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Gaussian analysis of two hemisphere observations of galactic cosmic ray sidereal anisotropies

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Abstract. We have analyzed the yearly averaged sidereal daily variations in the count rates of 46 underground muon telescopes by fitting Gaussian functions to the data. These functions represent the loss cone and tail-in anisotropies of the sidereal anisotropies model proposed by *Nagashima et al.* [1995a, b]. The underground muon telescopes cover the median rigidity range 143–1400 GV and the viewing latitude range 73°N–76°S. From the Gaussian amplitudes and positions we have confirmed that the tail-in anisotropy is more prominent in the southern hemisphere with its reference axis located at declination (δ) ~14°S and right ascension (α) ~4.7 sidereal hours. The tail-in anisotropy is asymmetric about its reference axis, and the observed time of maximum intensity depends on the viewing latitude of the underground muon telescopes. We also find that the declination of the reference axis may be related to the rigidity of the cosmic rays. We show that the loss cone anisotropy is symmetric and has a reference axis located on the celestial equator ($\delta \sim 0°$) and $\alpha \sim 13$ sidereal hours. We have used the parameters of the Gaussian fits to devise an empirical model of the sidereal anisotropies. The model implies that the above characteristics of the anisotropies can explain the observed north-south asymmetry in the amplitude of the sidereal diurnal variation. Furthermore, we find that the anisotropies should cause the phase of the sidereal semidiurnal variation of cosmic rays to be observed at later times from the northern hemisphere compared to observations from the southern hemisphere. We present these results and discuss them in relation to current models of the heliosphere.

1. Introduction

Daily variations in the count rates of cosmic ray recording instruments have been the focus of intensive research for many years. Coupled to the rotation of the Earth and the periodic sweeping of an instrument's viewing cone through a 360° strip of space, daily variations are recognized as providing information about anisotropies of cosmic ray intensity near the Earth. Depending on the time frame in which the variation is measured (for example, solar time or sidereal time), the information gained from analyses of daily variations can give insight into the density gradients of cosmic rays in the heliosphere and other solar modulation affects [e.g., *Bieber and Chen*, 1991; *Chen et al.*, 1991; *Ahluwalia*, 1994; *Ahluwalia and Sabbah*, 1993; *Hall et al.*, 1996, 1997a], heliospheric structure [*Nagashima et al.*, 1989] and the interplanetary magnetic field [*Mori and Nagashima*, 1979; *Swinson*, 1969, 1971; *Ahluwalia and Sabbah*, 1993]. More fundamental information can also be obtained such as detailed descriptions of the anisotropies which cause the daily variations or the physical mechanisms responsible for the anisotropies [e.g., *Ahluwalia and Erickson*, 1969; *Swinson*, 1969; *Yasue*, 1980; *Nagashima et al.*, 1989].

Compton and Getting [1935] recognized that a significant daily variation of cosmic rays in sidereal time (time frame fixed with respect to the stars) could represent a galactic or extragalactic anisotropy of cosmic rays. Since that time a wealth of knowledge has been obtained in an effort to confirm the existence of a significant sidereal daily variation and understand its origin [e.g., *Nagashima et al.*, 1989, 1995a, b; *Aglietta et al.*, 1996; *Cutler et al.*, 1981; *Cutler and Groom*, 1991; *Fenton and Fenton*, 1975; *Fenton et al.*, 1995; *Jacklyn*, 1966, 1986]. In an effort to minimize the effects of solar modulation, studies have usually been made from analyses of data from muon telescopes and air-shower arrays which cover the primary cosmic ray energy range of ~10^2–10^4 GeV and beyond. It is now accepted that a significant variation exists in sidereal time, the first harmonic of the variation having an amplitude less than ~0.1% of the daily mean intensity level and a time of maximum around the early hours of the sidereal day. This is the sidereal diurnal variation. The origin of the anisotropy which causes the diurnal variation is not understood, but for the last decade or so, researchers have thought that much of the variation was due to a process which has produced a loss cone or deficit in the flux of high-energy cosmic rays somewhere in the northern polar latitudes of the galaxy [*Nagashima et al.*, 1989] or that cosmic rays may have a higher density in the galactic plane than at polar latitudes [*Alexeenko and Navaara*, 1985;

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Bergamasco et al., 1990]. The anisotropy can be represented as two (or more) spherical harmonics and produces north-south symmetric and antisymmetric diurnal and semidiurnal variations at earth which superpose to produce the observed daily variation. The north-south antisymmetric term is important. The observed amplitude of the sidereal diurnal variation increases as the latitude of view moves from the northern geographical hemisphere across the equator to midsouthern latitudes [*Ueno et al.*, 1984; *Munakata et al.*, 1995; *Mori et al.*, 1995]. This asymmetry in the amplitude of the diurnal variation is called the north-south (NS) asymmetry of the sidereal diurnal variation. Its existence indicates that the anisotropy responsible for the diurnal variation is not a simple first-order anisotropy commonly associated with cosmic ray streaming but is more complicated; for example, the loss cone proposed above [*Nagashima et al.*, 1989], bidirectional streaming as suggested by *Jacklyn* [1966, 1986] or a combination of more than one anisotropy.

After considering the shapes of the sidereal daily variations in underground muon telescope data along with the results of the Mount Norikura air-shower experiment, *Nagashima et al.* [1995a, b] proposed that there are two anisotropic distributions of particles in the heliosphere, and these are responsible for the sidereal daily variation and the NS asymmetry of the diurnal variation. One of the anisotropies is the loss cone of galactic cosmic rays (deficit in 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 anisotropy. Both anisotropies are assumed to be axis symmetric, the loss cone having a symmetry axis aligned along a direction with right ascension (α) 12 sidereal hours and declination (δ) 20°N, while the tail-in anisotropy has an axis of reference aligned along a direction with α = 06 sidereal hours and δ = 24°S. They manifest as a daily variation in the data with a maximum and minimum value at 06 and 12 sidereal hours, 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 sidereal daily variation from the southern hemisphere are needed to compliment the substantial amount of data recorded from the northern hemisphere. Continuous multidirectional underground observations of cosmic rays from the southern hemisphere have been undertaken at Liapootah in Tasmania, Australia, since 1992. The component telescopes have various median rigidities of response above 500 GV and various latitudes of view in the southern hemisphere. The construction of this telescope completed the two-hemisphere network (THN) of underground muon telescopes, the rest of the network comprising northern hemisphere multidirectional telescopes located in Japan. Previously we examined the sidereal daily variations in the THN data by fitting Gaussian functions to the yearly averaged hourly count rates of many of the component telescopes in the data set. We did this to study the tail-in and loss cone anisotropies as distinct effects in the data. In contrast to the model of *Nagashima et al.* [1995a, b] we show, using Gaussian fits, that the tail-in anisotropy is asymmetric. This asymmetry causes the maximum in the daily variation to be observed at earlier sidereal times for more southern latitudes of view [*Hall et al.*, 1998, hereinafter referred to as paper I]. In paper I, we showed that there was a relationship between the right ascension of the tail-in anisotropy maximum and the viewing latitude or declination. We also found that the reference axis of the tail-in anisotropy is located in the southern celestial hemisphere and suggested that this southern position combined with the unique asymmetry of the anisotropy may be partly responsible for the NS asymmetry of the sidereal diurnal variation [*Hall et al.*, 1997b].

We have recently extended our analysis of the THN data to include as much data as possible (to the end of 1996 in the cases of the multidirectional telescopes) and have improved our analysis technique. In this paper we present the results of the analysis and a discussion of the origin of the anisotropies. By relating the parameters of the analysis to the anisotropies we devise a model of the anisotropies in the heliosphere and examine the diurnal and semidiurnal variations of cosmic rays which should be produced from the anisotropies. We will demonstrate that the anisotropies can produce a sidereal diurnal variation which has north-south asymmetry of the amplitude and a semidiurnal variation which may also have a particular signature that is consistent with observations. Note that although the cause of the tail-in anisotropy has not been confirmed as being related to the heliotail, we have opted to use the original terminology of the model throughout this paper. We also wish to reiterate our previous assertion about this analysis: we are in no way proposing that harmonic analysis is a poor method to examine cosmic ray daily variations. We are simply using another technique in an attempt to understand the sidereal daily variation of galactic cosmic rays.

