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Periodic solar time variations in the cosmic-ray muon component near sea level

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Abstract. Eight scintillation counters, each about 1·5 m^2, have been assembled in a muon telescope array at Winnipeg, Canada. Six telescopes (geometric factor about 750 cm^2 sr) have their axes approximately in the equatorial plane. For these, the asymptotic cones of acceptance are quite narrow with respect to asymptotic longitude, and they are therefore well suited for time variation studies. Two nearly vertical telescopes (geometric factor about 350 cm^2 sr) complete the array.

Experimental results obtained between 13th November 1966 and 5th May 1968 are presented. It is shown that the phase of the average diurnal anisotropy is consistent with the Parker and Axford theories alone, and its amplitude is dependent on the time in the solar cycle. Further, a semi-diurnal anisotropy is found, extra-terrestrial in origin, with intensity maxima at right angles to the interplanetary magnetic field.

1. Introduction

On average, the solar daily cosmic-ray intensity variation may be well approximated by first- and second-harmonic components, respectively named the diurnal and semi-diurnal anisotropies. A number of processes have been suggested as leading to various primary cosmic-ray anisotropies at the Earth. These include:

(i) The co-rotation theories of Parker (1964, 1967) and Axford (1965) which predict a streaming (i.e. a maximum) of cosmic rays from the 1800 h free-space direction.

(ii) The solar absorption of particles (Mercer and Wilson 1965, Sarabhai *et al.* 1965) leading to a deficiency (i.e. a minimum) of cosmic rays from about the 0900 h free-space direction.

(iii) The scattering at interplanetary magnetic irregularities in the presence of heliolatitudinal cosmic-ray density gradients, leading to minima along the field directions (usually toward the Sun) (Patel and Chasson 1968).

(iv) The consequences of heliolatitudinal cosmic-ray density gradients in a relatively smooth interplanetary field (Lietti and Quenby 1968, Subramanian and Sarabhai 1967), leading to intensity maxima from directions at right angles to the interplanetary field at the Earth's orbit, i.e. maxima from the 0300 h and 1500 h free-space directions.

Evidence for the above anisotropies was recently presented by Patel and Chasson (1968) on the basis of an extensive study of data from a number of super neutron monitors for the period 1964–65, near solar activity minimum. In this communication we wish to present results for an 18 month period, near a time of maximum solar activity, as observed by a meson telescope array which responds to considerably higher primary energies than do neutron monitors.

2. Muon telescope array

For a study of solar and sidereal time variations eight scintillation counters, each utilizing approximately 1·5 m^2 of plastic scintillator, have been assembled as a telescope array at Winnipeg, Canada (geographic longitude 97·2° west and geographic latitude 49·9° north, altitude 236 m). The physical orientation of the eight scintillation detectors is given in figure 1. All intervening building floors (the telescope 'absorbers') are omitted in the figure and distances are not drawn to scale. Detectors are numbered 1 to 8 and subsequently will be referred to by these numbers. Muon telescopes are then labelled by combining respective detector numbers. For example, telescope 1–5 is detector 1 in coincidence with detector 5, while telescope 12–78 is the summed output of detectors 1 and 2, in coincidence with the summed output of detectors 7 and 8.

The geometrical arrangement is that of three pairs of telescopes (1–5 and 3–5, 2–5 and 4–5, 1–6 and 3–6) having viewing directions which, projected on to the equatorial plane, are 15° west and east of south. (Telescopes 2–6 and 4–6 were not monitored as they are essentially parallel to and the same as telescopes 1–5 and 3–5 respectively.) In addition to these, the rates of two other fairly narrow-angle, almost vertical telescopes (12–78 and 34–78) were recorded. Specific geometric details of the eight telescopes are presented in table 1, with their average coincidence rates.

