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Constraints on Acceleration of Ultra-High-Energy Cosmic Rays in Fermi Gamma-Ray Sources

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We investigate the candidates of accelerator of ultra-high-energy cosmic rays (UHECRs) using the multi-wavelength spectral energy distributions, and discuss about the ability to accelerate UHECRs and constrain their physical conditions (acceleration site and size). The current experimental statistics of UHECRs is not sufficient for identification of the sources, although a spatial correlation between the arrival directions of UHECRs and nearby active galactic nuclei (AGNs) has been discussed using the data of the Pierre Auger Observatory and the Telescope Array. Some authors have discussed about the acceleration of UHECRs using various methods. Among them, Pe'er & Loeb (2012) derived constraints on the ability of AGNs to produce UHECRs by using observational quantities which are synchrotron peak luminosity and the peak flux ratio of inverse Compton scattering to synchrotron emission. For adopting this method, we need data of gamma-ray observation to determine the peak flux for high-energy region due to inverse Compton scattering. Thus, we focused on the Fermi Large Area Telescope gamma-ray sources. We investigated a spatial correlation between AGNs and the arrival directions of UHECRs, and we selected six AGNs as candidates of accelerator of UHECRs. We analyzed their spectral energy distributions by using multi-wavelength archival observational data. By introducing the constraints of Pe'er & Loeb (2012), we evaluate the physical conditions in the acceleration regions of these six AGNs and discuss whether they can accelerate to UHECRs. From the analysis, we found that three AGNs have ability to accelerate UHE protons to UHECRs in the AGN cores. Furthermore, we constrained the minimum size of the acceleration region for each source when UHE particles are accelerated in the AGN lobes. If UHE protons are accelerated, a few kpc-100 kpc are required as the minimum acceleration size. In the case of acceleration of heavy nucleus, the heavy particles can be accelerated in the AGN lobes if the size is larger than a few kpc. In this paper, we show that we achieved to establish a test method for individual candidate sources of acceleration of UHECRs.

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1. Introduction

The origin of cosmic rays is one of the important astrophysical problems. The acceleration sites and the acceleration mechanism of cosmic rays remain unsolved since their discovery 100 years ago. The arrival directions of cosmic rays that are observed at the Earth do not match with the position of actual source because cosmic rays have electric charges and deviated due to the Galactic magnetic field during the propagation from the source to the Earth. Thus, it is difficult to identify the origin of cosmic rays using the arrival directions of cosmic rays. Ultra-high-energy cosmic rays (UHECRs) ($E > 10^{18}$ eV) are believed to be coming to the Earth while keeping the information of direction of sources. The leading candidate sources of UHECRs are thought to be accelerated by, for example, gamma-ray bursts (e.g., [1]) and large-scale astronomical sources like active galactic nuclei (AGNs) (e.g., [2] [3]). Recently, a spatial correlation between UHECRs and nearby AGNs has been discussed using the data of the Pierre Auger observatory ($E > 5.7 \times 10^{19}$ eV) [4] and the Telescope Array ($E > 5.5 \times 10^{19}$ eV) [5]. However, it is hard to constrain the origin of UHECRs strongly only by a spatial correlation, because the statistics of UHECRs is not sufficient due to the current sensitivity of the cosmic-ray telescopes. By using these data, some authors have carried out the correlation studies with more detailed statistical methods (e.g. [6] [7]). However, UHECR data with more statistics are needed to draw a decisive conclusion from UHECR experiments. Here, to discuss the origin of UHECRs, multi-wavelength observations and its spectral energy distribution can be additional important clues. Some authors have discussed about acceleration of UHECRs using multi-wavelength observations (e.g., [8], [9] and [10]). Among them, Pe'er & Loeb (2012) [10] derived constraints on the capability of AGN to produce UHECRs by using observational quantities which are synchrotron peak luminosity and the peak flux ratio of inverse Compton scattering to synchrotron emission. However, the characteristics of individual AGNs have been scarcely discussed with multi-wavelength observations except for famous high-energy source (e.g., Centaurus A and M87). Thus, we focused on the possibility that is the other AGNs can become the candidate sources for accelerator of UHECRs. To discuss a possibility of UHECRs acceleration using multi-wavelength spectral energy distributions, we need the gamma-ray observation data to decide the peak flux for high-energy region due to inverse Compton scattering. Therefore, we used the third gamma-ray source catalog (3FGL) which has been compiled by using data of the Fermi satellite launched in 2008 [11] to search candidate sources. After that, we discussed whether the candidate sources can accelerate UHECRs by using Pe'er & Loeb method.

