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Solar modulation of galactic cosmic-ray anisotropy observed by the Tibet II air shower array at$<$10 TeV

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Abstract. We analyze the sidereal daily variation (SDV) of galactic cosmic-ray intensity observed by the Tibet II air-shower array during 29 months between October 1995 and August 1999. The high-count observations help us analyze the SDV with a great significance. We found that the magnitude of the observed SDV shows a significant seasonal change (1 cycle/year) with an amplitude exceeding 50% of the average SDV. This seasonal change in magnitude produces spurious solar (365 cycle/year) and extended sidereal (367 cycle/year) daily variations at side-band frequencies of the SDV (366 cycle/year). The observed solar daily variation corrected for this effect is consistent with the variation expected from the Compton-Getting anisotropy due to the earth's revolution around the sun. The extended sidereal daily variation observed is also consistent with the variation expected from the seasonal change of the SDV. The phase of maximum (minimum) SDV in March (September) suggests the influence of the large-scale solar magnetic field on the propagation of charged particles in the heliosphere. We discuss on such effect by comparing the observed SDV with that reproduced from the calculation of cosmic-ray orbits in a model heliosphere.

1 Introduction.

The galactic anisotropy of ~10TeV cosmic ray intensity

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gives us important information about the electromagnetic state of the outer heliosphere and interstellar space in the vicinity of the heliosphere. The average amplitude of the anisotropy is, however, known to be small as ~10^{-3} (0.1 %). Such a small anisotropy can be detected as the daily variation of the cosmic ray intensity in local sidereal time. Long term observations of the sidereal daily variation (SDV) of cosmic ray intensity by air shower arrays have consistently reported a significant average variation in sidereal time (Alexeenko and Navarra, 1985, Nagashima et al., 1989). Most investigators have concluded that the variation is small (<0.1%) and the apparent right ascension of its minimum intensity is somewhere around mid-day in local sidereal time. Presently, no common consensus exists about the production mechanisms of this anisotropy (Hall et al., 1999).

In analyzing the SDV with small amplitude, special attention should be paid to effects which can produce spurious variations. Nagashima et al. (1984) first reported that the annual modulation (1 cycle/year) of amplitude of the daily variation in solar time (365 c/y) can produce a spurious SDV (366 c/y). This spurious SDV is one of two component variations produced at the side band frequencies of the solar daily variation, at 365+1=366 c/y and 365-1=364 c/y. On the basis of this amplitude modulation model, Nagashima et al. proposed a technique to remove this spurious component from the data by using the observed anti-sidereal daily variation, the counterpart of the spurious SDV, at 364 c/y. Thus, the anti-sidereal daily variation (364 c/y) can be used as a measure of the spurious SDV contained in the data. It is also obvious from the amplitude modulation model that the variation in solar time should be kept as small as possible. The average daily variation in the solar time can be quite large, reflecting the variations of condition in the terrestrial atmosphere and the human activity in the solar time. If its amplitude changes in a year, therefore, this large variation in solar time (365 c/y) can easily produce the spurious SDV which seriously contaminate small signal due to the galactic anisotropy.

In the present paper, we analyze the SDV of cosmic ray intensity observed by the Tibet II air shower array during 29 months between October 1995 and August 1999. For the detail of the Tibet II air shower experiment, readers can refer to Amenomori et al. (2000). The shower events with primary energy and incident direction identified were first collected every hour. The average count rate was 3.1×10^5 counts/hour (87 Hz). The shower events in each hour were then classified into the “east” and “west” (E- and W-) groups according to the geographical longitude of the incident direction of each shower. The difference of average viewing longitudes of E- and W- groups is 43.5°. The hourly count in each group for a month is then binned according to its sidereal, solar and anti-sidereal local times and the individual average count rates for each month are obtained in these three time frames. Each average hourly count rate from total 29 months is then calculated, providing 24 (average) hourly values obtained from the complete set of data. We calculate the mean of these hourly values and the percentage deviation of each hourly value from the mean to obtain the average daily variations in local sidereal, solar and ant-sidereal times.

