MUON OBSERVATIONS

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Abstract. Muon observations are complementary to neutron monitor observations but there are some important differences in the two techniques. Unlike neutron monitors, muon telescope systems use coincidence techniques to obtain directional information about the arriving particle. Neutron monitor observations require simple corrections for pressure variations to compensate for the varying mass of atmospheric absorber over a site. In contrast, muon observations require additional corrections for the positive and negative temperature effects. Muon observations commenced many years before neutron monitors were constructed. Thus, muon data over a larger number of solar cycles is available to study solar modulation on anisotropies and other cosmic ray variations.

The solar diurnal and semi-diurnal variations have been studied for many years. Using the techniques of Bieber and Chen it has been possible to derive the radial gradient, parallel mean-free path and symmetric latitude gradient of cosmic rays for rigidities $<$200 GV. The radial gradient varies with the 11-year solar activity cycle whereas the parallel mean-free path appears to vary with the 22-year solar magnetic cycle. The symmetric latitudinal gradient reverses at each solar polarity reversal. These results are in general agreement with predictions from modulation models. In undertaking these analyses the ratio of the parallel to perpendicular mean-free path must be assumed. There is strong contention in the literature about the correct value to employ but the results are sufficiently robust for this to be, at most, a minor problem. An asymmetric latitude gradient of highly variable nature has been found. These observations do not support current modulation models.

Our view of the sidereal variation has undergone a revolution in recent times. Nagashima, Fujimoto and Jacklyn proposed a narrow Tail-In source anisotropy and separate Loss-Cone anisotropy as being responsible for the observed variations. A new analysis technique, more amenable to such structures, was developed by Japanese and Australian researchers. They confirmed the existence of the two anisotropies. However, they found that the Tail-In anisotropy is asymmetric and that both anisotropies had different positions from the prediction.

Most 27-day modulations are observed at neutron monitor rigidities but not so readily at higher rigidities. An exception to this is the Isotropic Intensity Wave modulation observed in the early 1980s and again in 1991. This modulation is very strongly related to the heliospheric sector structure and implies a significantly different cosmic ray density on either side of the neutral sheet.

The interpretation of most cosmic ray modulation phenomena requires good latitude coverage in both hemispheres. The closure of many muon observatories is a matter of concern. In the northern hemisphere a few new instruments are being constructed and spatial coverage is barely adequate. In the southern hemisphere the situation is far worse with the possibility that within a decade only the Mawson observatory in Antarctica will still be in operation.

1. Introduction

The observation of secondary cosmic ray muons commenced long before neutron monitors were developed. The earliest records of use for studies of galactic and he-

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liospheric phenomena come from ionization chamber measurements in the 1940s. Geiger-Müller counters and later plastic scintillators replaced these systems. Over the last twenty years low maintenance proportional counters have been employed instead of the Geiger-Müller counters. Unlike neutron monitors, muon detection systems are directional employing two or more trays of counters to deduce the arrival direction of ionizing muons (and occasional pions). Thus, the muon detector systems are truly telescopes. The latest generation of muon telescopes consists of multidirectional instruments employing more complex coincidence electronics to record muon arrivals from narrower apertures than previously achievable. A number of telescope systems are currently being designed for narrow aperture, multi-directional observations with spatial resolutions of less than 5^o.

In this review, surface and underground muon observations are considered on timescales from hours to the solar magnetic cycle. The discussion is broken into four broad themes, differences between neutron and muon observations, the observed long-term anisotropies (solar and sidereal), quasiperiodic variations and the future of muon observations. The question of isotropic solar cycle cosmic ray modulation is not considered here as it is fully discussed in relation to the lower energy neutron monitor results elsewhere in this volume.

Several excellent review papers have appeared covering aspects of muon observations and interpretation. The reader is directed to the Rapporteur papers from the International Cosmic Ray Conferences as a ready source of information. The most recent of these are Jokipii and Kota (1997), Kudela (1997) and Mori (1996). Three further reviews are worthy of mention, Jacklyn (1986), Venkatesan and Badruddin (1990), and Hall *et al.* (1996).

2. Differences Between Muon Telescope and Neutron Monitor Observations

Muon observations are complementary to neutron monitor studies. Neutron monitor observations extend from the lowest energies accessible to ground based observation up to approximately 50 GeV. Surface muon observations have significant responses from approximately 10 GeV to several hundred GeV whilst underground muon observations extend up to slightly above 1000 GeV. At the minimum of the muon observational range, the dominant modulation processes are similar to those seen by neutron monitors. With increasing energy, galactic effects are more prevalent and solar modulation disappears.

Muon telescopes are simple ionising radiation detectors arranged in two or more trays. These detectors produce output pulses of the order of 1ms whenever a charged particle passes through them. The direction of arrival of the muon is derived from the relative positions of the counters that recorded the muons passage. Because the muons are relativistic they cross the complete telescope in a much shorter time than the latent detection time. A simple coincidence in response between the telescope trays is all that is required to determine the arrival direction.

An example of the possibilities that new coincidence techniques allow was demonstrated by Jacklyn and Duldig (1987). In 2-tray muon telescopes there are a significant number of accidental coincidences caused by separate muons being detected, one in each tray, within the resolving time of the instrument. This gives rise to a false coincidence trigger or accidental. The standard technique to remove most of these accidentals is to construct telescope systems with three trays of detectors. This increases the cost of the system by 50% and similarly increases the telescope maintenance costs. The accidental rate, N_{A}, is simply:

$$N_{\mathrm{A}} = 2N_1N_2\tau,$$

where N_i is the background rate of tray i and τ is the coincidence resolving time.

For this equation to hold the resolving time must be longer than the dead time of the counters and much shorter than the average time between true coincidence events. Doubling the resolving time will double the accidental rate. The true count rate, N, is simply derived from the two resolving time rates.

$$N_\tau = N + N_{\mathrm{A}} \quad \text{and} \quad N_{2\tau} = N + 2N_{\mathrm{A}},$$

$$N_{\mathrm{A}} = N_{2\tau} - N_\tau \quad \text{and} \quad N = 2N_\tau - N_{2\tau}.$$

There is a small penalty in the statistical accuracy of the determination when compared with a direct three-tray coincidence measurement. This arises because of the differencing of two Poisson distributed rates to derive the true rate but the increased standard deviation is not large enough to be of concern.

The second significant difference between muon observations and neutron monitor observations is the correction of the data for local environmental effects. When considering short time scale variations (hours) it is permissible to use a total barometer coefficient to correct for atmospheric mass absorption similar to the standard neutron monitor correction. That is, an increased pressure indicates a greater mass of air over the site that will lead to greater absorption of muons through ionisation losses and a decrease in the observed count rate. For longer time scales a simple barometric correction is not sufficient.

The muon production process begins with the interaction of a cosmic ray primary with an atmospheric nucleus. A pion is produced which may interact with another atmospheric nucleus or decay into a muon. If a muon is produced it may decay and stop in the atmosphere or it may penetrate to the surface (or underground). A number of atmospheric variations are important in this process and depending on the site may have diurnal or seasonal variations that could influence anisotropy analyses.

The mean pion production in the atmosphere is at $\sim$125 mb pressure. The height of this pressure level in the atmosphere varies, particularly seasonally. The transit time through the atmosphere of the muons will be longer when this pressure level is located at a higher altitude and more muons will decay before reaching a detector.

The increase in height of this level arises from an expansion of the atmosphere when it is warmer and so this effect is known as the negative temperature effect.

When the temperature near the pion production level is higher the air density is lower and the likelihood of the pion interacting before it decays into a muon is reduced resulting in higher count rates. This is known as the positive temperature effect.

The influence of the two competing temperature effects depends on the particle energy and for muon telescopes located underground at depths of 40 hg cm^{-2} they cancel leaving only the mass absorption.

