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Cosmic-Ray Excess Flux from Heliomagnetotail

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Abstract

In Paper 1, the authors reported that the cosmic-ray sidereal daily variation in the energy region less than $E_U \sim 10^4$GeV was due to two kinds of anisotropy. One is the galactic anisotropy from the direction of the right ascension α_G=0h and the declination $\delta_G=-20^o$. The other is a newly discovered directional excess flux (called 'tail-in anisotropy') confined in a narrow cone with a half opening angle of $\sim 68^o$ from the direction ($\alpha_T = \sim$6h, $\delta_T = \sim -24^o$) and observed only in the energy region less than $\sim 10^4$GeV. It is suggested that the excess flux is of solar origin and the direction toward it seems to coincide with the expected heliomagnetotail direction (α_{TP}=6.0h; $\delta_{TP}=-29.2^o$) opposite to the proper motion of the solar system, but does not coincide with the expected tail direction (α_{TN}=4.8$\sim$7.2h; $\delta_{TN}=15^o \sim 17^o$) opposite to the relative motion of the system to the neutral gas.

In this paper, it is shown as one more evidence of the directional excess flux that the response to the excess flux is maximum at the winter solstice when the Earth is closest to the magnetotail and minimum at the remote side of the Earth's orbit from the tail, at the summer solstice. Owing to the discovery of the tail-in anisotropy, the observed phase shift of the sidereal diurnal (24h-) variation from 6 to 0h with the increase of energy, which has been one of the unsolved problems, can be explained by the relative contribution of this tail-in anysotropy and the galactic anisotropy.

1. Tail-in anisotropy

The space distribution of the tail-in anisotropy obtained in Paper 1, is also shown on the map in Fig. 1, together with the distribution of the galactic anisotropy (cf. Nagashima et al., 1989).

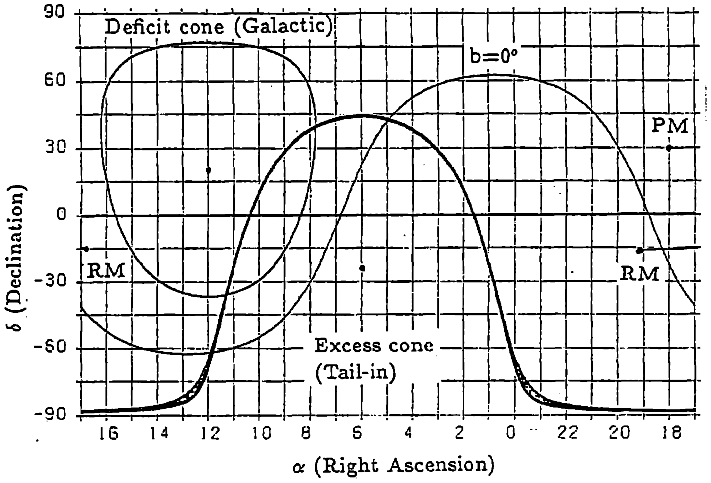

Fig. 1 The distribution of the tail-in and galactic anisotropies on the equatorial coordinate grid. Pm: Direction of proper motion of the solar system, RM: Direction of relative motion of the system to the neutral gas, b=0^o: Galactic equator.

In the figure, the excess cone of the tail-in anisotropy, within which all the directional excess flux is confined, is shown bounded by the thick line. A thinner line bounds the deficit cone of the galactic anisotropy, in which all the directional deficit flux is confined. As can be seen in the figure, a telescope directed to the region of $\delta >\sim 44^o$ or $\delta <\sim -37^o$ can observe either one of the galactic and tail-in anisotropies as it sweeps only the deficit or excess cone. On the other hand, a telescope directed to the intermidiate region of $\sim 44^o > \delta > -37^o$ successively sweeps the excess and deficit cones and would observe a complicate α-distribution of the variational intensity.