2. Data Analysis

The cosmic ray telescopes which make up the THN were described briefly in paper I. They are the multidirectional underground muon telescopes located in the northern hemisphere at Misato, Sakashita, and Matsushiro in Japan and in the southern hemisphere at Liapootah in Tasmania, Australia. We have also included data from underground muon telescopes at Hobart and Poatina in Tasmania and the north pointing telescope at Mawson, Antarctica. These stations are described in detail by *Mori et al.* [1976], *Fujimoto et al.* [1984], *Mori et al.* [1989, 1992], *Duldig* [1990], and *Humble et al.* [1992]. In the present study we have utilized all the available data of the telescopes which in most cases is until the end of 1996. We present important parameters of these stations in Table 1. The telescopes respond to primary cosmic rays with median rigidities (P_m) in the range 143–1400 GV.

The multidirectional telescopes are formed from two horizontal layers of plastic scintillator cells. Each layer is formed from an array of scintillator cells, each cell being made from a piece of plastic scintillator and one or two photomultiplier tubes. A cosmic ray muon passing through a cell produces scintillation radiation that is detected by the photomultiplier and signifies a single count. Coincident counts between certain cells from opposite layers gives directional information. The component telescopes are formed from the coincidence counts of identically combined cells, and the median angles of inclination of these component telescopes can be easily calculated. We have analyzed the data from all the vertical and inclined components of the underground muon telescopes except those north and south directed components of each station which view directly toward or over the rotation axis of the earth. We noticed that the coupling coefficients [*Nagashima*, 1971] for these components have very large values when normalized to the equator, presumably due to a large error in the asymptotic cones of view or a poor representation of the response of these

Table 1. Stations and Their Component Underground Muon Telescopes

Station	Years Analyzed	Detector Type	Number of Components Available	Number of Components Analyzed	Components With Significant Fits	Vertical Depth, mwe	Vertical Count Rate, 10^3 hour^{-1}	Geometrical Viewing Latitude Range, λ	Rigidity Range P_m, GV
Mawson	1973–1994	GM, P	2	1	N	31	180	45° S	165
Cambridge	1957–1983	GM	2	2	V*, N	36	115	43°S–0°	184–195
Misato	1975–1996	S	9	8	V, N, S, E, W, 2S, 2W, 2E	34	280	8°S–51°N	143–209
Sakashita	1978–1996	S	13	10	V, N, S, W, NE, NW, SE, SW, 2S	80	390	23°S–73°N	322–540
Matsushiro	1985–1996	S	17	12	V, N, S, W, NE, NW, SE, SW, 2S, 2E, 2W	220	19.5	17°S–70°N	565–861
Liapootah†	1993–1996	S	17	12	V, N, S, E, W, NE, NW, SE, SW, 2N, 2E, 2W	154	25	76°S–11°N	454–984
Poatina	1972–1995	GM, P	1	1	V	365	1.8	42° S	1400

The instruments are described as having a "detector type" of either Scintillator telescope (S), Proportional counters (P) or Geiger-Müller counters (GM). The vertical rock depth is given in meters of water equivalent (mwe). The Mawson underground muon telescope consisted of 3 GM telescope sections until 1982, which were then progressively replaced by proportional counter telescope sections. The Poatina underground muon telescope also originally comprised three GM counter telescope sections and has progressively been upgraded by the inclusion of two proportional counter sections since 1983. The number of components available at each station include all the highly inclined components (e.g., 3N, 3S, 3E, and 3W at Matsushiro and Liapootah) which were not considered in this analysis and the 2N and 2S components which were rejected from the analysis due to their poor values of coupling coefficients (see text). All components analyzed had significant Gaussians fitted except the Matsushiro 2E and Sakashita 2E components.

*Cambridge V component had an insignificant loss cone anisotropy (see section 3).

†The first year of available data from *Liapootah* [1992] has been excluded due to technical difficulties with some of the component telescopes during that year.

inclined components to the primary cosmic ray flux by the response function used in the calculations [*Mori et al.*, 1992]. This left us with the data from 46 component telescopes with reasonable statistical accuracy and confidence in our knowledge of their viewing directions and energy response to primary cosmic rays. Hence our study is confined to the analysis of data from component telescopes with geometrical viewing latitudes (λ) between approximately ±75° and P_m between 143 and 1400 GV. As outlined in our preliminary study, we fitted two Gaussian functions of arbitrary height, position, and width to the averaged sidereal daily variations of the hourly count rates of each component telescope in our database. The analysis procedure is described below.

Data with $P_m > 500$ GV are assumed to be free from atmospheric pressure and solar modulation effects. Data with $P_m < 500$ GV have each hourly record corrected for atmospheric pressure fluctuations. Variations with longer periods than 24 hours such as day-to-day variations and counter degradation are removed by subtracting the 24-hour running average from each hourly record. Atmospheric temperature effects at most of the shallow underground stations are known to be small or zero [*Mori et al.*, 1988; *Fenton et al.*, 1961], while temperature effects at Matsushiro are slightly larger. Those at Poatina and Liapootah are not known but would be similar to those at Matsushiro. In sidereal time analyses, it is assumed that these effects become small, and we have assumed that they are negligible.

Each hourly count rate (corrected for atmospheric pressure effects) for a month is binned according to its local sidereal and antisidereal hour and the individual average hourly count rates for each month are obtained in both time frames. Each average hourly count rate from all the months is then calculated, providing 24 (average) hourly values obtained from the complete set of data for each instrument. We calculate the mean of these hourly values and the percentage deviation of each hourly value from the mean to obtain the average daily variation recorded by each instrument in sidereal and antisidereal time. The error of each average hourly deviation is calculated from the scatter of the yearly averaged values about each final average hourly count rate.

We have noticed that the individual yearly average hourly deviations can be rather scattered about the final average hourly deviation. Prior to the above procedure being applied we attempted to reduce the final scatter by applying a method of data reduction to the individual hourly count rates. This was not done in paper I. For each component we examined the number of hourly records which had absolute deviations ($d_t = |\Delta I/I|$) from the 24-hour running average (about each record) between d_t and d_{t+1}, where the minimum deviation, $d_{\min}$, is zero and the maximum, $d_{\max}$, is the maximum deviation of all the records. We assumed that with enough hourly records a normal distribution with a mean of zero should describe the distribution of d_t values. Figure 1 shows the histogram of the (absolute) percent deviations of the hourly count rates recorded in data from the vertical underground muon telescope at Matsushiro. By examining the logarithm of the histogram values as a function of $(d_i)^2$ we used robust fitting techniques to determine the parameters of the normal distribution $(N(d_i))$ describing each set of data. Since

$$N(d_t) = Ae^{-1/2(d_t/\sigma)^2}, \quad (1)$$

where σ is the standard deviation of the distribution, then the slope (m) of a plot of $\ln(N)$ versus $(d_t)^2$ yields $m = -1/2\sigma^2$.

From m and inspecting the plots we determined the values of $(d_i)^2$ that were outside the normal distribution and rejected them from the analysis. The cutoff levels of $(d_i)^2$ corresponded to values of d_i greater than 3σ from the mean and usually 4σ, depending on the component. The $\ln(N)$ versus $(d_i)^2$ plot is also shown in Figure 1. This method of data reduction has little effect for most of the component telescope results but does reduce the final errors in the average hourly deviations by up to ~25% for some of the high-inclination

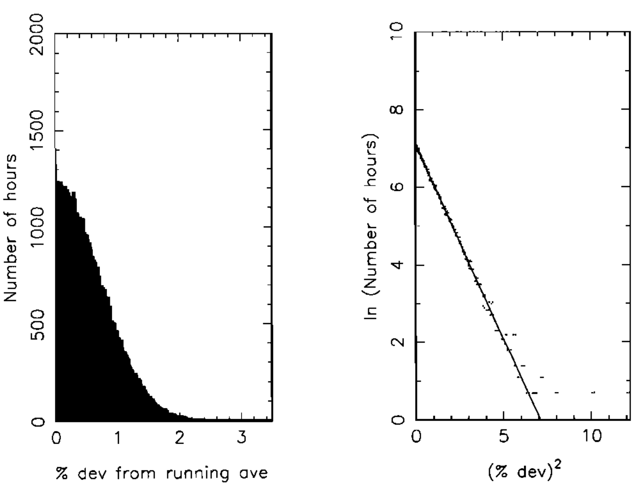

Figure 1. Distribution of (absolute) percent deviations from the 24-hour running average of hourly count rates for the Matsushiro vertical underground muon telescope. The fitted line has a slope of −0.97. The inferred standard deviation of the distribution is 0.71%. This can be compared to the standard deviation of 0.72% deduced from the counting rate. For this component we deemed records which had a (% deviation)^2 >7.1%^{2} (3.7σ) to be outside the distribution and rejected them from the analysis.

components. Once the data were reduced by the above method, we obtained the average sidereal and antisidereal daily variations of the hourly count rates. As mentioned previously, for daily variations recorded by instruments with median rigidities <500 GV, solar modulation effects need to be considered and removed. We need to remove the spurious sidereal diurnal variation present in the data which is caused by the annual modulation of the solar diurnal variation that arises from the semidiurnal anisotropy. This annual modulation also produces a variation in antisidereal time. We followed the Nagashima correction method [*Nagashima et al.*, 1985] which removes the spurious sidereal diurnal variation by taking into account the relation between the sidereal and the antisidereal variations. The final average percent daily variations ($D(t)$) from each telescope were then modeled as Gaussian functions and a mean level (C); that is,

$$D(t) = C + A_T e^{-\left(\frac{t-t_T}{\sigma_T}\right)^2} + A_L e^{-\left(\frac{t-t_L}{\sigma_L}\right)^2} \qquad (2)$$

The functions had arbitrary amplitudes (A_T, A_L), positions (t_T, t_L), and widths (σ_T, σ_L). One Gaussian with a positive amplitude represented the tail-in anisotropy (A_T, t_T, σ_T) and the other (with negative amplitude) represented the loss cone (A_L, t_L, σ_L).