Using radiosonde balloon measurements of the atmospheric profile, it is possible to undertake a multiple regression to determine the appropriate correction coefficients to apply for a given telescope. This technique was first described by Duperier (1944; 1949) using a simple regression equation:

$$\frac{\Delta I}{\overline{I}} = \beta_P \Delta P + \beta_H \Delta H + \beta_T \Delta T,$$

where the β's are respectively, the pressure, height (negative temperature) and (positive) temperature coefficients.

The derivation of these coefficients and some other second order corrections have been studied in detail by Dorman and Feinberg (1958), Dorman (1970, 1972), and Dorman and Dorman (1995). Another study of note is Lyons (1981).

Having considered some of the differences between neutron monitor and muon telescope observations let us now consider some of the results from muon studies. It should be noted that some of these results rely on analyses of both muon and neutron observations.

3. Solar Diurnal Anisotropy Observations

The solar diurnal anisotropy arises primarily from the corotation of cosmic rays with the heliomagnetic field (Forman and Gleeson, 1975; Parker, 1964). If this were the sole cause of the anisotropy, it would have an invariant phase of 18 hours local solar time after correction for geomagnetic effects. As can be seen from Figure 1, the phase is observed to vary significantly over the 22-year solar magnetic cycle (Ahluwalia and Fikani, 1997; Hall *et al.*, 1996, 1997). There are two schools of thought as to why this periodicity arises. The first group (Bieber and Chen, 1991a; Duggal and Pomerantz 1975; Duggal *et al.*, 1967; Forbush, 1967) believe that it is due to a varying component directed along the interplanetary magnetic field (IMF) line at $\sim$135° east of the Sun–Earth line. Others claim it is due to a varying radial anisotropy component (Ahluwalia, 1988a, b; Swinson *et al.*, 1990).

In contrast to this the free space amplitude, η_{SD}, of the anisotropy varies with the 11-year solar activity cycle (Ahluwalia and Fikani, 1997; Hall *et al.*, 1996, 1997); being larger at times of solar maximum.

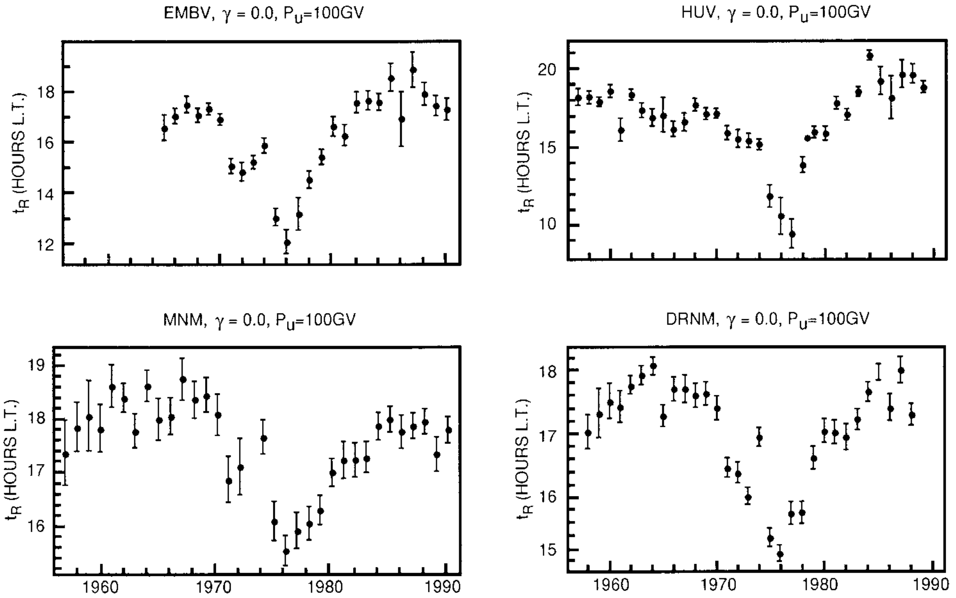

Figure 1. The free space phase of the solar diurnal variation observed in the northern and southern hemispheres by muon telescopes and neutron monitors (EMBV – Embudo Vertical; HUV – Hobart Underground Vertical; MNM – Mawson Neutron Monitor; DRNM – Deep River Neutron Monitor). (From Hall, 1995.

The upper limiting rigidity, P_u, of the anisotropy tends to be larger at times of solar maximum (Ahluwalia and Sabbah, 1993; Ahluwalia and Fikani, 1997; Hall *et al.*, 1996, 1997; Munakata *et al.*, 1997). There is agreement that P_u never exceeds 200 GV and that it reduces to about 50 GV around solar minimum. Ahluwalia (1991, 1992) discovered that P_u is correlated with the IMF magnitude. Hall *et al.* (1993) confirmed this result.

The spectrum of the anisotropy is less well determined. The power-law exponent, γ, would appear to range between 1.0 and -0.5 but to only attain positive values during the $A > 0$ solar polarity state (Hall *et al.*, 1997).

These parameters are shown in Figure 2.

4. The Modulation Parameters $\lambda_{\|}$, G_r, $G_{|Z|}$ and $G_{\perp}$

In their landmark papers (Bieber and Chen, 1991a, b; Chen and Bieber, 1993) Bieber and Chen showed how the modulation parameters $\langle \lambda_{\|} G_r \rangle$, and $G_{|Z|}$ could be derived from observations of the solar diurnal anisotropy. Here represents the average product of the parallel mean-free path and the radial gradient and $G_{|Z|}$ is the symmetrical latitudinal gradient. Using the notation of Hall *et al.* (1997), they showed:

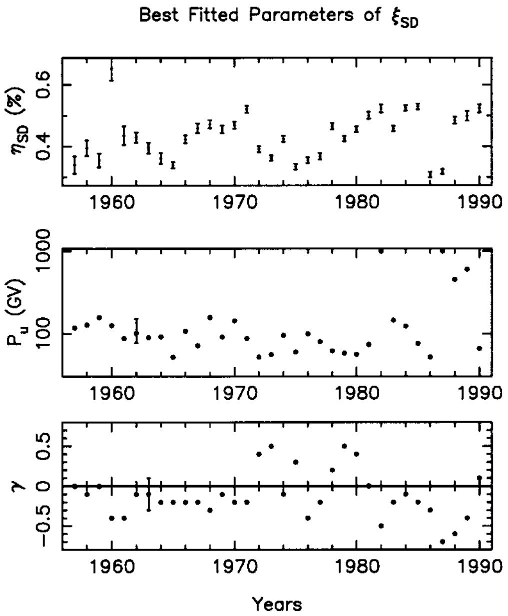

Figure 2. Yearly average best fit parameters of the solar diurnal anisotropy. Typical 1σ error bars are shown. (From Hall *et al.*, 1997.)

$$\langle \lambda_{\|} G_r \rangle = \frac{1}{\cos\chi}\left[\frac{A_{\mathrm{SD}}}{\delta A_1^1}\, G(P)\cos(\chi + t_{\mathrm{SD}} + \delta t_1^1) + \eta_{\mathrm{CG}}\sin\chi + \eta_{\mathrm{c}}\cos\chi\right],$$

where A_{SD} and t_{SD} are the yearly average values of the amplitude and phase of the solar diurnal variation, δA_1^1 and δt_1^1 are the coupling coefficients appropriate to the spectrum and cutoff, $G(P)$, of the anisotropy at the time, χ is the angle between the IMF and the Sun–Earth line (typically 45°), $\eta_{\mathrm{CG}} = 0.045\%$ is the Compton–Getting effect arising from the Earth's orbital motion and $\eta_{\mathrm{c}} = 0.6\%$ is the solar

wind convection component of the anisotropy.

$$G_{|Z|} = -\frac{\mathrm{sgn}(I)}{\rho}\left[\alpha\langle \lambda_{\|} G_r \rangle \sin\chi - \frac{A_{\mathrm{SD}}}{\delta A_1^1}\, G(P)\sin(\chi + t_{\mathrm{SD}} + \delta t_1^1) + \right.$$
$$\left. + \eta_{\mathrm{CG}}\cos\chi - \eta_{\mathrm{c}}\sin\chi\right]$$

where

$$\mathrm{sgn}(I) = \begin{cases} +1 & A > 0 \text{ IMF polarity states} \\ -1 & A < 0 \text{ IMF polarity states} \end{cases}$$

and ρ is the particle gyroradius.

