Solar Physics (2006) 236: 207–226
DOI: 10.1007/s11207-006-0142-1

A DETAILED COMPARISON OF COSMIC RAY GAPS WITH SOLAR GNEVYSHEV GAPS

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(Received 27 January 2006; accepted 10 April 2006)

Abstract. After increasing almost monotonically from sunspot minimum, sunspot activity near maximum falters and remains in a narrow grove for several tens of months. During the 2–3 years of turmoil near sunspot maximum, sunspots depict several peaks (Gnevyshev peaks). The spaces between successive peaks are termed as Gnevyshev Gaps (GG). An examination showed that the *depths* of the troughs varied considerably from one GG to the next in the same cycle, with magnitudes varying in a wide range ($<1\%$ to $\sim20\%$). In any cycle, the sunspot patterns were dissimilar to those of other solar parameters, qualitatively as well as quantitatively, indicating a general turbulence, affecting different solar parameters differently. The solar polar magnetic field reversal does not occur at the beginning of the general turmoil; it occurs much later. For cosmic ray (CR) modulation which occurs deep in the heliosphere, one would have thought that the solar open magnetic field flux would play a crucial role, but observations show that the sunspot GGs are not reflected well in the solar open magnetic flux, where sometimes only one peak occurred (hence no GG at all), not matching with any sunspot peak and with different peaks in the northern and southern hemispheres (north – south asymmetry). Gaps are seen in interplanetary parameters but these do not match exactly with sunspot GGs. For CR data available only for five cycles (19 – 23), there are CR gaps in some cycles, but the CR gaps do not match perfectly with gaps in the solar open magnetic field flux or in interplanetary parameters or with sunspot GGs. Durations are different and/or there are variable delays, and magnitudes of the sunspot GGs and CR gaps are not proportional. Solar polar magnetic field reversal intervals do not coincide with either sunspot GGs or CR gaps, and some CR gaps start *before* magnetic field reversals, which should not happen if the magnetic field reversals are the cause of the CR gaps.

1. Introduction

Sunspots have a major 11-year cycle. However, the maximum is not smooth but structured. Two or more peaks can be identified during the solar maximum. This splitting of activity, identified for the first time in the green corona line intensity data by Gnevyshev (1963, 1967), was earlier a subject of study mainly in the former Soviet Union (*e.g.* Gnevyshev, 1977 and references therein). Since then, a double-peak structure has been reported for several solar and interplanetary phenomena (details in the review by Storini *et al.*, 2003). It has been reported for cosmic ray modulation also, though this can happen only through the effects of solar phenomena on the heliosphere, where the main cosmic ray modulation occurs. For solar phenomena, Gnevyshev and co-investigators suggested that a dual-peaked activity is seen in each 11-year cycle, with a first peak (occurring at all the solar latitudes) at the end of the increasing phase and a second one (but at lower solar latitudes only) at the start of the declining phase. Hence, two waves of activity (partly superimposed in time) were proposed as the origin of the phenomenon. However, as described by Feminella and Storini (1997), the solar background activity tends to be single peaked and the double peak appearance is related only to the growing event importance in each layer of the solar atmosphere. These results indicate that dynamical activity phenomena should be superimposed on a quasi-stationary 11-year trend. Using Obridko and Shelting's (1992) findings, clues for a link between outstanding activity phenomena and the strength of the heliomagnetic field energy were found. On this ground, during the inversion of the polar heliomagnetic field, a decrease (or a gap) in the number of high energy events occurs (Gnevyshev Gap, GG). Alania *et al.* (1999) state that in the course of Sun's polar magnetic field reversal, a part of the Sun's energy is used up for this reversal process. This implies that during such periods the interaction between "local magnetic fields" (particularly those connected with the processes involved in the development of large and complex active regions, Bumba and Howard, 1965) and the "background magnetic field" is suppressed, and large-scale dynamical phenomena cannot reach the solar corona and hence they are not able to affect the interplanetary medium. The long-term behavior of the average current helicity of active regions demonstrates the GGs (Bao and Zhang, 1998; Storini *et al.*, 1999a,b), in agreement with Bieber and Rust's (1995) computations on the long-term magnetic flux released from the Sun (Feminella and Storini, 1997) and the observation of Cane *et al.* (1999) that during GG intervals the solar open magnetic flux attains the minimum value in each cycle (see some more details and contradictions in Kane, 2005a). Feminella and Storini (1997) demonstrated that during GG periods, intense solar activity is missing or it is really lower. It was also claimed that the solar atmospheric GG interval is more easily identified when parameters of energetic activity phenomena are considered. Moreover, the bimodal behavior of solar activity was stated to occur separately in each solar hemisphere (Feminella and Storini, 1997), which implies that using solar parameters for the Sun as a star, the GG valley can be masked by the different GG time occurrence in each hemisphere. On the other hand, during the past solar cycle 22, the GG occurrence was reported to be practically synchronous in both hemispheres and the dual-peak solar activity cycle was illustrated by several researchers (Feminella and Storini, 1997; Storini, Massetti, and Antalova, 1997; Storini *et al.*, 1997, 1999a; Ataç and Özguç, 1998; Bao and Zhang, 1998; Krainev *et al.*, 1998; Bazilevskaya *et al.*, 2000 among others).

