# Galactic Cosmic-ray Sidereal Anisotropies and the Heliosphere

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**Abstract**

By analyzing the sidereal daily variations recorded in 44 underground muon telescopes in two hemispheres, Hall et al. (1999) devised an empirical model of the cosmic-ray anisotropy. To investigate the influence of the large-scale structure on high-energy cosmic-ray propagation, we calculate cosmic-ray orbits in the model heliosphere obtained by Washimi and Tanaka (1996) from the MHD simulations of the heliosphere. By calculating the energy gain and loss of particles due to the electric field induced in the magnetized plasma flow, we present a model anisotropy of 10000 GeV particles traveling on nearly radial paths to the earth. The model shows an acceleration region existing in the apex ($\alpha$ : 260º - 20º) direction, due to the significant electric field induced on the apex sides of the solar wind termination shock. These results are discussed in relation with the anisotropy reported from the observations.

## 1 Introduction:

After considering the 24-hour profiles of the sidereal daily variations (SDVs) in underground muon telescope data along with the results of the Mt. Norikura air-shower experiment, Nagashima et al. (1998) proposed that there are two anisotropic distributions of particles in the heliosphere and these are responsible for the SDV and the north-south (NS) asymmetry of the diurnal variation. One of the anisotropies is the Loss-cone (LC) of galactic cosmic rays (deficit flux) and the other is an excess of cosmic-ray flux originating from close to the tail of the heliosphere which they called the Tail-in (TI) anisotropy. Both anisotropies are assumed to be axis-symmetric, the LC having a symmetry axis aligned along a direction with right ascension ($\alpha$) 1200 sidereal time and declination ($\delta$) 20ºN while the TI anisotropy has an axis of reference aligned along a direction with $\alpha$ = 0600 sidereal time and $\delta$ = 24ºS. They manifest as a SDV in the data with a maximum and minimum value at 0600 and 1200 sidereal time, respectively.

To confirm the existence of the NS asymmetry of the diurnal variation and to help clarify what is the best description of the sidereal anisotropy, it has been obvious for some time that accurate and copious observations of the SDV from the southern hemisphere are needed to complement the substantial amount of data recorded from the northern hemisphere. Continuous multidirectional underground observations of cosmic rays from the southern hemisphere have been conducted since 1992 at Liapootah in Tasmania, Australia to help form the two hemisphere network (THN) of underground muon telescopes, the rest of the network being comprised of northern hemisphere multidirectional telescopes located in Japan. Hall et al. (1999) analyzed the yearly averaged SDVs in the count rates of 44 underground muon telescopes in the THN by fitting Gaussian functions to the data. These functions represent the LC and TI anisotropies proposed by Nagashima et al. The telescopes cover the median rigidity range 143GV-1400GV and the viewing latitude range ±75º. They found that the TI anisotropy has its reference axis located at declination ~14ºS and right ascension ~4.7 sidereal hours. They showed that the TI anisotropy is asymmetric about the reference axis and its observed $\alpha$ depends on the viewing latitude of the telescopes. They also showed that the LC anisotropy is symmetric and has a reference axis located at the celestial equator and ~13 sidereal hours. From the parameters of the Gaussian fits they devised an empirical model of the sidereal anisotropies which implies that the above characteristics of the anisotropies can explain the north-south asymmetry in the amplitude of the sidereal diurnal variation. Furthermore, they found that the phase of the sidereal semi-diurnal variation of cosmic rays should be recorded at later times when measured from the northern hemisphere compared to observations made from the southern hemisphere.

Presently, no common consensus exists about the nature of the production mechanisms of both the LC and TI anisotropies. In this brief report, we investigate the influence of the large-scale heliospheric magnetic field structure on high energy cosmic-ray propagation, by calculating orbits of charged particles in the model heliosphere obtained from the three dimensional MHD simulations of the interaction between the solar wind and the interstellar medium by Washimi and Tanaka (1996). The stationary structure of the heliosphere was obtained from the simulation in the region between the inner and outer boundary spheres respectively at r = 50AU and r = 950AU from the sun. On the inner boundary, the solar wind was assumed to be radial and uniform with the speed of 400km/s (Washimi and Tanaka, 1996). By using the magnetic field and plasma parameters given by the MHD simulation at every mesh point, we first calculate the magnetic field at an arbitrary point by the linear interpolation. We then solved the equation of motion of the charged particle in the magnetic field by using the fourth order Runge-Kutta method. To simulate the propagation of galactic cosmic-ray protons from the interstellar space to the earth, we ejected the anti-protons from the earth into various directions and traced their orbits until particles reach the outer boundary. In the region of $r \leq 50AU$, we assumed the Parker's spiral magnetic field with the flat neutral sheet on the equator. The calculations were also made for different earth's locations around the sun corresponding to different seasons.