In our analysis of the average daily variations, we eliminate the variations arising from the atmospheric change and the instrumental deterioration, simply by subtracting the variations in W-group from those in the E-group (see Nagashima, et al., 1989 for the detail of this technique). Through an analysis using the atmospheric data recorded on site, we confirmed that this subtraction is very effective method to eliminate the common variation in both E- and W-group and pick up only the variation due to anisotropy, which has the different phases for the groups.

2 Results.

Figure 1 shows, by solid circles, the observed daily variations in local sidereal, solar and anti-sidereal times.

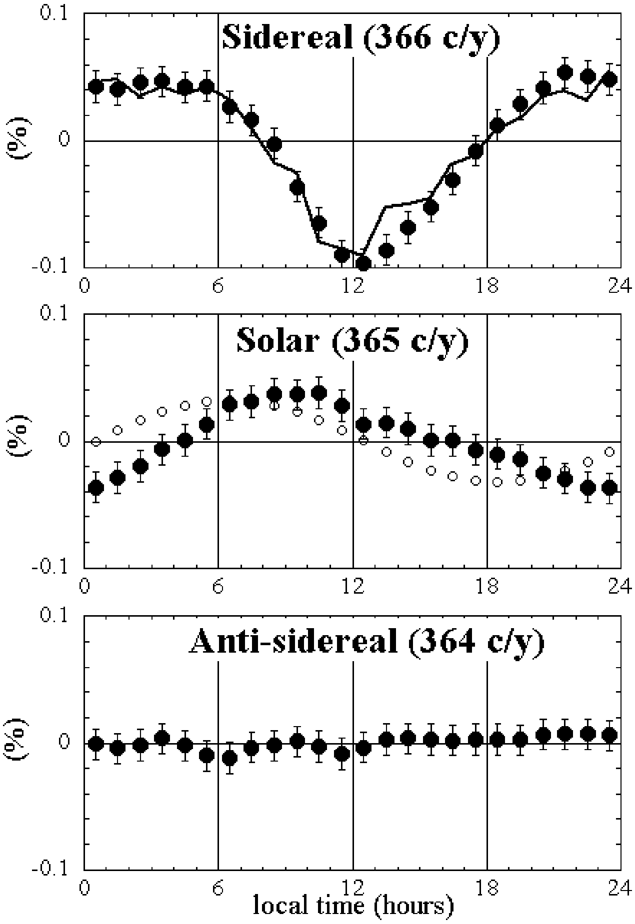

Figure 1. The average daily variations in the local sidereal (top), solar (middle) and anti-sidereal (bottom) times over 29 months between October 1995 and August 1999. The solid curve in the top panel shows the variation observed by Mt. Norikura air shower experiment over 12 years between 1975 and 1987.

Small and insignificant variation in the anti-sidereal variation in the bottom panel ensures that the SDV in the top panel contains only a negligible spurious variation due to the annual modulation of the solar daily variation, as described in the preceding section. Also shown by the solid curve in the top panel is the average SDV observed by the 3F component array of the Mt. Norikura air shower experiment over 12 years between 1975 and 1987 (Nagashima et al., 1989). The size of error bars attached to the data points are almost comparable to those for Norikura data. The SDV observed by Tibet II air shower array shows a remarkable agreement with the result by the Mt. Norikura air shower experiment, in spite of the difference in the observation period. Such agreement was already seen in the first 12 months data by the Tibet II air shower array (Munakata et al., 1999).

In the middle panel of Fig.1, we also note that the daily variation in the solar time is also significant. In this energy region around ~10TeV, no anisotropy can be expected from the solar modulation. Only the Compton-Getting anisotropy due to the earth's revolution around the sun can cause the daily (diurnal) variation in the solar time. The amplitude of this anisotropy is estimated to be about 0.05%. The observed variation, however, shows a significant deviation from the variation expected from this effect and shown by open circles.

