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Comparison of the variations of solar indices, interplanetary plasma parameters, and cosmic ray neutron monitor intensities during 1991–2001

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[1] For the 11-year interval 1991–2001, the monthly values of three solar indices, interplanetary plasma density N, wind speed V, and total magnetic field B, and cosmic ray neutron monitor intensities at six locations were subjected to spectral analysis. Solar indices showed similar spectra between themselves and so did the cosmic rays between themselves, but the periodicities of solar indices (~12, 20, 40 months) were diferent from the periodicities of cosmic rays (~17, 24, 60 months), while interplanetary N, V had ~13, 17, 28 months, and B had ~17 and 40 months. Thus solar periodicities do not invariably pervade into the interplanetary space or affect the cosmic rays. On the other hand, interplanetary plasma parameters and cosmic rays develop their own periodicities, unlike each other and unlike solar indices. During two intervals, each of 132 daily values, 11 October 1997–19 February 1998 (Event II) and 20 February–1 July 1998 (Event III), a spectral analysis of the daily values of solar indices showed a strong 27-day signal, but it was seen only in interplanetary N. Cosmic rays did not show the 27-day signal. Instead, significant signals were seen in cosmic rays at ~13.5 and 20 days, seen in solar indices also but much smaller than the 27-day signal. *INDEX TERMS:* 2104 Interplanetary Physics: Cosmic rays; 2134 Interplanetary Physics: Interplanetary magnetic fields; 2162 Interplanetary Physics: Solar cycle variations (7536); 7536 Solar Physics, Astrophysics, and Astronomy: Solar activity cycle (2162); *KEYWORDS:* solar indices, interplanetary parameters, cosmic rays

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1. Introduction

[2] Cosmic rays are energetic particles that are found in space and filter through our atmosphere. These are generally termed as GCR (galactic cosmic rays). The portion of the cosmic ray spectrum that reaches the Earth's atmosphere is controlled by the geomagnetic cutoff which varies from a minimum (theoretically zero) at the magnetic poles to a vertical cosmic ray cutoff of about 15 GV (ranging from 13 to 17) in the equatorial regions. (Note that GeV is a unit of energy, GV is a unit of magnetic rigidity).

[3] Cosmic rays are being regularly monitored by ground-based neutron monitors at several locations on the Earth for the last several decades. Observations so far indicate a clear solar cycle effect, with largest reductions in cosmic ray neutron monitor intensity during sunspot maximum years, a very good anti-correlation, (long-term variation [*Forbush*, 1954; *Ahluwalia and Wilson*, 1996 and references therein]). *Burlaga et al.* [1985] proposed that fast CMEs (coronal mass ejections) contribute to form a propagating diffusion region (heliocentric barrier) further out in the heliosphere so that GCR intensity never quite recovers at the Earth's orbit [*Burlaga et al.*, 1993]. Nevertheless, one would have expected it to remain constant at solar minima. It was noticed, however, that the GCR flux decreased systematically in the four consecutive solar activity minima during 1964–1997. *Stozhkov et al.* [2000] attributed this decrease to a possible supernova explosion that may have occurred about 10^4 to 5×10^5 years ago, but *Ahluwalia* [2000] offered a simpler explanation in terms of a systematic change in the magnetic state of the heliosphere as indicated by the base level of IMF intensity (B).

[4] The structures of the recovery in the 11-year cycle of cosmic rays in relation to the state of interplanetary magnetic field have been studied in detail by *Jokipii and Thomas* [1981] and further by *Ahluwalia* [2000]. For short-term effects the relationship between solar variations with interplanetary plasma parameters and further with cosmic ray Forbush decreases and geomagnetic storms is also discussed in detail in various publications [e.g., *Gonzalez et al.*, 1994 and references therein]. However, the Sun has other variations of intermediate periodicities, for example, ~25 month periodicity reported by *Shapiro and Ward* [1962], the 27-day periodicity related to solar rotation, etc. Are these reflected in cosmic ray intensities? Some similarities are reported in the literature [e.g., *Rybak et al.*, 2001 and references therein]. In this communication, data of solar

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indices, interplanetary plasma parameters, and cosmic ray neutron monitor intensities at a few selected locations are analyzed and the variations compared for 1991–2001 (11 years). A spectral analysis is also carried out using MEM (maximum entropy method) and results are compared with those of other workers [*Dorman and Ptuskin*, 1981; *Okhlopkov et al.*, 1986; *Attolini et al.*, 1987; *Xanthakis et al.*, 1989; *Kudela et al.*, 1991, 2002; *Valdés-Galicia et al.*, 1996; *Kato et al.*, 2001; *Caballero and Valdes-Galicia*, 2001].

2. Data

[5] The data used are daily values for (1) three solar indices, namely, Sunspot number, Lyman alpha, and the 2800 MHz 10.7 cm radio flux, (2) interplanetary plasma parameters N (number density), V (wind speed), B (total magnetic field), and (3) neutron monitor intensities at Calgary (51°N, 114°W, cut-off rigidity 1.09 GV), Kiel (54°N, 10°E, cut-off rigidity 2.32 GV), Moscow (55°N, 37°E, cut-off rigidity 2.42 GV), Climax (39°N, 106°W, cut-off rigidity 2.99 GV), Beijing (40°N, 116°E, cut-off rgidity 9.56 GV) and Haleakala (20°N, 56°W, cut-off rigidity 12.91 GV). Almost all data were obtained from the NOAA websites and are for 1991–2001. Data for Beijing neutron monitor are only for 1993 onwards but are included as these are among the few extending to 2001.

3. Plots

[6] Figure 1 shows the plots of monthly values (thin lines, for some parameters only) and their 12-month moving averages (superposed thick lines). The sunspot minimum occurred around 1996, and the maxima of sunspots occurred near 1991 and 2000, but the values near 2000 were lesser (~125, in contrast to ~150 in 1991). Lyman alpha values also were lesser in 2000 as compared with 1991. However, the 2800 MHz radio flux (F10) was almost the same in 2000 as in 1991. The interplanetary plasma parameters N and V did not follow the sunspot cycle. The N (number density) values were almost the same from 1991 to 1997 and then dropped rapidly in the next 2 years. The V (wind speed) values seem to have two maxima, one in 1994 and another in 2000. This feature, namely two solar wind maxima, one near the sunspot maximum and another in the declining phase of the sunspot cycle with a gap inbetween, is well-known and is depicted by the geomagnetic disturbance index Ap also [*Gnevyshev*, 1967] as seen from the plot of Ap (triangles) just below the V plot in Figure 1. The B values seem to have a variation similar to that of sunspots, though the values in 2000 (~5 nT) are lower than those in 1991 (~6 nT). The cosmic ray values have a variation opposite to that of sunspots.

[7] Whereas the overwhelming variation is the ~11-year cycle, the monthly values have considerable month-to-month variations. To detect the same, a spectral analysis was carried out for the series of the monthly values as well as for their 12-month moving averages, by the following methodology.

