A study of analysis method for the identification of UHECR source type

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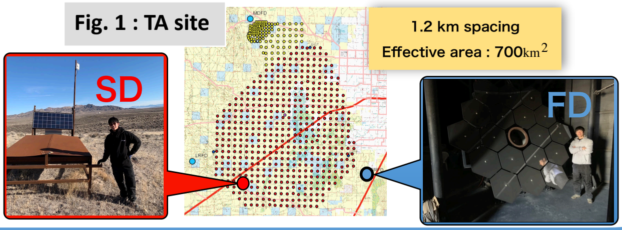
Abstract

The autocorrelation analysis using the arrival direction of Ultra High Energy Cosmic Rays (UHECR) has been previously reported by the Telescope Array (TA) experiment. It is expected that the autocorrelation function reflects the source distribution. We simulate the expected arrival direction distribution of the cosmic rays using the catalogs of candidate sources. We take into account random deflection in the magnetic fields, with the magnitude of deflection determined by the charge and energy of the cosmic rays, coherence length and magnitude of the extragalactic magnetic field, and by distance to source. In addition, in order to compare with the results of TA, we consider the TA exposure. We compare the autocorrelation of the arrival directions corresponding to different source catalogs with the isotropic distribution. We calculate the autocorrelation function for each type of source candidates using this procedure. We will discuss the ability of this method to identify the source type of UHECRs.

• Telescope Array Experiment

The TA experiment aims to identify the origin of ultra-high energy cosmic rays from observations using two types of detectors, Surface Detector (SD) and Fluorescence Detector (FD) , installed in Utah, USA, since 2008 [1].
The TA experiment has so far captured the signs of the UHECR's concentration from the direction of Ursa Major, based on 11 years of observations [2]. The TA experiment is continuously observing continues observations to verify these results. In addition, the TA x 4 experiment has partially started in 2019, enabling higher statistics observations [3].

Fig. 1 : TA site



• Autocorrelation Function

The clustering of CR events at a given angular scale appears in the autocorrelation function of the events [4][5]. The autocorrelation function is determined by the excess of pairs of events separated by a given angular distance δ as compared to a uniformly distributed set with the same total number of events. The procedure is as follows: for a given separation angle ψ, we count the number of pairs of data events that are separated by an angular distance δ less than ψ. Next, we generate a large number of uniformly distributed MC event sets that take into account TA exposure with the same number of events as the real dataset. In each MC set we count pairs of events in the same way as in the data, which gives the MC count for that set. For each value of ψ we then determine the fraction of simulated sets where the number of pairs is greater than or equal to the number of pairs in the data. This gives the P(ψ). When the value of P(ψ) is small, it means that the number of pairs is excessive (not uniform) at a certain angular scale. The clustering of UHECR events at E > 57EeV observed by the TA experiment (Fig. 2) shows the largest excess at distances between the events of about 20° and 30° [6]. I thought that This autocorrelation function would might reflect the distribution of the source.Therefore, we came up with the idea we may be able it might be possible to identify the source type from the characteristics of the autocorrelation function assuming the arrival direction from source.

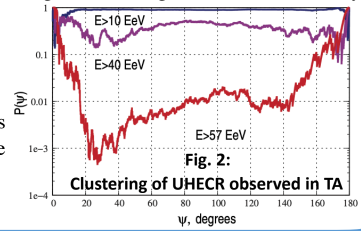


Fig. 2: Clustering of UHECR observed in TA

• Method

1. Selection of UHECRs source candidates from astronomical catalogs.
2. Simulation of arrival direction of cosmic ray assuming the source candidates.
3. Calculation of the autocorrelation function.
4. Comparison of the autocorrelation function between MC and the data.

• UHECRs Source Candidates

- Using the source list[7] presented at ICRC2019.
  - Assuming Radio Galaxies (RGs) as the likely origin of UHECR.
  - A list of 42 objects with 5 parameters (RA, Dec, P_1 [J_y], d [Mpc], type)

P_1/J_y : radio flux of the steep spectrum component of the source at 1GHz, d /Mpc : source distance, Type: FR-I, FR-II, SSRQ , BLU, BLO

- Since it is unlikely that cosmic rays arrive with uniform probability from 42 radio galaxies, we determined the fraction of events arriving from radio galaxies based on the ratio of P_1 to the cosmic ray flux F_{CR} arriving at Earth from celestial objects.

$$F_{CR} \propto \frac{1}{4\pi d^2}(4\pi d^2 P_1)^{\beta_L}$$

β_L : The relationship between the radio flux and the power of the jet is experimentally determined and is one of the parameters used to convert it to CR flux (for details, see [8].

• Expected Arrival Directions of CR

i) The accumulated deflection angle for propagation over a distance.