This formalism does not allow separation of the radial gradient from the parallel mean free path. However, the radial gradient may be determined directly from the North-South anisotropy discovered by Swinson (1969, 1971). Bieber and

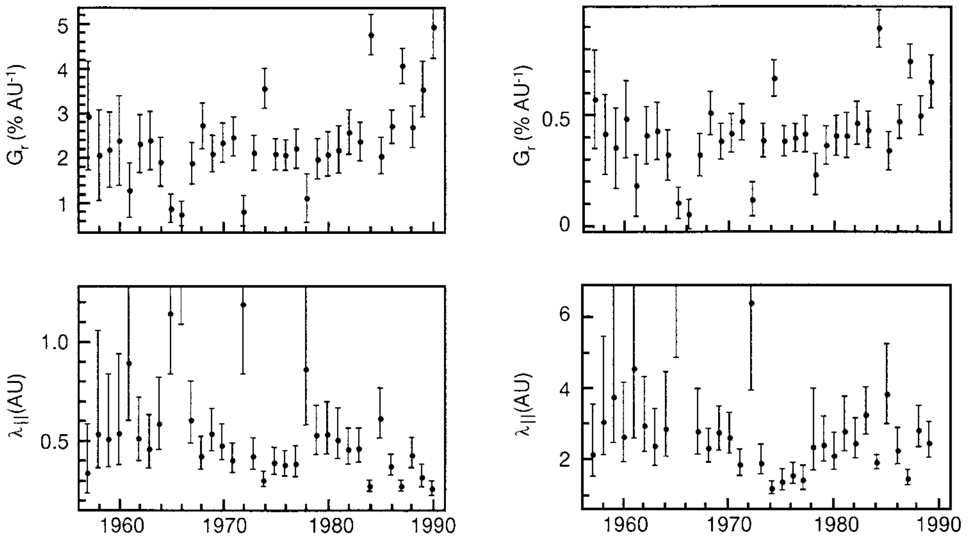

Figure 3. The radial gradient and mean-free path of cosmic rays at 1 AU for 17 GV (*left*) and 185 GV (*right*) particles. 1σ error bars are shown. (From Hall *et al.*, 1995.)

Chen (1991b), Chen and Bieber (1993) and Hall *et al.* (1994, 1995) described this technique. They showed:

$$G_r = \frac{-\xi_{\mathrm{NS}} \pm \sqrt{(\xi_{\mathrm{NS}})^2 + 4\rho \sin(I)\alpha(\overline{\lambda_{\|} G_r}) G_{|Z|}}}{2\rho \sin \chi},$$

where ξ_{NS} is the yearly averaged North-South anisotropy.

Using the techniques above a number of researchers have investigated the variation of $\lambda_{\|}$, G_r and $G_{|Z|}$. At neutron monitor rigidities Bieber and Pomerantz (1986) found the radial gradient had lower values at solar minimum and an average value of 1.6% AU^{-1}. They also found no dependence on the polarity state of the IMF. This result agrees with lower energy spacecraft measurements and was subsequently confirmed for higher rigidities by Yasue (1980) and Swinson (1988). Hall *et al.* (1994) found the same qualitative results for rigidities between 17 GV and 185 GV. The results from Yakutsk are also in broad agreement (Krymsky *et al.*, 1997). In the upper panels of Figure 3 we see the determination by Hall (1995) and Hall *et al.* (1997) of G_r at the lowest and highest rigidities in their studies. The absolute values of G_r vary slightly with the choice of α but the temporal variations are similar at both rigidities.

Also seen in Figure 3 are determinations of the parallel mean free paths at 17 and 185 GV. The low rigidity result confirms the results of Bieber and Chen who proposed that $\lambda_{\|}$ has a polarity dependence. There is a tendency to higher values at solar minimum in the $A < 0$ polarity state and this tendency appears slightly clearer at higher rigidities but further observations are needed to improve

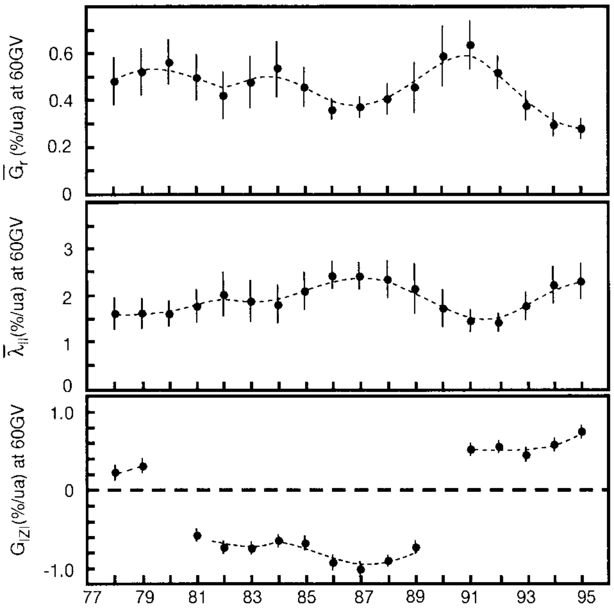

Figure 4. Modulation parameters derived from Japanese multi-directional telescopes. (From Munakata *et al.*, 1997.)

the timebase and statistics of this analysis. Recent results of Munakata *et al.* (1997) for higher rigidities (60–595 GV) are shown in Figure 4.

Many researchers have also investigated the latitudinal gradients. Research prior to Bieber and Chen's papers did not separate out the effects of symmetric and asymmetric (or unidirectional) gradients. In Figure 5 we see the results of Hall *et al.* (1997). These results are in agreement with Bieber and Chen (1991a) and Chen and Bieber (1993) and extend to higher rigidities. $G_{|Z|}$ shows a strong polarity dependence, reversing sense at each heliomagnetic reversal. $G_{|Z|} > 0$ implies a local minimum in the cosmic ray density at the neutral sheet as is shown for positive IMF polarity states. These results are confirmed and extended to later dates by Munakata *et al.* (1997) as seen in the bottom panel of Figure 4. The gradient attains its largest values at times of solar minimum. Another feature of these results is the apparently larger values of the gradient in the negative IMF polarity state. Ahluwalia (1993, 1994) and Ahluwalia and Sabbah (1993) have extended these results up to 300 GV showing that some solar modulation is present at this high rigidity. In the latter of these papers Ahluwalia also showed a correlation existed between $G_{|Z|}$ and the tilt of the heliospheric neutral current sheet.

In all these analyses it was necessary to assume a value for the ratio of the parallel to perpendicular mean-free path, α. Hall (1995) and Hall *et al.* (1995) were able to demonstrate that the results were relatively insensitive to the value of α in the range 0.01–0.1 but above this range the effects became significant. There has been some controversy in the literature regarding the correct value of α

