論文内容の要旨

Large Scale Anisotropy of Ultra-High Energy Cosmic Rays measured by Telescope Array Experiment

(テレスコープアレイ実験で測定した極高エネルギー宇宙線の広域異方性)

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1. Introduction

Telescope Array (TA) experiment observes the extensive air showers generated by Ultra-High Energy Cosmic Rays (UHECRs) using an array of Surface particle Detectors (SDs) and air Fluorescence Detectors (FDs). The TA is installed in the desert of Utah, USA, about 1400 m above sea level and at the location of 39.3° N and 112.9° W. Both SDs and FDs are used to reconstruct the energy, arrival direction and particle composition of the primary UHECR.

The cosmic rays consist mostly of charged particles, such as the proton and nucleus, and have a power law energy spectra extended up to 100 EeV (=10^{20} eV) or higher. Its arrival directions are highly isotropic owing to the random magnetic deflections caused by the space magnetic field during the propagation from the source to the Earth. So far, no astronomical object is identified as the source of cosmic rays, but this may change by the emergence of new large scale UHECR detectors such as the TA and Pierre Auger Observatory (PAO). First, relatively small magnetic deflections are expected by the Galactic Magnetic Field (GMF) for UHECR protons with energies above 10 EeV. Second, the interaction of UHECR protons with Cosmic Microwave Background (CMB) photons predicted by Greisen-Zatsepin-Kuzmin (GZK) limit the range of arriving UHECRs to relatively nearby galaxies (distance D $< \sim$100 Mpc) for energies above $\sim$50 EeV.

The PAO operated in Argentina claims the correlation between UHECR arrival directions for E $>$ 57 EeV and the location of the Active Galactic Nuclei (AGN) in the southern hemisphere sky, despite the PAO observes the mass composition above 10 EeV gradually changing from the proton to heavier nuclei. The slant depth of the shower maximum, Xmax, observed by the TA FD however indicates that the mass composition of UHECRs is dominantly proton for 2.5-25.0 EeV. The Xmax data of TA shows no indication of changing to heavier component at higher energies.

In this thesis, we report our search for the correlation of UHECRs with the local Large Scale Structure (LSS) of galaxies using TA SD data. We assume that the number of galaxies is a good tracer of the matter density distribution in the Universe, and the UHECR sources are distributed according to the matter density. We simulated the expected flux of UHECR protons by this condition and compared the result with the measured directions of UHECRs.

2. Telescope Array Detector

The air shower array of TA consists of 507 SDs deployed in 1.2 km spacing, covering the ground area of about 700 km^2. The area of SD is surrounded by 3 sets of FD stations, each with 12-14 fluorescence telescopes of 3 m diameter spherical mirrors and PMT mosaic cameras of 1° pixel resolution.

There are two layers of 3 m^2, 1.2 cm thick plastic scintillators in each SD. The scintillation light from each layer of scintillator is read out by a PMT using wave length shifter fibers. The waveform of the scintillator is read out when there are 3 or more adjacent SDs hit by 3 or more charged particles within 8 μsec coincidence window. Each waveform is stamped by the GPS timing of an accuracy of ∼11 ns. The location of each SD is determined by the same GPS to an accuracy of ∼50 cm in horizontal directions and ∼100 cm in vertical direction. The data acquisition was made using a commercial wireless LAN network module. The calibration of SD is performed every 10 minutes by histogramming the energy deposit of all the penetrating muons (∼ 700 Hz) at each SD.

3. Event Reconstruction

The geometry of an air shower (arrival direction) is reconstructed using the leading edge timing of hit SDs. The core location and the SD energy deposit with respect to the shower core location are then fitted by an empirical lateral distribution function (LDF). After several iterations between geometry and LDF fits, the energy deposit at 800 m from the shower core is determined from the LDF, which is then compared with the expectation of the Monte Carlo (MC) simulation of extensive air showers to determine the primary UHECR energy.