When the galactic cosmic ray (CR) flux was investigated, a clear evidence of a double-peaked trend in the CR modulation was found for two solar activity cycles (Storini, 1995; Storini and Pase, 1995; Storini, Massetti, and Antalova, 1997; Storini *et al.*, 1997). Another aspect underlined at that time was that huge Forbush decrease phenomena avoid the central part of the maximum solar activity phase. As mentioned in Storini *et al.* (2003), in the international cosmic ray context, there were other authors claiming for a period of relative quietness close to the sunspot maximum. Nagashima, Sakakibara, and Morishita (1991) showed that the occurrence of the most powerful solar cosmic-ray events (the so-called GLEs, ground-level enhancements) obey the rule of "event gap" during the high-latitude solar magnetic field reversals (which happens during the maximum activity phase), while Bazilevskaya *et al.* (1995) found in such periods a reduction of the power spectrum density of cosmic ray variations with a characteristic time of 26 – 29 days (see also Sabbah *et al.*, 1995; Vernova *et al.*, 1995). Storini *et al.* (2003) state that it is more easy to identify such features in the interplanetary medium than in the solar atmosphere, particularly when a time scale from about one to twelve months is used in the search. According to them, the GG reliability is very evident in: (i) the solar wind time series; (ii) the number of transient interplanetary perturbations (related to CMEs accompanied by solar flares); (iii) the number of transient interplanetary shocks; (iv) the number and fluence of energetic solar proton events; (v) the number of ground-level enhancements; (vi) the occurrence rate of extended bidirectional 1 MeV ion flows observed by IMP8; (viii) the CR variability; (ix) the occurrence of intense Forbush decreases (detailed references in Storini *et al.*, 2003, who have also discussed in detail the present views about the origin of the "Gnevyshev gap"). Recently, Ahluwalia and Kamide (2005) presented details about the association of the Gnevyshev gap with the frequency of Forbush decreases and the associated SSCs and claimed that the gap coincides with the epoch of solar polar magnetic field reversal. Storini and Laurenza (2003) presented results about the gaps in solar cycle 22 for counting rates of a muon telescope and three neutron monitors of different geomagnetic rigidity cutoffs, and found GG in all of these, using 13-month running averages.