Throughout this paper, we use the standard cosmology parameter (Ω_m = 0.3, Ω_Λ = 0.7, with H_0 = 70 km s^{-1} Mpc^{-1})

2. Search for AGN as Source Candidates of UHECRs

We selected the candidates of accelerator of UHECRs through the following steps: (1) we first investigated the spatial correlation between UHECRs detected by the Pierre Auger Observatory [4] or Telescope Array [5] and gamma-ray sources in the 3FGL [11]. We selected the AGNs with more than 1 UHECR within 4° from the position in the gamma-ray catalog. The selected region of 4° is based on the typical uncertainty of the arrival direction of UHE particle due to the deflection by

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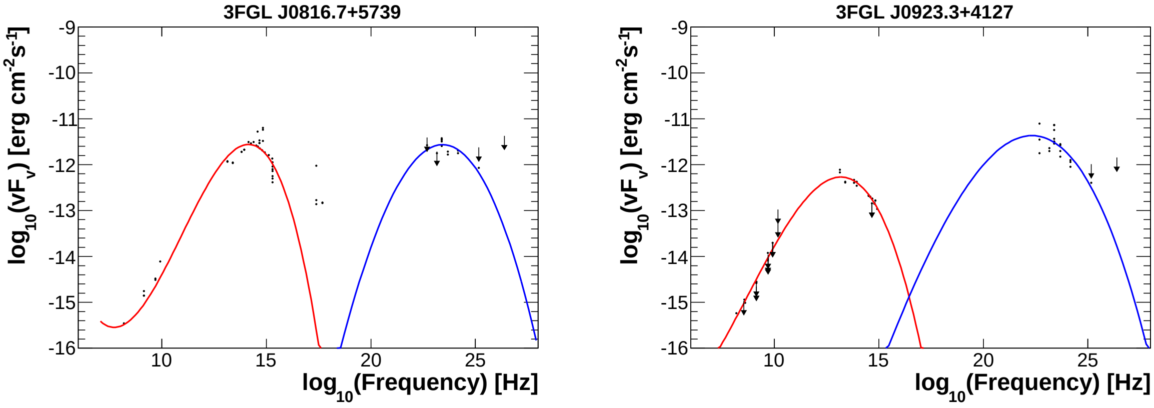
[*] Speaker.

Galactic magnetic field [12]. If heavy nucleus are accelerated, the deflection angle is possible to be larger than the case of protons. In this paper, we assumed the average deflection angle. In the case of the northern hemisphere, we used the observation data of Telescope Array. We used the observation data of Pierre Auger Observatory for the southern hemisphere. We found 183 AGNs that have the spatial correlation with UHECRs. (2) we selected the AGNs that has the redshifts (z) less than 0.1. This is because UHECRs above $10^{19.5}$ eV are expected to come from nearby extragalactic sources, since the energy loss by pion photoproduction or photodisintegration (e.g., [13], [14], [15]) with microwave background photons limits the propagation length to z$\sim$0.1. (3) the gamma-ray sources related to Centaurus A and M87 were excluded. They have been already studied as UHECR sources in detail (e.g., [10]). Finally, we found six AGNs as candidates of accelerators of UHECRs (see Table 1).