4. Method of Spectral Analysis

[8] For spectral analysis, the method used was MEM (maximum entropy method) [*Burg*, 1967; *Ulrych and Bishop*, 1975], which locates peaks much more accurately than the conventional BT [*Blackman and Tukey*, 1958] method. However, the amplitude (power) estimates in MEM are not very reliable [*Kane*, 1977, 1979; *Kane and Trivedi*, 1982]. Hence MEM was used only for detecting all the possible peaks T_k (k = 1 to n), using LPEF (length of the prediction error filter) as 50% of the data length. These T_k were then used in the expression

$$\begin{aligned} f(t) &= A_o + \sum_{k=1}^{n} [a_k \sin(2\pi t/T_k) + b_k \cos(2\pi t/T_k)] + E \\ &= A_o + \sum_{k=1}^{n} r_k \sin(2\pi t/T_k + \phi_k) + E, \end{aligned}$$

where $f(t)$ is the observed series and E is the error factor. A multiple regression analysis (MRA) [*Bevington*, 1969] was then carried out to estimate A_o (a_k, b_k), and their standard errors (by a least squares fit). From these, amplitudes r_k and their standard error σ_k (common for all r_k in this methodology, which assumes white noise) were calculated. Any r_k exceeding 2σ is significant at a 95% (a priori) confidence level.

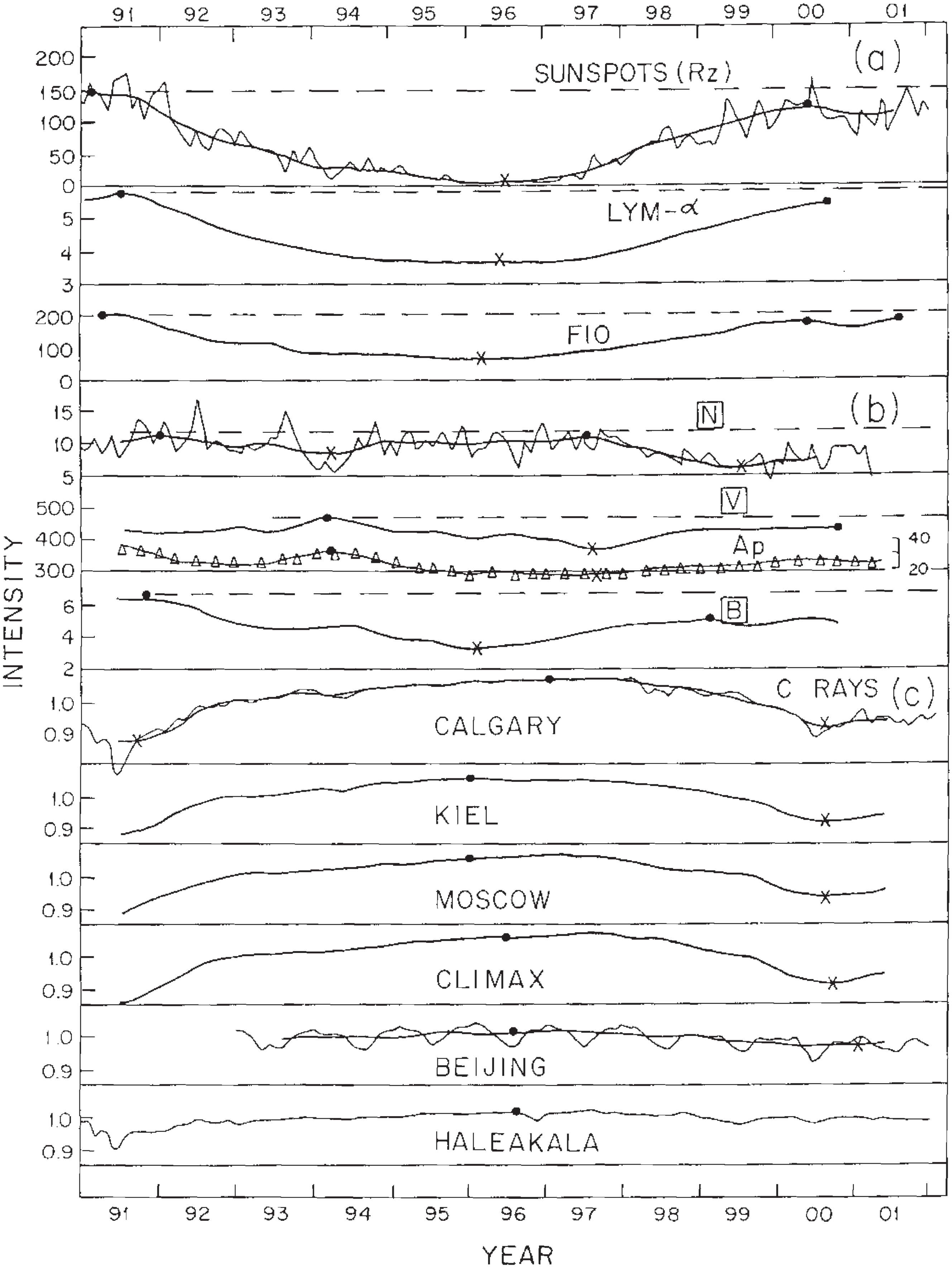
5. Spectra

[9] Figure 2 shows the spectra (amplitudes versus periodicity T in months) for monthly means and the 12-month moving averages (12-m) for solar indices and interplanetary parameters. Note that the abscissa scale is log (T). The hatched portion indicates the 2σ limit and amplitudes protruding above the hatched area are significant at a better than 95% confidence level. The following may be noted:

(1). For the solar indices, there is a prominent periodicity near 100 months, roughly representing the 11-year cycle. For detecting such a cycle, a sample of ~11 years (132 months) only is certailnly inadequate. In the *Blackman and Tukey* [1958] method, such a sample would be useful only for studying periodicities of ~50 months or less. It is to the credit of the MEM that it detects periodicities even comparable to the data length, but with errors of ~20–30%. For interplanetary N, V, B, this periodicity is indicated as lesser than 100 months. Anyway, the present purpose is not to examine the 11-year cycle, but many other smaller periodicities, with amplitudes much smaller than the ~11-year periodicity.

(2). In the monthly values, the solar indices have periodicities near ~11, 22, and 45 months, all of borderline significance. In the 12-m values, only ~22 and 45 months are seen. For the interplanetary N and V, the monthly values

Figure 1. (opposite) Plots of monthly values (thin lines) and 12-month moving averages (superposed thick lines) for (a) solar indices Sunspots (Rz), Lyman alpha, and 2800 MHz flux (F10), (b) Interplanetary parameters N (number density), V (wind speed), B (magnetic field) (the triangles are for geomagnetic index Ap), (c) Cosmic ray neutron monitor intensities at Calgary, Kiel, Moscow, Climax, Beijing, and Haleakala.


