Cosmic ray anisotropy observed by GRAPES-3 air shower array

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Abstract: So far a genuine sidereal anisotropy of galactic cosmic rays was reported by Nagashima et al. and Hall et al., more recently by Milagro and Tibet groups in sub-TeV energy region. We have also reported a sidereal anisotropy of low energy cosmic rays in GeV energy region observed by GRAPES-3 large tracking muon detector. GRAPES-3 muon detector is also used to measure muon content of an air shower which is induced by high energy galactic cosmic ray of $\geq$10TeV. Here we report a sidereal anisotropy of galactic cosmic rays observed by GRAPES-3 air shower array in combination with muon detector using the data from 2000 to 2006.

Keywords: anisotropy, sidereal, cosmic ray

1 Introduction

Observation of sidereal time anisotropy of the cosmic ray is an effective method for determining the structure of magnetic field in the interstellar space near boundary of the heliosphere which is not understood yet very well. A possible anisotropy would reflect the general charactaristic of propagation of cosmic rays in the galactic magnetic fields. Nagashima et al. have studied sidereal time variation for various energies of cosmic rays. A number of experiment such as air shower measurements at Mt. Norikura (2750 m a.s.l), muon intensity measurements at Nagoya (sea level), muon measurements at Sakashita (underground) and Hobart(underground, Australia). These meaurements have indicated the existence of two kinds of sidereal time anisotropies, namely an intensity excess at sidereal time of 6 hour RA and deficit at 12 hour RA. These are respectively called Tail-IN (TI) and Loss-cone (LC) anisotropies. In addition, Hall et al. (1999) have analyzed the data from many muon stations all over the world (sea level and underground) and have obtained results similar to that of Nagashima et al. and have displayed their results in the form of a contour map on the celestial sphere.

The observation of the sidereal variation at low rigidities is indispensable for the determination of the three dimensional direction of galactic anisotropy, which cannot be realized by observations only in the high rigidity region. From this point of view, it is worthshile to examine the exsistence of the sidereal daily variation of galactic cosmic rays.

The anisotropy of galactic cosmic ray intensity in the energy region of $\geq$ 10 TeV gives us an important information on the structure of magnetic field of the heliosphere and the local interstellar space around the heliosphere, where cosmic rays propagate to the Earth. The anisotropy of galactic cosmic rays were measured via the sidereal daily variation of cosmic ray intensity by several experiments. On the basis of the sidereal variation observed in the TeV region, most of the previous investigations reported that small amplitude and a phase of maximum somewhere between 23-3hours in the local sidereal time(LST). these observations are consistent with the large scale diffusive

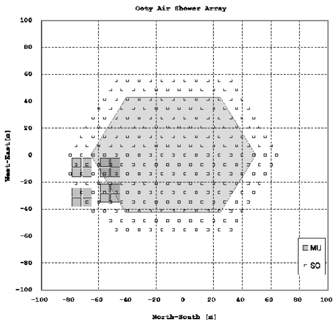

Figure 1: The GRAPES-3 experimental system with 257 scintillator detectors and 16 muon detector modules

propagation of cosmic rays.

Here we present the new results of a sidereal anisotropy of the galactic cosmic rays using the data of GRAPES-3 air shower array of 7-years from 2000 to 2006. Furthermore measuring muon content in an air shower by GRAPES-3 large area tracking muon detector, we tried to apply muon cut condition on all air shower events to suppress hadronic component to see an anisotropy of galactic cosmic rays with low hadronic component.

2 GRAPES-3 experiment

The experimental system of the GRAPES-3 (**G**amma **R**ay **A**stronomy at **P**eV **E**nergy**S** Phase-**3**) experiment consists of a densely packed array of scintillator detectors and a large area tracking muon detector. The EAS array consists of 257 plastic scintillator detectors shown in Fig. 1, each of 1 m^2 in area. These detectors are deployed with an inter-detector separation of only 8 m. The array is being operated at Ooty in south India (11.4°N, 76.7°E, 2200 m altitude).

In order to achieve the lowest possible energy threshold, a simple 3-line coincidence of detectors has been used to generate the Level-0 trigger, which acts as the fast GATE and START for the analog to digital and time to digital converters (ADCs and TDCs), respectively. As expected, this trigger selects a large number of very small and local showers and also larger showers whose cores land very far from the physical area of the array. Therefore, it is also required that at least 10 out of the inner 127 detectors should have triggered their discriminators within 1 μs of the Level-0 trigger. This Level-1 trigger with an observed EAS rate of 13 Hz is used to record the charge (ADC) and the arrival time (TDC) of the pulses from each detector [5]. The pulse charge is later converted into the equivalent number of minimum-ionizing particles (MIPS) using the most probable charge for a single MIP measured using the trigger from a small area (20×20 cm^2) scintillation counter telescope.