Using a set of hybrid events, for which the energies were measured both by SD and FD, we re-scaled the energy of all the SD events by -27% such that the SD measured energy equals with the FD measured energy. This is done because the energy by FD is determined experimentally whereas the energy by SD entirely relies on the air shower MC simulation with significant ambiguities of hadronic interaction models at ultra-high energy.

To keep the accuracy of reconstruction, the distance from the shower core to the array boundary is required to be larger than 1.2 km and the reconstructed zenith angle of the shower is required to be smaller than 45°. The trigger and reconstruction efficiency of the TA SD array reaches almost 100% when the energy of UHECRs is above 10 EeV with these conditions. The observation with the SD array is continuous to have a duty cycle close to 97%, which gives no seasonal bias for the acceptance. These features are important to explore the anisotropy of arrival directions.

For the following analysis, we use SD events collected for 3 years from May 11, 2008 to May 1, 2011. The number of events are 856, 49 and 20 for 3 different energy thresholds of E >10, 40 and 57 EeV. The threshold of 40 and 57 EeV are chosen following the preceding claim of event clustering and the AGN association (by AGASA and PAO experiments). The energy and angular resolution of the reconstructed data is estimated to be about 20% and 1.5° above 10 EeV.

4. Simulation of Expected Flux

Expected flux maps from the local LSS of the matter are calculated using the galaxies listed in 2 Mass Extended Source Catalogue (XSCz). In order to represent the LSS matter distribution, we selected those galaxies in the XSCz catalog for the distance less than 250 Mpc and with an apparent magnitude less than 12.5 in the Ks band (2.2μm). We assumed a constant matter distribution beyond 250 Mpc. The galaxies within 5 Mpc was not included to avoid non-statistical overweight (∼ D^{-2}) from these galaxies. The number of darker galaxies below the limit of 12.5 was estimated at each distance and additional weight was attached to the selected galaxies.

We assumed all the selected galaxies have the same equal UHECR (proton) flux at the origin with an energy spectrum of $E^{-2.62}$. The expected flux on the Earth was then summed up considering the energy modulation during the propagation from the origin to the Earth. The energy dissipation by the interaction with the CMB and by the redshift of the expanding universe was considered. The interaction of the UHECR proton with the CMB includes the photo-production of pions and the pair production of e^+e^-.

The deflection by the GMF was implemented by using a spiral disk model of P.Tinyakov et al. and a toroidal halo model of M.Prouza et al. as shown in Fig.1. The strength and the thickness of the halo field was chosen such that they consistently explain the Faraday rotation measures compiled by M.Pshirkov et al. based on NRAO VLA Sky Survey data, and the observed isotropy of UHECR arrival directions above 10 EeV. The calculation of the GMF deflection was made by ejecting the anti-proton isotropically from the Earth and compiling the results at 100 kpc.

A Gaussian smearing is further added to the calculated flux to represent the deflections by the random component of the galactic and the extra-galactic magnetic field, and the experimental resolution of the arrival angle determination. We assumed a constant smearing angle (σ_s) independent of the UHECR energy. The final flux map, with σ_s between $3° - 25°$ as a free parameter, was produced by weighting the geometrical exposure of the TA SD array.

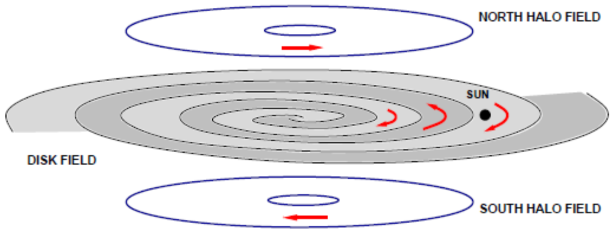

Figure 1: Schematic view of the Galactic Magnetic Fields (from M.Pshirkov et al.).

