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The study of Periodic Variation of Cosmic Ray intensity with the Tibet III Air Shower Array

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Abstract: The periodicities of cosmic ray intensity variation are analyzed using Lomb-Scargle Fourier transformation method with about 37 billion cosmic ray events recorded by Tibet III Air Shower Array during the period from November 1999 to November 2005. To eliminate meteorological effect, we adopt East-West subtraction method. According to our analysis, besides the well known solar diurnal, sidereal diurnal and sidereal semi-diurnal periodic modulations at a level of 10^{-3}, no other periodicity is found to have large enough significance from 1 hour to 2 years in energy range from 3.0 TeV to 12.0 TeV.

Introduction

The periodic variation of cosmic ray(CR) intensity is important in understanding the origin, acceleration, evolution and propagation of CR[1]. It also provides useful information in studying galactic and helio-magnetic field.

In the energy region from a few TeV to several tens TeV, previous observations of Tibet Air Shower array have shown that the sidereal daily anisotropy of CR was roughly on the order of 0.1%[1][2].

As the helio-magnetic field does not affect the multi-TeV cosmic rays(CRs)[1], the galactic magnetic field, or local CR sources, or other mechanisms are responsible for sidereal daily modulation[1]. Solar diurnal anisotropy of CR is largely contributed by a kinetic process called CG effect[3]due to the Earth's orbital motion around the sun which has been reported with a small magnitude of 0.05%[4]. At the high energy (above 10 TeV), the modulation is fairly consistent with CG anisotropy, while at the lower energy the solar diurnal variation is found to have additional contribution other than CG effect[1][4]. The solar modulation may be responsible for additional CG effect.

MACRO[5]has analyzed the time series of their muons rate to search for CR flux periodic variation by Lomb-Scargle spectral analysis[6]. They reported a 365 days periodicity corresponding to the seasonal flux variation. In addition, from their power spectrum with frequency being around the solar diurnal frequency, many peaks were found with marginal significance. It would be interesting to perform the MACRO analysis with our Air Shower array data which is in a much larger size and should have more statistical power.

The Fourier amplitude spectrum analysis is a powerful technique in searching for the periodic signal in time series[7]. However, the unevenly sampled time series may cause spurious contribution to the spectrum analysis. The Lomb-Scargle method [6][8] can eliminate this effect and is known to be a powerful tool to find, and test significance of weak periodic signals from such kind of data sample[9][10].

This work maximally extends the modulation signal search [11] in a wider periodicity interval from 1 hour to 2 years with Tibet III Air Shower array data incorporating the Lomb-Scargle spectral analysis method[6].

Experiment

The Tibet Air Shower experiment has been successfully operated at Yangbajing (90.522° E, 30.12° N; 4300 m above sea level) in Tibet, China, since 1990[1].

The experiment was gradually enlarged and upgraded to current scale (Tibet III array) by increasing the number (Tibet I to Tibet II) and density (Tibet II to Tibet III) of detectors. The Tibet III array, used in the present analysis, was completed in the late of 1999. The Tibet III array covers an area of 22,050 m^2 and consists of 533 scintillation detectors of 0.5 m^2. The Tibet III array has a modal energy of about 3 TeV and the trigger rate is about 680 Hz. Based on moon shadow analysis, the array was estimated to have an angular resolution of 0.9° from Monte Carlo simulations at multi-TeV energy[12][13].

Analysis

In this work, the sample of data was accumulated in the running of Tibet III Air Shower Array for 1318.9 live days from November 1999 to November 2005.Air shower events are selected with the following criteria: zenith angle of arrival direction is less than 45° and air shower core is inside the array. The data sample is further divided into three groups according to their characterized primary energy of 4.0, 6.2 and 12TeV.

The daily and yearly event rates vary by $\pm$2% and $\pm 5\%$, arising mainly from the atmospheric change[4]. To eliminate this meteorological effect and possible instrumental effect when studying the CR's primary periodic variation with very small amplitude, we adopted the East-West subtraction method[4]. The selected events are filled in either of the two histograms in a bin size of about 3 minutes, according to events' arrival time. In total, 2^{20} numbers of bins are used to contain 6 years' of data (from November 1999 to November 2005). One histogram is reserve for events from east direction and another for events from west direction according to the geographical longitude of shower events' incident direction. Then we subtract these two histograms and normalize this difference by the sum of two histograms to form the relative intensity difference, and we further divide this relative difference by the hour angle separation averaged over the east and west events to get the differential relative intensity distribution.In the time frame, we can reconstruct the physical variation by "integrating" over time variable[4].

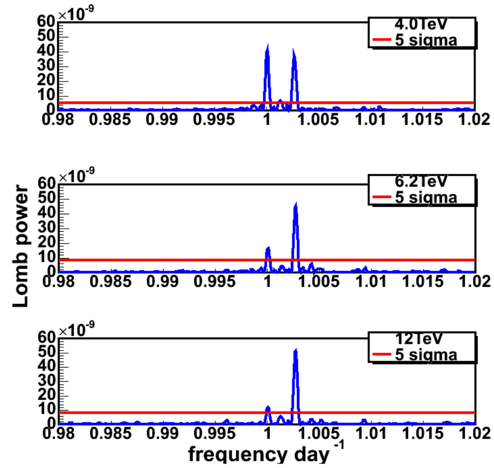

Figure 1: Lomb power of the frequency day^{-1} around solar diurnal day for Tibet III Air Shower Array experimental data for different representative energies: (Up) 4.0TeV, (Middle)6.2TeV, (Bottom)12.0TeV. The 5σ is shown by red line.