An iterative computer method [*Press et al.*, 1990] was employed to fit 48 sidereal hours of data with two sets of the above model (equation (2)) separated by 24 hours. The best fit was made by examining the value of χ^2 over the central 24 hours. This was done to ensure that the cyclic nature of the data was at least approximated by the model. A large range of initial conditions was used to ensure a minimum χ^2 had been found for the final solution, and we rejected from the intermediate solutions those that had widths <1 hour (our temporal resolution) or amplitudes that were 4 times greater than the maximum deviation of the average hourly count rate. This helped to find solutions for some of the components with relatively low statistical accuracy such as the inclined telescopes at Liapootah.

At this point we need to discuss our motivation for much of the work presented in the remainder of this paper. We originally used this Gaussian fitting method to examine the maxima and minima of the daily variations separately and thus investigate the components of the tail-in and loss cone anisotropies model. The method has allowed us to gain some simple understanding of the anisotropies and their distribution in the heliosphere. By examining the Gaussian parameters (paper I and *Hall et al.* [1997b]) we have some insight of how we may model the anisotropy of cosmic rays as a function of time (or right ascension, α), λ and P_m. With this apriori knowledge we will attempt to describe the anisotropy (ξ) as the sum of two separable functions of α, declination (δ) and P_m, one function describing the tail-in anisotropy (ξ_T) and the other describing the loss cone anisotropy (ξ_L):

$$\xi = \xi(\alpha, \delta, P_m) = \xi_T(\alpha, \delta, P_m) + \xi_L(\alpha, \delta, P_m) \qquad (3)$$

The final form of (3) will become clear later in the paper. Essentially, we assume that we can model the α dependence by a function similar to (2) and that the δ dependence can also be approximated by a series of Gaussian functions. The appropriate coefficients of the functions will be determined from the analysis of the fitted parameters (A_T, t_T, σ_T) and (A_L, t_L, σ_L) derived from each of the 46 telescopes.

We have examined the resulting best fit parameters of (2) to determine the rigidity and latitude spectra of the two anisotropies. These are used to determine an appropriate form of (3), and we use the model in an attempt to explain the cause of the NS asymmetry of the sidereal diurnal variation.

3. Results

Previously (paper I, Figure 1), we showed the high quality of fitting which we could obtain from data recorded at the high count rate underground muon telescope at Sakashita in Japan. Those results indicated that the tail-in and loss cone anisotropies could be resolved and analyzed by fitting (2) to the data and that the data were well approximated by the model. Here, in Figure 2 we present some of the results (repeated for 2 days) from the Matsushiro underground muon telescope. The Matsushiro underground muon telescope is located at a similar latitude to that of Sakashita, but the vertical depth of rock above the telescope is 220 meters of water equivalent (mwe) compared to 80 mwe for that of Sakashita. The corresponding median rigidities of the component telescopes at Matsushiro are 2–4 times higher than at Sakashita with a substantial reduction in hourly count rates caused by the increase in median primary rigidities and the smaller surface areas of the telescopes compared to those at Sakashita. Even though the noise and uncertainties are large in the higher-rigidity data, we can still obtain reasonably good fits (usually the reduced χ^2 values are between 1 and 1.5), but occasionally, we do not get what one may have intuitively expected, and in some cases the results are not significant. Nonetheless, of the 46 component telescopes analyzed in this study only two sets of data resulted in a fit for both of the anisotropies that was not significant (Matsushiro east and Sakashita east viewing components) and the Cambridge vertical component had a loss cone fit that was also not significant.

We see from Figure 2 that the south viewing instruments

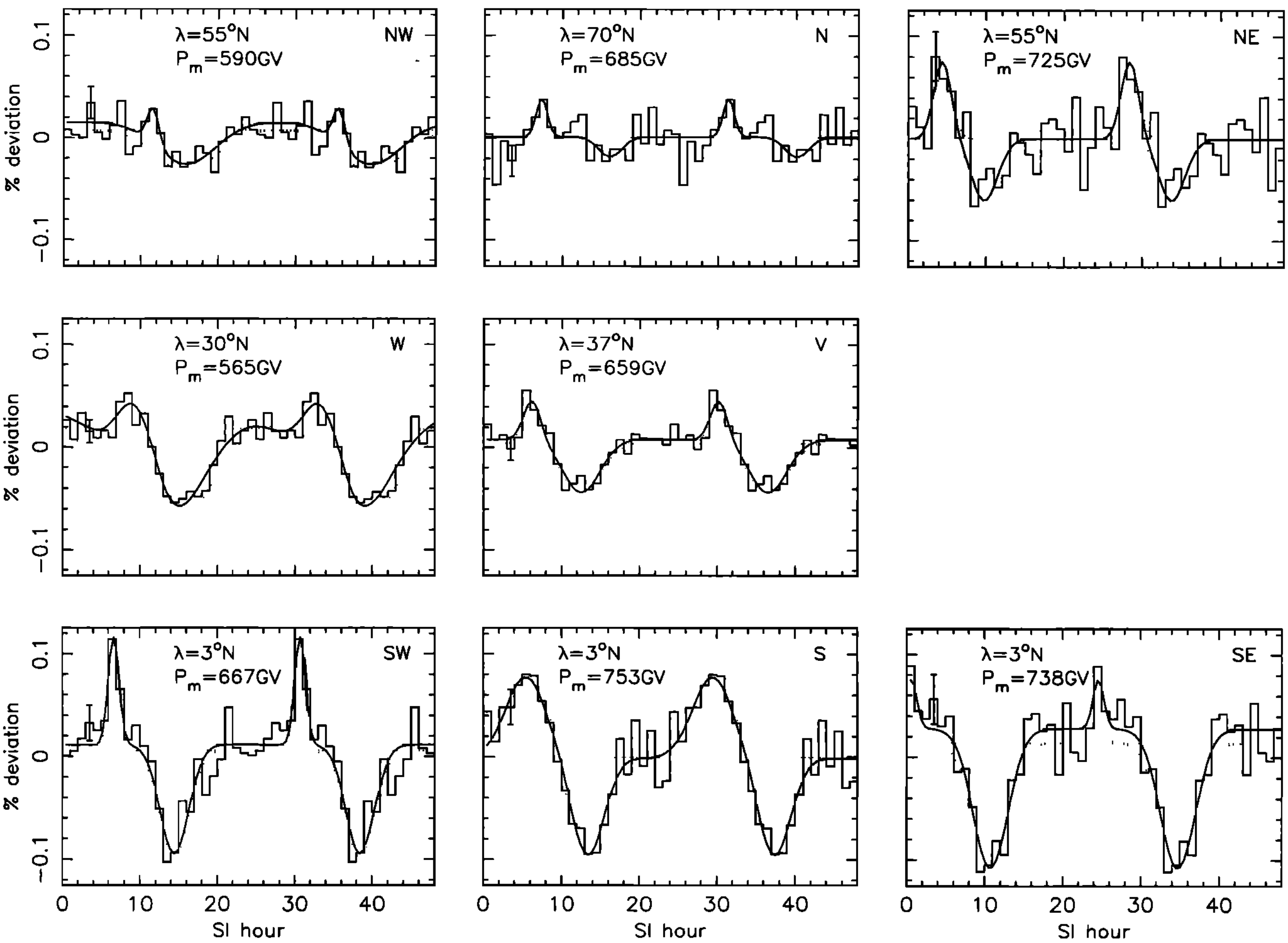

Figure 2. Sidereal daily variations recorded at the Matsushiro underground muon telescope station from 1985 to 1996. Components shown are the northwest (NW), north (N), northeast (NE), west (W), vertical (V), southwest (SW), south (S), and southeast (SE). Errors have been included on each the third hours. The Gaussian functions are shown as the dotted lines, while the overall fit is shown as the solid line. Note that we have shown the data repeated over 2 days for clarification of the daily variations and that the fitted parameter results for the E component are insignificant within errors.

have a larger daily variation (consistent with many previous observations of the sidereal anisotropies [e.g., *Mori et al.*, 1995]) and that the east viewing component telescopes respond to the anisotropies at earlier times than the west viewing components. The position of the tail-in anisotropy appears to have a latitude dependence as pointed out previously in our earlier papers. We will discuss this in more detail below. We present these results as typical of those from the deep underground muon telescopes (Matsushiro and Liapootah). They can be compared to the results obtained from instruments which record a much higher hourly count rate and have a longer counting period in Figure 1 of paper I.