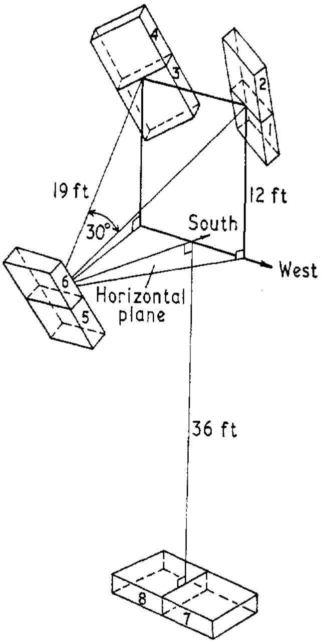

Figure 1. A perspective diagram (not to scale) showing the physical orientation of the eight detectors, omitting all intervening building floors (the telescope 'absorbers').

Table 1. Geometric details of the eight muon telescopes

Telescope	Azimuth angle (east of north)	Zenith angle	Solid angle (sr)	Geometric factor (approx.) (cm^2 sr)	Coincidences per hour (approx.)
1–5	197·8°	51·2°	0·050	780	7700
3–5	162·2°				
2–5	205·5°	39·2°	0·045	700	9580
4–5	154·5°				
1–6	194·9°	64·2°	0·050	750	3330
3–6	165·1°				
12–78	270·0°	6·4°	0·010	340	8750
34–78	90·0°				

For telescopes 1–5 to 3–6 of table 1, i.e. all the 'inclined' telescopes, veto pulses were supplied by any twofold coincidence between detectors 1 to 4 and/or a coincidence between detectors 5 and 6. For telescopes 12–78 and 34–78, veto pulses were supplied following a coincidence between the combined detectors 12 and 34.

3. Asymptotic cones of acceptance

The asymptotic coordinates of these telescopes were calculated as described by McCracken *et al.* (1962), and are presented in figure 2. A characteristic feature of the asymptotic coordinate curves for all of these telescopes and particularly for the 'inclined' ones is the relatively small spread in asymptotic longitude for each as compared with that for telescopes scanning the equatorial plane from locations near the geographical equator. For comparison, the broken curve of figure 2 shows the large spread in asymptotic longitude coordinates (shifted by 170°) of a vertical telescope at Kampala (geographic longitude 32·6° east, geographic latitude 0·3° north). The coordinates corresponding to a primary magnetic rigidity of 19 GV on this Kampala curve are off scale some 25° of longitude beyond the point for 22·5 GV.

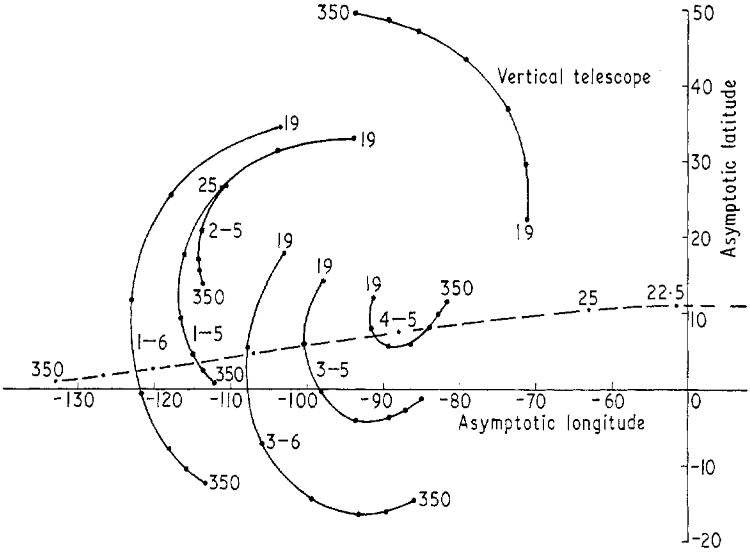

Figure 2. Asymptotic cones of acceptance for the muon telescopes. The broken curve shows the asymptotic coordinates of a vertical telescope situated at Kampala (geographic longitude 32·6° east, geographic latitude 0·3° north). The points marked correspond to primary magnetic rigidities of 19, 25, 35, 55, 95, 150 and 350 GV except for one at 22·5 GV on the broken Kampala curve.