Following the above mentioned procedure, we build up a time series of CR intensity variation, and the Lomb Scargle power spectrum $P_N(\omega)$ can be calculated according to the formula described in (Scargle)[10][14]. $P_N(\omega)$ follows exponential distribution, the probability of $P_N(\omega) > z$ is as[10]:

$$P(> z) \cong Ne^{-z} \qquad (1)$$

where N is the number of the time series data.

Result and discussion

The results of our spectrum analysis for data sets at different energies are shown in Figure 1 for periodicities that are close to one solar diurnal day. The 5σ is calculated by the equation1. There are two clearly separated peaks with significance value above 5σ. The one with periodicity at 1 corresponds to solar diurnal modulation and the other

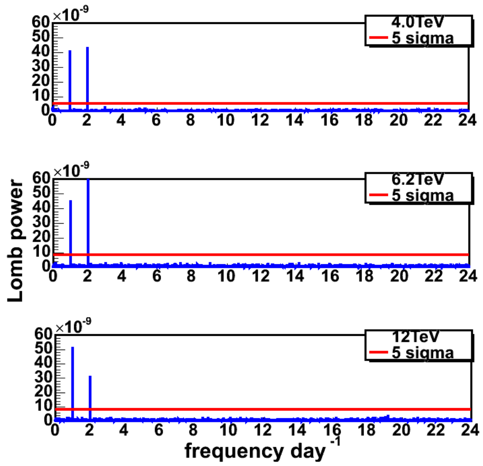

Figure 2: Lomb Power of the frequency day^{-1} between 2 years and 1 hour for Tibet III Air Shower Array data for different representative energies: (Up) 4.0TeV, (Middle) 6.2TeV, (Bottom) 12.0TeV. The 5σ is shown by red line.

at 1.0027 corresponds to sidereal diurnal variation. With such a large statistic data sample, no ”MACRO” signal can be observed[5]. One can see from Figure 1 that there exists a small peak just above 5 standard deviation for 4.0TeV data sample between solar and sidereal diurnal signal. More study are needed to thoroughly understand whether it is a true signal or not.

Enlarging the periodicity range to cover from 1 hour to 2 years, Figure 2 shows the result of power spectrum analysis. Besides the signal with periodicity close to one solar day, a new peak is visible with 2.0054 solar day periodicity and has a significance value well above 5σ. It corresponds to the sidereal semi-diurnal modulation and indicates that sidereal daily modulation can be described by the first and second harmonics.The solar diurnal variation is well fitted by a sinusoid. It may provide us a physical implication on origin of the anisotropy that no harmonics were higher than third order. No other signals were found from 1 hour to 2 years. No other periodicities of solar periodic activity verities that solar activity doesn't effect relative variation of CR at TeV energy. Eliminating the solar activity effect can provide particular convenience and simplification when we study the solar and sidereal diurnal anisotropy.

Table 1: Power amplitude Z, probability $P_N(\omega) > Z$ and significance sig of the solar diurnal peak

Energy TeV	Z $\times 10^{-8}$	probability	sig σ
4.0	4.1	1.5×10^{-80}	18.9
6.2	1.9	3.2×10^{-22}	9.6
12	1.6	2.9×10^{-19}	8.9

Table 2: power amplitude Z_1 of the sidereal diurnal modulation, probability $P_N(\omega) > Z_1$ pro_1 and significance sig_1 of the sidereal diurnal peak. Power amplitude Z_2 of the sidereal semi-diurnal modulation, probability $P_N(\omega) > Z_2$ pro_2 and significance sig_2 of the sidereal semi-diurnal peak.

Energy TeV	Z_1 $\times 10^{-8}$	pro_1	sig_1 σ
4.0	3.7	1.3×10^{-70}	17.7
6.2	4.8	3.1×10^{-63}	16.7
12	5.4	3.4×10^{-77}	18.6

Energy TeV	Z_2 $\times 10^{-8}$	pro_2	sig_2 σ
4.0	4.3	7.8×10^{-83}	19.2
6.2	5.7	1.4×10^{-75}	18.4
12	3.2	3.3×10^{-43}	13.7

In addition, from Figure 1 and Figure 2, we can find that the sidereal daily modulation shows little energy dependence while the solar diurnal modulation has large energy dependence. Table 1lists the Lomb power amplitude, the power's probability and the power's significance of solar diurnal modulation at different energies. The amplitude of solar variation decreased with the increasing of cosmic ray energy. These results are fairly consistent with our previously published result[1][4]. Table 2 lists the same results of sidereal diurnal and sidereal semi-diurnal modulation at different energies as solar diurnal modulation.

Conclusion

We analyzed 37 billion CR events recorded by Tibet III Air Shower Array from November 1999 to November 2005. In the language of frequency, we clearly found three significant signals, each corresponds to solar diurnal, sidereal diurnal and sidereal semi-diurnal modulation, but no other periodicity between 1 hour and 2 years was detected. The sidereal daily variation can be described by the first and second harmonics and shows small energy dependence . The solar daily variation can be described by the first harmonic alone and shows large energy dependence.

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