The expected flux map obtained for each σ_s was compared with the skymap of measured UHECRs. The compatibility of the UHECR (data) and the expected flux (model) was checked by using the one dimensional (in the flux) Kolmogorov-Smirnov (KS) test for three models;

- isotropic flux distribution (**isotropy model**)
- flux distribution of protons originated in the XSCz galaxies and arriving the Earth without having the GMF deflections (**LSS proton model without GMF**)
- flux distribution of protons originated in the XSCz galaxies and arriving the Earth experiencing the GMF deflections (**LSS proton model with GMF**)

5. Results and Discussion

Skymaps of observed UHECRs by TA SD array are shown for energy thresholds of E > 10, 40 and 57 EeV together with the expected flux from the **isotropy model** (Figure 2) and from the **LSS proton model with GMF** (Figure 3). Green points indicate the arrival directions of UHECRs in the Galactic coordinate. Shaded areas (in 5 steps) correspond to the level of the flux, the darker the higher flux, and each shaded area contains one fifth of the total expected flux. This way of shading means that the consistency of the data with the model is best demonstrated when each shaded area is equally populated with the UHECR events.

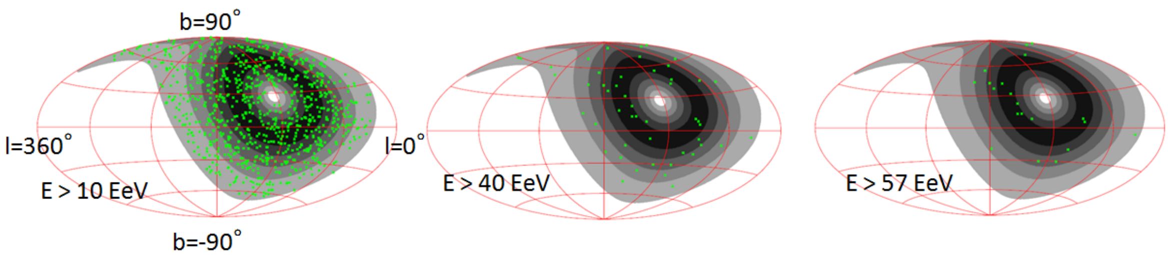

Figure 2: Skymap of UHECRs overlaid with the expected flux from the isotropy model.

Fig.4 shows the KS test probability for 3 models. The abscissa is the parameterized Gaussian smearing angle (σ_s) and the ordinate is the KS compatibility (p-value) of the data with the tested models. The p-values corresponding to 5% and 0.3% confidence level (CL) are also indicated by horizontal lines.

The compatibility of UHECR data with the isotropy model is indicated by black triangles in Figure 4. It is independent of the smearing angle as expected, and the compatibility is good for all energy regions.

The red squares and blue circles represent the compatibility with LSS proton model with and without GMF deflection. The compatibility with the proton LSS model without GMF deflection is below 0.3% CL for E > 10 EeV and $\sigma_s < 25°$, and below 5% CL for E > 57 EeV and $\sigma_s < 17°$. Assuming the anticipated σ_s by the GMF as small as 3° for 40 EeV and 10°-15° for 10 EeV by M.Pshirkov is correct, the LSS proton model without GMF is difficult to explain the UHECR arrival directions.

The compatibility with the proton LSS model improves significantly with an introduction of the GMF deflection as shown by the red squares in Figure 4. The compatibility larger than 5% is obtained for E > 10 EeV and

