

High amplitude anisotropic events (HAE) in cosmic ray diurnal variation during Solar cycle 23

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Cosmic ray (CR) intensity shows significant diurnal variations of day-to-day most probable amplitudes of $\sim 0.5\%$ (annual vector averages $< 0.35\%$), often with wave trains of high amplitude anisotropic events (HAEs) and low amplitude anisotropic events (LAEs). Using the pressure-corrected data for the neutron monitor at Calgary (51°N , 114°W , cut-off rigidity 1.09 GV) during Solar cycle 23 (1996-2005), trends were removed by subtracting 24-hour running means from the hourly values. In the residues, days were searched when the maximum value of the diurnal amplitudes exceeded 1.0%. It was noticed that there were several HAE single events (amplitude exceeding 1.0% only on one day, not on the previous or succeeding day), double events (amplitudes exceeding 1.0% on two successive days), triple events (three successive days), and so on, with some having 10 or more days in succession. These events occurred at all levels and phases of CR variations, namely when CR daily values were almost constant for several days, or when daily values decreased slowly or increased slowly (few percent in several days, including 27-day variations) or just before the start of a Forbush decrease (FD) or during the recovery of a FD (During the main phase of sharp, strong FDs, the diurnal variation is highly distorted and difficult to access, hence omitted from the study). The occurrence of HAEs was found to be unrelated to geomagnetic indices or any interplanetary near-Earth parameters and is probably related to features in remote regions of the heliosphere.

Keywords: Cosmic ray diurnal variation, High amplitude anisotropic event (HAE), Low amplitude anisotropic event (LAE), Solar cycle 23

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1 Introduction

Cosmic rays (CR) are mostly of extra-galactic origin but suffer considerable modulation (reduction of intensity) in the heliosphere and in near-Earth environment. Apart from a solar cycle variation where intensity observed on the Earth is minimum during sunspot maximum (anticorrelation), there are 27-day oscillations, sharp short-term reductions called Forbush decreases (FD), and diurnal variations. The measurements started in the beginning of the twentieth century with ionization chambers, followed by meson telescopes. A day-night difference was noticed (maximum near noon, amplitudes less than 0.5%), but the statistical accuracy was not good enough for individual days. Only values averaged over long intervals (months and years) could be studied. Sarabhai & Kane¹, Thambyahpillai & Elliot², and Forbush³ demonstrated that diurnal amplitudes of the cosmic ray intensity were larger at sunspot maximum, while during sunspot minimum, diurnal amplitudes were lesser and time of maxima shifted to earlier hours. With the advent of neutron monitors in

the early 1950s, the diurnal variation could be studied with better accuracy. Amplitudes were larger (0.5% or more) and could be detected even for individual days. Kane⁴ showed that there was a 27-day recurrence tendency in days of large amplitudes. Soon after, it was observed that there occurred often a number of consecutive days as high amplitude anisotropic events (HAE) and low amplitude anisotropic events (LAE). Mavromichalaki^{5,6} observed that during specific time intervals, the enhanced diurnal variations showed a maximum around 1600 hrs LT and explained it as caused by the superposition of convection and field-aligned diffusion due to an enhanced density gradient of $\sim 8\% \text{ AU}^{-1}$. Fluckiger⁷ attributed the enhanced amplitudes to changing conditions in the interplanetary space. During high speed solar wind streams (HSSWS), the amplitudes and phases are reported to be different from those of other days^{8,9}. Several statistical studies have been reported. HAEs and LAEs have maxima shifted to later or earlier hours as compared to average pattern¹⁰. Kananen *et al.*¹¹ reported changes in the diurnal amplitude and

the phase depending upon the polarity of IMF. The relationship with high Ap have also been claimed¹². However, some of these conclusions are contradicted by Kumar *et al.*¹³

For a rigorous study (for example Ahluwalia & Dorman¹⁴ and references therein) of establishing the heliospheric origin of the HAE phenomena, data from a network of neutron monitors and muon detectors from the global sites need to be used, the diurnal variation data need to be converted into diurnal anisotropy data, and the anisotropy amplitudes need to be related to the heliospheric transport parameters using solar wind data. However, for a particular HAE event in contrast to the succeeding days of lower amplitudes, it was seen that the interplanetary parameters (solar wind speed and the total magnetic field) were not strikingly different. Hence, this methodology was abandoned and only a simplistic approach was adopted using data from only one neutron monitor (Calgary). In the present paper, HAEs are studied during the Solar cycle 23 (1996-2005).

