrinos in various models of cosmological evolution and composition [15]. The flux of cosmogenic neutrinos is sensitive to cosmological evolution models of UHECR sources and has uncertainty by about two order of magnitude even for pure proton composition (see also Ref. 20). Thus, the flux will provide a good constraint of cosmological evolution of UHECR sources. Large neutrino detectors, such as IceCube, which completed full construction recently, could access cosmogenic neutrinos in the cases of some reasonable cosmological source evolution models. On the other hand, the cases when heavy nuclei are dominant predict very low flux because secondary nucleons by photodisintegration are main providers of neutrinos. Baryonic resonance can produce mesons and then neutrinos, but this process can work above $10^{21.5}$ eV for irons. Therefore, the flux of cosmogenic neutrinos also provides indirect information on UHECR composition.

On the other hand, UHE electromagnetic particles produced by photomeson production and Bethe-Heitler process interact with cosmic background photons and generate electromagnetic cascade. As a result, secondary UHE electromagnetic particles contribute to extragalactic γ-ray background below 100 GeV [16]. However, the γ-ray background do not provide a strong hint of UHECR sources because of strong competitors such as blazars. Recently, it has been pointed out that the same mechanism is a promising scenario to reproduce the observed spectra of extremely high-peaked BL Lac objects [17]. Note that UHE γ-rays can arrive at the Earth from nearby sources before significant energy-loss, which are a smoking gun of UHECR sources [18].

---

[b]Astrophysicists usually use the word "heavy nuclei" for nuclei up to irons.

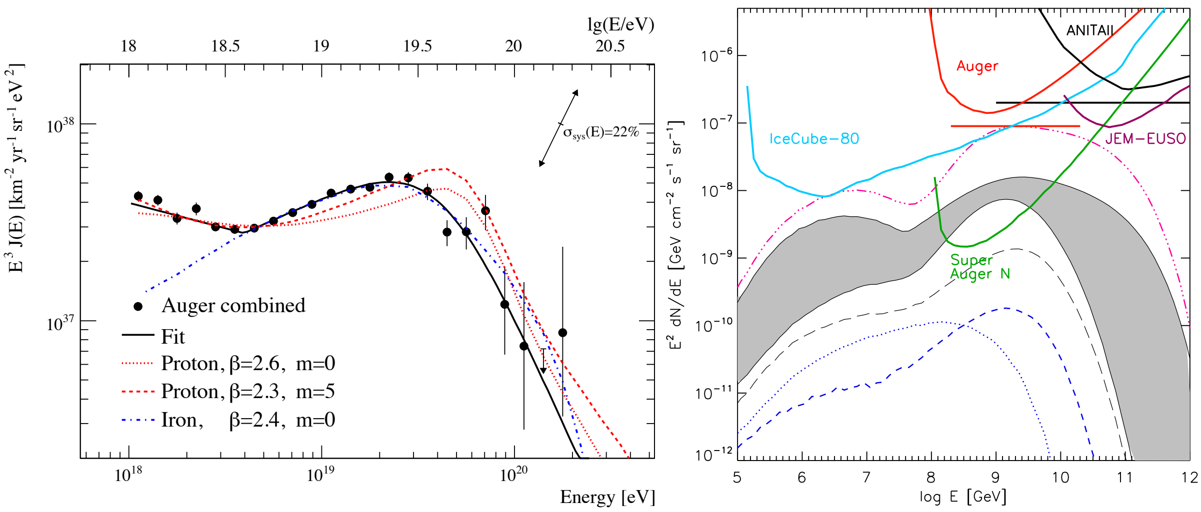

Figure 2: *Left*: UHECR spectrum observed by the PAO and results of spectral modeling[22]. *Right*: Flux of cosmogenic neutrinos calculated in various models[27]. Magenta and black lines and black regions are the flux calculated in different cosmological evolution models of UHECR sources on the assumption of pure proton composition. Blue dotted and dashed lines are calculated for an iron-rich mixed composition model and pure iron composition, respectively, without cosmological evolution of sources.

3 Cosmic Magnetic Fields

The universe is magnetized, although the origin of its magnetic fields is unclear and an important research topic in astrophysics and cosmology. Cosmic magnetic fields, including the Galactic magnetic field (GMF) and extragalactic magnetic fields (EGMFs), affect the propagation of UHECRs. The propagation trajectories of UHECRs are deflected by GMF and EGMFs, so that their arrival directions are generally different from the direction of their sources. This provides difficulty of identifying UHECR sources. However, if the cosmic magnetic fields are weak enough to predict small deflection angles of UHECRs, i.e., even a few degree, the arrival directions of UHECRs give us a direct information on their sources. Thus, the estimation of their deflection angles is important. Here, UHECR composition plays an essential role because the deflection angles are proportional to nuclear number.