91 92 93 94 95 96 97 98 99 00 01
SUNSPOTS (Rz)
(a)
200
150
100
50
0
LYM-α
5
4
3
F10
200
100
0
N
(b)
15
10
5
V
500
400
300
Ap
40
20
B
6
4
2
C RAYS (c)
CALGARY
1.0
0.9
KIEL
1.0
0.9
MOSCOW
1.0
0.9
CLIMAX
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BEIJING
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HALEAKALA
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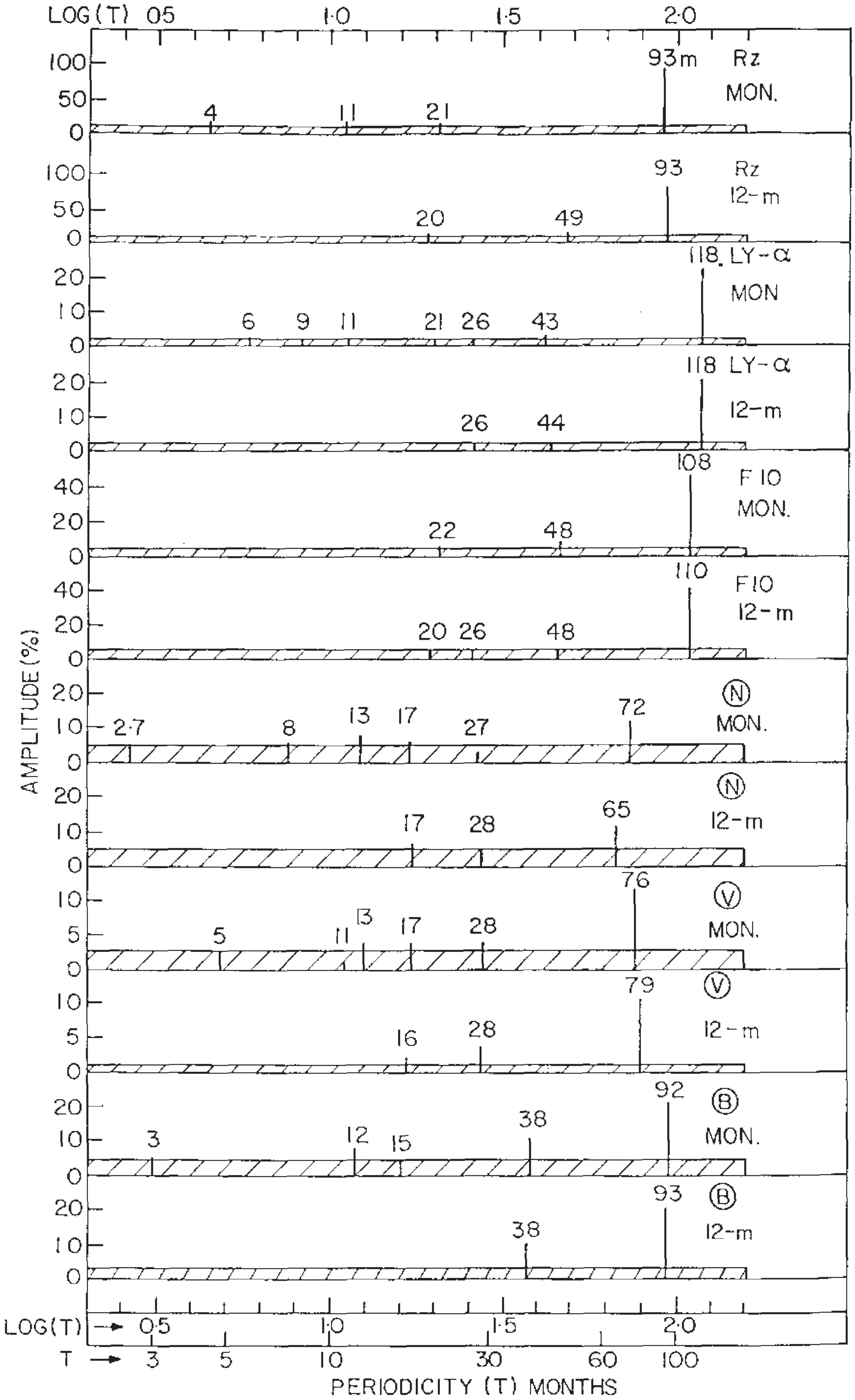
INTENSITY
YEAR


LOG(T) 05 1·0 1·5 2·0
100
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93m
4
11
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Rz
MON.
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20
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20
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118 LY-α
MON
6 9 11 21 26 43
118 LY-α
12-m
26 44
40
108
F 10
MON.
22 48
110
F10
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20 26 48
AMPLITUDE (%)
Ⓝ
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2·7 8 13 17 27 72
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17 28 65
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5 11 13 17 28 76
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16 28 79
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PERIODICITY (T) MONTHS

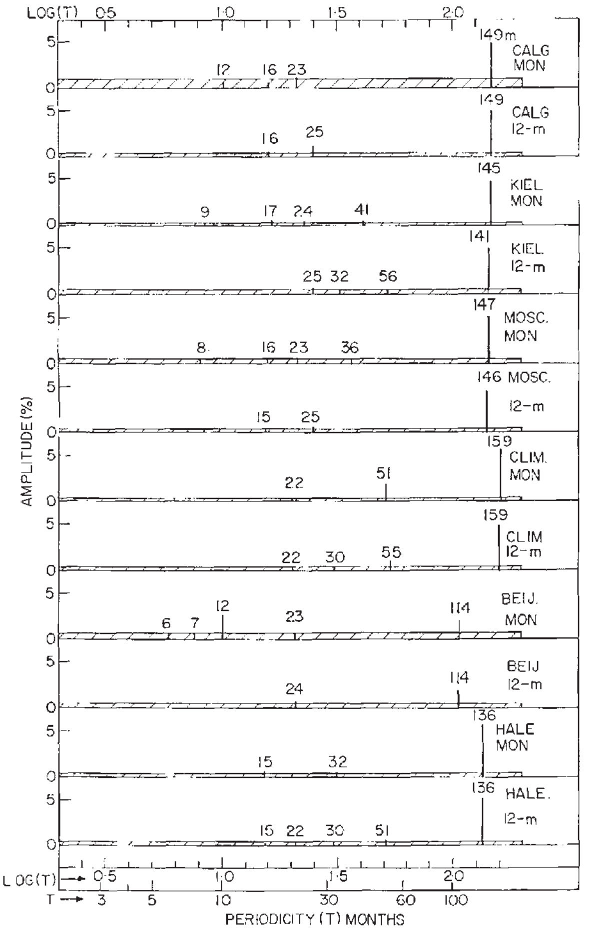

Figure 3. Spectra (amplitudes versus periodicities T in months) for the series of monthly means and their 12-month moving averages (12-m) for the cosmic ray neutron monitor intensities at Calgery, Kiel, Moscow, Climax, Beijing, and Haleakala. The hatched portion indicates the 2σ limit and amplitudes protruding above the hatched area are significant at a better than 95% confidence level. Note that the abscissa scale is log (T).