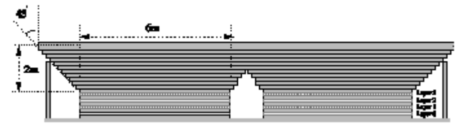

Figure 2: A muon station has four muon detector modules each consisting of 232 proportional counters. There are four muon stations inside the air shower array (Fig. 1).

The 560 m^2 GRAPES-3 muon detector J[10](B consists of 4 super-modules in Fig.2 , each in turn having 4 modules. Each module with a sensitive area of 35 m^2 consists of a total of 232 proportional counters (PRCs) arranged in 4 layers, with alternate layers placed in orthogonal directions. Two successive layers of PRCs are separated by 15 cm thick concrete. The energy threshold of 1 GeV for vertical muons, has been achieved by placing a total of 15 layers of concrete blocks (total absorber thickness $\sim$550 g.cm^{-2}) above the Layer-1. The concrete blocks have been arranged in the shape of an inverted pyramid to provide adequate shielding up to a zenith angle of 45°.

At higher energies, where observations have to be necessarily made with particle detector arrays at high altitudes, the muon content of showers offers itself as a possible parameter to discriminate against showers initiated by nuclear cosmic rays. Fig.3 shows charactalistic shower particle distribution pattern in shower plane for different primaries. Each shower was produced by simulation using CORSIKA code. As mentioned above, muon station of GRAPES-3 can measure the direction of muon content of a shower.

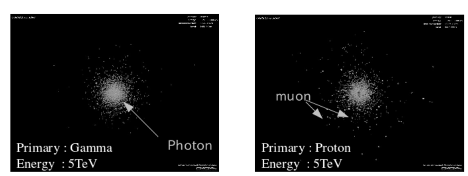

Figure 3: Images of particle distribution in different shower. Data used for the shower image has been created by CORSIKA. Left is gamma induced shower and right is proton induced one.

Because the area spread of shower particle distribution, the number of muons detected by muon detector is dependent on location of the shower core which lands inide the air shower array. Therefore an efficiency of the detecor for both gamma ray detection and hadron rejection will also change. Fig.4 shows the variation of both the detection efficiency for gamma rays and rejection efficiency for hadrons for different shower size and different area which

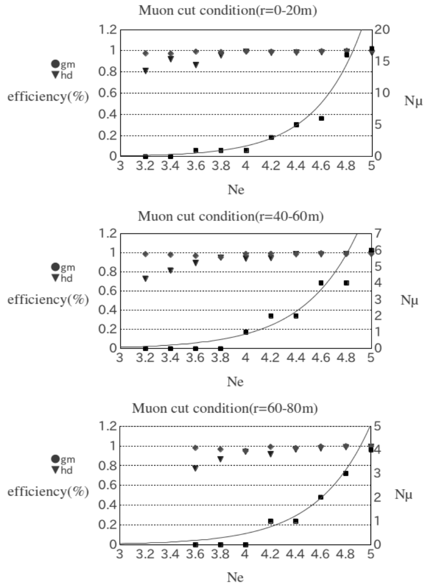

Figure 4: Muon cut conditions for several shower size and area in the GRAPES-3 air shower array. Circle shows the gamma ray detection efficiency and triangle shows the proton rejection efficiency.

is distant from the muon detector.

One of the most critical parameter in the study of direction of primary cosmic rays using a particle detectorarray is good angular resolution. This requires an accurate determination of the relative arrival time of the shower frontat various detectors. The high density of the detectors in GRAPES-3 enabled an angular resolution of 0.7° to be obtained at energies as low as 30 TeV. Angular resolution of the GRAPES-3 was estimated by 2-D Gaussian fit to the Moon shadow data.

During the data period of this analysis from 2000 to 2006, GRAPES-3 air shower array keeps stable good performance mainly on the angular resolution. Fig. 5 shows the Moon shadow clearly seen in the all cosmic rays flux detected by GRAPES-3 air shower array. The Moon shadow gives us a resonable estimation of an angular resolution of GRAPES-3 air shower array of about ~1.1° above thereshold energy.