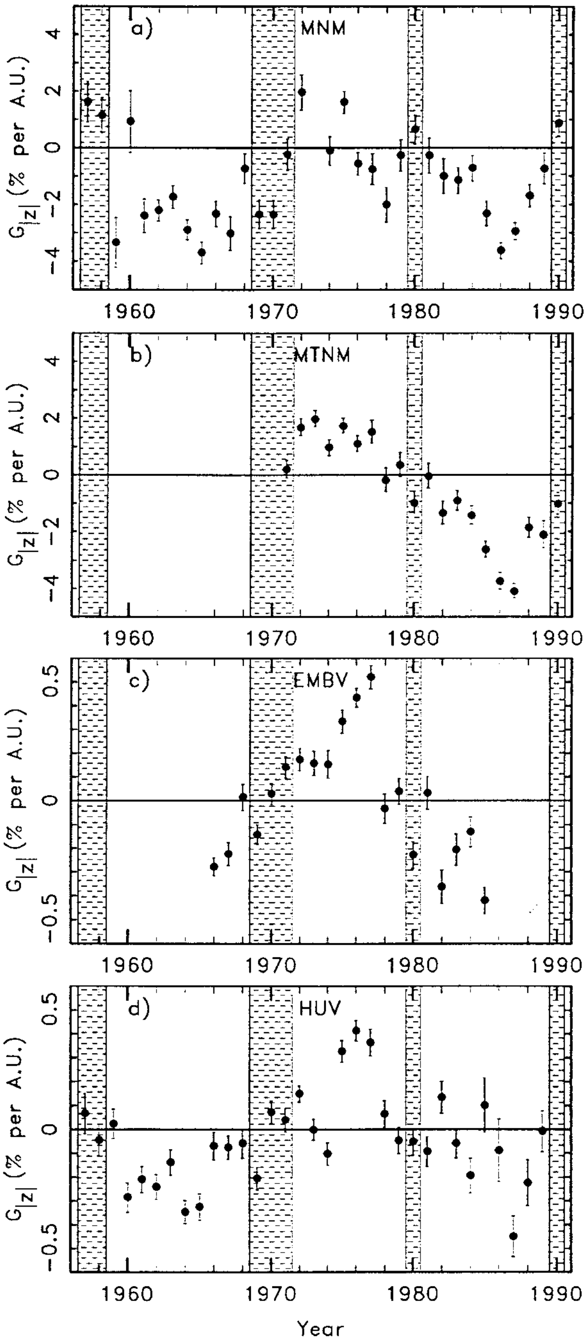

Figure 5. Derived $G_{|Z|}$ for a range of rigidities. (a) Mawson neutron monitor ($P_{\mathrm{med}} = 17$ GV); (b) Mt. Wellington neutron monitor ($P_{\mathrm{med}} = 17$ GV); (c) Embudo vertical muon telescope ($P_{\mathrm{med}} = 135$ GV); (d) Hobart vertical underground muon telescope ($P_{\mathrm{med}} = 185$ GV). 1σ error bars are shown. (From Hall *et al.*, 1997.)

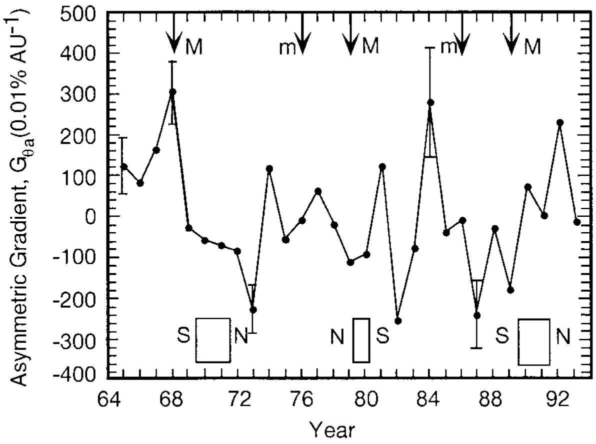

Figure 6. $G_\perp$ derived from Deep River NM data. Also shown with arrows are the times of solar maximum (M) and solar minimum (*m*). The shaded areas represent solar field reversals. (From Ahluwalia and Dorman, 1997.)

to employ. Ip *et al.* (1978) estimated a value of 0.26 for rigidities above 0.3 GV. Alania *et al.* (1983) proposed a value of 0.3. Ahluwalia and Sabbah (1993) found that the average value was 0.09. Bieber and Chen assumed a value of 0.01. Hall *et al.* (1995) undertook a preliminary analysis to derive upper limits for α at various rigidities. For 17 GV particles the upper limit was 0.17 in the $A > 0$ polarity state and 0.3 in the $A < 0$ polarity state. For 185 GV particles the limits were 0.3 and 0.85, respectively. Further study is required to settle this issue.

Before concluding our discussion of gradients we must finally consider the asymmetric gradient, here referred to as $G_\perp$. There are two basic techniques for deriving $G_\perp$. The long-term variation of the cosmic ray density can be monitored as the earth moves around its orbit each year. The inclination of the orbit to the helioequator will result in the earth swinging from 7° north to 7° south over a six month period. Thus the ground based detectors are sampling from regions, on average, further above or below the neutral sheet depending on the season. The more popular technique relies on the east-west anisotropy generated by the vertical gradient in the same way as the north-south anisotropy arises from the radial gradient.

Chen *et al.* (1991) employed neutron monitor data to derive $G_\perp$. They found that $G_\perp$ was present and variable but that the variations did not appear to correlate with solar activity or polarity.

Ahluwalia and Dorman (1997) found a persistent southward gradient between 1965 and 1968 followed by a period of northward gradient between 1969 and 1973. They found the 1974 gradient directed southward and it reverted to northward in 1975. After that time no discernible gradient was evident until a northward gradient emerged for two years 1979 and 1980. Similar variability was found throughout the 1980s and early 1990s. We can see their results in Figure 6 for low rigidities but similar results were derived from Embudo and Socorro telescopes at 135 and 300 GV median rigidities respectively.

Two explanations have been proposed for asymmetric behavior across the neutral sheet. Bieber (1988) suggested that the north-south asymmetry in the IMF spiral angle may be responsible. Alternatively, hemispheric asymmetries in solar activity, as indicated by sunspot numbers, may be responsible (Shea *et al.*, 1989; Swinson *et al.*, 1991). Chen *et al.* (1991) found that either proposition gave a good correlation and it is not yet clear which model is superior.

5. The Solar Semi-Diurnal Anisotropy

The solar semidiurnal anisotropy arises either from the symmetric latitudinal density gradient or from pitch angle scattering. Ahluwalia and Fikani (1996a, b) published a major study of the solar semi-diurnal anisotropy. In these papers they reported that no evidence for sector dependence of the anisotropy could be found. They confirmed the $\cos^2$ dependence on effective viewing latitude, λ_E. Their analysis covered a rigidity range of 10–330 GV. Figure 7 reproduces their amplitude and phase results. They described the spectrum of anisotropy with a two component power law and found that the exponents and the rigidity at which they changed were solar activity and solar polarity dependent. Furthermore they determined that the upper limiting rigidity of the anisotropy varied between $\sim$50 GV at solar minimum and $\sim$100 GV at solar maximum and that there was a polarity dependence present.

More recently, Munakata *et al.* (1998) studied the variation using a northern and southern hemisphere pair of multidirectional surface muon telescopes for the period 1992–1995. Their results agree with the longer-term studies of Ahluwalia and Fikani. They found that the observed phase of the variation was consistent with either cause.

The anti-sidereal variation is believed to arise from the annual modulation of the diurnal component of the second order solar anisotropy. They found that the anti-sidereal phases were also consistent with either production model. They were able to show, however, that the amplitude ratio between the solar semidiurnal and the anti-sidereal variations was not consistent with the symmetric latitudinal density gradient being the cause. They thus conclude that, at least for the period 1992 –1995, the solar semidiurnal variation the anti-sidereal variations arise primarily from a pitch angle scattering anisotropy and can not be due solely to a symmetric latitudinal density gradient. Munakata *et al.* (1999) also observed a concurrent enhanced sidereal diurnal variations in these telescopes and attribute this to an asymmetric density gradient.