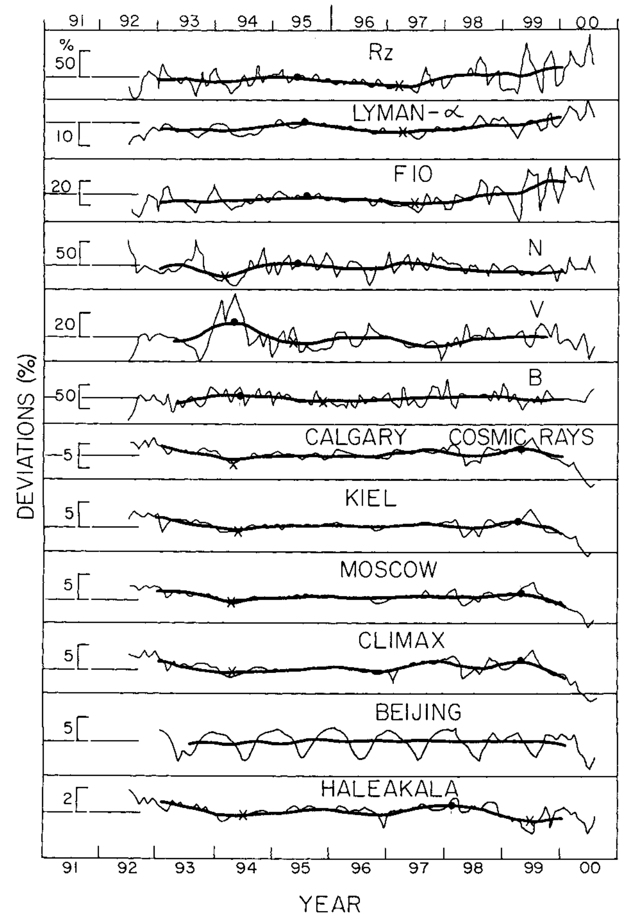

Figure 4. Plots of the percentage deviations of monthly values (thin lines) and 12-month moving averages (superposed thick lines) for (a) solar indices Sunspots (Rz), Lyman alpha, and 2800 MHz flux (F10), (b) Interplanetary parameters N (number density), V (wind speed), B (magnetic field) (c) Cosmic ray neutron monitor intensities at Calgary, Kiel, Moscow, Climax, Beijing, and Haleakala.

indicate periodicities of ~13, 17 and 28 months, different from those of the solar indices. Interplanetary B shows a significant periodicity at ~38 months.

[10] Figure 3 shows the spectra for the cosmic ray neutron monitor intensities. Here, many periodicities are seen, but the common ones are ~16, 24, 32, 50 months and near ~140 months. Some of these match with those of solar indices and/or interplanetary parameters.

6. Results for Detrended Values

[11] Since the 11-year trend is overwhelming, the other periodicities look very small and one may suspect distortion effects. *Kane and Trivedi* [1986] show that in the MEM, presence of a large trend does not affect the smaller periodicities. However, the trends considered there were linear. In the present case, the 11-year trend is almost sinusidal. To remove this trend, 3-year moving averages (moving averages over 37 monthly values, to get the centering correct) were calculated and subtracted from the original monthly values. Figure 4 shows the plots of the detrended values in percentages, monthly values as thin lines and 12-m values as superposed thick lines. The following may be noted: (1) The detrending is probably not perfect for 1999–2000 as the 3-year moving averages would be lesser than the actual values, but this is not expected to affect the spectra very much. (2) The monthly values (thin lines) have considerable month-to-month fluc-

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Figure 2. (opposite) Spectra (amplitudes versus periodicities T in months) for the series of monthly means and their 12-month moving averages (12-m) for the solar indices Rz, Lyman alpha, F10, and the interplanetary parameters N, V, B. The hatched portion indicates the 2σ limit and amplitudes protruding above the hatched area are significant at a better than 95% confidence level. Note that the abscissa scale is log(T).

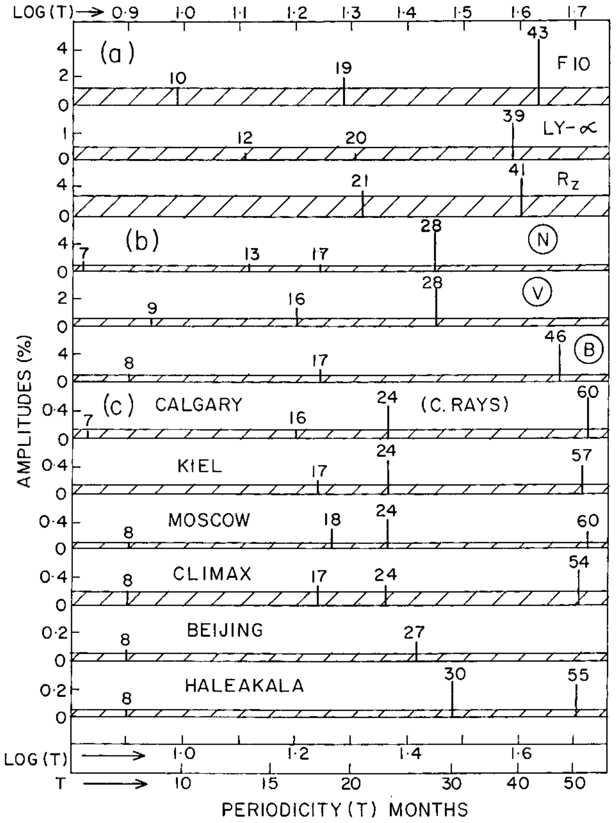

Figure 5. Spectra (amplitudes versus periodicities T in months) for the series of percentage deviations of monthly values for (a) solar indices Sunspots (Rz), Lyman alpha, and 2800 MHz flux (F10), (b) Interplanetary parameters N (number density), V (wind speed), B (magnetic field) (c) Cosmic ray neutron monitor intensities at Calgary, Kiel, Moscow, Climax, Beijing, and Haleakala. The hatched portion indicates the 2σ limit and amplitudes protruding above the hatched area are significant at a better than 95% confidence level. Note that the abscissa scale is log (T).

tuations, but these are very small in the quiet Sun years 1995–1997. (3) The monthly cosmic ray values at Beijing show a strong seasonal variation, unlike that for any other location. Some systematic errors are suspected. (4) The percentage fluctuations in cosmic rays are about an order of magnitude lesser than those of other parameters.

[12] Figure 5 shows the spectra. Comparing Figures 2, 3, and 5, the following is indicated: (1) The solar indices have periodicities near ~12, 20, 40 months. (2) The interplanetary N and V have periodicities near ~13, 17, 28 months. B has ~17 and 40 months. (3) Cosmic rays have ~17, 24 and 60 months. (4) Many of these periodicities are highly significant and hence reliable, are common to similar indices, and mostly different for the solar indices, cosmic rays, and interplanetary parameters.

7. Variations of Daily Values

[13] To study the day-to-day variations, the period selected was 11 October 1997–1 July 1998. *Kane et al.* [2001] and *Kane* [2002a, 2002b] show that in the 26-month interval 1 June 1997–1 August 1999, divided in six events of 132 consecutive days each, Event I and IV had no 27-day oscillations, but events II, III, V, and VI had strong 27-day fluctuations in many solar indices. Here, event II (11 October 1997–19 February 1998, 132 days) and event III (20 February–1 July 1998, 132 days) are considered.