3. Results

We investigated the observation data with multi-wavelength using the archival data from the ADI Science Data Center (ASDC) [17]. An AGN has a spectral energy distribution with a wide energy range, resulting from high-energy electrons producing synchrotron emission at low energies, and high-energy emission via inverse Compton scattering (IC) process. Each peak flux is shown by $(\nu F_\nu)_{\mathrm{peak,sync}}$ and $(\nu F_\nu)_{\mathrm{peak,IC}}$, respectively. By using the ratio of two peak fluxes $Y = (\nu F_\nu)_{\mathrm{peak,IC}}/(\nu F_\nu)_{\mathrm{peak,sync}}$, we can evaluate the physical conditions in the acceleration region of these AGNs (see section 4). Thus, we need to decide each peak flux by fitting the observed data. We fitted the data with polynomial function in order to phenomenological reproduce spectrum [16]. Fig. 1 shows the spectral energy distributions of each AGNs. The lines show the result of fitting for each energy region. The characteristics of each AGN, the peak flux of each emission region and the ratio of the peak flux are shown in Table 1.



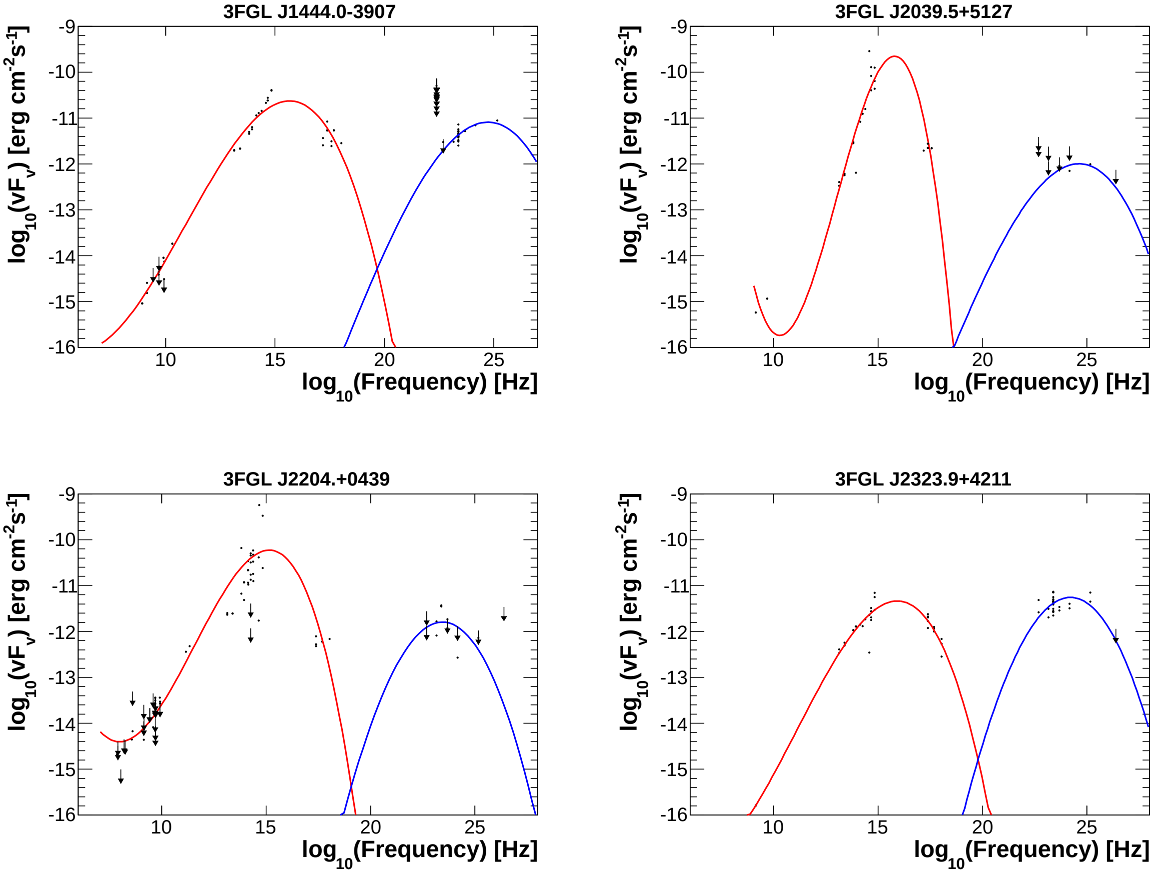


Figure 1: Spectral energy distributions of six selected AGNs. We plotted the result of multi-wavelength observations using ASDC [17]. Red line shows the result of fitting for the low-energy region due to synchrotron. Blue line shows the result of the fitting for high-energy region due to inverse Compton scattering. We used the data from the radio to X-ray for the low-energy region, and used gamma-ray data for the high-energy region.