In all the works so far for various parameters (including interplanetary and cosmic rays), a gap anywhere between the first and the last peaks of sunspots is considered a gap directly comparable with all other gaps. No attention is paid as to whether the beginnings of these gaps matched within 2 – 3 months. This is important, because for ascertaining a cause-effect relationship, the *cause must precede* (*or coincide with*) *the effect, not follow it*. In a recent paper, Kane (2005a) illustrated the Gnevyshev gaps (GGs) in several solar parameters, indicated some dissimiliarities when monthly data were used, and suggested that the term GG should be used only for solar parameters. In the present communication, gaps are illustrated on short time-scales (months) for solar and interplanetary parameters and for CR intensities to check whether the gaps (occurring during the 2 – 3 year interval near sunspot maximum) are qualitatively *similar and synchronous* (within 2 – 3 months) in all these parameters. Data were obtained from the NOAA websites (SPIDR etc.) for solar and interplanetary parameters and for CR neutron monitors, and for muons from the Nagoya University website, *http://www.stelab.nagoya-u.ac.jp/ste-www1/div3/muon/muon3.html.*

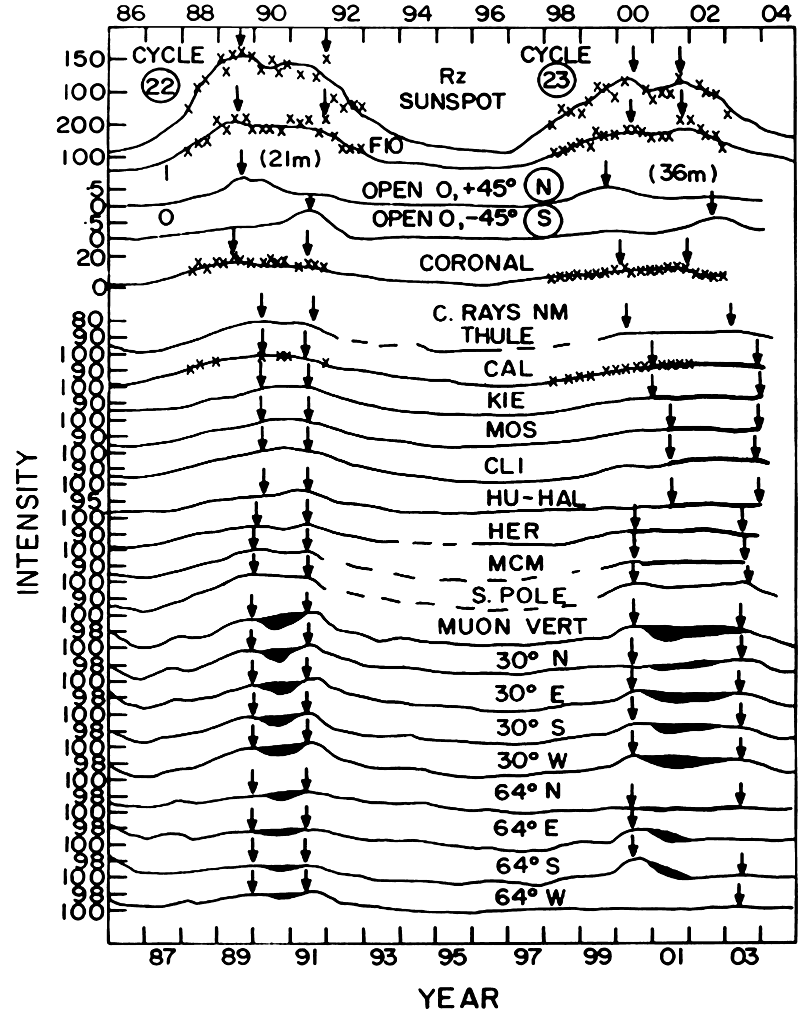

Figure 1. Plots of 3-monthly means (*crosses*) and 12-monthly running means (*full lines*) during sunspot cycles 22 and 23 (1986 – 2004) for sunspot numbers Rz, 2800 MHz solar radio emission F10, solar magnetic open flux at low solar latitudes, northern N, 0 to +45° and southern S, 0 to −45°, coronal green line index, cosmic ray neutron monitors at Thule, Calgary, Kiel, Moscow, Climax, Huancayo-Haleakala, Hermanus, McMurdo, South pole, and Nagoya muon telescopes for vertical, and inclined at 30° and 64° N, E, S, W.