[14] Figure 6 shows the plots of percentage values. *Kane* [2002b] showed that the 27-day fluctuations were very clear with largest amplitudes in the radio emissions in the corona, the amplitudes were smaller in the chromosphere (e.g., Lyman alpha) and the fluctuations were somewhat complicated in the photosphere (sunspot numbers). These characteristics are seen in Figure 6 for the solar indices sunspots (Rz), Lyman alpha, and F10 and the ~27-day oscillations are evident. For interplanetary parameters the data were intermittant for the first half (event II) but fairly continuous for the latter half (event III). The thick line is a 5-day moving average. For the cosmic rays the first half is characterized by strong oscillations of ~13–14 day spacings, while the latter half is characterized by a strong Forbush decrease during days 175–205. The bottom plots are for geomagnetic indices Ap and Dst and show a

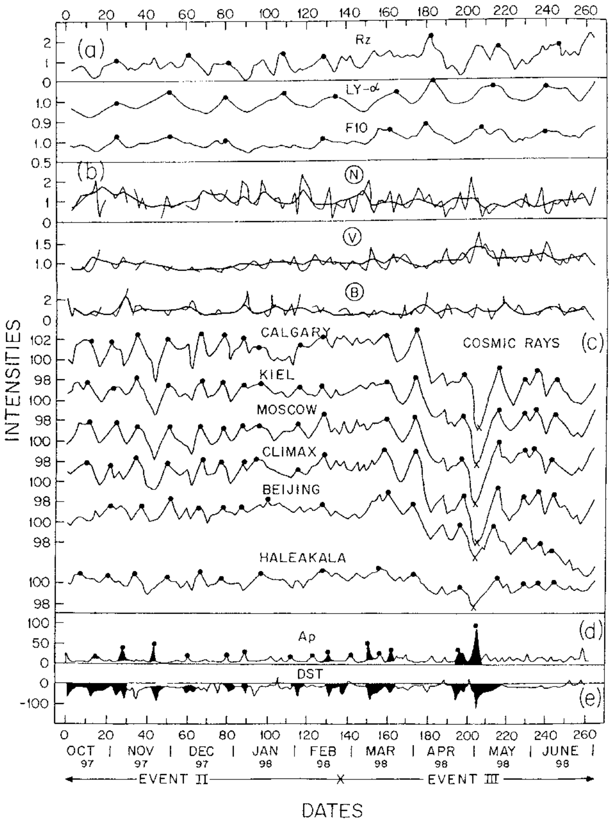

Figure 6. Plots of the percentage deviations of daily values (thin lines) and their 12-month moving averages (superposed thick lines) for (a) solar indices Sunspots (Rz), Lyman alpha, and 2800 MHz flux (F10), (b) Interplanetary parameters N (number density), V (wind speed), B (magnetic field) (c) Cosmic ray neutron monitor intensities at Calgary, Kiel, Moscow, Climax, Beijing, and Haleakala, (d, e) Geomagnetic indices Ap and Dst, for the period 11 October 1997–1 July 1998, events II and III, 264 days.

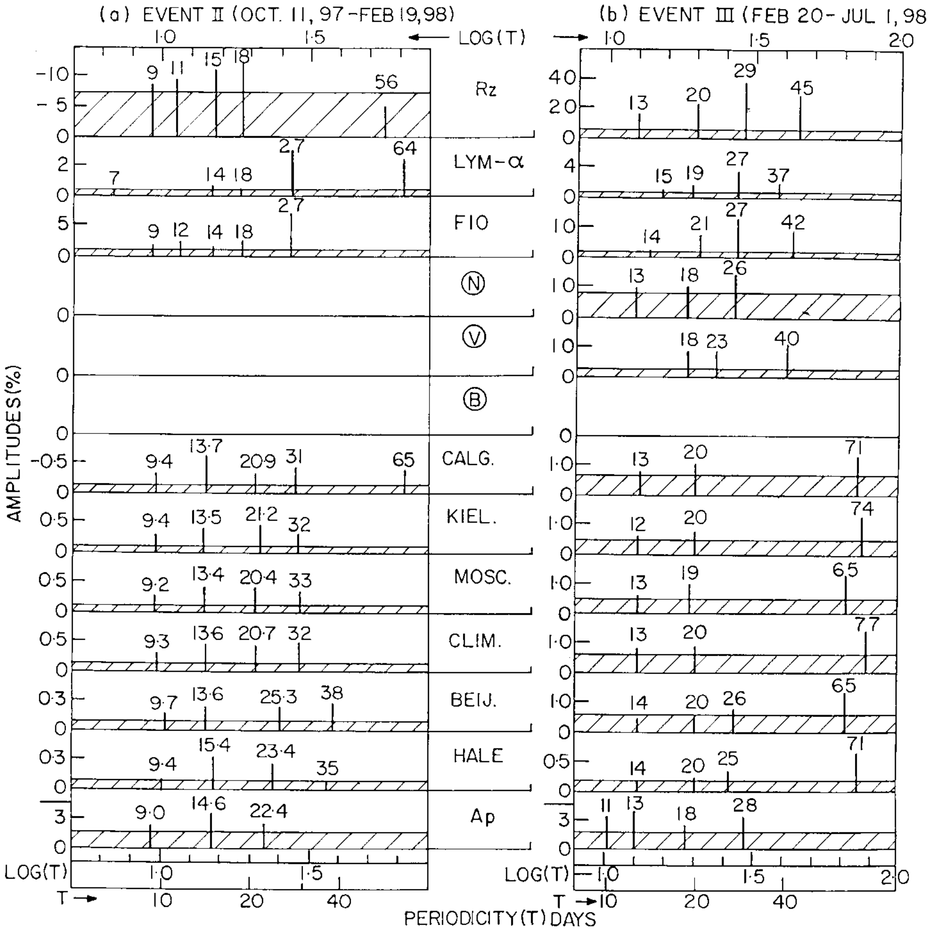

Figure 7. Spectra (amplitudes versus periodicities T in days) for the series of percentage deviations of daily values for the various parameters, for (a) event II, 132 days, 11 October 1997–19 February 1998 and (b) event III, 132 days, 20 February–1 July 1998. The hatched portion indicates the 2σ limit and amplitudes protruding above the hatched area are significant at a better than 95% confidence level. Note that the abscissa scale is log (T).

geomagnetic storm near day 205. Thus the cosmic ray storm had started several days before the geomagnetic storm. Spectra were obtained for the first half (event II) and second half (event III) separately and are shown in Figure 7a for event II and Figure 7b for event III. The following may be noted:

(1). In both events II and III, Lyman alpha and F10 show 27 days as the strongest periodicity, but it is missing in the sunspot data. Thus complications of the photospheric dynamics seem to obscure the solar rotation effects. However, besides the 27-day signal, there are other signals too, which are not insignificant. These cause (or reflect?) the irregular spacing between successive peaks in Figure 6.

(2). The N, V, B data are intermittant in event II and hence not amenable to spectral analysis. In event III the spectrum of N has a 26-day signal, but V does not have it. Data for B are intermittant and spectra could not be calculated.

(3). In cosmic rays, the largest signal in event II is near ~13.5 days, but an additional significant signal is at ~20.5 days, and a barely significant signal is at ~9.5 days. These signals are seen consistently at Calgary, Kiel, Moscow, and Climax, but not at Beijing and Haleakala. The Ap has somewhat similar signals.

(4). In cosmic rays the event III shows consistent signals at ~13 and 20 days. Ap has somewhat similar signals. For cosmic rays, a large signal is seen near ~65 days, but it is probably a mathematical manifestation of the strong Forbush decrease.