The GMF in the Galactic disk is relatively well understood thanks to Faraday rotation measurements from Galactic pulsar. In the disk the GMF has a spiral component with $\sim 3\mu$G roughly following the spiral arm of the Milky Way as well as turbulent components with 0.5 - 2.0 times as large as the spiral component and its correlation length of $< 10^2$ pc [19]. The propagation of UHE protons in the GMF was systematically investigated in Ref. 30 based on the parametrization of the GMF by Ref. 31. The deflection angles of protons depend on their arrival directions, reflecting GMF structures, and typically $\sim 5°$ in bisymmetric spiral field models at $\sim 6 \times 10^{19}$ eV. The propagation of UHE nuclei has been recently studied in detail [22]. Their deflection angles also depend on their arrival directions, and the typical deflection angle of irons is $\sim 50°$ at $\sim 6 \times 10^{19}$ eV. Since the deflection is much larger, it is more sensitive to GMF models than that in the case of protons. Thus, precise understandings of GMF structures are required to estimate the source positions of UHECRs if heavy nuclei are dominant.

On the other hand, the nature of EGMFs is poorly known because of few observational constraints. Faraday rotation measurements of distant quasars indicate $B\lambda^{1/2} < (10\ \mathrm{nG})(1\ \mathrm{Mpc})^{1/2}$ for averaged EGMFs, where λ is the correlation length of EGMFs[23]. The distribution of EGMFs is expected to be structured from numerical simulations as well as matter distribution in the universe [24,25]. Synchrotron radiation of energetic electrons and Faraday rotation measurements indicate that dense regions, i.e., clusters of galaxies, have magnetic fields of ~ 0.1 - a few μG

[26]. However, magnetic fields in the other regions, such as filamentary structures and voids are highly uncertain. Recently, γ-ray spectra of blazars with extremely hard spectral indice implies a lower bound of magnetic fields in voids as $\sim 10^{-18}$ - 10^{-17} G [27]. As for magnetic fields in filamentary structures, detailed simulations of cosmological structure formation with magnetic fields indicates the order of 10 nG [25]. At present, volume filling factors of these magnetized structures highly depend on modeling of EGMFs [28]. Thus, we should keep it in mind that the deflection angles of UHECRs also depend on EGMF modeling in current understandings [24,29], although the typical deflection angle of UHECRs can be simply estimated as $\sim 2.5^\circ Z(E/10^{20}\ \mathrm{eV})(d/100\ \mathrm{Mpc})^{1/2}(B/1\ \mathrm{nG})(\lambda/1\ \mathrm{Mpc})^{1/2}$ for averaged EGMFs. Future surveys of Faraday rotation measurements by Square Kilometer Array will provide further strong constraints on EGMF strength and structures.

3.1 Arrival Direction Distribution of UHECRs

A main motivation to construct larger UHECR detectors is to see anisotropy in the arrival direction distribution of UHECRs, which is expected to reveal source positions directly. Observationally, the PAO reported anisotropy following galaxy distribution in nearby universe [30], whose significance is $\sim 3\sigma$ in the newest data [31]. Conversely, the HiRes did not find significant anisotropy based on the same analysis method as the PAO, although its total exposure is smaller than PAO's [32]. Thus, conservatively, anisotropy at the highest energy is not established yet. However, theoretically, several estimations have indicated possible anisotropy and correlation with nearby sources within a few degree scale on the assumption of pure proton composition [33], although it depends on EGMF modeling. A recent study of anisotropy in ion-dominated composition shows that next generation UHECR experiments can detect anisotropy even in pessimistic cases within ~ 20 - 30°, and a few nearby sources can be observed by UHECRs [34].

Anisotropy is also an indirect way to infer UHECR sources. The anisotropy reported by the PAO indicates that the local number density of UHECR sources is $\sim 10^{-4}\ \mathrm{Mpc}^{-3}$ in proton-dominated composition [35,36]. This number can constrain UHECR sources by being compared with the local number density of known astrophysical objects. As a result, some classes of strong radio galaxies were already disfavored from this number [35]. Although this discussion implicitly assumes steady sources of UHECRs, this number is still meaningful even in the case that UHECRs are produced by transient phenomena, such as GRBs and AGN flares. Considering the delay of arrival time between UHECRs and neutral particles emitted from a source at the same time and the observed UHECR flux, the rate of UHECR production and energy budget required for UHECRs can be constrained [37]. Strategies for these estimations work even in ion-dominated composition, but the power of constraints becomes much weaker because of larger deflection. So, the determination of composition is important even in this viewpoint.

4 Summary

Physics on the propagation of UHECRs has been summarized with highlights of recent progress on UHECR researches and the importance of determining the composition of UHECRs has been demonstrated. Composition measurements are quite important to identify unknown sources and to understand the nature of UHECR sources, which are the primary purposes of UHECR experiments. In order to well understand the composition experimentally it is essential to understand not only the systematic errors of UHECR experiments but also better modeling of hadronic interactions at energies above which particle accelerators can reach. Interactions of UHECRs with photon fields in the universe produce high-energy secondary neutrinos and γ-rays, which have complementary roles to resolve the mystery of UHECR sources.