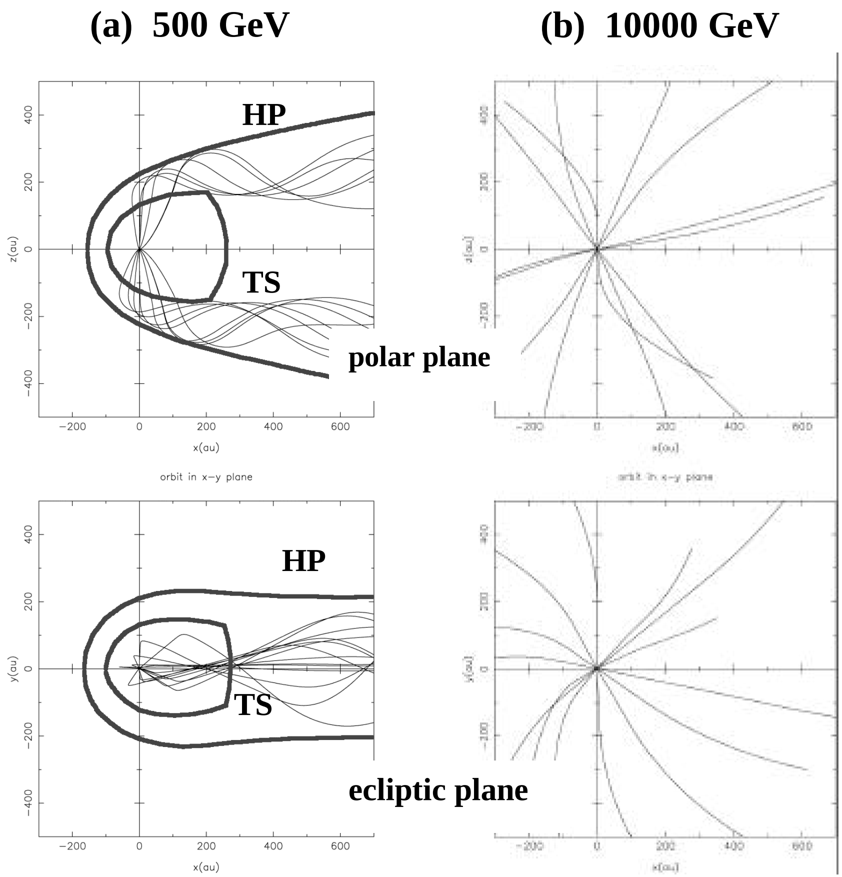


**Figure 1:** Orbits of 500 GeV (a) and 10000 GeV (b) cosmic-rays in the MHD model heliosphere. Top and bottom panels show the projections of orbits on the polar and ecliptic planes, respectively. The approximate positions of the heliopause (HP) and solar wind termination shock (TS) are indicated by thick lines in (a).

## 2 Results:

Figure 1 shows the sample orbits of 500 GeV (a) and 10000 GeV (b) cosmic-ray protons in the model heliosphere. Upper and lower panels show respectively the projections of orbits on the polar and ecliptic planes. In this figure, the Parker's field in the inner heliosphere directs away from (toward) the sun in the northern (southern) hemisphere above (below) the flat neutral sheet on the equator, corresponding to the positive solar magnetic polarity. The thick lines in Figure 1(a) indicate approximate locations of the solar wind termination shock (TS) and the heliopause (HP). It is clear that most of 500 GeV particles are arriving at the earth from the heliotail with their orbits significantly deflected at the magnetic wall formed in the upstream region of the interstellar wind between the TS and HP. This apex- and anti-apex asymmetry in orbits is much less in 10000 GeV cosmic-rays observed by the air shower experiments. It is also seen that the 500 GeV cosmic-rays in the inner heliosphere arriving from the polar region due to the gradient and curvature drift.

The anisotropy at the earth might be produced if the energy gain or loss of particle prior to its arrival at the earth is different on different orbit in Figure 1. As the observed magnitude of the anisotropy is ~0.07 % at 500 GeV (Hall et al., 1999), the energy to be added by the acceleration is estimated to be ~100 MeV. A possible candidate of such acceleration or deceleration is the energy change ( $\Delta E$ ) due to the electric field induced in the magnetized plasma flow, expressed as

$$\Delta E(\alpha,\delta,r,\boldsymbol{r}_E,E) = \int_r^{r_E} \boldsymbol{E}\cdot d\boldsymbol{s} \qquad (1)$$

where $\boldsymbol{B}$ is the magnetic field, $\boldsymbol{E} = -\boldsymbol{v}\times\boldsymbol{B}$ the electric field induced in the plasma flow $\boldsymbol{v}$, $d\boldsymbol{s}$ the displacement vector along the orbit of a particle with energy $E$ (>> $\Delta E$ ). We calculate $\Delta E$ for every particle incident to the earth from $\alpha$ and $\delta$ , along with its orbit between a position at a radial distance $r$ and the earth at $\boldsymbol{r}_E$. The anisotropy of cosmic-ray intensity is then evaluated with $\Delta E$ , as