2 Data and plots

The data for the neutron monitor at Calgary (51°N, 114°W, cut-off rigidity 1.09 GV) available at ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/COSMIC_RAYS/calgary.tab has been used. The hourly counting rate is ~1200000 and the standard error is only ~0.1%. Figure 1 illustrates CR variations at Calgary during Solar cycle 23. Figure 1(a) shows sunspot number Rz and CR monthly values (thin lines) and 3-monthly running averages (superposed thick lines). The CR plot is upside down, so that the rough parallelism between Rz and CR implies anticorrelation. As it can be seen, the matching is not perfect. In particular, Rz started increasing in June 1996 (shown by arrow) while CR changes (decreases) started in Feb 1998 (shown by arrow), i.e. ~20 months later. Figure 1(b) shows the plots of the observed daily values of Calgary CR for four successive 6 month intervals Jul-Dec 2001, Jan-June 2002, Jul-Dec 2002 and Jan-June 2003. As it can be seen, there are several peaks about 27-days apart and there are several FDs

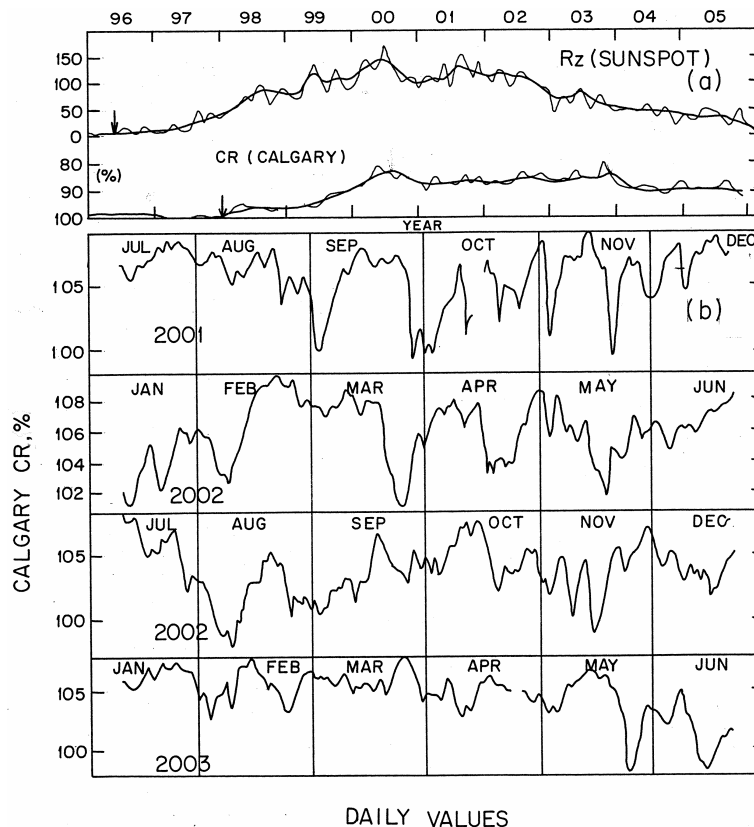


Fig.1—Plots for Solar cycle 23 (1996-2005): (a) Sunspot number Rz and CR monthly values (thin lines) and 3-monthly running averages (superposed thick lines). CR plot is upside down so that the rough parallelism between Rz and CR implies anti-correlation; (b) Plots of the daily values of Calgary CR (arbitrary units) for four successive 6-month intervals: Jul-Dec 2001, Jan-June 2002, Jul-Dec 2002, and Jan-June 2003