2. Annual variation of tail-in anisotropy

As the sidereal daily variation at Hobart muon vertical telescope (λ_C=43°S) expresses purely the T-variation due to the tail-in anisotropy (cf. Fig. 1), we can use it for the study of the annual modulation of the tail-in anisotropy in the heliomagnetosphere. Fig. 2 is an imaginary sketch showing the plausible annual variation of the excess flux from the heliomagnetotail. In the figure, the response to the flux is maximum at the winter solstice when the Earth is closest to the tail and minimum when it is farthest from the tail, at the summer solstice. As a result, the anisotropy would produce on the Earth a sidereal (SI-) diurnal vareation (frequency f_{SI}=366 cycle/year) with an annual modulation of amplitude; its movement is shown by arrows along the 6h-axis on the SI-harmonic dial in Fig. 2c. The modulation can be analytically expressed by two variations with side-band frequencies of f_{SO} (=f_{SI}−1) and f_{SI2} (=f_{SI}+1). In the case of the straight-line amplitude modulation (Fig. 2c), these sideband variations can be expressed by two separate vectors, SO and $SI2$, of the same amplitude but of differing phase as shown on the corresponding harmonic dials in Figs. 2b and 2d, the SO-dial for the solar diurnal vector and the $SI2$-dial for a 24-hour variation (called the extended sidereal diurnal variation) in a newly defined day which is shorter than the solar day by about 8 minutes and synchronized with solar and sidereal times at the autumnal equinox (Nagashima et al., 1983). The SO- and $SI2$-vectors, shown parallel and opposite at the head of the average SI-vector in Fig. 2c, rotate respectively clockwise and counter clockwise with an angular velocity (ω) of 2π/year, starting from their indicated positions at the autumnal equinox. Their resultant sum expresses annual modulation of amplitude, as shown on the dial of Fig. 2c. By observing these vectors one can confirm the existence of the tail-in anisotropy. Although the sideband SO-vector would be masked by another large SO-vector of solar origin, other vectors (SI, $SI2$) might be detectable in low energy region where the influence of the galactic anisotropy would be negligible. It is noted here that, generally, an annual modulation can describe any ellipse besides a straight line on the SI-harmonic dial. Whatever the case, provided the maximum and minimum fluxes are observed respectively at the winter and summer solstices, no change occurs in the SO- and $SI2$-vectors in Fig. 2 except for their amplitude ratio (cf. Nagashima and Ueno, 1971). Therefore, as far as the observed $SI2$-vector has a phase 12h, the existence of annual modulation due to the tail-in anisotropy can be recognized.

Fig.3 shows the observed SI- and $SI2$-vectors at Hobart during 1958-1983 (Nagashima et al., 1985). The phase of $SI2$-vector closely agree with the expected value shown in Fig. 2, indicating the existence of the expected annual modulation of the tail-in anisotropy in the heliomagnetosphere. The annual variation of the SI-vector can be visualized on the assumption that the associated sideband SO-vector, not directly observable, has the expected phase of 0h and the same amplitude as the $SI2$-vector (cf. Fig. 2). The modulation characteristics show that the anisotropy almost disappears at the remote side of the Earth's orbit from the tail.

3. Energy dependence of galactic and tail-in anisotropies

As reported in Paper 1, the cosmic-ray sidereal daily variation in the energy region less than 10^4GeV shows the co-existence of the variations due to the galactic and tail-in anisotropies (G- and T-variations). The first harmonic G_1- and T_1-vectors of the G- and T-variations have different phases from each other, one is 0h and the other is 6h. Therefore, the resultant sum of G_1- and T_1-vectors would change its phase depending on their relative contribution. This idea gives a satisfactory explanation to the phase shift of the observed first harmonic vectors from 6 to 0h with increase of energy in Fig. 4, which has been one of the unsolved problem of the sidereal variation from the standpoint of the heliomagnetic modulation of single galactic anisotropy (Nagashima et al., 1982). Accordingly, the 0h- and 6h-components of the observed vector could be regarded as the G_1- and T_1-vectors, respectively. Their energy spectra are shown in Fig. 5. T_1-vector shows a maximum near 10^3GeV and tends to zero near 10^4GeV. The uprising trend of T_1-spectrum with energy in low energy region is consistent with the previously estimated spectrum in Paper 1. This gives another support for the interpretation of the observed phase shift of the first harmonic vectors in Fig. 4. It is emphasized that the confinement of T_1-spectrum in the region less than $\sim 10^4$GeV suggests that the tail-in anisotropy is of non-galactic origin.