Table 1: The characteristics of the candidates source of accelerator of UHECRs

Source Name	Ra (J2000) [deg]	Dec (J2000) [deg]	Redshift (z)	$(\nu F_\nu)_{\rm sync}$ [erg cm^{-2} s^{-1}]	$(\nu F_\nu)_{\rm IC}$ [erg cm^{-2} s^{-1}]	Y
3FGL J0816.7+5739	124.1827	57.6603	0.054	2.76×10^{-12}	2.72×10^{-12}	0.99
3FGL J0923.3+4127	140.8460	41.4634	0.028	5.37×10^{-13}	4.30×10^{-12}	8.00
3FGL J1444.0−3907	221.0090	−39.1299	0.065	2.36×10^{-11}	8.13×10^{-12}	0.34
3FGL J2039.5+5217	309.894	52.2984	0.053	2.23×10^{-10}	1.01×10^{-12}	0.005
3FGL J2204.4+0439	331.1039	4.6657	0.027	5.92×10^{-11}	1.61×10^{-12}	0.03
3FGL J2323.9+4211	350.9813	42.1839	0.059	3.81×10^{-12}	5.25×10^{-12}	1.38

Source name, right ascension and declination are cited from the 3FGL [11]. The redshifts are cited from NASA/IPAC Extragalactic Database [18], and the Roma BZCAT-5th edition [19]. The peak fluxes and the ratio of peak fluxes are obtained from the fitting (Fig. 1).

4. Discussion and Summary

By using the fitting results, we constrained the physical condition (e. g., acceleration site and size). We discussed a possibility of UHECRs acceleration in the turbulent outflow (see section 4.1) or at the termination shock of the giant AGN lobes (see section 4.2) using the synchrotron peak luminosity and the ratio of peak fluxes.

4.1 The possibility of acceleration in the AGN core

UHE photons from an AGN are typically produced by inverse Compton scattering of high-energy electrons with the low energy photons emitted by the synchrotron radiation from the same electrons (SSC model). If so, the ratio of the fluxes at high and low photon energies can be used as a probe of the physical conditions in the AGN cores.

Firstly, we briefly explain the conditions of Pe'er & Loeb (2012) [10]. Assuming that UHECRs acceleration results from electromagnetic process within an expanding plasma, the requirement that the accelerated particles are confined to the acceleration region is equivalent to the requirement that the acceleration time is shorter than the dynamical time. In the case that a primary source of emission in AGNs is the core, a constraint on the minimum synchrotron luminosity that is needed for a source to be able to produce UHECRs can be written as,

$$L_{\mathrm{peak,sync}} \geq 4.1 \times 10^{44} Y \left(\frac{\eta \mathrm{E}_{20}^{\mathrm{ob}}}{Z} \right)^{2} \beta^{2} \delta^{2}. \tag{4.1}$$

Here, $L_{\mathrm{peak,syn}}$, $Y = (\nu F_\nu)_{\mathrm{peak,IC}}/(\nu F_\nu)_{\mathrm{peak,sync}}$, $\mathrm{E}_{20}^{\mathrm{ob}}$ and $\delta = \left[\Gamma\left(1-\beta\cos\theta^{\mathrm{ob}}\right)\right]$ are peak synchrotron luminosity, ratio of peak flux for synchrotron emission and inverse Compton scattering, observed energy of the particle in unit of 0.5×10^{20} eV and the Doppler factor for an observing angle θ^{ob}, respectively [10]. $\eta \geq 1$ is a dimensionless factor, whose exact value is determined by the uncertain details of the acceleration mechanism. Γ and β are the Lorentz factor and characteristics velocity within the sources. We assumed $(\eta \mathrm{E}_{20}^{\mathrm{ob}}/Z)\beta\delta = 1$ and $\mathrm{E}_{20}^{\mathrm{ob}} = 0.5\times10^{20}$ eV, where Z is the atomic number of proton, silicon and iron, respectively (proton: Z = 1, silicon: Z = 14, iron: Z = 26). Fig. 2 shows the allowed region of the synchrotron luminosity as a function of $(\nu F_\nu)_{\mathrm{peak,IC}}/(\nu F_\nu)_{\mathrm{peak,sync}}$.