4. Mean asymptotic longitudes and latitudes

Differential response functions as calculated by Krimsky *et al.* (1966) were utilized in connection with the asymptotic cones of acceptance to evaluate the mean telescope asymptotic viewing directions up to primary energy limits of 100 and 200 GeV. These limits define approximately the energy regions in which the diurnal and semi-diurnal anisotropies are thought to exist (Patel and Chasson 1968, Subramanian and Sarabhai 1967).

For improved statistical accuracy the telescope rates were combined to correspond to two equatorial telescopes A and B, defined as

$$\begin{aligned}\text{telescope A} &= (1\text{–}5)+(2\text{–}6)+(1\text{–}6)+(2\text{–}5)\\ &\simeq 2\times(1\text{–}5)+(1\text{–}6)+(2\text{–}5)\\ \text{telescope B} &= (3\text{–}5)+(4\text{–}6)+(3\text{–}6)+(4\text{–}5)\\ &\simeq 2\times(3\text{–}5)+(3\text{–}6)+(4\text{–}5).\end{aligned}$$

The approximate equations arise since telescopes 2–6 and 4–6 were not monitored. A third and final telescope combination, called V, is defined as

$$\text{telescope V} = (12\text{–}78)+(34\text{–}78)$$

For telescope V the differential response function has a maximum at primary energy near 15 GeV, while for the more inclined telescopes A and B the maximum occurs near 35 GeV. In comparison, the response function for neutron monitors peaks at a lower value of about 6 GeV (Lockwood and Webber 1967).

The mean asymptotic viewing directions of A and B were calculated as weighted averages of the mean coordinates of the component telescopes. The weighting factors were proportional to the component telescope counting rates.

5. Meteorological correction of the data

The daily mean rates of the various telescopes were correlated in linear regression analyses with the daily means of atmospheric pressure, ground-level temperature, 31 day running average ground-level temperature, pressure-corrected Deep River neutron monitor rate and also the 31 day running average corrected neutron rate in a fashion similar to that described by Carmichael *et al.* (1966, 1967). The use of distant neutron monitor rates for such an analysis has been discussed by Briggs *et al.* (1969 a). It was found, in agreement with work reported by Peacock *et al.* (1968), that the atmospheric coefficients for both inclined and vertical telescopes were equal within the estimated statistical errors. The coefficients deduced in the above five-parameter regression analyses were then used to remove the effects of fluctuations in hourly values of atmospheric pressure, hourly values of 24 h running ground-level temperatures and also hourly values of 31 day (or 744 h) running average ground-level temperatures. The validity of such corrections is fully discussed by Briggs (1969).

6. Selection of data for analysis

A total of 540 days between 13th November 1966 and 5th May 1968 was considered in determining the average solar daily intensity variation for each telescope. However, 42 days, considered abnormal, were rejected in the analyses. These rejected days included:

(i) 23 days influenced by Forbush decreases (as established by significant intensity changes ($\gtrsim 2\%$) in the corresponding Deep River neutron monitor data).

(ii) 19 days of pronounced diurnal variations, as reported by Mathews *et al.* (1969) and Briggs *et al.* (1969 b).