of 5-10%. The diurnal variation is not seen here as only daily values are shown. An inspection of the hourly values showed that high amplitude days were in plenty. Figure 2 shows the plots for selected monthly intervals in successive panels, for Nov-Dec 2001 and July-Aug 2002, all near sunspot maxima of cycle 23. As it can be seen, there are several wave trains during quiet intervals (CR intensity almost at a constant level), during intervals when CR increased or decreased slowly, as also during sharp CR decreases (FDs). To isolate and get quantitative estimates of the diurnal variation, 24-hour running means were calculated and subtracted from the observed hourly values (detrending). Figure 3 shows plots for a sample interval 2-14 Nov 2001 (shown earlier in the first half of the top panel of Fig. 2). The top plot Fig. 3(a) is for actual hourly values. Daily variation is seen but the major feature is a strong FD (~10% decrease of CR intensity at Calgary) on 6 Nov 2001. When 24-hour running means are subtracted, the residues are as shown in Fig. 3(b). Now, only the diurnal variation is seen, with a maximum at ~2400 hrs UT (~1600 hrs LT for Calgary), fairly regular, except that on 6 Nov 2001 when a strong FD occurred, the diurnal variation is highly distorted (shaded portion). Thus, during sharp FDs, it is almost impossible to locate and

estimate the magnitude of diurnal variation. Figures 3(c) and (d) show plots of the residues for two more sequences, namely 6-18 July 2002 and 1-13 Aug 2002 (earlier shown in the third and fourth panels of Fig. 2). Since these did not include the main phase of any FD, the diurnal variations are fairly smooth, with maxima near 2400 hrs UT (1600 hrs LT).

All CR data for 1996-2005 were examined. These showed many days of high amplitude waves in all years. Since the most probable day-to-day diurnal amplitudes are expected to be about 0.5%, a lower limit for HAEs was set at about 1.0% (arbitrarily) and days were located for the following different categories:

- Days when the diurnal amplitude exceeded 1.0% only on that day and amplitude was less than 1.0% on the previous and succeeding days (single events)
- Two consecutive days when diurnal amplitudes exceeded 1.0%
- Three consecutive days when diurnal amplitudes exceeded 1.0% and so on up to 10 or more consecutive days. For each year, the occurrence frequency of these categories was noted. Figure 4 shows the plots of occurrence

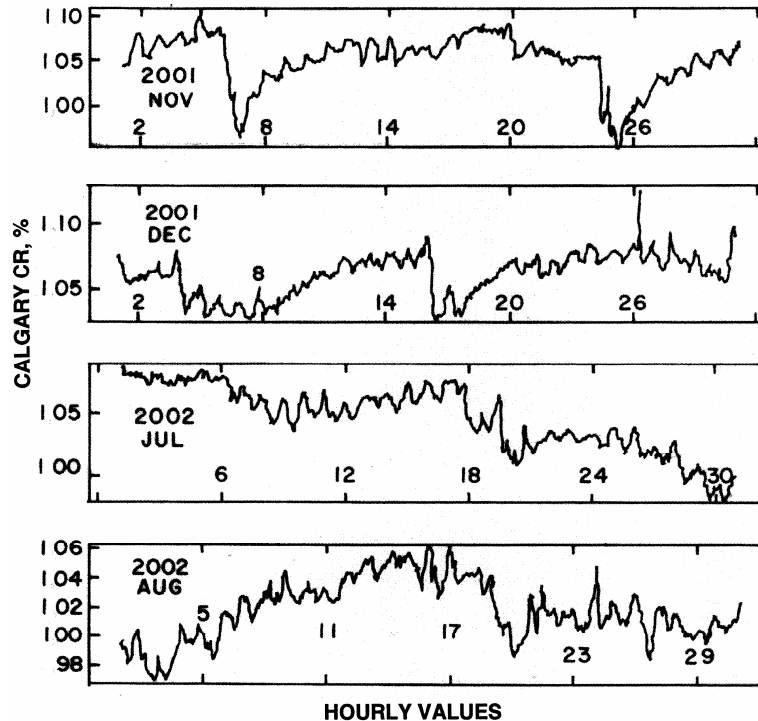


Fig.2—Plots of CR Calgary (arbitrary units) for selected monthly intervals in successive panels: for November 2001, December 2001, July 2002, and August 2002