3.1. Anisotropy Positions: t_T, t_L

We examined the dependence of t_T and t_L on the longitude of view of the telescopes referenced to their vertical viewing directions. There are definite linear dependencies as discussed previously (see Figure 2 of paper I) and we removed these by normalizing t_T and t_L to the vertical viewing direction.

Figure 3 shows the resulting distributions of the normalized t_T and t_L as a function of P_m and λ. As concluded in our previous paper, we find very little dependence of the normalized t_T and t_L on P_m. We formally calculated the linear correlations of t_T and t_L with P_m and found that the chances of random correlations occurring from our data set are 74% in the case of the tail-in anisotropy and 35% in the case of the loss cone anisotropy, indicating that t_T and t_L are probably independent of P_m.

A most exciting result from our preliminary studies was that of the latitude distributions of the positions of the Gaussians, particularly t_T. As shown in Figure 3b, the loss cone is fitted at around 13 hours sidereal time at all latitudes, but the tail-in anisotropy is observed at later times as the latitude of view increases to the north. We suggested that this relative configuration of the anisotropies is partly responsible for the NS asymmetry of the sidereal diurnal variation. An initial investigation was reported by *Hall et al.* [1997b]. Detailed discussions appear later in this paper. The latitude distribution of the loss cone is clearly constant. A least squares fit to determine any linear dependencies indicates that the constant term for the loss cone anisotropy is 12.99 sidereal hours and the correlation coefficient suggests that the chances of the very weak linear dependence (0.005 hours per degree of latitude) being a ran-

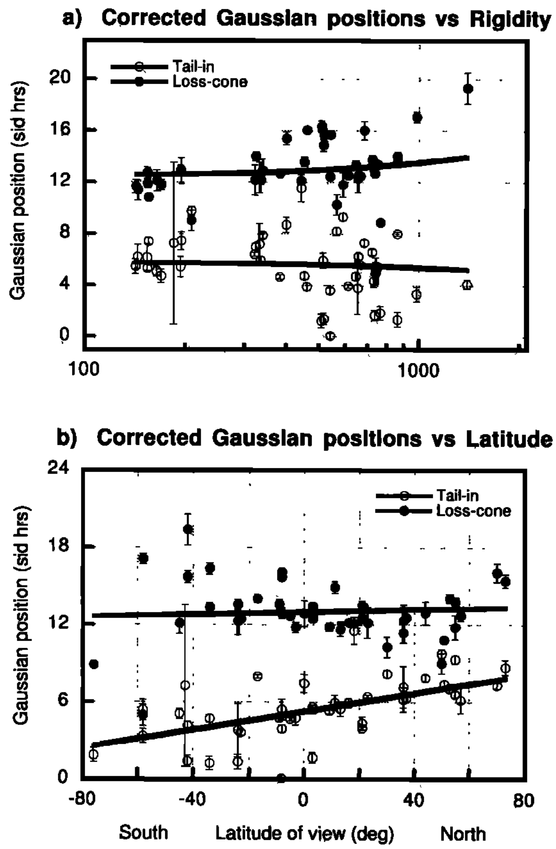

Figure 3. (a) Rigidity spectra of the corrected Gaussian positions. (b) Latitude distributions of the corrected Gaussian positions. Errors are the standard errors of the fitted parameters. The linear correlations between the Gaussian positions and median rigidity and latitude of view are shown as the solid lines.

dom occurrence is 57%. On the other hand, the tail-in anisotropy is latitude dependent. The distribution is best described by a straight line with a constant term of 5.25 sidereal hours (at 0° latitude) and a latitude dependence of 0.36 ± 0.01 sidereal hours per 10° of latitude. The correlation coefficient between t_T and λ is 0.50, which has a probability of occurring by chance of only 0.05%. Hence we are confident that this effect is real and that we need to include this effect in our model (equation (3)).

3.2. Anisotropy Amplitudes: A_T, A_L

In our previous analyses we examined the latitude and rigidity distributions of the fitted amplitudes (A_T and A_L) of the tail-in and loss cone anisotropies. To do this accurately, one should obtain the rigidity spectra of A_T and A_L free from latitude effects and normalize the data to some arbitrary rigidity to examine the latitude distributions free from rigidity effects. We previously assumed that there was no correlation between P_m and λ so that we could use all the data available to determine the rigidity spectra of the anisotropies. We assumed that any latitude variations in the data would just contribute to the scatter of the data about the correct rigidity spectra. Here we have devised a scheme to eliminate cross correlations so that instead of fitting for the effects in two steps we are able to calculate the rigidity and latitude distributions simultaneously. We assumed that the rigidity spectra of A_T and A_L could be described by a power law spectrum normalized to 500 GV and that the latitude distributions were approximated by Gaussian functions.

$$A_i(\lambda, P_m) = a_i\left(\frac{P_m}{500}\right)^{\gamma_i} e^{-[(\lambda-\Phi_i)/\Sigma_i]^2}, \qquad i = T, L \qquad (4)$$

where the subscript i can imply either the tail-in (T) or the loss cone (L) anisotropy. The parameters a_T and a_L are the best fit normalized amplitudes of the latitude distributions, γ_L and γ_T are the best fit spectral indices of the anisotropies, Σ_T and Σ_L are the best fit widths of the latitude distributions and Φ_T and Φ_L are the best-fit central latitudes of the distributions. This function will be used to help describe the dependence of the anisotropies on δ and P_m (equation (3)) later.

The best fit parameters of (4) are presented in Table 2. The results are very similar to what we obtain using the two-step procedure employed previously (indicating that the correlations between λ and P_m are small). Figures 4a and 4b, present the values A_T and A_L, respectively, normalized to the central position of the fitted latitude distributions (i.e., at $\lambda = \Phi_T$ and Φ_L) along with the rigidity spectra determined from the above procedure. Figures 4c and 4d present the values of A_T and A_L, respectively, normalized to $P_m = 500$ GV and the best fit latitude distributions.

We can see that the tail-in anisotropy has a maximum when viewed from latitudes of ~14° ± 3° south. This is reasonably consistent with Nagashima et al.'s model which placed the tail-in anisotropy at around 24° south although a little more towards the equator. On the other hand, the loss cone has a maximum on the equator. This is in stark contrast to the conclusions of *Nagashima et al.* [1995a]. We will discuss possible reasons for the difference later.

3.3. Model of Anisotropies From Gaussian Parameters

We can derive an empirical model of the anisotropy as a function of δ (from λ), α (from sidereal time), and P_m, by using the parameters in Table 2 and the latitude dependencies of t_T and t_L.