7. First and second harmonic anisotropies

The results of Fourier analysis (first and second harmonics only) of the mean daily variations of all telescopes are presented in table 2, together with the mean asymptotic

Table 2. Analysis of the average daily intensity variations

Telescope	Mean asymptotic longitude (deg)		1st harmonic		2nd harmonic	
	Primary energy ≤100 GeV	Primary energy ≤200 GeV	Amplitude (%)	Time of max.† (h LT)	Amplitude (%)	Time of max.† (h LT)
34–78	−73·3	−74·2	0·085 ±0·017	1530 ±0045	0·050 ±0·025	0201 ±0153
12–78	−81·4	−83·8	0·098 ±0·020	1627 ±0046	0·033 ±0·024	0117 ±0244
4–5	−87·0	−86·2	0·147 ±0·021	1704 ±0032	0·084 ±0·023	0220 ±0103
3–5	−93·0	−91·7	0·107 ±0·024	1831 ±0052	0·079 ±0·024	0340 ±0110
3–6	−95·6	−93·6	0·128 ±0·036	1812 ±0105	0·084 ±0·030	0312 ±0122
2–5	−111·6	−112·1	0·123 ±0·021	1848 ±0039	0·099 ±0·021	0404 ±0050
1–5	−115·3	−115·0	0·122 ±0·023	1912 ±0043	0·115 ±0·025	0415 ±0050
1–6	−119·7	−118·4	0·102 ±0·036	1828 ±0120	0·082 ±0·029	0325 ±0121
V	−77·1	−78·8	0·091 ±0·013	1600 ±0033	0·040 ±0·017	0143 ±0138
B	−91·3	−90·1	0·121 ±0·013	1753 ±0024	0·081 ±0·013	0236 ±0036
A	−114·6	−114·4	0·120 ±0·012	1859 ±0023	0·104 ±0·013	0407 ±0028

† To obtain free-space directions these times must be corrected for mean asymptotic longitude as described in § 7.

longitudes calculated for primary-energy limits of 100 and 200 GeV as discussed in § 4. The telescopes are listed in order of decreasing asymptotic longitude so that any given extra-terrestrial effect, such as the time of maximum of a solar-produced Fourier harmonic, should be recorded progressively later in local time (LT) reading from top to bottom in the table. The free-space directions of the Fourier maxima are obtained by adding to the times of table 2 the differences, expressed in hours, between the mean asymptotic longitudes and the station longitude ($-97{\cdot}2°$).

For an energy cut-off of 100 GeV in the calculations of mean asymptotic longitude, the averaged result of all independent telescopes for the free-space direction of the first-harmonic anisotropy is 1751 ± 0020 h. For a 200 GeV cut-off this result becomes 1753 ± 0020 h. (The results are thus quite insensitive to the assumed cut-off.) These free-space directions for the first-harmonic anisotropy agree very well with the Parker and Axford streaming theories which predict a maximum at 1800 h. It is therefore suggested that in the *average* daily intensity variation for the said period (excluding Forbush decrease and pronounced diurnal variation interferences) no other significant anisotropy of first-harmonic nature was present.

Prior to the neutron monitor analyses of Ables *et al.* (1966) there was considerable doubt (e.g. Rao *et al.* 1963, Katzman and Venkatesan 1960) regarding the very existence of an extra-terrestrial second-harmonic anisotropy. For the present data, the order of second-harmonic observations agrees with that to be expected for these particular telescopes scanning an extra-terrestrial anisotropy. With mean asymptotic coordinates for a 100 GeV upper energy cut-off, the second-harmonic anisotropy yields average free-space directions for maxima corresponding to 0303 ± 0027 h and 1503 ± 0027 h. For the quiet days considered, these phases are in very good agreement with the semi-diurnal models of Lietti and Quenby (1968) and Subramanian and Sarabhai (1967), which predict maxima at 0300 h and 1500 h. We thus also conclude that these muon results, corresponding to higher primary energies, indicate a genuine semi-diurnal anisotropy.