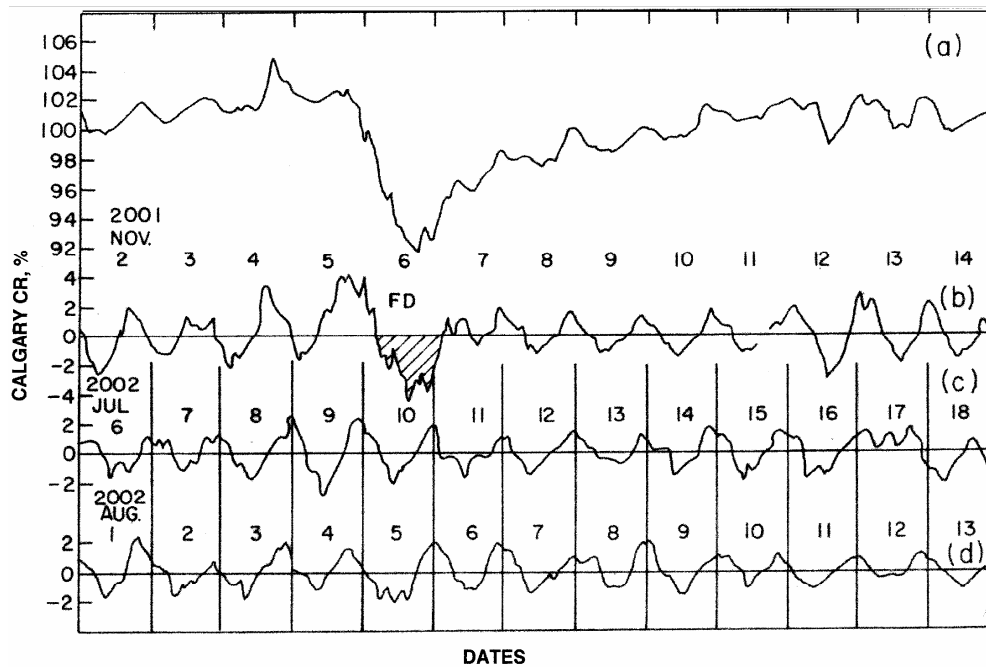


Fig.3—Plots of CR Calgary (arbitrary units) for: sample interval 2-14 Nov 2001- (a) actual hourly values, and (b) residues when 24-hour running means are subtracted; Plots of the residues for - (c) 6-18 July 2002, and (d) 1-13 Aug 2002

frequencies for ten years 1996-2005. The following may be noted:

- (i) The single events were largest in the year 1996 (quiet sun year). In other years, the frequency was almost the same except in 1999 when the frequency was considerably lower.
- (ii) The double events seem to have higher frequencies in alternate years, but this could be just a chance.
- (iii) Sequences of three, four, five and six events are more frequent in high sunspot years but the year 2005 seems to have large frequencies.
- (iv) Sequences of seven, eight and nine events are frequent in the declining part of solar activity (2004-2005).
- (v) Sequences of 10 or more events are only slightly larger in high sunspot activity years and still substantial in the declining sunspot activity years (2004-2005).

Overall, all sequences seem to occur in all years, but longer HAE sequences probably occur more in high solar activity years as well as in the declining phase of solar activity. These could be responsible for larger magnitudes of the average diurnal variation during such periods.

Analysis of HAE and LAE using the neutron monitor at Calgary for the previous solar cycles

(1965-1990) has been reported earlier by Ananth *et al.*¹⁵, who mentioned that the high amplitude days did not indicate any significant correlation with solar activity.