[15] To study possible periodicities in the 50–150 day range, the daily values of the 264-day data for events II and III were averaged (not moving averages) over 5 days and the series of 52 points (each an average over 5 days) so obtained were subjected to spectral analysis. The spectra are shown in Figure 8. In solar indices as well as in interplanetary parameters, a strong peak is seen near 26 days (solar rotation), a minor, barely significant peak near ~40 days, and an insignificant peak near ~60 days. In cosmic rays, there is the peak at ~13 days, but its amplitude has reduced considerably because of the averaging over 5 days. An insignificant peak appears near ~24 days, and significant peaks occur near ~70 days and 160

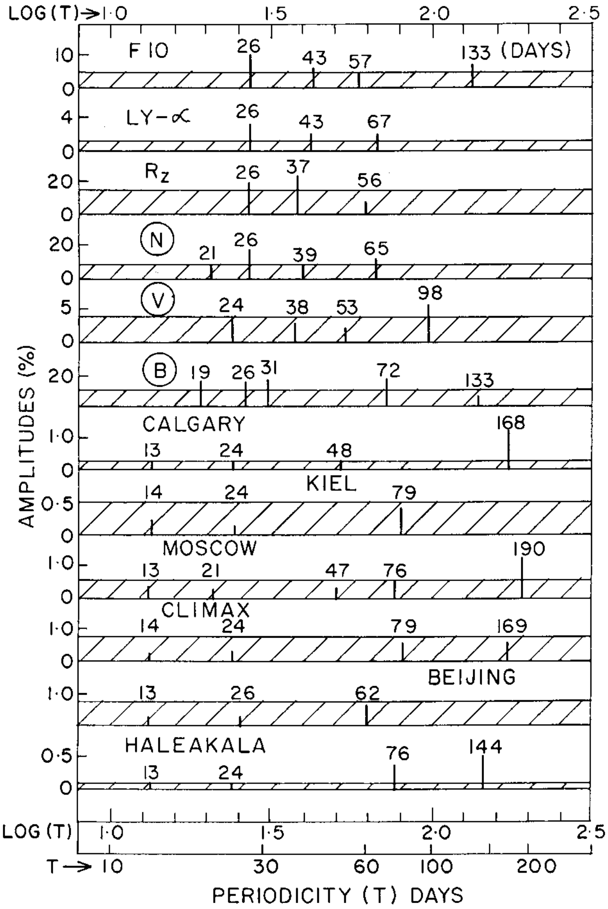

Figure 8. Spectra (amplitudes versus periodicities T in days) for the series of percentage deviations of 5-day averages of daily values for the various parameters, for (a) events II and III, 52 values, 11 October 1997–1 July 1998. The hatched portion indicates the 2σ limit and amplitudes protruding above the hatched area are significant at a better than 95% confidence level. Note that the abscissa scale is log (T).

days. Again, the larger ones may be a mathematical manifestation of the large Forbush decrease.

8. Comparison With the Results of Other Workers

[16] In Figures 2, 3, 5, 7, and 8 the periodicities are shown as single lines. Do these have any widths? None are shown because of the following reason. In MEM the peaks obtained are very sharp. Using artificial samples [*Kane*, 1977, 1979], it was shown that with a 100-data point sample, periodicities near 2–3 are detected with an accuracy of ~±0.03 (3.1, 3.2, 3.3 could be resolved, something unthinkable in the *Blackman and Tukey* [1958] method), those near 10 with an accuracy of ~±0.1, while for higher periodicities inaccuracies were larger (20.0 ± 0.5; 40 ± 1). Even periodicities comparable with the data length are detected though with large errors (80 ± 5). In MEM the steps can be chosen as small as one wants. In the present case, steps were chosen uniformly as 0.0025 of log values (e.g., 0.3010, 0.3025, 0.3040, corresponding to periodicities 2.00, ~2.01, 2.02; 1.0010, 1.0035 1.0060, corresponding to periodicities 10.02, 10.08, 10.14, etc.). For periodicities 12.0 and 13.0, there were ~14 points available for the power versus periodicity plot, and widths were almost nil.

[17] In earlier works [*Dorman and Ptuskin*, 1981; *Okhlopkov et al.*, 1986; *Attolini et al.*, 1987; *Xanthakis et al.*, 1989], a periodicity of ~1–2 years is mentioned as not correlated with solar activity but probably related to the dynamics of the solar cavity. *Kudela et al.* [1991] analyzed cosmic ray neutron monitor data for 1965–1989, examined periodicities in a wide range (2 days to 11 years), did not find any selective and long-range stable periodicity, but noticed an abrupt change in both the level and shape of the power spectrum at the periodicity of ~20 months (1.7 years). Later, *Valdes-Galicia et al.* [1996] reported a quasi-periodicity of ~1.7 years, which was not persistent over many solar cycles and did not have the character of a narrow line. *Kato et al.* [2001] showed the center of this quasiperiodicity at ~1.8 years. *Kudela et al.* [2002] showed that this periodicity was insignificant in the interval 1991–2001 but was more pronounced in the previous cycle 1980–1990. Also, this periodicity was noticed in IMF and its long-term behavior was different from that in cosmic rays. In the present analysis, cosmic rays (Figure 5) show periodicities of ~17 months (1.4 years, barely significant) and ~24 months (2 years, highly significant), while solar indices show ~20 months (1.7 years, barely significant). Considering the high accuracy of detection of periodicities in MEM, the cosmic ray periodicities of 17 and 24 months cannot be considered as similar to the 20 months of solar indices (in agreement with *Dorman and Ptuskin* [1981]), though it is tempting to bracket all these in a broad band of 17–24 months. In *Kudela et al.* [2002], a periodicity of 1.3–1.4 years is reported as better correlated with heliospheric magnetic field B. In the present analysis too, the periodicity of 17 months is seen in interplanetary N, V, B in the vicinity of Earth, agreeing with the speculation of *Dorman and Ptuskin* [1981] that this may be related, not to the solar activity as such but to the dynamics of the solar cavity. *Richardson et al.* [1994] had reported a solar wind oscillation of 1.3 year period.

[18] In Figure 5, a periodicity of ~60 months (~5 years) is strongly indicated in cosmic rays. In solar indices and IMF-B, only 40 months (~3.3 years) are indicated. Thus neither solar activity directly nor IMF-B near Earth are associated. Analyzing a long series of sunspot numbers, *Cole* [1973] found significant peaks near 10.4, 8.4, and 5.5 years. *Attolini et al.* [1987] found coherence between sunspot numbers and cosmic rays at these periodicities but, like *Dorman and Ptuskin* [1981], cautioned that the connection may not be directly with solar activity. The hypothesis of relationship with solar cavity could not be tested owing to lack of data about the cavity or the heliospheric boundary. Later, *Whang and Burlaga* [1993] studied the motion of the termination shock over an 11-year period (1978–1988) and found that the location of the shock is anti-correlated with the sunspot number. Recently, *Whang and Burlaga* [2000] reported the results of a study of the varying location and conditions of the termination shock over a 34-year period (1966–2000). Reading out the annual values of the location (in units of AU) of the terminal shock from *Whang and*

Burlaga [2000, Figure 3], we carried out a spectral analysis, which yielded three significant periodicities, namely, 5.13 years (amplitude 1.8 ± 0.4 AU), 9.60 years (amplitude 6.2 ± 0.4 AU), and 14.45 years (amplitude 3.7 ± 0.4 AU), (about a mean location value of ~80 AU). For the same interval the sunspot numbers yielded periodicities of 2.38 years (amplitude 5.1 ± 3.8), 5.07 years (amplitude 7.5 ± 3.8), and 10.29 years (amplitude 62.4 ± 3.8). The prominent periodicity in both was ~10 years (not 11 years), but more important, there was a ~5 year periodicity in both, though weak in sunspots. Thus this periodicity might be related to the solar activity as such, but weakly, and might be related more to the heliospheric cavity or boundary. The differences in the spectral compositions of cosmic rays and interplanetary parameters near Earth are expected in general, since cosmic ray intensity reflects the global heliospheric distribution of B, while N, V, B measured by satellites near Earth are of local character.