The amplitude of the first-harmonic anisotropy falls off as $\cos \Lambda$, where Λ is the mean asymptotic viewing latitude (Rao *et al.* 1963). The models of Subramanian and Sarabhai (1967) and Lietti and Quenby (1968) predict a more rapid fall-off for the semi-diurnal amplitude, namely $\cos^2 \Lambda$ or $\cos^3 \Lambda$ respectively. Unfortunately, the errors associated with all the amplitude results in table 2 do not permit a test of these predictions. There is, however, some indication that the second-harmonic amplitude does fall off more rapidly than does the first-harmonic for telescopes V and A (or B). The mean asymptotic latitudes in question are 35°, 12° and $-1°$ for V, A and B respectively. (These results are quite insensitive to assumed upper energy cut-offs.)

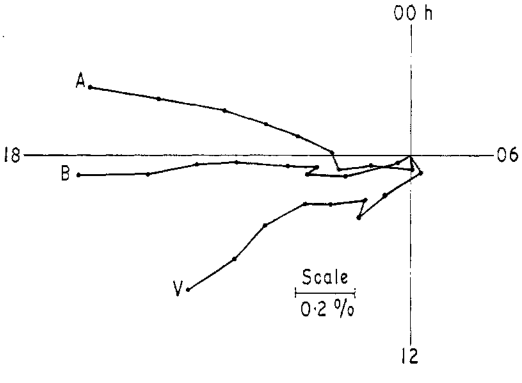

Figure 3. Bimonthly average diurnal anisotropy vectors for telescopes A, B and V plotted sequentially on a 24 h harmonic dial.

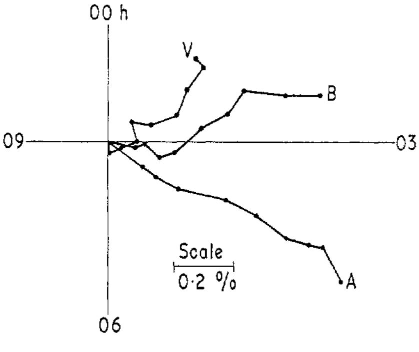

Figure 4. Bimonthly average semi-diurnal anisotropy vectors for telescopes A, B and V plotted sequentially on a 12 h harmonic dial.

8. Long-term changes in the solar anisotropies

A study of the diurnal and semi-diurnal anisotropies was performed on a bimonthly average basis throughout this 18 month portion of the solar cycle approaching maximum activity. Figures 3 and 4 are sequential plots of average bimonthly vectors for telescopes A, B and V. Figure 3 represents the diurnal anisotropy on a 24 h harmonic dial while figure 4 is applicable to the semi-diurnal anisotropy on a 12 h harmonic dial.

For the diurnal anisotropy there are rather striking differences between the first group of four vectors (eight months of data) for all telescopes and the last group of five vectors (ten months of data), as figure 3 indicates. The former period contains abrupt changes of phase associated with rather small amplitudes. For the latter months the phases are considerably more stable, while the amplitudes continually increase to approximately twice those of the initial eight months. These larger amplitudes correspond to near maximum solar activity as observed in the monthly sunspot number.

The semi-diurnal vectors do not show the same amplitude increase as a function of time. Also, the rather abrupt phase changes for telescope V are not well correlated with those of A and B, as they were for the diurnal anisotropy. This apparent inconsistency can be accounted for by the larger statistical errors (not presented) associated with the smaller semi-diurnal amplitudes.

9. Conclusions

The free-space direction of the average diurnal anisotropy was found to be consistent with the Parker and Axford co-rotation models. For this particular period no other significant first-harmonic anisotropies were present in the average quiet day intensity variation. The anisotropy amplitude increased markedly with increasing solar activity over the 18 months analysed.

Having demonstrated the extra-terrestrial nature of the semi-diurnal anisotropy we found its free-space maximum intensity directions to be essentially at right angles to the interplanetary magnetic field at the Earth's orbit, in agreement with the models of Lietti and Quenby (1968) and Subramanian and Sarabhai (1967). These observations are therefore evidence for the proposed cosmic-ray density gradients perpendicular to the ecliptic plane. Further, the semi-diurnal amplitude remained relatively constant throughout this study.

Acknowledgments

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