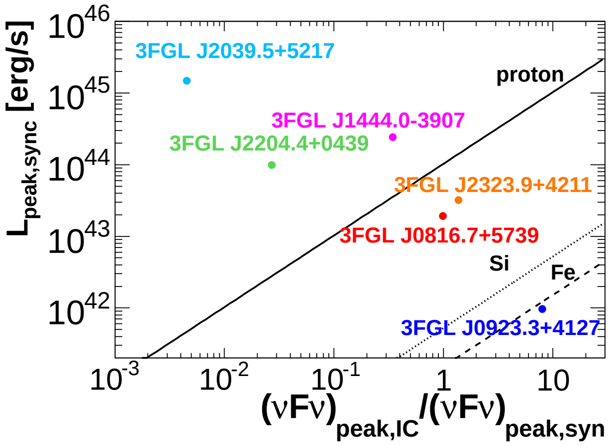


Figure 2: The calculated values for each AGNs are marked. The solid line, dotted line and dashed line show the boundaries that is capable of accelerating UHECRs, as a function of $Y = (\nu F_\nu)_{\mathrm{peak,IC}}/(\nu F_\nu)_{\mathrm{peak,sync}}$. We assumed $(\eta \mathrm{E}_{20}^{\mathrm{ob}}/\mathrm{Z})\beta\delta = 1$, where $\mathrm{E}_{20}^{\mathrm{ob}} = 0.5 \times 10^{20}$ eV, and Z is the atomic number of proton, silicon and iron, respectively (proton: $Z = 1$, silicon: $Z = 14$, iron: $Z = 26$).

For the previous study of Centaurus A and M87, Pe'er & Loeb reported that UHECRs cannot be accelerated in the AGN cores, unless UHECRs are composed of heavy nuclei [10]. However, we found that three AGNs (3FGL J1444.0−3907, 3FGL J2039.5+5217 and 3FGL J2204.4+0439) have abilities to accelerate UHECRs in the AGN cores even if the UHECRs are composed ultra-high-energy protons. For 3FGL J0816.7+5739 and 3FGL J02323.9+4211, UHECRs are accelerated in the AGN cores if UHECRs are composed heavy elements such as silicon and iron. In the case of 3FGL J0923.3+4127, UHECRs are unlikely to be accelerated by the AGN core even if the accelerated element is iron. From these results, we suggested that the three AGNs have ability of acceleration of UHE protons in the AGN cores.

4.2 The possibility of acceleration in the AGN lobe

In the case of the acceleration of UHECRs in the AGN lobes, the seed photons for the inverse Compton scattering in this region are thought to be the cosmic microwave background (CMB) or extra-galactic background light (EBL). The minimum size of acceleration region is calculated by Eq. 4.2.

$$R_{\rm acc} \geq \left(\frac{(\nu F_\nu)_{\rm peak,IC}}{(\nu F_\nu)_{\rm peak,sync}}\right)^{1/2} \left(\frac{1}{8\pi u_{\rm ex}}\right)^{1/2} \left(\frac{\eta {\rm E}^{\rm ob}_{20}}{Z}\right) \beta\delta \tag{4.2}$$

Here, $u_{\rm ex}$ is the energy density of CMB/EBL radiation fields. In this paper, we conservatively used $u_{\rm CMB} \simeq 4\times10^{-13}$erg cm^{-3} [10]. We assumed $(\eta {\rm E}^{\rm ob}_{20}/Z)\beta\delta = 1$ and ${\rm E}^{\rm ob}_{20} = 0.5\times10^{20}$ eV. We can constrain the acceleration size by Eq. (4.2). Fig. 3 shows the minimum acceleration size as a function of the ratio of peak fluxes, and we indicated the minimum acceleration size in Table 2.