From the distributions of A_T and A_L presented above we can describe the variation of anisotropy with respect to δ and P_m by (4). Using the results presented in Figures 2 and 3, we know that (2) is a good representation of the α variation of the anisotropy but that it needs to be modified slightly to explicitly include the dependence of t_T on latitude. The width parameters of the original Gaussian fits (σ_T, σ_L) from all the telescopes in the THN and the latitude distributions of t_T and t_L allow us to approximate the α variations ($\xi_T(\alpha)$, $\xi_L(\alpha)$) of the anisotropy as

$$\xi_i(\alpha) = e^{-\left\{\frac{[\alpha-\tau_i(\delta)]}{\overline{\sigma_i}}\right\}^2}, \qquad i = T, L \qquad (5)$$

where $\overline{\sigma_T}$ and $\overline{\sigma_L}$ are the averages of the fitted widths of the Gaussians from all the components in the THN and $\tau_T(\delta)$ and

Table 2. Best Fit Parameters of (4) Describing the Latitude and Rigidity Distributions of A_T and A_L

Parameters	Tail-In Anisotropy	Loss Cone Anisotropy
a_i	0.072 ± 0.002	−0.077 ± 0.002
γ_i	0.70 ± 0.04	0.86 ± 0.04
Σ_i, deg	75.4 ± 4.4	55.0 ± 2.4
Φ_i, deg	−14.3 ± 3.0	−0.3 ± 1.6

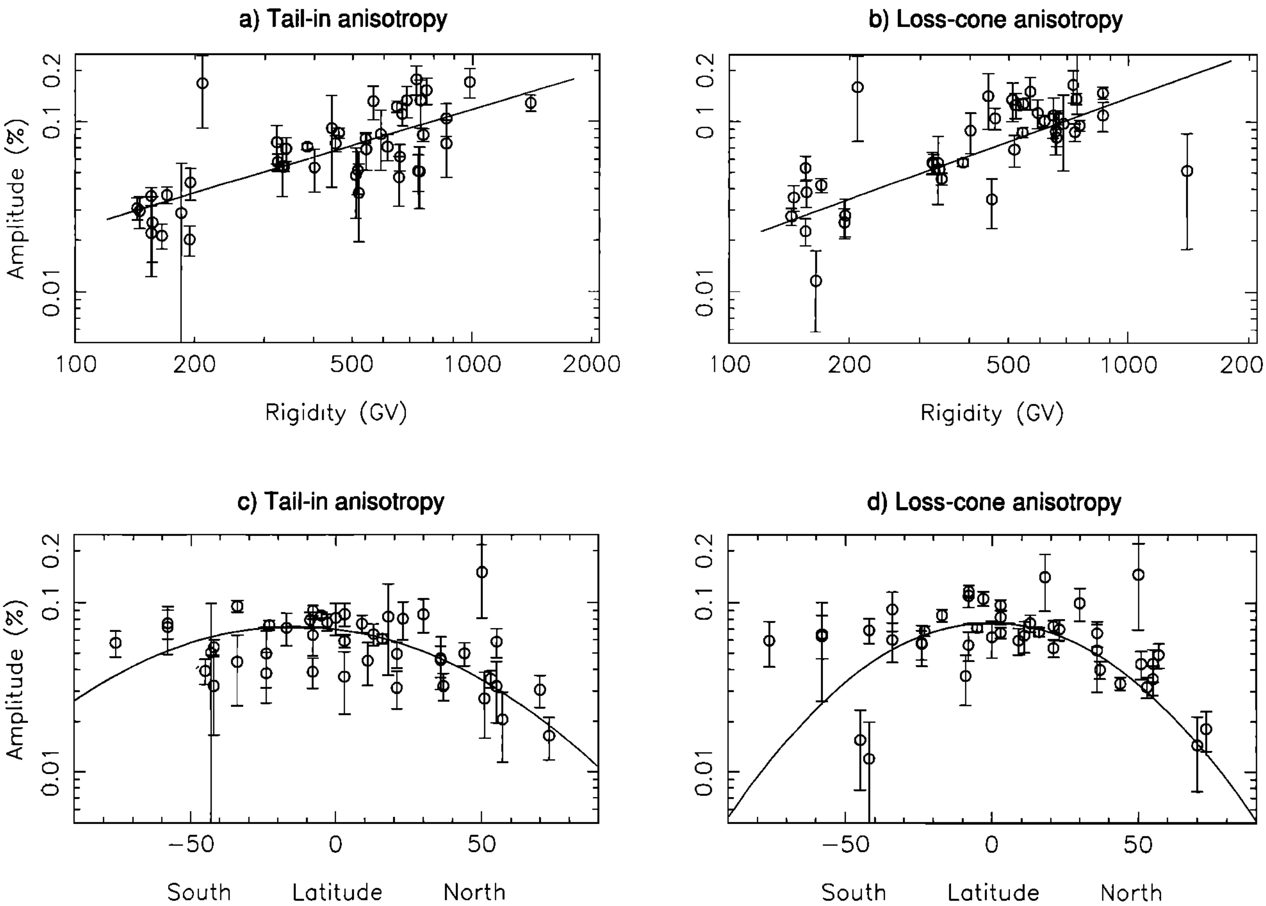

Figure 4. (a, b) Rigidity spectra of the fitted Gaussian amplitudes of the tail-in (A_T) and loss cone (A_L) anisotropies, respectively, normalized to the center of the latitude distributions by the fitted parameters Σ_T and Φ_T (for the tail-in anisotropy) and Σ_L and Φ_L (for the loss cone anisotropy) in Table 2. The solid lines are the fitted rigidity spectra normalized to a_T and a_L at 500 GV. (c, d) are the fitted Gaussian amplitudes of the tail-in (A_T) and loss cone (A_L) anisotropies, respectively, normalized to 500 GV by the spectral index γ_T (for the tail-in anisotropy) and γ_L (for the loss cone anisotropy) and plotted as a function of viewing latitude. The solid lines are the fitted latitude distributions from Table 2 with amplitudes a_T and a_L.

$\tau_L(\delta)$ explicitly describe the latitude distributions of t_T and t_L. For the loss cone, $\tau_L(\delta)$ is 12.99 sidereal hours and constant for all values of δ. For the tail-in anisotropy, $\tau_T(\delta)$ is the linear dependence of t_T on latitude determined previously and is $\tau_T(\delta) = 0.036\delta + 5.25$ sidereal hours.

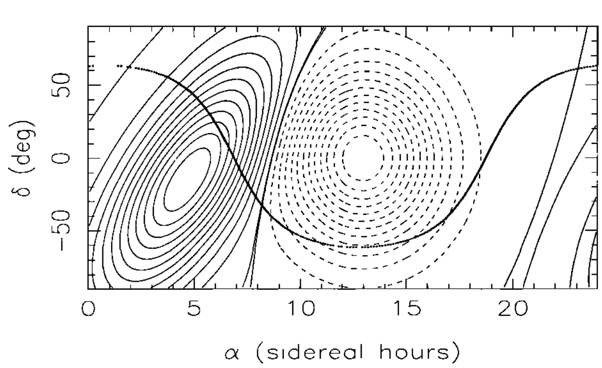

Figure 5. Contours of the values of anisotropy calculated from (6) at 500 GV. The solid contours indicate the tail-in anisotropy (positive values of ξ) and the dashed contours indicate the loss cone anisotropy (negative values of ξ). The bold dotted line is the galactic equator. The contours range between 0.072% and −0.077% in steps of 0.006%.

By combining the loss cone and tail-in components of (4) with those of (5) we are able to explicitly describe the anisotropy in the heliosphere (equation (3)) as a function of α, δ, and P_m.

$$\xi = \xi(\alpha, \delta, P_m) = \xi_T(\alpha, \delta, P_m) + \xi_L(\alpha, \delta, P_m)$$

$$= \sum_{i=T,L} a_i \left(\frac{P_m}{500}\right)^{\gamma_i} e^{-\left(\frac{\delta-\Phi_i}{\Sigma_i}\right)^2} e^{-\left(\frac{\alpha-\tau_i(\delta)}{\sigma_i}\right)^2} \qquad (6)$$

All the parameters of (6) have been determined except the average widths ($\overline{\sigma_T}$ and $\overline{\sigma_L}$) of the original fits. We found that there are no obvious relationships between the fitted widths and P_m or λ and that the values of σ_T and σ_L are highly variable. This is a rather large problem with the analysis which we feel is related to the statistical accuracy of the deep underground data. For this reason we have only been able to use the average values of the widths in (6). These are 2.8 ± 1.2 sidereal hours for $\overline{\sigma_T}$ and 3.4 ± 1.8 sidereal hours for $\overline{\sigma_L}$.

In Figure 5 we present the results of calculating the percent anisotropy (from (6)) in celestial coordinates normalized to an arbitrary value of 500 GV of rigidity. Note the tail-in anisotropy produces maximum anisotropy of 0.072% at $\delta = -14.3°$ and $\alpha = 4.7$ sidereal hours. The loss cone has a maximum deficit of −0.077% at $\delta = -0.3°$ and $\alpha = 12.99$ sidereal hours. We can see that the loss cone is essentially symmetric about its

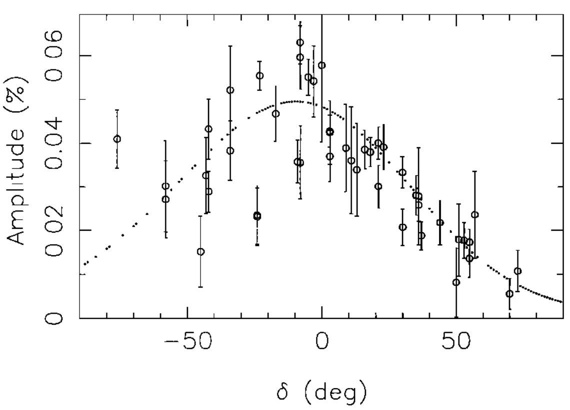

Figure 6. The amplitude of the first harmonic of the model as a function of declination at 500 GV. The dotted line is the calculation of the amplitude at each degree of declination. The measured amplitudes of the first harmonics in the THN data are shown.

reference axis (the widths along the α and δ axes are 51° and 55°, respectively). The tail-in anisotropy is much more asymmetric and skewed.