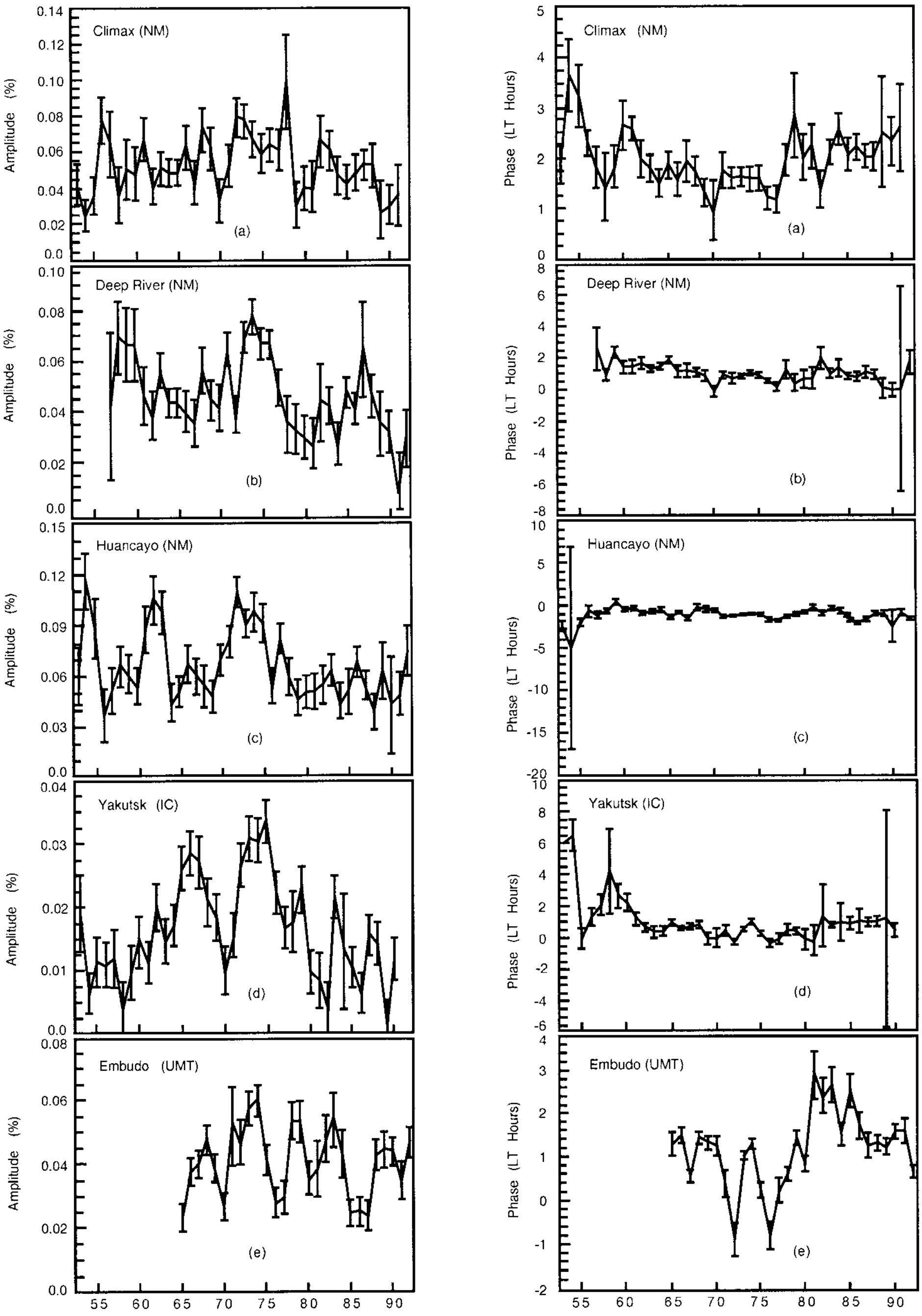

Figure 7. The amplitude (*left*) and phase (*right*) of the solar semidiurnal anisotropy at increasing effective rigidities. (a) Climax neutron monitor; (b) Deep River neutron monitor; (c) Huancayo neutron monitor; (d) Yakutsk ion chamber; and (e) Embudo underground muon telescope. (From Ahluwalia and Fikani, 1996a.)

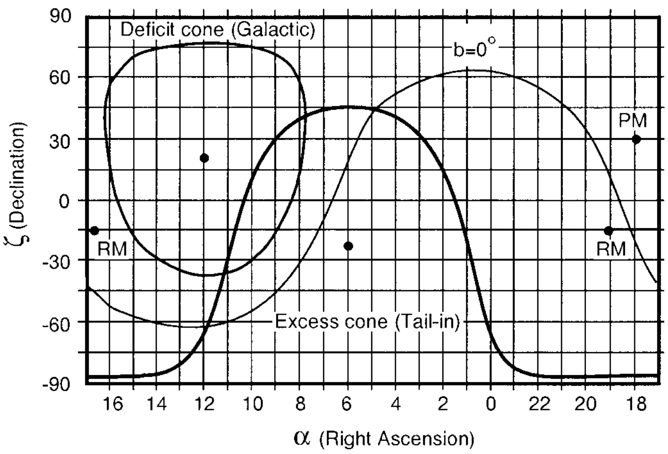

Figure 8. The Tail-In and Loss cone anisotropy model. PM is the direction of proper motion of the solar system. RM is the direction of motion relative to the neutral gas. (From Nagashima *et al.*, 1998.)

6. Sidereal Anisotropies

Our view of sidereal variations has changed markedly over the past few years. For an excellent review of the state of knowledge before this revolution, the paper by Jacklyn (1986) is highly recommended. In this review, Jacklyn considered observations from 1958 to 1984 that showed the existence of both a uni-directional and a bi-directional galactic anisotropy. The bi-directional anisotropy was evident up to about 1970 but has been suppressed since that time. The unidirectional anisotropy appeared to have a maximum at 3 hr sidereal time.

During the 1980s it became increasingly apparent that there was an asymmetry in the northern to southern hemisphere sidereal response. A thorough investigation of this and other asymmetric phenomenon at muon energies was warranted. Japanese researchers from Shinshu and Nagoya universities and Australian researchers from the University of Tasmania and the Australian Antarctic Division collaborated to install multi-directional surface and underground telescopes in Tasmania at approximately the co-latitude of similar Japanese instruments. This collaboration confirmed the asymmetry for ∼1 TeV particles (Munakata *et al.*, 1995).

A major change in our interpretation of the sidereal daily variation started in 1994: Nagashima *et al.* (1995a) first proposed that the Tail-In and Loss cone anisotropies are responsible for the observed variation and hemispheric asymmetry.

These ideas were further developed over the next few years (Nagashima *et al.* 1995b, c; 1998). They proposed a galactic anisotropy, characterized by a deficit flux, centred on RA 12 hr, Dec. 20°. In addition to this deficit anisotropy they postulated a cone of enhanced flux, of ∼68° half opening angle, centred on RA 6 hr, Dec. −24°. This source is termed the Tail-In anisotropy because of its close

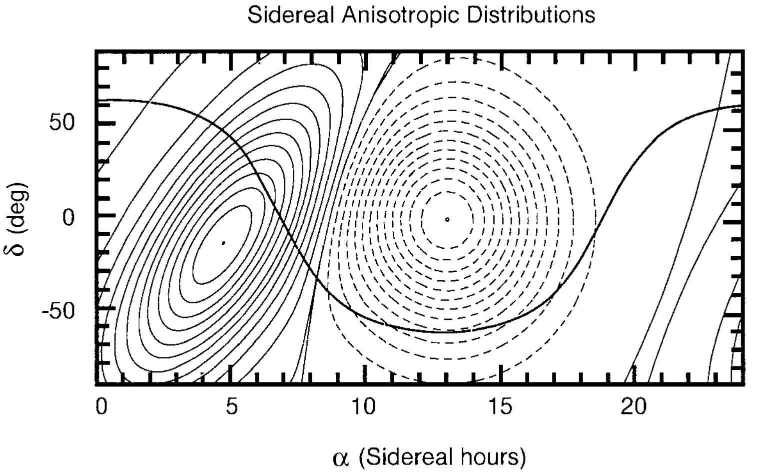

Figure 9. The Tail-In and Loss cone anisotropies derived by Hall *et al.* (1998b, 1999).

proximity to the possible heliomagnetic tail (RA 6.0 hr, Dec. −29.2°) opposite to the proper motion of the solar system. It was noted that this is not opposite to the expected tail (RA 4.8 hr, Dec. 15°−17°) of the solar system motion relative to the neutral gas. The model also required that the Compton-Getting effect does not exist up to rigidities of $\sim 10^4$ GeV. A schematic representation of the model is shown in Figure 8.