3 Relation with terrestrial and interplanetary parameters

Figure 5 shows a plot of the daily values of: (a) amplitude (%) of the diurnal variation; and (b) its hour/time of maximum (LT) versus the daily values of the geomagnetic disturbance index (A_p) for the two-month interval Nov-Dec 2001. About 60 pairs are shown. Very high values of A_p are not considered as these are usually related to severe FDs when diurnal variation gets distorted. As can be seen, the scatter is very large, implying lack of relationship. The big dots are averages over A_p ranges 2-3, 3-4, etc. and the vertical bars are standard errors. These are very large and nothing definite can be said about relationship with A_p , which probably does not exist. The correlations with A_p are very low (amplitudes versus A_p : +0.22; phase versus A_p : -0.05; amplitudes versus phases: -0.02) For comparison, some more parameters were considered namely, geomagnetic Dst, interplanetary parameters: number density (N), solar wind speed (V), total magnetic field (B), its components B_x , B_y , B_z , and the IMF sector structure

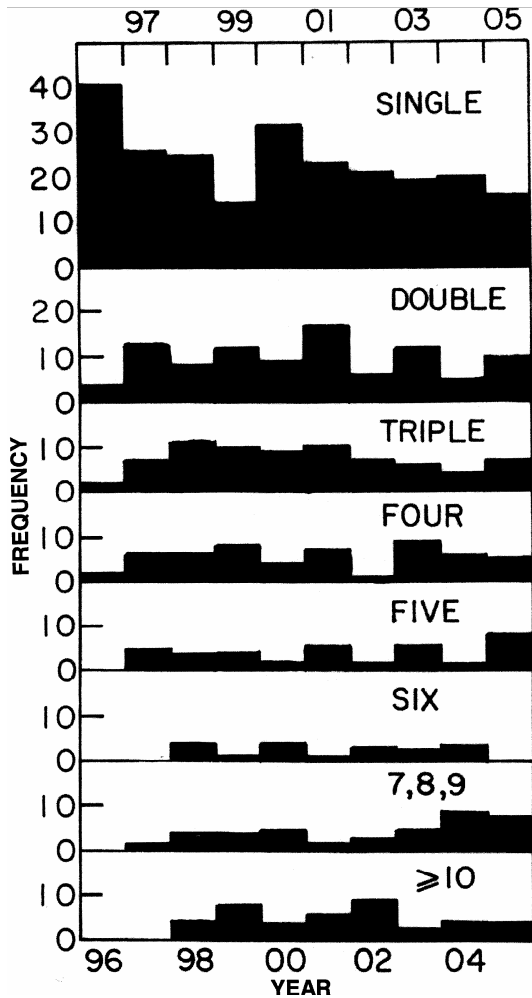


Fig.4—Plots (histograms) of the occurrence frequencies of HAEs of different durations (one day, two consecutive days, three consecutive days, etc.) for ten years 1996-2005

(away B: -1 ; toward R: $+1$). Table 1 gives their inter-correlations.

As can be seen in Table 1, almost all correlations are low. Exceptions are the obvious A_p with Dst (-0.77), A_p with interplanetary total field B ($+0.66$), sector structure with B_x ($+0.71$) and with B_y (-0.80); but the amplitudes and phases of the HAEs are not related to anything on or near Earth. Even the interplanetary B_x component (where direction inward or outward was distinguished by sign) has a low correlation with the diurnal amplitude ($+0.18$) as well as with diurnal phase (-0.13).

Figure 6 shows an example where a HAE (3-7 December) was followed by a LAE (8-14 December) 2001. The vertical line indicates the transition from high amplitudes to low amplitudes. The top plot is for Calgary CR hourly

values and the next plot is for the residues when 24-h running mean is subtracted. Further plots are for interplanetary number density N and solar wind speed V , followed by geomagnetic A_p and Dst. Only V shows a significant drop after the vertical line, but this could be fortuitous. A_p and Dst values indicate a calm interval (values less than 10 nT). Interplanetary B is also small (<10 nT), B_z is very small, and B_x and B_y show changes of a few nT but not exactly near the vertical line. The rectangles between B_x and B_y show the sector structure. It is R (towards Sun) for 3-9 December and B (away from the Sun) after 9 December. For 3-7 December, R matched with HAE, but for 8-9 December R matched with LAE. Thus, all these parameters seem to be unrelated to the HAEs and LAEs. Many other intervals like Nov-Dec 2001 were examined but all showed results similar to the above, namely low correlations, indicating no certain relationships.