By harmonically analyzing the model anisotropy as a function of δ we are in the exciting position to determine the validity of the empirical model by comparing the harmonics to those observed in data recorded at various latitudes of view around the Earth. Figure 6 shows the amplitudes of the first harmonics of the sidereal variations determined at each degree of δ from the results in Figure 5. We also present the amplitudes of the first harmonics of the daily variations in the data of the THN normalized to 500 GV by an arbitrary rigidity spectrum with spectral index of 0.78 (the average of the spectra of the tail-in and loss cone anisotropies). The results from the model have ~10° of NS asymmetry which causes the amplitude at 40° south to be ~0.04% while the amplitude is 0.025% at 40° north (a factor of 1.6). We see that the NS asymmetry of the modeled amplitudes is in good agreement with the NS asymmetry observed in the sidereal diurnal variations of the data in the THN. Specifically, the north-south asymmetry in the modeled amplitudes is in good agreement with that determined from the data at Liapootah V (unnormalized amplitude = 0.045 ± 0.007%, λ = 42° south, P_m = 519 GV) and Matsushiro V (unnormalized amplitude = 0.023 ± 0.004%, λ = 37° north, P_m = 659 GV). The unnormalized data from these two components give a good indication of the NS asymmetry due to their similar northern and southern latitudes of view and median rigidities of response without knowledge of the true rigidity spectrum. The unnormalized ratio is 2.0 ± 0.5 while the normalized ratio of these amplitudes is 2.3 ± 0.5%. Note that if the declination of the reference axis of the tail-in anisotropy was more southward in the model we would expect a larger NS asymmetry in the amplitudes, a point we will refer to later.

In the following section we will discuss the results presented above and the departure of the empirical model from the original model of *Nagashima et al.* [1995a, b]. We will also tentatively make some suggestions as to the origin of the tail-in anisotropy and its characteristics.

4. Discussion

The model presented above is fundamentally the same as the model of *Nagashima et al.* [1995a, b]. That is, both models have two anisotropic distributions coexisting in celestial space, one an excess of particles and the other a deficit. One difference is that the anisotropies are approximated by Gaussian distributions whereas in the previous model the anisotropies were described by a binary function of the pitch angle of the particles with respect to the reference axes, particles with pitch angles less than some maximum value would contribute to the anisotropy, all other particles contributed nothing. Quantitatively, the declination of the reference axis of the loss cone appears to be rather different to that of the original model, but in fact, coupled to the α of the reference axis, the reference axis of the loss cone is still located at quite high latitudes of the galactic northern hemisphere (~60°), in reasonable agreement with the previous analysis of *Nagashima et al.* [1989] although slightly lower. Aside from these differences, the dramatic departure from the previous model is our conclusion that the tail-in anisotropic distribution is such that the measured α depends on the declination of view of the cosmic ray telescopes (i.e., $\tau_T(\delta)$). With this effect and the equatorial position of the loss cone we get almost the same amount of NS asymmetry in the first harmonic as we observe in the data. If we repeat the harmonic analysis of the model anisotropies but ignore $\tau_T(\delta)$, the amount of NS asymmetry in the amplitude is reduced (but there is still a small amount of asymmetry related to the southern position of the reference axis of the tail-in anisotropy). If we place the two reference axes at the positions suggested by the original model, ignore $\tau_T(\delta)$ but keep all the other parameters the same, we actually get a NS asymmetry of the first harmonic but in the opposite sense to that which is observed. If $\tau_T(\delta)$ is included in these calculations, we get almost no NS asymmetry at all. Therefore it is our conclusion that within the framework of our analysis, the declinations of the reference axes of the anisotropies and the declination dependence of α are both important effects which contribute to the NS asymmetry of the sidereal diurnal variation.

In considering the differences between the two models we note that the model of Nagashima et al. leads to predictions about the phases of the first and second harmonics of the variations in the data. According to their model, the phase of the diurnal variation would be related to the relative contributions of the two effects but should be observed at earlier times when viewed from the northern hemisphere compared to the southern hemisphere. Their model also predicts that the phase of the second harmonic should be 0600 sidereal time at all latitudes. Our model predicts that the phase of the sidereal diurnal variation (normalized to 500 GV) should be slightly earlier when viewed from the southern hemisphere (2.5 sidereal hours at 40° south compared to 3.5 sidereal hours at 40° north), but the data from the THN were rather scattered, and no trends within this narrow region of time (1 hour) were observable. However, an examination of the second harmonic was more fruitful. Figure 7 shows the phase of the second harmonic (semi-diurnal variation) as a function of δ predicted by the harmonic analysis of the above empirical model. Figure 7 also shows the phase of the semi-diurnal variations observed in our THN data set. We have normalized the observed phases to the vertical viewing direction (i.e., removed longitude effects) but have not considered geomagnetic effects which should be small.

Harmonically analyzing the model as function of declination indicates that the phase of the second harmonic (ϕ_2) should increase from ~0500 sidereal time at 40° south to 0700 sidereal time at 40° north (dotted line of Figure 7). The results from the

THN data appear to follow this. The coefficient of linear correlation between ϕ_2 (of the data) and declination is 0.8 which has a chance of randomly occurring from our data set of <0.001%. This suggests that the effect is real. Considering the average values of ϕ_2 around declinations of 40° (±10°) south and north (3.5 ± 2.0 and 6.7 ± 0.7, respectively), we cannot discount the possibility that the phase of the second harmonic is always close to 0600 sidereal time, but the evidence is highly suggestive that ϕ_2 does increase to later times as the viewing directions move toward more northern latitudes, as the model implies. Although in the past most investigators have qualitatively concluded that the phase of the sidereal semidiurnal variation at these rigidities is close to 0600 [e.g., *Nagashima et al.*, 1991; *Mori et al.*, 1995], it would seem that high-resolution analyses of this effect need to be undertaken if we are to fully understand the sidereal anisotropies. As a final comment pertaining to the semidiurnal variation we note that Cutler and Groom (1989) analyzed underground muon data recorded over a 10-year period at the Utah underground muon telescope ($P_m \sim 1500$ GV, $\lambda = 40.5°$ north) and concluded that the sidereal semi-diurnal variation had a phase of 8.4 ± 1.1 sidereal hours (note the error is also quoted as ±0.5 hours in their paper), in reasonable agreement with the prediction of our model.

The tail-in and loss cone anisotropy model proposed by *Nagashima et al.* [1995a, b] suggested that two distinct anisotropic distributions of high-energy galactic cosmic rays coexist and are responsible for the observed sidereal daily variation. They also suggested that independent analyses of the rigidity and latitude effects were needed to further elucidate these anisotropies. We have used their ideas to examine the parameters of Gaussian functions fitted to sidereal daily variations. On the basis of our results, we feel that the model should be revised to include the asymmetric and skewed tail-in anisotropy and the position of the loss cone should be more equatorial than previously suggested. Here we discuss briefly why the original model may not have included these effects. In the original model the reference axis of the loss cone has a declination of 20°N. This value is the solution to the analysis of the data recorded at the Mount Norikura air-shower array in Japan [*Nagashima et al.*, 1989] by using a method of least squares to fit a model to the first three harmonics in the data. In fact, there were two solutions to that analysis, the other was $\delta = 15°$ south. There were also other solutions between these limits which were good approximations. The lower limit was rejected on the basis that the sidereal diurnal variation in data from the Liaweenee air-shower array in Tasmania, Australia, is the same size as the antisidereal diurnal variation recorded there. This implies that the only sidereal variation recorded at that site is of a spurious origin. They also concluded that the loss cone did not extend to such southern latitudes from their analysis of the muon data from the Cambridge vertical (V) underground muon telescope [*Nagashima et al.*, 1995a]. Our analysis of those data yielded a statistically insignificant loss cone amplitude. Furthermore, a small but significant loss cone amplitude was observed by the Mawson underground muon telescope. These results confirm that the loss cone amplitude is indeed small at rigidities observed by shallow depth detectors. The analysis of the higher-energy data from Poatina and Liapootah at those southern latitudes resulted in positions of the loss cone five and two sidereal hours respectively later than the 1300 hours concluded from our analysis (the reader can see the large amount of scatter in the results from the southern hemisphere in our Figure 3b). Analysis of the data from the southern pointing instruments at Liapootah also yields inconsistent positions of the loss cone possibly due to the low statistical quality of the data. We feel that it is important to point out that our results for the loss cone in Figures 3b and 4b may not be very accurate in the southern hemisphere and that even though we calculate the loss cone to extend far into the southern hemisphere this may be caused by a lack of statistics. This analysis should be far more accurate within a few years.