One aspect of the model is problematical. Usually the sidereal diurnal variation is analyzed harmonically. The proposed shape of the Tail-In anisotropy is not well suited to sinusoidal fits. This was apparent to the Japan–Australia collaboration who developed an alternative analysis technique. They fitted gaussian functions to the sidereal daily variation. The gaussians had variable width and size (height or depth). They used the two hemisphere network of muon telescopes described above and some additional telescopes from other sites. Their results were in broad agreement with the model of Nagashima, Fujimoto and Jacklyn. The rigidity spectra and latitude distribution were consistent with the model. However, they found that the Tail-In anisotropy was asymmetric about its reference axis (Hall *et al.*, 1998a). They also demonstrated that their results were consistent with observed harmonic vectors derived by earlier studies. Their subsequent and more complete analysis (Hall *et al.*, 1998b, 1999) covered the rigidity range 143−1400 GV and a viewing latitude range of 73°N−76°S. They confirmed that the Tail-In anisotropy is asymmetric about its reference axis, which is located at RA ∼4.7 hr, Dec. ∼ −14°S. They also determined that the Tail-In reference axis position may be rigidity dependent. The Loss cone anisotropy was found to be symmetric and its reference axis located on the celestial equator at RA ∼13 hr, Dec. ∼0°. Figure 9 shows their determination of the two sidereal anisotropies. These positions are somewhat different from those proposed by Nagashima, Fujimoto and Jacklyn. The technique applied by Hall *et al.* (1998b, 1999) is more sophisticated and has greater observational coverage. It remains to be seen if their result can be explained by heliospheric structures or interactions with the local galactic arm.

7. 27-Day Recurrences At High Rigidities

27-day recurrence phenomena are often restricted to neutron monitor rigidities. However, there has been one significant modulation phenomenon recorded at rigidities in excess of 100 GV. Jacklyn *et al.* (1984a, b, 1987) reported the discovery of isotropic sinusoidal variations in both neutron monitor and underground muon telescope data during 1982, 1983 and 1984. Using data from underground telescopes in Japan, Australia and Antarctica, Jacklyn *et al.* (Figure 10) showed that a 1.0% modulation closely tied to the neutral sheet sector structure near earth was isotropic. This modulation was separated from the north-south anisotropy using its different (flat) spectrum. It was found to be larger than the north-south anisotropy and in phase with in it the southern hemisphere and in antiphase in the northern hemisphere. In 1982 the waves had a period of 27 days consistent with the 2-sector IMF structure present at the time. The waves appeared suddenly in mid-year and decayed slowly to below statistical fluctuations by November. In 1983 the waves reappeared suddenly in early August, this time with a 13.5-day period. The IMF at this time exhibited a 4-sector structure showing the strong correlation between the isotropic waves and the IMF. Again, the modulation persisted for several months, slowly reducing in amplitude. The modulation amplitude in 1983 was about 0.4% which may have been related to the smaller sector size. In 1984 the modulation again appeared suddenly in early September, decaying away by the end of the year. The amplitude was smaller than the previous two years. This modulation was not observed again during the 1980s. Recently, Fujii (1998) reported evidence of similar waves in Mawson data from 1992. This later occurrence has not been thoroughly investigated yet. The cause of the sudden onset and slow decay of the modulation remains a mystery.

8. Surface and Underground Observatories

The number of underground and surface muon observatories has been in rapid decline over the past few decades. We have seen the closure of a number of major facilities including London, Budapest, Ottawa, Embudo, Socorro, Bolivia and Misato. Only three new installations at Mt. Norikura (Japan), Liapootah and Hobart (Australia) have been commissioned in the same period. Other major observatories continuing in operation are Moscow, Yakutsk, Nagoya, Matsushiro, Sakashita, Takeyama, Hobart, Cambridge, Poatina and Mawson. The long-term future of Cambridge, Poatina and the two installations in Hobart are very uncertain. The proposed high angular resolution hodoscope for Finland by Tanskanen *et al.*

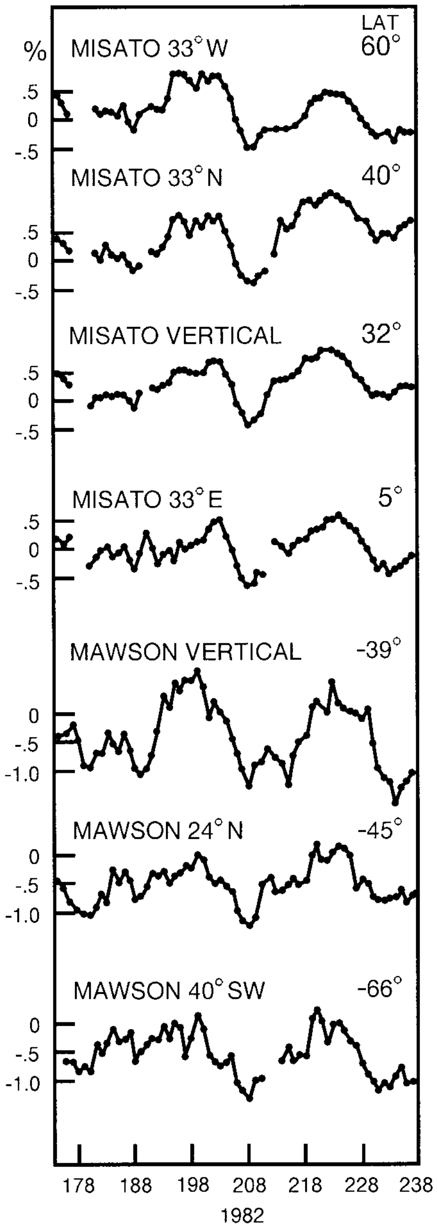

Figure 10. 1982 isotropic intensity waves. The wave amplitudes are shown in %. Effective latitudes of view for each instrument are also given. (From Jacklyn *et al.*, 1987).

and the upgrade of the Moscow system are valuable additions to our dwindling resource. A further new surface muon telescope system has been very recently installed in Mexico comprising two trays of 4 m^2 and sited at 2274 m altitude (J. Valdes, private communication).

It is clear that high angular resolution systems will play a significant role in advancing our understanding of transient phenomena but they may also help unravel the detailed structure of the Tail-In and Loss cone sidereal anisotropies. A Shinshu University proposal for two new large area narrow-angle telescope system located in Japan and Australia could be important in such studies.

9. Conclusion

It is an exciting time in muon observational research. The landmark work of Bieber and Chen has opened new avenues of investigation into some of the most important parameters of cosmic-ray modulation. We now have a baseline of high quality observations of about two solar magnetic cycles. We are just beginning to see what aspects of modulation are universal to the solar activity and magnetic cycles and what aspects are peculiar to particular cycles. In the future, we can expect to further unravel these features. The new ideas of Nagashima, Fujimoto and Jacklyn have changed forever our view of sidereal effects. Together with observations by the distant Voyager and Pioneer spacecraft, this new view may well pave the way to a better understanding of the true shape, dimensions and structure of the heliosphere and its interaction with the local interstellar medium.

The interpretation of most cosmic ray modulation phenomena requires good latitude coverage in both hemispheres. The northern hemisphere has barely adequate coverage but the future for southern hemisphere observations is less satisfactory. Within the next decade, muon observations in the southern hemisphere may be limited to the Mawson observatory in Antarctica. It is therefore incumbent on us all to encourage and support continuing or new experiments involving southern hemisphere muon observations.

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References

Ahluwalia, H. S.: 1988a, ‘The Regimes of the East-West and the Radial Anisotropies of Cosmic Rays in the Heliosphere’, *Planetary Space Sci.* **36**, 1,451 – 1,459.

Ahluwalia, H. S.: 1988b, ‘Is there a Twenty Year Wave in the Diurnal Anisotropy of Cosmic Rays?’, *Geophys. Res. Lett.* **15**, 287–290.

Ahluwalia, H. S.: 1991, ‘The Limiting Primary Rigidity for the Cosmic Ray Diurnal Anisotropy and the IMF’, *Proc. 22nd Int. Cosmic Ray Conf.* **2**, 125–128.