3 Data and Analysis

A total of 1.9×10^9 showers have been collected over a total live time of 11.9×10^7 s, spread over a 7-year period, from 2000 to 2006. For each EAS, the core location, the shower age 's' representing the steepness of the Nishimura-Kamata-Greisen (NKG) lateral distribution function and the shower size N_e have been determined using the observed particle densities, following the minimization procedure discussed in detail by Tanaka et al [7]. Also, for each shower, the zenith (θ) and the azimuth (ϕ) angles have been calculated using the time information from the TDCs, also following the minimization procedure described by Tanaka et al [7].

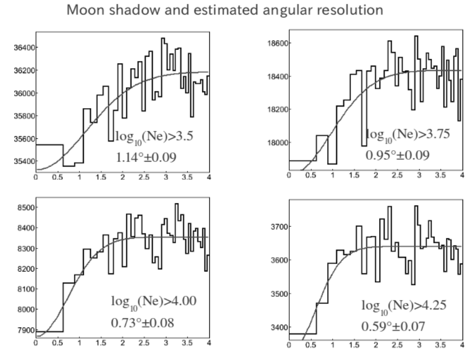

Figure 5: Moon shadow seen in various annular regions centered on the direction of the Moon for four energy regions, with the data period from 2000 to 2006.

The direction of each air shower events are transformed into the equitorial coordinates, and binned from -0° to 360° in right ascension and from -90° to 90° in declination into square cells with a bin size of 3°. Each cell are normalized by the average of its declination bands. The map data has been converted to the 2-D vizualized map using General Mapping Tool which is an open source map creating tool(Fig.6). In the all sky map, near neighbor cells are smoothed by special algorithm of GMT. Fig.7 shows the variation of significance value in the right ascension which were calculated in each declination bands.

As mentioned in the Section 2, to pick up gamma rays from a large amount of cosmic rays, we have to measure the muon content in an air shower and apply suitable cut condition, the number of muons, on each cosmic ray induced shower. In this analysis, we applied "zero-muon" criteria for the cut condition on each shower in order to suppress hadronic component of cosmic rays. This condition will be able to detect $\sim$95% gamma rays for all energy region above threshold energy, while it rejects only about 90% hadrons, which means there are still large amount of hadronic cosmic rays.

4 Conclusion

In this analysis using the data set of 7-years from 2000 to 2006, we obtained a large scale anisotropy of galactic cosmic rays for all particles in the energy region of above about 10 TeV. In the all sky map of all particle(Fig.6), two

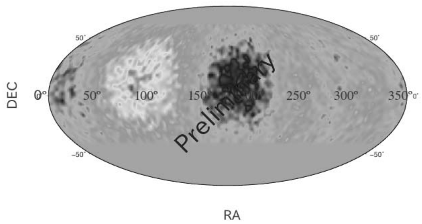

Figure 6: all sky map seen in all cosmic rays detected by GRAPES-3 air shower array in the energy of about 10^{13}eV

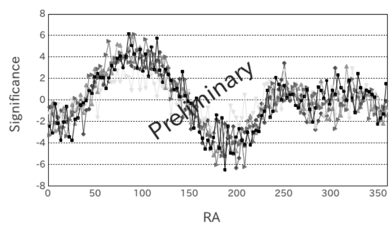

Figure 7: Variation of significance value in the right ascension for several declination bands.

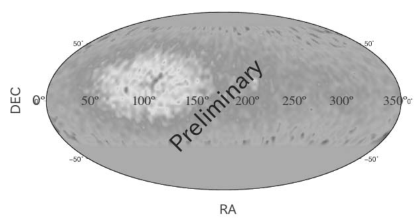

Figure 8: all sky map of cosmic rays with the "zero-muon" criteria detected by GRAPES-3 air shower array in the energy of about 10^{13}eV

kinds of anisotropy are visible, intensity excess at around 6 hour RA and deficit at around 12 RA. Further more we applied "zero-muon" criteria on each air shower to suppress hadronic component of cosmic rays and also produced the all sky map in the same procedure as in the case of all particle(Fig.4). The sky map of hadron suppressed cosmic rays also has an anisotropy with somewhat smooth structure, not like all particle sky, with an excess of intensity at around 6 hour RA. Since we know that there is still large amount of cosmic rays remained which survived the "muon-zero" criteria, we have to do still more clearance of cosmic rays to approach the low hadronic cosmic ray sky which means the sky of gamma ray candidates.

We reported a sidereal anisotropy of both all cosmic rays and cosmic rays with hadron suppression ,which would include less hadronic cosmic rays, observed by GRAPES-3 air shower array in combination with muon detector using the data from 2000 to 2006.

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