References

1. E. Waxman, *Phys. Rev. Lett.* **75**, 386 (1995); M. Vietri, ApJ **453**, 883 (1995); K. Murase *et al*, *Phys. Rev.* D **78**, 023005 (2008)
2. P. L. Biermann and P. A. Strittmatter, ApJ **322**, 643 (1987); F. Takahara, Prog. Theor. Phys. **83**, 1071 (1990); C. D. Dermer *et al*, New J. Phys. **11**, 065016 (2009); H. Takami and S. Horiuchi, Astropart. Phys. **34**, 749 (2011)
3. P. Blasi, R. I. Epstein, and A. V. Olinto, ApJ **533**, L123 (2000); J. Arons, ApJ **589**, 871 (2003); K. Murase, P. Meszaros, and B. Zhang, *Phys. Rev.* D **79**, 103001 (2009); K. Kotera, *Phys. Rev.* D **84**, 023002 (2011)
4. H. Kang, D. Ryu, and T.W. Jones, ApJ **456**, 422 (1996)
5. A. M. Hillas, ARA & A **22**, 425 (1984)
6. R. U. Abbasi *et al*, *Phys. Rev. Lett.* **104**, 161101 (2010)
7. J. Abraham *et al Phys. Rev. Lett.* **104**, 091101 (2010)
8. K. Greisen, *Phys. Rev. Lett.* **16**, 748 (1966); G. T. Zatsepin and V. A. Kuz'min, JETP Lett. **4**, 78 (1966)
9. H. Takami *et al*, Astropart. Phys. **31**, 201 (2009)
10. T. Yamamoto *et al*, Astropart. Phys. **20**, 405 (2004)
11. The Pierre Auger Collaboration, arXiv:0906.2189
12. V. Berezinsky, A. Z. Gazizov, and S. I. Grigorieva, *Phys. Lett.* B **612**, 147 (2005)
13. D. Allard, E. Parizot, and A. V. Olinto, Astropart. Phys. **27**, 61 (2007)
14. V. Berezinsky and G. Zatsepin, *Phys. Lett.* B **28**, 423 (1969)
15. K. Kotera, D. Allard, and A. V. Olinto, JCAP **10**, 013 (2010)
16. G. B. Gelmini, O. Kalashev, and D. Semikoz, JCAP **01**, 044 (2012)
17. W. Essey *et al*, ApJ **731**, 51 (2011); K. Murase *et al*, ApJ **749**, 63 (2012)
18. K. Murase, *Phys. Rev. Lett.* **103**, 081102 (2009)
19. R. Beck, Space Sci. Rev. **99**, 243 (2001)
20. H. Takami and K. Sato, ApJ **681**, 1279 (2008)
21. T. Stanev, ApJ **479**, 290 (1997)
22. G. Giacinti *et al*, JCAP **08**, 036 (2010)
23. P. Blasi, S. Burles, and A. V. Olinto, ApJ **514**, L79 (1999)
24. G. Sigl, F. Miniati, and T. A. Ensslin, *Phys. Rev.* D **68**, 043002 (2003); K. Dolag *et al*, JCAP **01**, 009 (2005)
25. D. Ryu *et al*, Science **320**, 909 (2008)
26. J. P. Vallèe, New Astron. Rev. **48**, 763 (2004)
27. K. Dolag *et al*, ApJ **727**, L4 (2011); C. D. Dermer *et al*, ApJ **733**, L21 (2011); K. Takahashi *et al*, ApJ **744**, L7 (2012)
28. K. Kotera and A. V. Olinto, ARA & A **29**, 119 (2011)
29. H. Takami, H. Yoshiguchi, and K. Sato, ApJ **639**, 803 (2006); S. Das *et al*, ApJ **682**, 29 (2008); K. Kotera and M. Lemoine, *Phys. Rev.* D **77**, 123003 (2008)
30. J. Abraham *et al*, Science **318**, 938 (2007)
31. The Pierre Auger Collaboration, Astropart. Phys. **34**, 314 (2010)
32. R. U. Abbasi *et al*, Astropart. Phys. **30**, 175 (2008)
33. E. Waxman, K. B. Fisher, and T. Piran, ApJ **483**, 1 (1997); H. Takami and K. Sato, ApJ **678**, 606 (2008)
34. H. Takami, S. Inoue, and T. Yamamoto, arXiv:1202.2874
35. H. Takami and K. Sato, Astropart. Phys. **30**, 306 (2009)
36. A. Cuoco *et al*, ApJ **702**, 825 (2009)
37. J. Miralda-Escude and E. Waxman, ApJ **462**, L59 (1996); K. Murase and H. Takami, ApJ Lett. **690**, L13 (2009); H. Takami and K. Murase, ApJ **748**, 9 (2012)