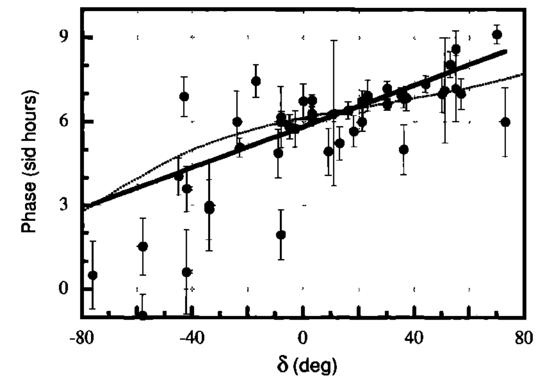

Figure 7. Phase of the sidereal semidiurnal variation recorded in the data of the THN corrected for longitude effects. The solid line is the linear correlation between the phase of the semidiurnal variation and declination. The dotted line is the calculation of the phase of the second harmonic as a function of declination from (6).

The original analyses of the Nagoya, Sakashita, and Cambridge-V data made by *Nagashima et al.* [1995a, b] made two reasonable assumptions: that the data recorded at Mt. Norikura had no variation caused by the tail in anisotropy and that the data recorded at Cambridge-V had no variation caused by the loss cone. The data from all the muon telescopes except Cambridge-V were then normalized to the Mount Norikura results in a rather arbitrary manner so that the effects of the loss-cone could be removed. The tail-in anisotropy was then derived from the first harmonics of the residual variations. To determine the latitude distribution and rigidity spectrum of the tail-in anisotropy, data from four instruments were used. Our conclusions about the tail-in anisotropy are in surprisingly good agreement with those from *Nagashima et al.* [1995a, b] except of course with that of the latitude dependence of the right ascension of the tail-in anisotropy. Close inspection of their determinations of the phase of the tail-in anisotropy shows that those of the northern viewing telescopes are at slightly later times, especially that determined from the Nagoya vertical surface muon telescope, perhaps indicating that their results also contained some latitude dependence.

Nagashima et al. [1995a] argue that the tail-in anisotropy is somehow caused by the heliospheric tail, which is formed by the interaction of the solar wind plasma and the local interstellar medium (LISM). Their analysis [*Nagashima et al.*, 1995b] of the annual modulation of the sidereal diurnal variation from this anisotropy provides strong evidence for the origin being close to the heliotail. *Czechowski et al.* [1995] have modeled the transport of anomalous cosmic rays in the heliosphere and shown that their density will increase in the heliospheric tail compared to the density in the direction of the oncoming interstellar plasma. *Pauls and Zank* [1996] have shown that vortices of solar plasma flow will occur in the

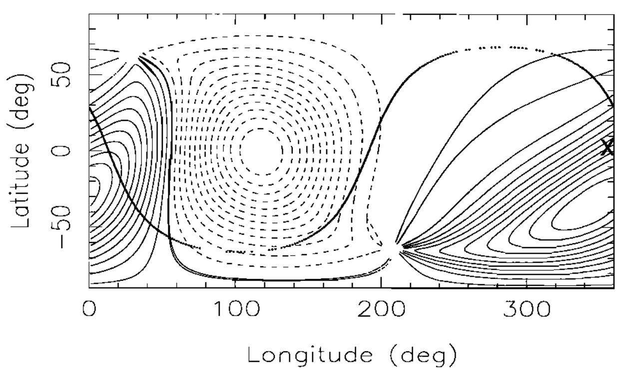

Figure 8. Same contours of anisotropy as in Figure 5 but in the heliospheric coordinate system. The cross denotes the downstream direction of the flow of the LISM.

heliotail from their model of the interaction of the solar wind and the local interstellar plasma. It is therefore possible that the heliotail has some relation to the tail-in anisotropy even in the high-energy region of 100 GeV to 1 TeV. An alternative possibility is related to the intersection of the viewing cones of the telescopes with the anisotropy in the galactic plane. *Wdowczyk and Wolfendale* [1983] concluded that γ rays with energies $>10^{14}$ eV in the galactic plane could cause the bulk of the sidereal anisotropy observed by extensive air-shower arrays (EASA). *Alexeenko and Navarra* [1985] modeled the flux of galactic γ rays expected at the Baksan EASA ($P_m = 10^{13}$–10^{14} V) and showed that the expected flux had a sidereal daily variation in good agreement with the observed daily variation. *Bergamasco et al.* [1990] analyzed the sidereal daily variation of the Artyomovsk underground muon telescope ($P_m = 1800$ GV) and concluded that the data were consistent with a higher density of cosmic rays at the galactic equator than that in the northern polar regions. If the tail-in anisotropy observed with underground muon telescopes is related to the distribution of cosmic rays in the galactic disk then the dependence of the observed right ascension on latitude of view may be related to the intersection of the telescopes' cones of views with the galactic plane. From Figure 5, however, we see that the orientation of the galactic plane in celestial coordinates does not have any readily apparent relation with the tail-in anisotropy.

If the interpretation of the origin of the tail-in anisotropy is correct, then its dependence on latitude of view may represent the orientation of the heliotail. Recent observations [*Witte et al.*, 1993] indicate that the neutral gas (hydrogen and helium) of the LISM is moving relative to the heliosphere with a velocity of ~26 km s^{-1} toward a downstream direction of $\delta = +19.8°$ and $\alpha = 70.8°$ (4.7 sidereal hours). It is assumed that the LISM plasma has the same velocity as the LISM neutrals. If no other quantities interact significantly with the solar wind other than the LISM plasma we could expect that the resulting heliotail may lie in a direction parallel to the downstream coordinates. The results presented here, and those of *Nagashima et al.* [1995a, b], indicate that if the tail-in anisotropy is coming from the heliotail then the latter's position is not where we expect it to be. In this case, other significant interactions must also be shaping the heliosphere. This may be possible. For example, a recent numerical model of the interaction between the heliosphere and the LISM included the effects of the solar wind speed increasing as a function of heliolatitude [*Pauls and Zank*, 1996]. The results of this model indicated that the distance from the inner heliosphere to the heliopause would be larger over the poles of the Sun than in the equatorial region. This elongation of the heliosphere could also occur in the tail. Note that when the interaction between the LISM neutral atoms and the solar wind was included in their calculations [*Zank and Pauls*, 1996], this distortion was reduced but still present. The turbulence in the heliotail which we mentioned earlier was not present in the results of these calculations.

There are other interactions between the solar wind and interstellar medium which may cause asymmetries in the structure of the heliosphere (see the reviews by *Baranov* [1990], *Suess* [1990, and references therein] for detailed descriptions of the processes which form the heliosphere). For example, *Holzer* [1989] has modeled the heliosphere-LISM interaction and included the magnetic pressure from an arbitrary galactic magnetic field (GB) and interactions between the solar wind plasma and LISM neutral particles. Previous estimates of the magnitude (0.1–0.3 nT) and direction (oriented in the galactic plane) of the GB are far from certain [*Berezinskii et al.*, 1990]; the galactic plane being almost perpendicular to the heliospheric equator. Recent attempts at deriving this quantity more accurately [*Rand and Kulkarni*, 1989; *Rand and Lyne*, 1994] have concluded that the ordered component of the GB may have a circular geometry in the galaxy and that in our neighborhood it is directed toward a galactic longitude of ~90°. This is almost perpendicular to the motion of the LISM [*Frisch*, 1994, 1995]. This implies that the GB is almost aligned (within ~20°) with the solar axis, directed toward the north. Holzer's results show that we might expect the heliosphere to be distorted by a galactic magnetic field such that the heliosphere is compressed at its flanks which are parallel to the GB, the amount of compression depending inversely on the alignment of the GB with the axis of the heliotail. Figure 8 shows the same contours as in Figure 5 but in the heliospheric coordinate system. We can see that much of the tail-in distribution is highly compressed causing the asymmetry. If the tail-in anisotropy is giving us information about the heliotail, then from a comparison of Holzer's conclusion with our compressed contours, we may be able to infer that the GB has very little alignment with the axis of the heliotail. Note that while this is consistent with a GB directed toward high heliospheric latitudes, the contours in our results are compressed along the wrong sides of the distribution to be completely consistent with the conclusions of *Holzer* [1989]. *Baranov and Zaitsev* [1995] have modeled the interaction of the solar wind and the LISM plasma and included a GB aligned with the flow of the LISM plasma. They also find that a compression of the heliosphere is likely compared to the unmagnetized case although the compression is symmetric about the flow velocity vector. Therefore it would seem that one possible reason for the asymmetry of the tail-in anisotropy could be the effect of the galactic magnetic field on the structure of the heliosphere.