[19] For periodicities of the order of days the present analysis selected two intervals of 132 days each, during the rising phase of solar activity of cycle 23 (11 October 1997–1 July 1998), when solar indices had a strong 27-day oscillation. This was not reflected in cosmic rays. Instead, a very strong signal was obtained in cosmic rays at ~13 days and a smaller but significant signal at ~20 days. The solar activity did have these signals, but barely significant. Thus some other nonsolar origin seems to be involved. *Caballero and Valdés-Galicia* [2001] analyzed the data of neutron monitors at Climax, Mexico, and Huancayo-Haleakala for 1990–1991, 1992–1994, 1995–1996, and 1997–1999 and found periodicities of 115 ± 6, 78 ± 3, 57 ± 4, 38 ± 2, and 27 ± 3 days, in general, common with solar indices. Some of these were transient, but the 38-day periodicity was reported to be present all the time. Our results cannot be compared with theirs directly because of different lengths of intervals, but our intervals (October 1997–July 1998) would be in their interval 1997–1999, wherein they report periodicities of only 57 ± 4, 38 ± 2, and 27 ± 3 days. In samples of 132 days, one cannot expect a 115-day periodicity to be detected easily. Our Figure 7a shows a 65-day periodicity at Calgary only, while Figure 7b shows 65–77 day periodicities in all cosmic rays. This could be the same as 78 days of *Valdés-Galicia* [2001], but probably not the same as their 57 days. We see the 38-day periodicity only in Figure 7a and only for cosmic rays at Beijing. *Valdés-Galicia* [2001] do not mention a 13-day periodicity. It might be a special feature of the interval we have chosen.

9. Conclusions and Discussion

[20] For the 11-year interval 1991–2001, the monthly values of (1) solar indices: sunspot number, Lyman alpha and 2800 MHz radio emission F10, (2) interplanetary plasma parameters: density N, wind speed V, and total magnetic field B, and (3) cosmic ray neutron monitor intensities at Calgary, Kiel, Moscow, Climax, Beijing, and Haleakala, were subjected to spectral analysis. Solar indices showed similar spectra between themselves and so did the cosmic rays between themselves, but the periodicities of solar indices (~12, 20, 40 months) were different from the periodicities of cosmic rays (~17, 24, 60 months), while interplanetary N, V had (~13, 17, 28 months) and B had ~17 and 40 months. Thus a simple scenario in which the solar periodicities would pervade into the interplanetary space and affect the cosmic rays as well as the IMF (observed near the vicinity of the earth) simultaneously, does not seem to be valid.

[21] For the 132-day intervals 11 October 1997–19 February 1998 (event II) and 20 February–1 July 1998, event III, a spectral analysis of the daily values of solar indices showed a strong 27-day signal, but it was seen only in interplanetary N. Cosmic rays did not show the 27-day signal. Instead, significant signals were seen in cosmic rays at ~13 and 20 days (seen in solar indices also but much smaller than the 27-day signal).

[22] Besides the solar rotation peak at 27 days, peaks at 13.5 days can also occur in solar indices. These can be a second harmonic of the 27-day peak, but *Donnelly and Puga* [1990] have shown that a 13–14 day periodicity comes mainly from episodes of solar activity with two peaks per rotation from two groups of active regions roughly 180° apart in solar longitude. However, in such a case, the spectral analysis would show a 13–14 day signal. In the present case the 13–14 day signal is weak or nonexistant in the solar indices, but is very prominent in the cosmic rays. Another possible parameter where a 13.5–day periodicity may manifest is the spiral magnetic field structure, where the solar global field is stretched out in the solar equatorial plane in sectors of ingoing and outgoing fields. If there are two sectors of outgoing magnetic fields sandwitched between two sectors of ingoing magnetic fields, and these affect the cosmic rays, a 13.5–day periodicity would be seen. Sector structure data "Vostok Inferred Interplanetary Magnetic Field" are given in NOAA website, with negative values representing T (field directed toward the Sun) and positive values representing A (field directed away from the Sun), but these are presently available only up to 1994. We compared the sector structure data with cosmic ray data (daily values) for the first three months of 1993, but the sector stucture was not clearly evident in this interval and no conclusions could be drawn. The effects on cosmic rays related to the magnetic sector structures need further exploration.

[23] Before reaching the earth, galactic cosmic rays suffer two modulations. In the *Burlaga et al.* [1985] scenario, the cosmic rays encounter a heliocentric barrier formed by the accumulated effect of fast CMEs (coronal mass ejections). Many CMEs (but not all) are associated with solar flares and as these are more frequent at sunspot maximum, the barrier is strongest at sunspot maximum and the cosmic ray depletion is then largest. This is the cause of the 11-year trend. Further, on short timescales, the cosmic rays would encounter a blob or a magnetic bottle [*Gold*, 1962] in the interplanetary space and access to the inside of the blob would be difficult, reducing the cosmic ray intensity inside the blob. If the earth happens to be inside such a blob, the cosmic ray neutron monitor intensities would show reductions called Forbush decreases. Figure 6 (days 175–205) illutrates this feature. The geomagnetic storm (Ap high and Dst low) intensified only from day 203 onwards up to day 213, but cosmic rays started decreasing from day 175 onwards (28 days before the Dst onset), indicating that this blob had spread over a large portion of the interplanetary space radially outward from the Sun and had already started

modulating the incoming cosmic rays much before the plasma of the blob could enter the earth's magnetosphere through the magnetotail (with Bz negative). (Incidentally, the 13.5-day fluctuations are seen even when the Forbush decrease is on). Thus the long-term and very short-term effects are understood. For intermediate periodicities it seems that the periodicities of solar indices neither result in blobs which could obstruct the cosmic rays nor affect the heliosphere as a whole in a one-to-one way, and the effects fizzle out by contributing only to the barrier in a rough way. Thus intermediate-term solar periodicities not affecting the cosmic ray levels in a systematic way is conceivable. What is puzzling is that some other periodicities are seen in cosmic rays as well as interplanetary plasma parameters, unrelated to the Sun. In case of N, V, B, this is known. A solar flare lasting for only a few minutes may be associated with a CME, but the later evoluition (blobs and magnetic bottles) and propagation of the CME futher in interplanetary space may have nothing to do with any solar phenomenon. The Bz component inside the blob is not regular and hence the effects in Earth's magnetosphere are also sporadic. Since shocks are produced not only by solar flares but also by stream-stream interactions (high-speed solar wind impigning on low-speed solar wind, both in a spiral, *Gonzalez et al.* [1994]) and the latter may survive for more than 27 days, interplanetary N, V (and geomagnetic Ap) can show a 27-day recurrence tendency. However, for cosmic rays, one does not see any mechanism which could produce strong periodicities like the 13.5-day periodicity, unrelated to anything on the Sun, except perhaps through the sector structure. This needs further exploration.