Ahluwalia, H. S.: 1992, ‘A Correlation Between IMF and Limiting Primary Rigidity for the Cosmic Ray Diurnal Anisotropy’, *Geophys. Res. Lett.* **19**, 633–636.

Ahluwalia, H. S.: 1993, ‘Hale Cycle Effects in Cosmic Ray East-West Anisotropy and Interplanetary Field’, *J. Geophys. Res.* **98**, 11 513–11 519.

Ahluwalia, H. S.: 1994, ‘Cosmic Ray Transverse Gradient for a Hale Cycle’, *J. Geophys. Res.* **99**, 23 515–23 521.

Ahluwalia, H. S. and Dorman, L. I.: 1997, ‘Transverse Cosmic Ray Gradients in the Heliosphere and the Solar Diurnal Anisotropy’, *J. Geophys. Res.* **102**, 17 433–17 443.

Ahluwalia, H. S. and Fikani, M. M.: 1996a, ‘Cosmic Ray Solar Semidiurnal Anisotropy 1. Treatment of Experimental Data’, *J. Geophys. Res.* **101**, 11 075–11 086.

Ahluwalia, H. S. and Fikani, M. M.: 1996b, ‘Cosmic Ray Solar Semidiurnal Anisotropy 2. Heliospheric Relationship of Anisotropy Parameters’, *J. Geophys. Res.* **101**, 11 087–11 093.

Ahluwalia, H. S. and Fikani, M. M.: 1997, ‘Observed Solar Diurnal Variation of Cosmic Rays 1965 –1994’, *Proc. 25th Int. Cosmic Ray Conf.* **2**, 125–128.

Ahluwalia, H. S. and Sabbah, I. S.: 1993, ‘Cosmic Ray Diurnal Anisotropy for a Solar Magnetic Cycle’, *Planetary Space Sci.* **41**, 113–125.

Alania, M. V., Aslamazashvili, R. G., Djapiashvili, T. V., and Tkemaladze, V. S.: 1983, ‘The Effect of Particle Drift in Cosmic Ray Anisotropy’, *Proc. 18th Int. Cosmic Ray Conf.* **10**, 91–94.

Bieber, J. W.: 1988, ‘North-South Asymmetry of the Interplanetary Field Spiral’, *J. Geophys. Res.* **93**, 5903–5907.

Bieber, J. W. and Chen, J.: 1991a, ‘Cosmic Ray Diurnal Anisotropy, 1936–1988: Implications for Drift and Modulation Theories’, *Astrophys. J.* **372**, 301–313.

Bieber, J. W. and Chen, J.: 1991b, ‘Solar Magnetic Cycle Variation of Cosmic Ray Gradients and Scattering Mean Free Path’, *Proc. 22nd Int. Cosmic Ray Conf.* **3**, 525–528.

Bieber, J. W. and Pomerantz, M. A.: 1986, ‘Solar Cycle Variation of Cosmic Ray North-South Anisotropy and Radial Gradient’, *Astrophys. J.* **303**, 843–848.

Chen, J. and Bieber, J. W.: 1993, ‘Cosmic-Ray Anisotropies and Gradients in Three Dimensions’, *Astrophys. J.* **405**, 375–389.

Chen, J., Bieber, J. W., and Pomerantz, M. A.: 1991, ‘Cosmic Ray Uni-Directional Latitude Gradient: Evidence for North-South Asymmetric Solar Modulation’, *J. Geophys. Res.* **96**, 11 569–11 585.

Dorman, L. I.: 1970, ‘Barometer Effect of Cosmic Rays and Changes of the Energy Spectrum and Cut-Off Rigidities’, *Proc. 11th Int. Cosmic Ray Conf.* **2**, 715–719.

Dorman, L. I.: 1972, *Meteorological Effects of Cosmic Rays*, Nauka Moscow, p. 212 (in Russian).

Dorman, L. I. and Dorman, I.V.: 1995, ‘Cosmic-ray Atmospheric Electric Field Effects’, *Can. J. Phys.* **73**, 440–443.

Dorman, L. I. and Feinberg, E. L.: 1958, ‘On the Nature of the Cosmic Ray Variations’, *Proc. 4th Int. Cosmic Ray Conf.* **4**, 393–432.

Duggal, S. P. and Pomerantz, M. A.: 1975, ‘Long Term Changes in the Solar Diurnal Anisotropy’, *Proc. 14th Int. Cosmic Ray Conf.* **4**, 1209–1213.

Duggal, S. P., Pomerantz, M. A., and Forbush, S. E.: 1967, ‘Long-term Variation in the Magnitude of the Diurnal Anisotropy of Cosmic Rays’, *Nature* **214**, 143–155.

Duperier, A.: 1944, ‘A New Cosmic-Ray Recorder and the Air Absorption and Decay of Particles’, *Terrest. Magn. Atmospheric Electricity* **49**, 1–7.

Duperier, A.: 1949, ‘The Meson Intensity at the Surface of the Earth and the Temperature at the Production Level’, *Proc. Phys. Soc.* **62**, 684–696.

Forbush, S. E.: 1967, ‘A Variation with a Period of Two Solar Cycles, in the Cosmic-Ray Diurnal Anisotropy’, *J. Geophys. Res.* **72**, 4937–4939.

Forman, M. A. and Gleeson, L. J.: 1975, ‘Cosmic Ray Streaming and Anisotropies’, *Astrophys. Space Sci.* **32**, 77–94.

Fujii, Z.: 1998, ‘High Energy Cosmic Ray Isotropic Intensity Waves’, *Proc. 2nd Mini-International Conference: Beyond Solar Horizon*, STE Laboratory, Nagoya University, Japan, pp. 85–86.

Hall, D. L.: 1995, ‘Modulation of High Energy Cosmic Rays in the Heliosphere’, Ph.D. Thesis, University of Tasmania.

Hall, D.L., Humble, J.E., and Duldig, M.L.:1993,‘Radial and Latitudinal Density Gradients in Cosmic Rays Derived from the Solar Diurnal Variation’, *Proc. 23rd Int. Cosmic Ray Conf.* **3**, 679–682.

Hall, D. L., Humble, J. E. and Duldig, M. L.: 1994, ‘Modulation of High Energy Cosmic Rays in the Heliosphere’, *J. Geophys. Res.* **99**, 21 443–21 455.

Hall, D. L., Duldig, M. L., and Humble, J. E.: 1995, ‘The Parallel Mean-Free Path of Galactic Cosmic Rays at 1 AU’, *Proc. 24th Int. Cosmic Ray Conf.* **4**, 607–610.

Hall, D. L., Duldig, M. L., and Humble, J. E.: 1996, ‘Analysis of Sidereal and Solar Anisotropies in Cosmic Rays’, *Space Sci. Rev.* **78**, 401–442.

Hall, D. L., Duldig, M. L., and Humble, J. E.: 1997, ‘Cosmic Ray Modulation Parameters Derived from the Solar Diurnal Variation’, *Astrophys. J.* **482**, 1038–1049.

Hall, D. L., Munakata, K., Yasue, S., Mori, S., Kato, C., Koyama, M., Akahane, S., Fujii, Z., Fujimoto, K., Humble, J. E., Fenton, A. G., Fenton, K. B., and Duldig, M. L.: 1998a, ‘Preliminary Analysis of Two-Hemisphere Observations of Sidereal Anisotropies of Galactic Cosmic Rays’, *J. Geophys. Res.* **103**, 367–372.

Hall, D. L., Munakata, K., Yasue, S., Mori, S., Kato, C., Koyama, M., Akahane, S., Fujii, Z., Fujimoto, K., Humble, J. E., Fenton, A. G., Fenton, K. B., and Duldig, M. L.: 1998b, ‘Gaussian Analysis of Two Hemisphere Observations of Sidereal Daily Variations of Galactic Cosmic Rays’, *Proc. 25th Int. Cosmic Ray Conf.* **2**, 137–140.