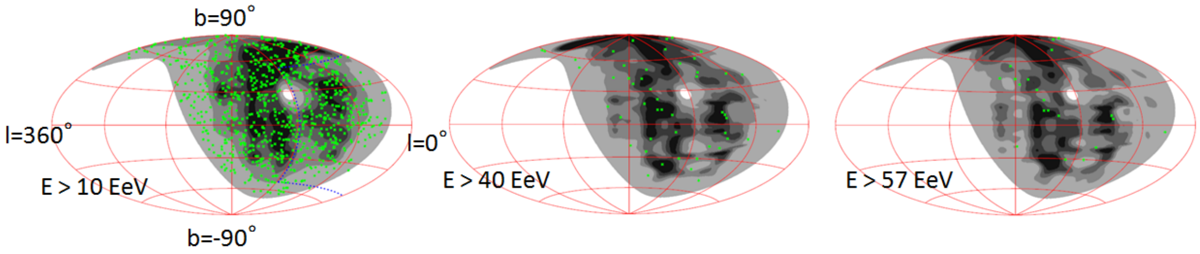

Figure 3: Skymap of UHECRs overlaid with the expected flux from the LSS proton model with GMF. The flux map in the Figure corresponds to $\sigma_s = 6°$.

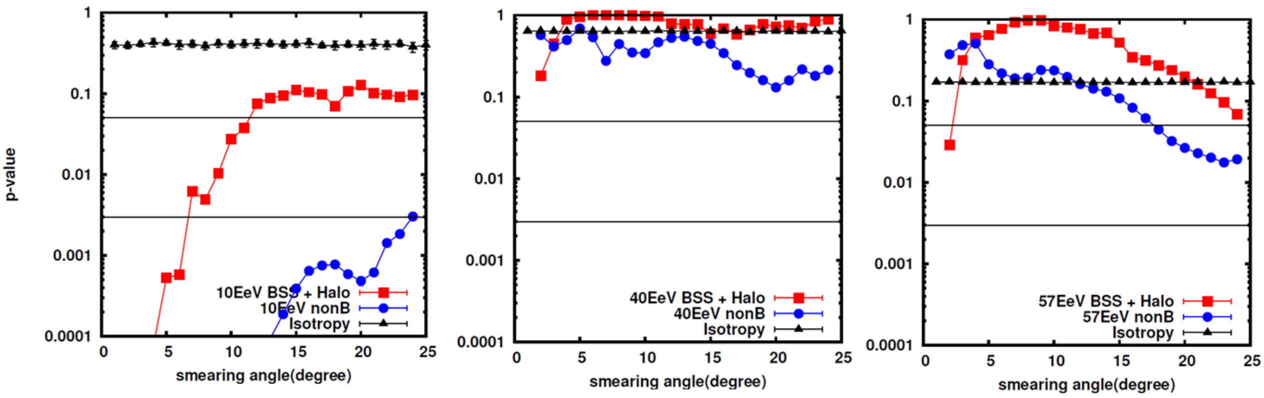

Figure 4: Compatibility between the model and the UHECR data with σ_s (abscissa) as a free parameter. Black:isotropy model, Blue:LSS proton model without GMF, Red: LSS proton model with GMF.

$\sigma_s < 12°$, and for E > 57 EeV and $\sigma_s < 3°$. It should be noted that the applied galactic halo field, although it was chosen to be consistent with the existing Faraday rotation measures, is relatively strong (4 μG) and thick (1.2 kpc, FWHM).

6. Summary

We observed the UHECRs using the SD array of TA, and compared their arrival directions with the expectation from the isotropy and the LSS proton models. No significant deviation from the anisotropy was observed.

The data for E > 40 EeV can be explained also by the expected proton flux originating from the nearby large scale structure of galaxies, propagating in the space, and experiencing the energy dissipation through the interaction with the CMB and the deflection by the galactic magnetic field. The statistics, 49 events for E > 40 EeV and 20 events for E > 57 EeV, is however not sufficient to distinguish the LSS proton model from the isotropy model.

At lower energies of E > 10 EeV, the data (856 events) is consistent with the LSS proton model only when the deflection by the GMF is taken into account and the random angular smearing larger than 12° is added. Given the UHECR is proton in this energy range as suggested by the Xmax measurement of TA, this may suggest an existence of relatively strong halo magnetic field in our galaxy, or a significant angular smearing of UHECRs during the propagation through the galactic and extra-galactic random magnetic fields.