An important feature of Fig.1 is that the SDV in the top panel is as large as twice of the solar daily variation in the middle panel. According to the amplitude modulation model described in the preceding section, this means that the small variation in the solar time can easily be affected by the spurious variation produced by the annual modulation of amplitude of the SDV, if such annual modulation actually exists. We examined this in Fig.2 showing the average SDV in six "seasons". The expected contribution from the Compton-Getting anisotropy is subtracted from the data in each panel. It is seen that the observed SDV plotted by solid circles is changing through a year with the maximum (minimum) amplitude in February-March (September-October). According to the amplitude modulation model, such annual variation (1 c/y) of the SDV (366 c/y) can cause the spurious variations at side band frequencies of 366-1=365 c/y and 366+1=367 c/y, that is, the solar and extended sidereal daily variations. On the basis of this model, we made a best-fitting calculation between the observed and expected daily variations in the six "seasons" in Fig.2. The observed daily variations in the solar and extended sidereal times are also obtained in the six "seasons" in Fig.2 and best-fitted as well as the SDV. The best fitted parameters of this calculation is the relative magnitude and phase of the annual variation of the SDV amplitude, which is assumed to be sinusoidal variation. The solid curves in Fig.2 show the best-fitted annual variations with the amplitude of 65 % of the average SDV in Fig.1 and the phase of maximum at March 11.

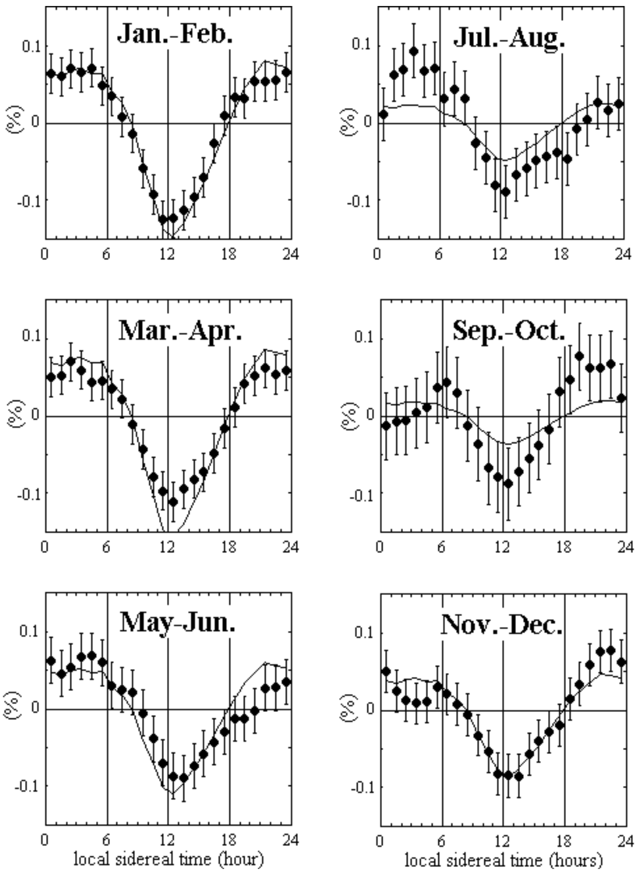

Figure 2. The average sidereal daily variations in six "seasons" of January-February, March-April, May-June, July-August, September-October and November-December. Also shown by solid curves are the best-fitted variations derived from the amplitude modulation model (see text). The variation expected from the Compton-Getting effect is subtracted from the observed variation in each "season".

The solid curves in the upper and lower panels of Fig.3 shows respectively the expected solar and extended sidereal daily variations averaged over six seasons. Also shown by solid circles are the observed daily variations. The spurious solar daily variation obtained from the best-fitting calculation is subtracted from the observed variation in the upper panel. In both panels, the average deviation of the observed data from the expected values are within the error. Particularly, it is shown in the upper panel that the disagreement seen between the observed solar daily variation and the Compton-Getting effect in the middle panel of Fig.1 is well dissolved by taking the spurious variation due to the annual modulation of the SDV into account.