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References

Ahluwalia, H. S., On galactic cosmic ray flux decrease near solar minima and imf intensity, *Geophys. Res. Lett.*, *27*, 1603–1606, 2000.

Ahluwalia, H. S., and M. D. Wilson, Present status of the recovery phase of cosmic ray 11-year modulation, *J. Geophys. Res.*, *101*, 4879–4883, 1996.

Attolini, M. R., S. Cecchini, and M. Galli, A search of cosmic ray variations generated by pulsations in the heliosphere, *Astrophys. Space Sci.*, *134*, 103–114, 1987.

Bevington, P. R., *Data Reduction and Error Analysis for the Physical Sciences*, pp. 164–176, McGraw-Hill, New York, 1969.

Blackman, R. B., and J. W. Tukey, *The Measurement of Power Spectra*, p. 190, Dover, Mineola, N. Y., 1958.

Burg, J. P., Maximum entropy spectral analysis, paper presented at the 37th Meeting, Soc. of Explor. Geophys., Oklahoma City, October, 1967.

Burlaga, L. F., F. B. McDonald, M. N. Goldstein, and A. J. Lazarus, Cosmic ray modulation and turbulent interaction regions near 11 AU, *J. Geophys. Res.*, *90*, 12,027–12,039, 1985.

Burlaga, L. F., F. B. McDonald, and N. F. Ness, Cosmic ray modulation and the distant heliospheric magnetic field: Voyager 1 and 2 observations from 1986 to 1989, near 11 AU, *J. Geophys. Res.*, *98*, 1–11, 1993.

Caballero, R., and J. F. Valdés-Galicia, Galactic cosmic ray fluctuations during solar cycle 22 and 23 at high altitude neutron monitors, *Adv. Space Res.*, *27*, 583–588, 2001.

Cole, T. W., Periodicities in solar activity, *Solar Phys.*, *30*, 103–110, 1973.

Donnelly, R. F., and L. C. Puga, Thirteen-day periodicity and the center-to-limb dependence of UV, EUV, and X-ray emission of solar activity, *Solar Phys.*, *130*, 369–390, 1990.

Dorman, L. I., and V. S. Ptuskin, The expected pulsations of the heliosphere relevant to cosmic ray variations, *Astrophys. Space Sci.*, *79*, 397–404, 1981.

Forbush, S. E., Worldwide cosmic ray variations, 1937–1952, *J. Geophys. Res.*, *59*, 525–542, 1954.

Gnevyshev, M. N., On the 11 year cycle of solar activity, *Solar Phys.*, *1*, 107–120, 1967.

Gold, T., Magnetic storms, *Space Sci. Rev.*, *1*, 100–114, 1962.

Gonzalez, W. D., et al., What is a geomagnetic storm?, *J. Geophys. Res.*, *99*, 5771–5792, 1994.

Jokipii, J. R., and B. Thomas, Effects of drifts on the transport of cosmic rays, IV, Modulation by a wavy interplanetary current sheet, *Astrophys. J.*, *243*, 1115–1122, 1981.

Kane, R. P., Power spectrum analysis of solar and geophysical parameters, *J. Geomagn. Geoelect.*, *29*, 471–495, 1977.

Kane, R. P., Maximum Entropy Spectral Analysis of some artificial samples, *J. Geophys. Res.*, *84*, 965–966, 1979.

Kane, R. P., Periodicities in the time series of solar coronal radio emissions and chromospheric UV emission lines, *Solar Physics*, *205*, 351–359, 2002a.

Kane, R. P., Short-term and long-term variability of solar emissions in recent years, *J. Geophys. Res.*, *107*(A10), 1289, doi:10.1029/2001JA000290, 2002b.

Kane, R. P., and N. B. Trivedi, Comparison of maximum entropy spectral analysis (MESA) and least-square linear prediction (LSLP) methods for some artificial samples, *Geophysics*, *47*, 1731–1736, 1982.

Kane, R. P., and N. B. Trivedi, Effects of linear trend and mean value on maximum entropy spectral analysis, *Earth Planet. Sci.*, *95*, 201–208, 1986.

Kane, R. P., H. O. Vats, and H. S. Sawant, Short-term periodicities in the time series of solar radio emissions at different solar altitudes, *Solar Phys.*, *201*, 181–190, 2001.

Kato, C., F. Mcdonald, and S. Yasue, Long-term periodic variations (1.8 year) of cosmic rays in the outer heliosphere, Proc. 27th Intl. Conf. on Cosmic Rays, Hamburg, Germany, pp. 3589–3592, 7–15 August 2001.

Kudela, K., A. G. Ananth, and D. Venkatesan, The low-frequency spectral behavior of cosmic ray intensity, *J. Geophys. Res.*, *96*, 15,871–15,875, 1991.

Kudela, K., J. Rybak, A. Antalova, and M. Storini, Time evolution of low-frequency periodicities in cosmic ray intensity, *Solar Phys.*, *205*, 165–175, 2002.

Okhlopkov, V. P., L. S. Okhlopkova, and T. N. Charakchyan, Annual cosmic ray variations in the lower atmosphere, *Geomagn. Aeron.*, *26*, 19–22, 1986.

Richardson, J. D., K. L. Paularena, J. W. Belcher, and A. Z. Lazarus, Solar wind oscillations with a 1.3 year period, *Geophys. Res. Lett.*, *21*, 1559–1560, 1994.

Rybak, J., A. Antalova, and M. Storini, The wavelet analysis of the solar and cosmic ray data, *Space Sci. Rev.*, *97*, 362–369, 2001.

Shapiro, R., and F. Ward, A neglected cycle in sunspot numbers?, *J. Atmos. Sci.*, *19*, 506–508, 1962.

Stozhkov, Y. I., P. E. Pokrevsky, and V. P. Okhlopkov, Long-term negative trend in cosmic ray flux, *J. Geophys. Res.*, *105*, 9–17, 2000.

Ulrych, T. J., and T. N. Bishop, Maximum Entropy Spectral Analysis and autoregressive decomposition, *Rev. Geophys.*, *13*, 183–200, 1975.

Valdés-Galicia, J. F., R. Pérez-Enríquez, and J. A. Otaola, The cosmic-ray 1.68-year variation: A clue to understand the nature of the solar cycle?, *Solar Phys.*, *167*, 409–417, 1996.

Whang, Y. C., and L. F. Burlaga, Termination shock: Solar cycle variations of location and speed, *J. Geophys. Res.*, *98*, 15,221–15,230, 1993.

Whang, Y. C., and L. F. Burlaga, Anticipated Voyager crossing of the termination shock, *Geophys. Res. Lett.*, *27*, 1607–1610, 2000.

Xanthakis, J., H. Mavromichalaki, and B. Petropoulos, Time evolution of cosmic-ray intensity modulation, *Solar Phys.*, *122*, 345–363, 1989.

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