Ref. [9]

$$\theta \cong Z \times 0.25^\circ \left(\frac{d}{\lambda_B}\right)^{\frac{1}{2}} \left(\frac{\lambda_B}{1\,Mpc}\right)\left(\frac{B}{10^{-9}\,G}\right)\left(\frac{E}{10^{20}\,eV}\right)^{-1}$$

Z : charge number d : distance to source λ : coherence length B : magnetic field E : energy

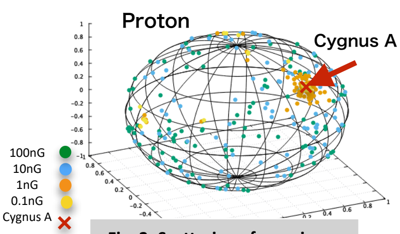
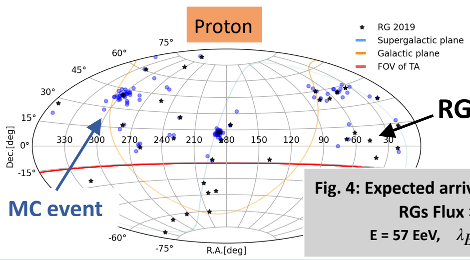


Fig. 3: Scattering of cosmic ray protons arriving from Cygnus A

ii) Assuming random walk

Since cosmic rays do not always scatter at the same angle, but scatter stochastically, the degree of scattering in the direction of arrival is reproduced using the von Mises Fisher distribution, which is a two-dimensional Gaussian distribution on a sphere. Fig. 3 shows the degree of scattering of cosmic ray protons from Cygnus A in the RGs list, and Fig. 4 shows the arrival direction distributions of cosmic ray proton and iron expected from the RGs list.



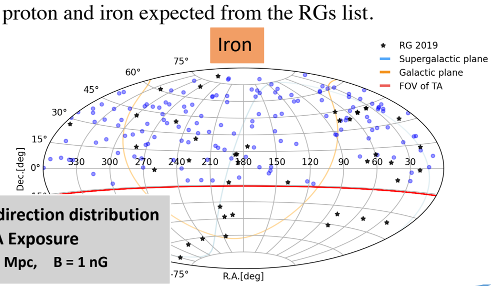


Fig. 4: Expected arrival direction distribution
RGs Flux × TA Exposure
E = 57 EeV, λ_B = 1 Mpc, B = 1 nG

• Autocorrelation of Arrival Direction Distribution

Examine the correlation of arrival directions between MC events. The autocorrelation function is calculated by comparing n^{iso}_{corr} and n^{MC}_{corr}. The distribution of P(ψ) is obtained by comparing the 10^2 set of MC distributions with the 10^5 set of isotropic MC distributions, since the distribution of arrival directions expected from the RGs list varies from simulation to simulation even under the same conditions. For each separation angle ψ, determine the median P_{med} of the distribution and the 68% region $P_{\pm 34\%}$ from it. Fig. 5 shows the results of the clustering excess of CR arriving from radio galaxies obtained from the simulation.

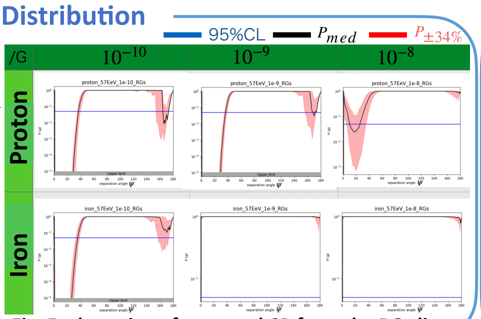


Fig. 5: clustering of expected CR from the RGs list

• Summary

We calculated the autocorrelation function of the expected CR arrival direction distribution from the RGs list. The results in Fig. 5, when assuming three types of magnetic fields and two types of nuclei, each show a characteristic structure. When the deflection is large, the distribution is almost isotropic. When the deflection is small, the change in the distribution is very small. In order to further confirm these results, we would like to determine the cosmic ray energy according to the energy spectrum of the source and to consider the energy loss distance by GZK suppression for each particle species.We also hope to increase the number of data sets of isotropic MC and MC direction of arrival distributions, so that We may be able to check the minimum value of P(ψ).
And we would like to use this analysis method for different source types.

Reference

[1]T. Abu-Zayyad et al., Nucl. Instrum. Meth. A 689, 87 (2012) [2]K. Kawata et al., PoS(ICRC2019)310 [3]E. Kido et al, PoS(ICRC2019) 312, [4] Abu-Zayyad, et al.,The Astrophysical Journal, 757:26(11pp), 2012 September 20 [5]P. Tinyakov et al., PoS(ICRC2015) 326 [6]PTEP, **2017**, 12A104 [7]J.P.Rachen, et al., ICRC2019, Pos 396 [8]B.Eichmann, JCAP 05 (2019) 009 [9]M.Nagano, et al.,Rev. Mod. Phys., Vol. 72, No. 3, July 2000