3 Summary and discussion.

We found a significant sidereal daily variation (SDV) of cosmic ray intensity observed by the Tibet II high count air shower experiment. The insignificant anti-sidereal daily

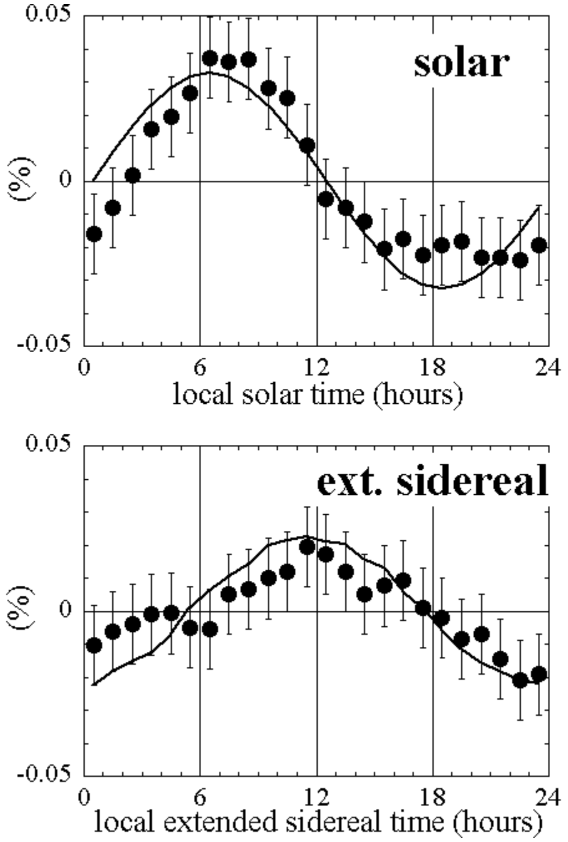

Figure 3. The observed (solid circles) and expected (solid curves) daily variations in the local solar (upper panel) and extended sidereal (lower panel) times. The expected variations are derived from the best-fitting calculation between the observed and expected seasonal variations (see text). The expected spurious variation obtained in the solar time is subtracted from the data in the lower panel.

variation ensures that the spurious variation caused by the annual modulation of the solar daily variation is also insignificant. We also found the seasonal variation of amplitude of the SDV, which can cause the spurious daily variations in the solar and extended sidereal times. On the basis of the amplitude modulation model, we performed a best-fitting calculation between the observed and expected seasonal variations and derived the spurious components expected in the solar and extended sidereal times. When this spurious component is subtracted from the observed variation, a good agreement is obtained between the solar daily variations observed and expected from the Compton-Getting anisotropy due to the earth's revolution around the sun. The observed variation in the extended sidereal time also showed a good agreement with that expected from the amplitude modulation model.

We now discuss on the mechanism responsible for the observed seasonal variation in the amplitude of the SDV. We first note that the obtained phase of the maximum amplitude in March, when the right ascension of the earth is around 180°, coincides with the phase of the maximum intensity deficit (named the "loss-cone" by Nagashima et a., 1989) at 1200 local sidereal time. This implies that the detector on the earth observes the deficit through the solar dipole magnetic field located in between the earth and the loss-cone in September. In March, on the other hand, the detector observes the loss-cone with the dipole magnetic filed behind the earth. The influence of the dipole filed on the cosmic-ray orbits, therefore, can qualitatively cause the seasonal variation observed. To confirm this "shadow" effect of the solar magnetic field, we performed the calculation of orbits of anti-protons ejected from the earth at every 5° of geographic longitude and latitude. The observed SDV can be reproduced by sampling the loss-cone anisotropy outside the heliosphere along each orbit. In this calculation, we used the model heliosphere derived from the MHD simulation of the interaction between the solar wind and the interstellar plasma by Washimi and Tanaka (1996). By repeating the calculation in various seasons corresponding to various locations of the earth around the sun, we found the phase of the minimum amplitude of the reproduced SDV in March, in agreement with the data analysis in the preceding section. The reproduced phase of the maximum amplitude, on the other hand, is found in May suggesting the deviation of the seasonal variation from the sinusoidal change which is assumed in our best-fitting analysis in the preceding section. The amplitude of the reproduced seasonal variation is also found to be about five times smaller than that derived from the data analysis. Both the calculation and analysis in more detail are now in progress.

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