Hall, D. L., Munakata, K., Yasue, S., Mori, S., Kato, C., Koyama, M., Akahane, S., Fujii, Z., Fujimoto, K., Humble, J. E., Fenton, A. G., Fenton, K. B., and Duldig, M. L.: 1999, ‘Gaussian Analysis of Two Hemisphere Observations of Galactic Cosmic Rays Sidereal Anisotropies’, *J. Geophys. Res.* **104**, 6737–6749.

Ip, W. H., Fillius, W., Mogro-Campero, A., Gleeson, L.J., and Axford, W. I.: 1978,‘Quiet Time Interplanetary Cosmic Ray Anisotropies Observed from Pioneer 10&11’, *J.Geophys.Res.* **83**, 1633–1640.

Jacklyn, R. M.: 1986, ‘Galactic Cosmic Ray Anisotropies in the Energy Range (10^{11}–10^{14}eV)’, *Proc. Astron. Soc. Australia* **6**, 425–436.

Jacklyn, R. M. and Duldig, M. L.: 1987, ‘The Determination of the Accidental Rate in the Output of a 2-Tray Gas Counter Telescope’, *Proc. 20th Int. Cosmic Ray Conf.* **4**, 380–383.

Jacklyn, R. M., Duldig, M. L., and Pomerantz, M. A.: 1984a, ‘Cosmic Ray Intensity Waves and the North-South Anisotropy’, *Proc. Astron. Soc. Australia* **5**, 581–586.

Jacklyn, R. M., Duldig, M. L., and Pomerantz, M. A.: 1984b, ’Anisotropic and Isotropic Intensity Waves’, *Proc. Int. Symp. Cosmic Ray Modulation in the Heliosphere*, Iwate University, Morioka, Japan, pp. 76–82.

Jacklyn, R. M., Duldig, M. L., and Pomerantz, M. A.: 1987, ‘High-Energy Cosmic Ray Intensity Waves’, *J. Geophys. Res.* **92**, 8511–8518.

Jokipii, J. R. and Kota, J.: 1997, ‘Galactic and Anomalous Cosmic Rays in the Heliosphere’, *Invited, Rapporteur and Highlight Papers, 25th Int. Cosmic Ray Conf.* **8**, 151–174.

Krymsky, G. F., Krivoshapkin, P. A., Mamrukova, V. P., and Skripin, G. V.: 1997, ‘Long-Term Variations of the Cosmic Ray Anisotropy’, *Proc. 25th Int. Cosmic Ray Conf.* **2**, 149–151.

Kudela, K.: 1997, ‘Quasiperiodic Variations and Terrestrial Environment’, *Invited, Rapporteur and Highlight Papers, 25th Int. Cosmic Ray Conf.* **8**, 175–191.

Lyons, P.R.A.: 1981, ‘Atmospheric Effects of High Energy Cosmic Rays’, Ph.D. Thesis, University of Tasmania.

Mori, S.: 1996, ‘Cosmic Ray Modulation Ground Based Observations’, *Nuov. Cim.* **19C**, 791–804.

Munakata, K., Yasue, S., Mori, S., Kato, C., Koyama, M., Akahane, Fujii, Z., Ueno, H., Humble, J. E., Fenton, A. G., Fenton, K. B., and Duldig, M. L.: 1995, ‘Two Hemisphere Observations of the North-South Sidereal Asymmetry at $\sim$1 TeV’, *J. Geomagn. Geoel.* **47**, 1103–1106.

Munakata, K., Miyasaka, H., Hall, D.L., Yasue, S., Kato, C., Fujii, Z., Fujimoto, K., and Sakakibara, S.: 1997, ‘Long Term Variation of Cosmic-Ray Diurnal Anisotropy Observed by a Network of Multi-Directional Muon Telescopes in a Wide Range of Rigidity’, *Proc.25th Int. Cosmic Ray Conf.* **2**, 77–80.

Munakata, K., Kitawada, T., Yasue, S., Mori, S., Kato, C., Koyama, M., Akahane, S., Hall, D. L., Fujii, Z., Fujimoto, K., Humble, J. E., Fenton, A. G., Fenton, K. B., and Duldig, M. L.: 1998, ‘Solar Semidiurnal Anisotropy of Galactic Cosmic Ray Intensity Observed by the Two-Hemisphere Network of Surface-Level Muon Telescopes’, *J. Geophys. Res.* **103**, 26 851–26 857.

Munakata, K., Kitawada, T., Yasue, S., Mori, S., Kato, C., Koyama, M., Akahane, S., Hall, D. L., Fujii, Z., Fujimoto, K., Humble, J. E., Fenton, A. G., Fenton, K. B., and Duldig, M. L.: 1999, ‘Enhanced Sidereal Diurnal Variation of Galactic Cosmic-Rays Observed by the Two-Hemisphere Network of Surface-Level Muon Telescopes’, *J. Geophys. Res.* **104**, 2511–2520.

Nagashima, K., Fujimoto, K., and Jacklyn, R. M.: 1995a, ‘The Excess Influx of Galactic Cosmic Rays from the Tailend Side of the Heliomagnetosphere, Inferred from their Sidereal Daily Variation’, *Proc. Int. Mini-Conference on Solar Particle Physics and Cosmic Ray Modulation*, STE Laboratory, Nagoya University, Japan, p. 93.

Nagashima, K., Fujimoto, K., and Jacklyn, R. M.: 1995b, ‘Cosmic-Ray Sidereal Daily Variation, Showing of the Coexistence of the Galactic and Heliomagnetotail-In Anisotropies’, *Proc. 24th Int. Cosmic Ray Conf.* **4**, 652–655.

Nagashima, K., Fujimoto, K., and Jacklyn, R. M.: 1995c, ‘Cosmic-Ray Excess Flux from the Heliomagnetotail’, *Proc. 24th Int. Cosmic Ray Conf.* **4**, 656–659.

Nagashima, K., Fujimoto, K., and Jacklyn, R. M.: 1998, ‘Galactic and Heliotail-In Anisotropies of Cosmic-Rays as the Origin of Sidereal Daily Variation in the Energy Region $< 10^4$ GeV’, *J. Geophys. Res.* **103**, 17 429–17 440.

Parker, E. N.: 1964, ‘Theory of Streaming of Cosmic Rays and the Diurnal Variation’, *Planetary Space Sci.* **12**, 735–749.

Shea, M. A., Smart, D. F., Swinson, D. B., Humble, J. E., McKinnon, J. A., and Abston, C. C.: 1989, ‘Solar Activity Asymmetries and Their Possible Effect on the High Energy Cosmic Ray Perpendicular Gradient’, *Adv. Space Res.* **9**, 221–224.

Swinson, D. B.: 1969, ‘Sidereal Cosmic Ray Diurnal Variations’, *J. Geophys. Res.* **74**, 5591–5598.

Swinson, D. B.: 1971, ‘Solar Modulation Origin of ‘Sidereal’ Cosmic Ray Anisotropies’, *J. Geophys. Res.* **76**, 4217–4223.

Swinson, D. B.: 1988, ‘Long Term Variations of the Cosmic Ray North-South Anisotropy and the Radial Cosmic Ray Gradient at High Rigidity’, *J. Geophys. Res.* **93**, 5890–5896.

Swinson, D. B., Regener, V. H., and St. John, R. H.: 1990, ‘Correlation of Cosmic Ray Diurnal Anisotropies with the Interplanetary Magnetic Field over 21 Years’, *Planetary Space Sci.* **38**, 1387–1398.

Swinson, D. B., Humble, J. E., Shea, M. A., and Smart, D. F.: 1991, ‘Latitudinal Cosmic Ray Gradients: Their Relation to Solar Activity Asymmetry’, *J. Geophys. Res.* **96**, 1757–1765.

Venkatesan, D. and Badruddin: 1990, ‘Cosmic-Ray Intensity Variations in the 3-Dimensional Heliosphere’, *Space Sci. Rev.* **52**, 121–194.

Yasue, S.: 1980, ‘North-South Anisotropy and Radial Density Gradient of Galactic Cosmic Rays’, *J. Geomagnetism and Geoelectricity* **32**, 617–635.

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