In Figure 8, we have also included the position of the downstream direction of the flow of the LISM neutral atoms. We can see explicitly that the location of the tail-in anisotropy reference axis (taken as the maximum intensity of the anisotropy) does not coincide with the downstream direction. This does little to verify that the origin of the anisotropy is the heliotail. It is possible, though, that the heliotail is not formed in the immediate downstream direction in the presence of the GB. For example, *Washimi and Tanaka* [1996] have modeled the solar wind-LISM interaction in the presence of a GB while neglecting the LISM neutral atoms. They aligned the GB with the solar rotation axis (from south to north) and perpendicular to the LISM flow direction. Their results showed that the neutral sheet in the heliosheath is deflected northward under the influence of the interstellar medium which may imply that the heliotail would also be deflected north. This deflection is opposite to our result but illustrates that asymmetries in the heliosphere can be caused by interactions between the solar wind and the interstellar medium. It is not known how the orientation of the solar magnetic dipole would contribute to this effect (H. Washimi, private communication, 1998).

In concluding our discussion of the asymmetry in the tail-in anisotropy we find ourselves in a fairly noncommittal position. The anisotropy does not appear to come from where one would expect the heliotail to be, but the orientation may imply that the interaction of the heliosphere and the LISM produces asymmetries in the system which cause the tail to exist at a previously unanticipated position. This may reflect the effect of the interactions of the galactic magnetic field and/or other components of the LISM with the solar wind to form the heliosphere. The discussion above could best be described as conjecture. We have offered the ideas as a preface to more serious analyses and expert discussion of the future. We have discussed the tail-in anisotropy in the context of being related to the heliotail, but it is also reasonable to assume that its origin may be some other mechanism. Here we have advocated the view that if the tail-in anisotropy is originating in the heliotail then we may be remotely sensing the interactions of the solar wind with the galactic magnetic field and other components of the LISM.

We noted in section 3.3 that there would be more NS asymmetry in the first harmonic of the model if the declination of the tail-in anisotropy was south of the 14°S that we determined. We have previously [*Hall et al.*, 1997b] found that the amount of NS asymmetry obtained when the empirical model is based on data from telescopes with $P_m > 300$ GV is greater than that which is reported in this paper. We now have some understanding of the cause of this. We have repeated the calculation of the latitude distributions (equation (4)) of the two anisotropies by successively removing the Gaussian fit results corresponding to component telescopes with $P_m < X$ GV, where X is a multiple of 100 GV up to 700 GV. We kept the spectral indices fixed at the previously determined values of γ_T and γ_L. Figure 9 presents the results of the final fitted central latitude positions as a function of the minimum median rigidity of the component telescopes in the calculations.

The results show that there may be a dependence of the tail-in anisotropy latitude position on rigidity. We calculated the correlation coefficient between the fitted position and the minimum median rigidity. The linear functions of regression are also shown in Figure 9. The correlation coefficient of the weak linear dependence of the loss cone results on P_m is 0.28 which has a probability of occurring by chance of 50% (number of points is 8). The correlation coefficient of the tail-in anisotropy regression is −0.92. This has a probability of occurring by chance of only 0.3%. It seems highly likely therefore that there is a dependence of the tail-in anisotropy latitude distribution on rigidity while the loss cone has no such dependence. We are unable to explain this and will investigate this interesting effect in the future.

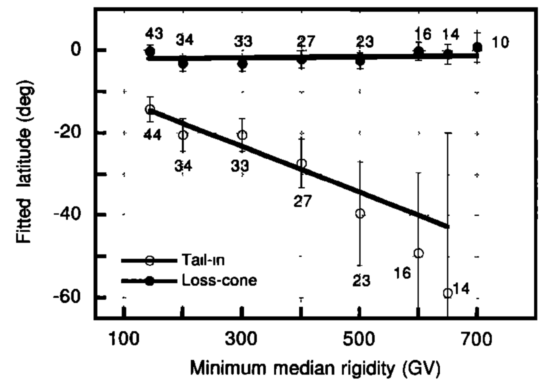

Figure 9. Fitted central latitude positions (from equation (4)) of the tail-in and loss cone anisotropies. The labels of each point indicate the number of instruments used for each calculation. Note we could not get a result for the tail-in anisotropy when the minimum median rigidity was 700 GV so a calculation was made at 650 GV.

5. Summary

We have analyzed the sidereal daily variations of the average hourly count rates of 46 components of the two-hemisphere network of cosmic ray underground muon telescopes. This network was formed during the joint research program of the cosmic ray groups at the Shinshu and Nagoya Universities, the University of Tasmania, and the Australian Antarctic Division.

We have fitted two Gaussian functions of arbitrary amplitudes, positions and widths to the average sidereal daily variations of each of the component telescopes, one Gaussian represents an excess of cosmic rays called the tail-in anisotropy and the other represents a deficit in the flux of particles called the loss cone anisotropy. These anisotropies are the constituents of a recent model of the sidereal anisotropy of cosmic rays: the tail-in and loss cone anisotropies model proposed by *Nagashima et al.* [1995a, b]. We have undertaken an analysis of the resulting Gaussian parameters to examine the rigidity and latitude spectra of the magnitudes and right ascensions of the two anisotropies. We conclude that the loss cone anisotropy has a maximum deficit located at the celestial equator and right ascension 13 hours sidereal time. It also appears to be rather symmetric about this axis in space. We have taken this to be the direction of the reference axis. The corresponding coordinates of the reference axis of the loss cone are high in the northern galactic hemisphere and are reasonably consistent with the results of the original analysis [*Nagashima et al.*, 1989] which preceded the tail-in and loss cone anisotropy model. The location of the reference axis of the anisotropy does not depend on rigidity.

We find that the tail-in anisotropy has a rather different nature. It has a maximum value of anisotropy at declination 14° south, right ascension 4.7 hours, (southern galactic hemisphere), in reasonably good agreement with the original model, but the corresponding time of maximum count rate of a cosmic ray telescope will be earlier for those in the southern hemisphere compared to those in the northern hemisphere. By assuming that the heliotail is responsible for the tail-in anisotropy and after considering previous simulations of the processes which form the heliosphere, we conclude that the galactic magnetic field and other components of the interstellar medium may be responsible for the heliospheric tail having a compressed geometry and a direction not directly aligned with the flow of the interstellar medium. Our results may indicate that we can indirectly observe these effects in the latitude dependence of the right ascension of the tail-in anisotropy and the southern declination of the reference axis of the anisotropy.

We have shown how the analysis of the Gaussian parameters can lead to a description of the sidereal anisotropy of cosmic rays and that the resulting empirical model which we devised can reproduce the NS asymmetry of the sidereal diurnal variation which is observed in data. We conclude that the declinations of the reference axes of the anisotropies and the declination dependence of the right ascension of the tail-in anisotropy both contribute to the NS asymmetry. We tested the validity of the model further, and found that it implies that the phase of the sidereal semidiurnal variation should be earlier in data collected in the southern hemisphere compared to that in the data collected in the northern hemisphere. The data of the two-hemisphere network support this claim when analyzed for the sidereal semidiurnal variation.

Unlike the loss cone, we find that the reference axis of the tail-in anisotropy depends on the minimum median rigidity of the telescopes used in the analysis. We cannot explain this but plan to investigate it in the future. We would also like to repeat the analyses by separating the data into epochs of constant solar magnetic polarity to investigate the effects (if any) of the Sun on the anisotropies. Our analysis relies heavily on the observations of the sidereal daily variations in data recorded at Liapootah in the southern hemisphere. This multidirectional telescope began operating in 1992 (during the $A > 0$ polarity state) and will not have the opportunity to record cosmic rays during the opposite polarity state until the next century. It would be very inaccurate to attempt a quantitative comparison of the analyses of the present data separated into epochs of constant magnetic polarity before this time although a qualitative comparison may be worthwhile. Before that time, we hope to devise a method of analysis similar to that of the coupling coefficients formalism that will allow us to calculate the spectra by fully taking into account the different energy responses of the telescopes and not just consider the geometrical latitudes of view and median rigidities as we have in this paper.

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