Time Dependence of Loss-Cone Amplitude measured with the Tibet Air-Shower Array

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Abstract: The galactic cosmic-ray anisotropy at TeV energies has a large-scale deficit region distributed around 150 to 240 degrees in right ascension, which is called "Loss-Cone". The Milagro experiment in the U.S. detected a significant increase in the Loss-Cone amplitude at 6 TeV from July 2000 to July 2007, and argued that it could be due to variations in the heliosphere in relation to solar activities. In this presentation, we report on the time dependence of the Loss-Cone amplitude from November 1999 through December 2008 measured with the Tibet air-shower array. No time dependence was found in the Loss-Cone amplitude at energies of 4.4, 6.2, and 11 TeV. If the increase in the Loss-Cone amplitude Milagro detected were genuine, the same tendency would be seen at sub-TeV energies where the anisotropy is far more sensitive to solar activities. Matsushiro underground muon observation at 0.6 TeV during the corresponding period, however, reported no significant increase of the Loss-Cone amplitude.

Keywords: Tibet, galactic cosmic rays, sidereal anisotropy, TeV energies, Loss Cone

1 Introduction

Past cosmic-ray experiments that observed the cosmic-ray anisotropy in the sidereal time frame consistently reported that in the anisotropy there are two distinct broad structures with amplitudes of $\sim$0.1%; one is a deficit in the cosmic-ray flux called "Loss-Cone", distributed around 150° to 240° in Right Ascension, and the other an excess called "Tail-In", distributed around 40° to 90° in Right Ascension. Figure 1 shows the two-dimensional relative intensity map in the equatorial coordinate system of galactic cosmic rays observed by the Tibet air-shower experiment at 5 TeV, in which Loss-Cone and Tail-In can be clearly seen. How these structures are created remains unknown until today.

The Milagro observatory is a large water Cherenkov detector for observations of TeV gamma rays and charged cosmic rays which was in operation in New Mexico, the U.S., from July 2000 to July 2007 [1]. Using $\sim 10^{11}$ air-shower events with the median energy of 6 TeV, Milagro reported on the time dependence of the large-scale cosmic-ray anisotropy in the sidereal time frame [2]. They measured the time dependence of the maximum depth of Loss-Cone, based on the one-dimensional profiles of the anisotropy obtained by projecting at one-year intervals the observed relative cosmic-ray intensities onto the right ascension coordinate. Consequently they reported a significant steady increase in the Loss-Cone amplitude.

2 Analysis and Results

The Tibet air-shower array has been operating successfully since 1990 at 90.522° E, 30.102° N and 4300 m above sea level. The air-shower events collected during the period from November 1999 through December 2008 (1916 live days) are used for analysis. After our standard data selections, the air-shower events are divided into three energy bins the modal energy values of which are 4.4, 6.2, and 11 TeV, respectively. To investigate the time dependence of the Loss-Cone amplitude, the air-shower events are further divided into four time bins: from November 18 1999 to October 10 2001, from December 5 2001 to November 18 2003, from December 14 2003 to November 15 2005, and from December 7 2005 to December 6 2008. Using the All-Distance Equi-Zenith Angle Method [3], we create the one-dimensional (1D) profiles of the cosmic-ray relative intensities by projecting all the relative intensities in the declination (δ) range from $-15°$ to $75°$ onto the right ascension (α) coordinate. Figure 2 (a) shows, for instance, the 1D profile of the relative intensity in the sidereal time frame at 6.2 TeV from November 1999 to October 2001. We fit the obtained 1D profiles of the relative intensities by a function with three Fourier components:

$$R(\alpha) = 1 + \sum_{i=1}^{3} a_i \cos i(\alpha - \alpha_i), \qquad (1)$$

where $R(\alpha)$ denotes the cosmic-ray relative intensity at right ascension α, a_i the amplitude of the i-th component of the Fourier series, and α_i the phase at which the variation of the i-th component reaches its maximum. The relative intensity values at the maximum depth of Loss-Cone are then calculated from the obtained best-fit functions. The statistical error of the relative intensity is calculated simply by propagating the statistical errors of the six parameters in Equation (1). The main systematic error to be accounted for is the amplitude of the anisotropy observed in the anti-sidereal time frame (364.2422 cycles/yr), because a possible seasonal change of the solar daily variation due to solar activities might produce a spurious variation in the sidereal time frame, which can be estimated by the daily variation observed in the anti-sidereal time frame. We evaluate the systematic errors, therefore, by the amplitudes observed in the anti-sidereal time frame (364.2422 cycles/yr), and add them to the statistical errors linearly. Figure 2 (b) shows, for instance, the 1D profile of the relative intensity in the anti-sidereal time frame at 6.2 TeV from November 1999 to October 2001. We finally obtain the time dependence of the Loss-Cone amplitude at 4.4, 6.2, and 11 TeV, as shown in Figure 3 (a).

3 Discussions

Figure 3 (a) clearly shows that the amplitude observed by the Tibet experiment is quite stable at 4.4, 6.2, and 11 TeV, contrary to Milagro's results. We fit the data with the linear function with two parameters: $p_0(\mathrm{MJD} - 53000) + p_1$. Table 1 shows the results of the fittings.

Table 1 shows that the p_0 value reported by the Milagro experiment, $(-0.97 \pm 0.11) \times 10^{-4}$ [%/day] at the median energy of 6 TeV, is inconsistent with those observed by the Tibet experiment at 4.4, 6.2, and 11 TeV, at confidence levels of 6.1σ, 6.6σ, and 6.7σ, respectively. Our results clearly show that there is no such time dependence in the sidereal daily variation as observed by Milagro, during the period from November 1999 to December 2008. Milagro argued that the time dependence of the sidereal daily variation they observed could be due to variations in the heliosphere in relation to solar activities. If the increase in the Loss-Cone amplitude Milagro detected were genuine, the same tendency would be seen at lower energies < 1 TeV, where the sidereal daily variation is much more sensitive to solar activities. Figure 3 (b) shows the sidereal daily variation observed at 0.6 TeV by Matsushiro underground muon observatory [4]. It is confirmed from Figure 3 (b) that the Loss-Cone amplitude is also rather stable at 0.6 TeV during the corresponding period. The linear two-parameter fit to the Matsushiro's data gives $p_0 = (0.32 \pm 0.22) \times 10^{-4}$ [%/day], which is again inconsistent with Milagro's data at a confidence level of 5.3σ.

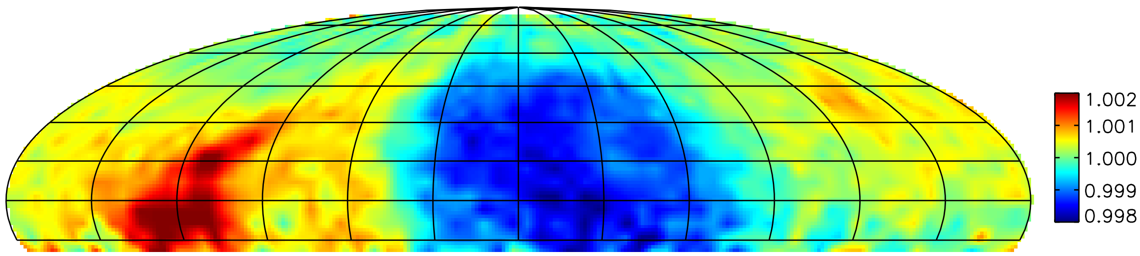

Figure 1: Two-dimensional relative intensity map in the equatorial coordinate system of 5 TeV galactic cosmic rays observed by the Tibet air-shower experiment.