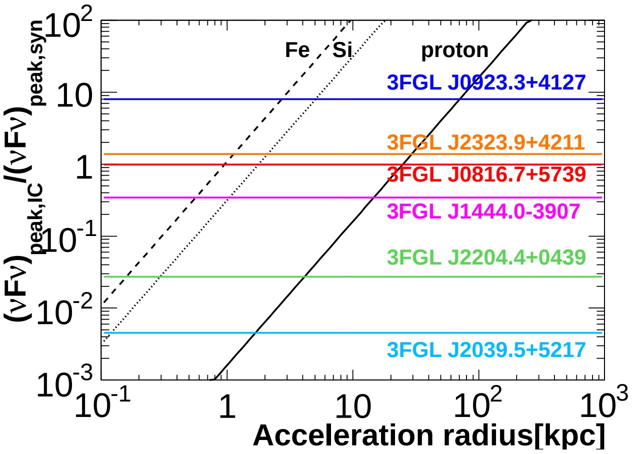


Figure 3: Minimum size of acceleration region that allows acceleration of UHECRs to 0.5×10^{20} eV, as a function of the ratio Y. The solid line, the dotted line and dashed line show the boundaries that are the case of proton, silicon and iron, respectively (proton: $Z=1$, silicon: $Z=14$, iron: $Z=26$). The color horizontal lines show the ratio of the peak flux of each AGN. The intersection points show the minimum size of the acceleration region, and the right side of the each point allows the acceleration of UHECRs.

PoS(ICRC2015)530

Table 2: Minimum acceleration size (R_{acc}) of each AGNs

Source Name	R_{acc} (proton) [kpc]	R_{acc} (Si) [kpc]	R_{acc} (Fe) [kpc]
3FGL J0816.7+5739	24.84	1.77	1.03
3FGL J0923.3+4127	70.72	5.05	2.94
3FGL J1444.0−3907	14.67	1.05	0.61
3FGL J2039.5+5217	1.68	0.12	0.07
3FGL J2204.4+0439	4.11	0.29	0.17
3FGL J2323.9+4211	29.33	2.10	1.22

From these results, we constrained the minimum size for acceleration of UHECRs at the AGN lobe. In the case that accelerate nucleus are protons, the lobe size is required a few kpc-100 kpc. On the other hand, for heavy nucleus, the minimum acceleration size is about 0.1- a few kpc.

4.3 Summary and Future plan

We discussed whether the selected AGNs can accelerate UEHCRs using the peak synchrotron luminosity and the ratio of peak fluxes. We found that three AGNs have the ability to accelerate UHECRs in the AGN cores even if the UHECRs are composed of UHE protons. Also, we found that the other two AGNs can accelerate UHECRs which are composed of heavy nuclei such as silicon and iron. Furthermore, we constrained the minimum acceleration size of the AGN lobes. If UHE protons are accelerated, the acceleration size is required a few kpc-100 kpc. In the case of acceleration of heavy nucleus, they can be accelerated in the AGN lobes if the size is larger than a few kpc. From these results, we achieved to establish a test method for individual candidate sources, although the systematic discussions of the possibility of acceleration of UHECRs had been scarcely done so far. We note that the composition of UHECRs is still debated. Telescope Array group shows that protons are accelerated to UEHCRs energies [20]. However, the Pierre Auger Observatory group reported the $X_{\max}$ distributions show that the heavy nucleus become dominant for composition of UHECRs as the energy increases [21]. Acceleration of high-energy-protons is not ruled out from the results of our investigations. It is suggested that UHE protons can be accelerated in the AGN cores.

When we investigated the spatial correlation between UHECRs and AGNs in the 3FGL, we found 69 AGNs that are not known these redshifts. Furthermore, we found 120 unidentified gamma-ray sources that have the spatial correlation with UHECRs. These sources could be candidates of accelerator of UHECRs. We have a plan that we observe these sources with optical telescopes to determine the redshifts and the types of gamma-ray sources. If the sources are AGNs and less than $z < 0.1$, we can discuss whether the sources can accelerate UHECRs using the method in this paper. Some sources have been already observed by SOAR 4 m optical telescope.

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