$$\Delta I / I \sim \gamma\Delta E / E \qquad (2)$$

where $\gamma$ is the exponent of energy spectrum of the isotropic intensity $I$ (>> $\Delta I$ ). We calculate 2,522 $\Delta E$ 's at every 5 º of $\alpha$ (0 º to 360 º) and $\delta$ (-90º to +90º) for a set of $r$ , $\boldsymbol{r}_E$ and $E$ . Figure 2(a) shows a contour map of $\Delta E$ in the $\alpha$ - $\delta$ space for $E =$ 10000 GeV. Particles with such high energy travel on nearly radial paths to the earth (see Figure 1(b)). The solid and broken lines in this figure represent respectively the positive (acceleration) and negative (deceleration) values of $\Delta E$ . In Figure 2(a), we set $r$ = 300 AU from the sun and choose $\boldsymbol{r}_E$ to be the earth's position in March. The contours show the acceleration region existing in the apex ( $\alpha$ : 260º - 20º) directions. This is due to the electric field induced on the apex side of TS, which is pointing the down stream of the interstellar wind in the positive magnetic polarity. The maximum and minimum values of $\Delta E$ in this figure are respectively ~150 MeV and ~-200 MeV, corresponding to $\Delta I / I$ of ~0.005 % with $\gamma$ =2.65. It is also possible to calculate $\Delta E$ for 500 GeV particles in Figure 1(a), but the interpretation of the result would not be straightforward like that of Figure 2(a) for 10000 GeV particles. The orbits of low energy particles are significantly deflected at the magnetic wall on TS and not aligned with the electric field. We also need to know the magnetic structure in more detail, as the orbits of low energy particles can be affected by relatively small scale structures in the heliosphere as well.

Figure 2(b) shows the $\alpha$ dependence of $\Delta I / I$ calculated from $\Delta E$ in Figure 2(a) and expected to be observed with an equator-viewing detector on the earth. The overall profile with a deficit of flux centered at around $\alpha$ =180º is qualitatively consistent with the air shower measurements at Baksan and Mt. Norikura (Alexeenko and Navarra, 1985, Nagashima et al., 1989), but the expected magnitude (~ ±0.005 %) of $\Delta I / I$ is about ten times smaller than the observations (~ ±0.05 %). It is also noted that the electric field responsible for $\Delta E$ is expected to reverse its direction in the negative solar magnetic polarity. Such magnetic cycle dependence, however, has not been reported from the long term observation of the sidereal diurnal variation of air-shower count rate (Nagashima et al., 1989). It is concluded therefore that we need to have more dynamic and realistic model of the heliosphere for accurate calculations of the anisotropy, which can be quantitatively compared with the observation. Washimi and Tanaka (1999) have recently presented such a MHD model of the heliosphere incorporating both the 11 year activity- and 22 year magnetic-cycle variations of the sun.

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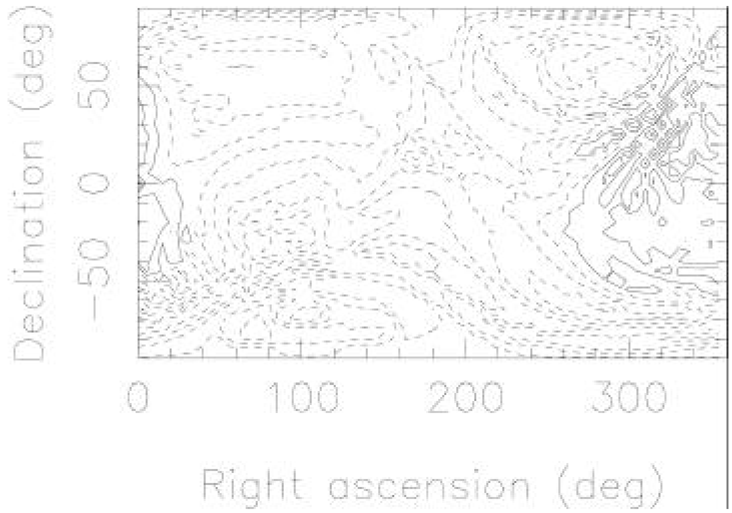
**(a)**




**(b)**

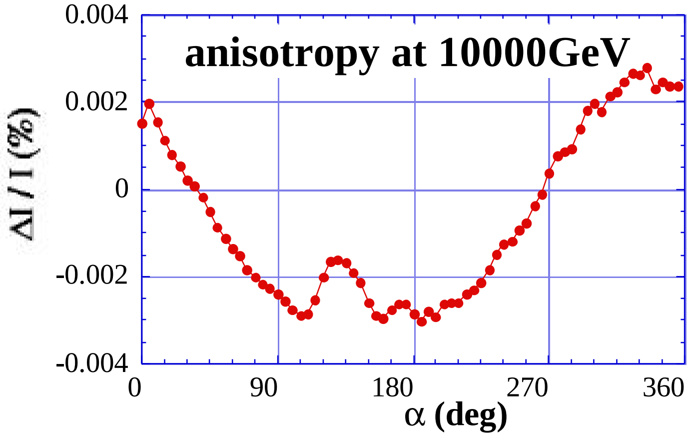



**Figure 2:** Contour map of $\Delta E$ in the celestial space (a), and the anisotropy $\Delta I / I$ in % expected to be observed by an equator-viewing detector on the earth (b). The solid and broken lines in (a) represent respectively the positive (acceleration) and negative (deceleration) values of $\Delta E$ .

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