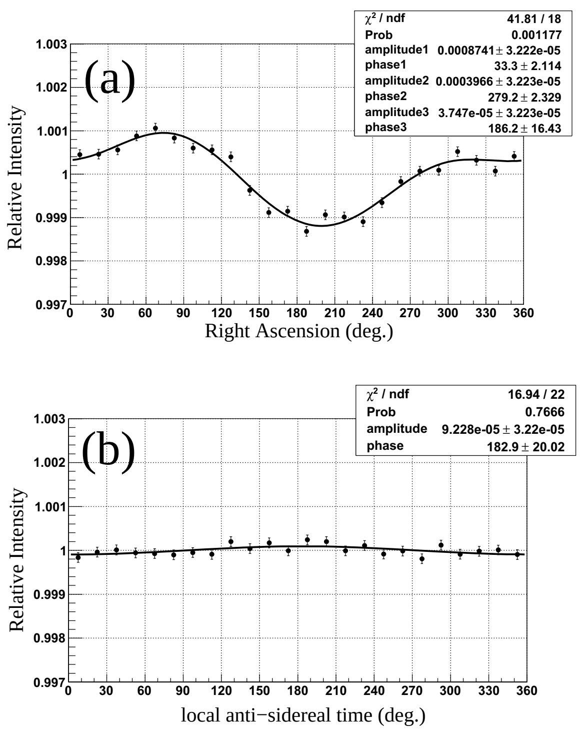

Figure 2: (a) The sidereal daily variation observed by the Tibet experiment at 6.2 TeV from December 2001 to November 2003. The best-fit function with three Fourier components is shown by the black line. (b) The anti-sidereal daily variation observed by the Tibet experiment at 6.2 TeV from December 2001 to November 2003. The best-fit sinusoidal curve is shown by the black line.

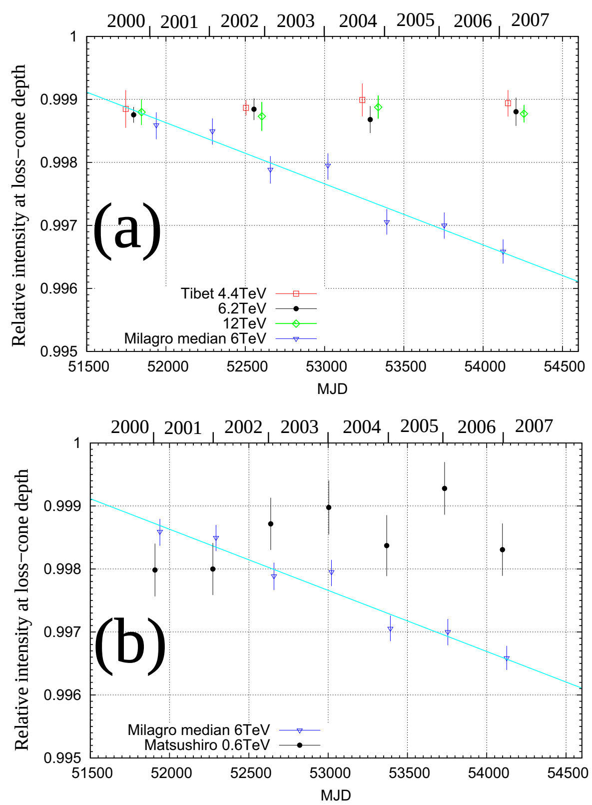

Figure 3: Time dependence of the maximum depth of Loss-Cone observed by the Tibet experiment at 4.4, 6.2, 12 TeV (a) and the Matsushiro underground muon observatory at 0.6 TeV (b) [4], along with Milagro's data represented by blue open inverse triangles and the best-fit linear function to Milagro's data. The data and their errors by the Matsushiro underground muon observatory are multiplied by three, to compensate for the attenuation of the amplitude in the sub-TeV energy region. All the error bars in (a) and (b) are the linear sums of the statistical and systematic errors.

Table 1: Results of linear two-parameter fittings to the data shown in Figure 3 (a). The fitting function is $p_0(\mathrm{MJD} - 53000) + p_1$. The p_0 value reported by the Milagro experiment at the median energy of 6 TeV is $(-0.97 \pm 0.11) \times 10^{-4}$ [%/day].

Energy (TeV)	$p_0(\times 10^{-4})$ [%/day]	p_1	χ^2/ndf
4.4	0.05 ± 0.13	0.998897 ± 0.000093	0.1051/2
6.2	0.004 ± 0.099	0.998773 ± 0.000093	0.3953/2
11	-0.002 ± 0.095	0.998797 ± 0.000093	0.3092/2

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