4 Conclusions and discussion

The reported fact that HAE wave trains can last for more than 10 days suggests that their origin is not in parameters in or near-Earth environment, which have changes lasted only a few days (Dst recovery may last for several days, but it is not related to interplanetary parameters and is related to ring current dissipation in the plasmasphere). Hence, reports where some of these events (generally short-lived, ~ 4 days) showed some relationship with near-Earth interplanetary parameters could be chance coincidences.

Once the diurnal variation of cosmic rays was experimentally established, theoretical explanations were given^{16,17} on the basis of an azimuthal corotation mechanism, which would give a convective component along the direction of solar wind (radially outward from the Sun). Gleeson & Axford¹⁸ estimated its magnitude as $\sim 0.6\%$, but owing to the actual detector response and several other factors, the observed amplitudes would be $\sim 0.4\%$ (ref. 19). McCracken *et al.*²⁰ suggested that diurnal variation can be caused by two factors, namely a convection vector radially outward from the Sun (as above) and a magnetic-field-aligned diffusion vector. Forman & Gleeson²¹ incorporated this idea and gave a more elaborate formulation of cosmic ray anisotropy consisting of four terms, where the first term was the Compton-Getting effect, the second term was the parallel diffusion term, the third term was a perpendicular diffusion term, both these with respect

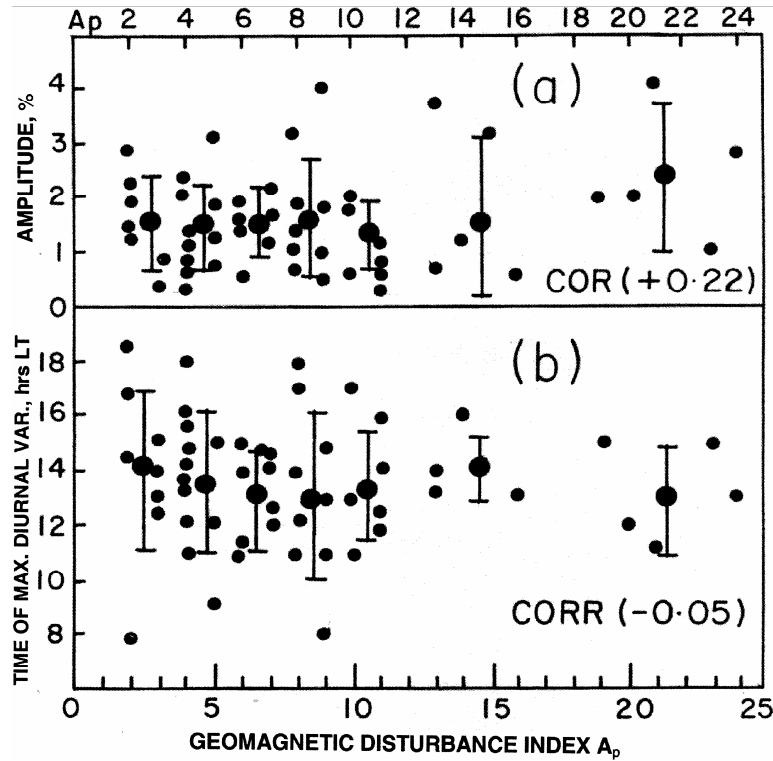


Fig.5—Plot of daily values of: (a) maximum value (%) of the diurnal variation amplitudes; and (b) its hour of maximum (LT) versus daily values of geomagnetic disturbance index (A_p) for the two-month interval Nov-Dec 2001. About 60 pairs are shown. The big dots are averages over A_p ranges 2-3, 3-4, etc. and vertical bars are standard errors

Table 1— Intercorrelations for the two month interval Nov-Dec 2001 (~60 pairs) between diurnal amplitudes and phases; geomagnetic Dst and A_p ; interplanetary number density (N), solar wind speed (V), total magnetic field (B): its components B_x , B_y , B_z , and the IMF sector structure (away -1; toward +1)