Acknowledgment

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Fig. 2 Annual modulation on the Earth's orbit of the excess flux from the heliomagnetotail (a) and the associated diurnal harmonic vector; SO (b), sidereal SI (c) and extended sidereal $SI2$ (d). Thick arrows express the flux. WS, SS: the winter and summer solstice; VE, AE: the vernal and autumnal equinox; ω: angular velocity (2π/year). The SO- and $SI2$-vectors on SI-dial in (c) rotate respectively clockwise and counter-clockwise with ω, starting from the autumnal equinox, and their resultant express the annual modulation of the SI-vector.

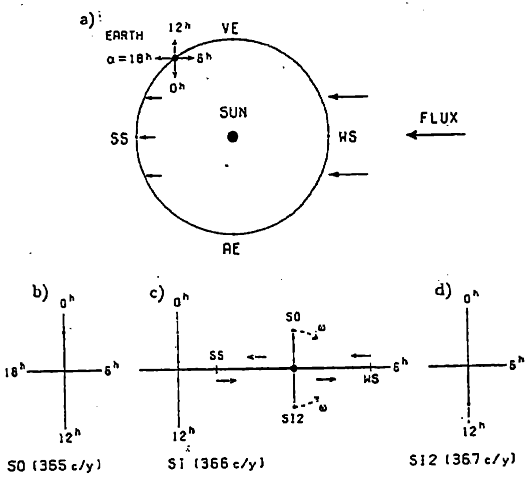

Fig. 2

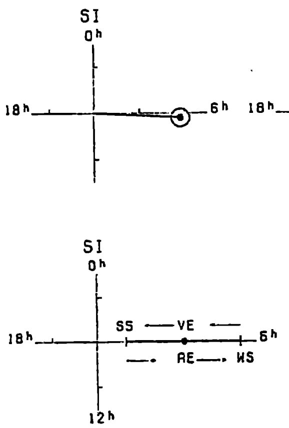

Fig. 3 *SI*- and *SI*2-vectors observed at Hobart (Lat.=43°S, Long.=147°E; Median energy= 184GeV, and the annual modulation of *SI*-vector inferred from *SI*2-vector (at the bottom). The error expresses dispersion of yearly vector.

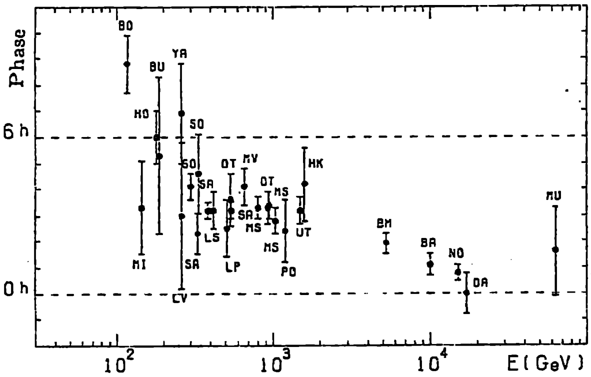

Fig. 4 Energy dependence of the phase of the observed *SI*-vector. All the vectors except several in high energy region are either those of the vertical intensities corrected for the influence of the solar diurnal variation, or those for the equatrially-pointed telescope which do not require the above correction owing to the negligible influence.

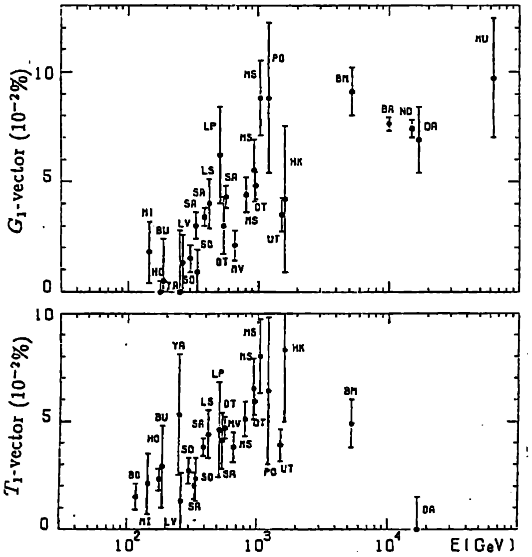

Fig. 5 Energy spectra of T_1- and G_1-vector due to the tail-in and galactic anisotropy. The dependence of the vector on the declination (δ) of the telescope was corrected by a correction factor $1/\cos\delta$.