	Phase	Amp	A_p	Dst	N	V	Int.B	Int. B_x	Int. B_y	Int. B_z	Sector
Phase hr	1.00										
Amp %	0.00	1.00									
A_p	-0.26	0.16	1.00								
Dst	0.06	-0.10	-0.77	1.00							
N	0.00	0.09	0.04	0.35	1.00						
Speed (V)	0.08	0.09	0.30	-0.50	-0.44	1.00					
Int.B	-0.08	0.13	0.66	-0.26	0.40	0.25	1.00				
Int. B_x	-0.13	0.18	0.46	-0.21	0.20	0.37	0.40	1.00			
Int. B_y	0.05	-0.17	0.06	-0.04	0.12	-0.20	0.24	-0.53	1.00		
Int. B_z	-0.08	0.08	0.30	0.02	0.47	0.25	0.57	0.53	-0.01	1.00	
Sector	0.04	0.21	-0.08	0.04	0.07	0.20	-0.11	0.71	-0.80	0.25	1.00

to the ecliptic component B_{xy} of the interplanetary magnetic field B, depending only on the garden-hose direction of B but not on its sense (inward or outward), and a fourth term depending upon the magnitude as well as sense of B_{xy} (inward or

outward), and of B_z (northward or southward). The second, third and fourth terms involved density gradients of cosmic rays, parallel and perpendicular to the ecliptic plane. Several researchers have reported that most of the time, the first two terms were

adequate enough²²⁻²⁴. However, Rao *et al.*²⁴ observed a few sequences of low-amplitude days when the diffusion vectors deviated from the garden hose direction, and interpreted these as evidence for a perpendicular diffusion (third term). Hashim & Bercovitch²⁵ grouped data according to days of outward and inward B_{xy} and observed a difference and interpreted it as due to N-S gradient of cosmic ray intensity during 1967-1968. In the present analysis, as also earlier by Kane²⁶⁻²⁸, no clear relationship was seen between amplitudes and phases of HAE and any near-Earth parameter. Burlaga *et al.*²⁹ proposed that fast coronal mass ejections (CMEs) contribute to form a propagating diffusion region (heliocentric barrier) further out in the heliosphere, so that CR intensity never quite recovers at the earth's orbit³⁰.

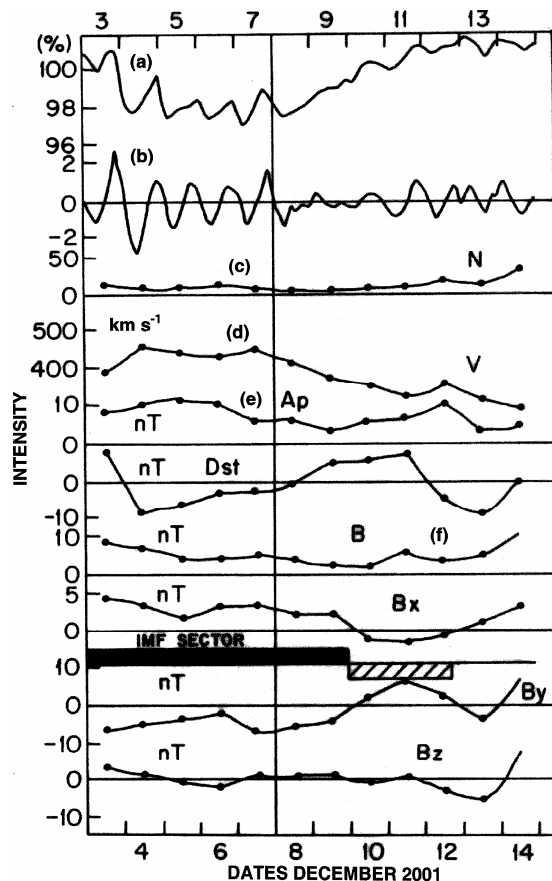


Fig.6—An example where a HAE (3-7 Dec 2001) was followed by a LAE (8-14 Dec 2001). Vertical line indicates transition from the observed high amplitudes to low amplitudes: (a) Calgary CR hourly values; (b) residues when 24-hour running mean is subtracted; (c) interplanetary number density (N); (d) solar wind speed (V); (e) geomagnetic Ap and Dst; (f) interplanetary Bx, By, Bz. The rectangles between Bx and By show the interplanetary magnetic field sector structure

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