2. Plots

Figure 1 shows the plots of 12-monthly running means (full lines) and the 3-monthly values (crosses) for sunspots Rz, the 2800 MHz solar radio flux F10, solar open magnetic flux for solar low latitude belts 0 to +45° and 0 to −45° (Wang and Sheeley, 2002), Coronal green line index, and CR neutron monitor intensities at the locations Thule (77°N, 69°W, cut-off rigidity <1 GV), Calgary (51°N, 114°W, cut-off rigidity 1.1 GV), Kiel (54°N, 10°E, cut-off rigidity 2.3 GV), Moscow (55°N, 37°E, cut-off rigidity 2.4 GV), Climax (39°N, 106°W, cut-off rigidity 3.0 GV), Huancayo (12°S, 75°W, cut-off rigidity 12.9 GV) Haleakala (20°N, 56°W, cut-off rigidity 12.9 GV), Hermanus (34°S, 19°E, cut-off rigidity 4.6 GV), McMurdo (78°S, 167°E, cut-off rigidity <1 GV) and South Pole (90°S, cut-off rigidity <1 GV), and for Nagoya muons (35°N, 137°E, cut-off rigidity for Vertical, 11.5 GV; 30°N, 12.9 GV; 30°E, 16.2 GV; 30°S, 11.3 GV; 30°W, 9.4 GV). Two basic features are evident, namely, the 11-year solar cycle changes and the structures (double peaks) near the sunspot maximum years. Only the latter will be discussed in detail in the present communication. The following may be noted:

(1) In cycle 22, both sunspots Rz and solar radio flux F10 show double peaks near sunspot maxima, crudely in 12-monthly means but more prominently in 3-monthly means, with peak separations of ~30 months in cycle 22 and ~21 months in cycle 23. Bazilevskaya *et al.* (2000) mentioned that the structured maximum appeared to be due to the superposition of two quasi-oscillating processes with characteristic time-scales of 11 years and of 1 – 3 years (quasi-biennial oscillations) and that the absolute amplitude of the quasi-biennial oscillations depended on the 11-year cycle phase and reached its maximum at the maximum of the 11-year cycle. This was confirmed in a general way in Kane (2005b,c), but Kane (2005b) emphasized that there were many periodicities shorter than the QBO also.

(2) The low-latitude open flux shows *only one peak* in each hemisphere in each of the cycles 22 and 23, and the peaks in S occur several months later than those in N. In cycle 22, the N and S peaks were 21 months apart, while in cycle 23, these were 36 months apart. Thus, the matching between the magnetic peaks with sunspots and F10 is not good. In cycle 22, the open flux peak N almost coincides with the first peak of Rz, but in cycle 23, the open flux peak N occurred several (~9) months *earlier* than the first Rz peak.

(3) The coronal green line index probably had double peaks in both cycles 22 and 23, with peak separations of about 24 months in both.

(4) In CR neutron monitor counting rates, the two peaks are not clearly discernable in the 12-month running means, and a broad plateau seems to have lasted for ~18 months in cycle 22 and ~36 months in cycle 23. For muon counting rates of the Nagoya telescope, there are peaks in cycle 22 and 23 similar to those for CR neutron monitors, but the troughs between the peaks are smaller for higher zenith angles. Overall, the magnitudes of trough depths for muons are very small ($<1\%$).

Since 12-monthly running means seemed to reduce the Gnevyshev gap GG considerably, plots on finer time scales were examined. Figure 2 shows the plots of monthly values (thin lines) with 3-monthly means superposed (thick lines), near sunspot maxima for cycle 22 (1988 – 1992) in the left half and for cycle 23

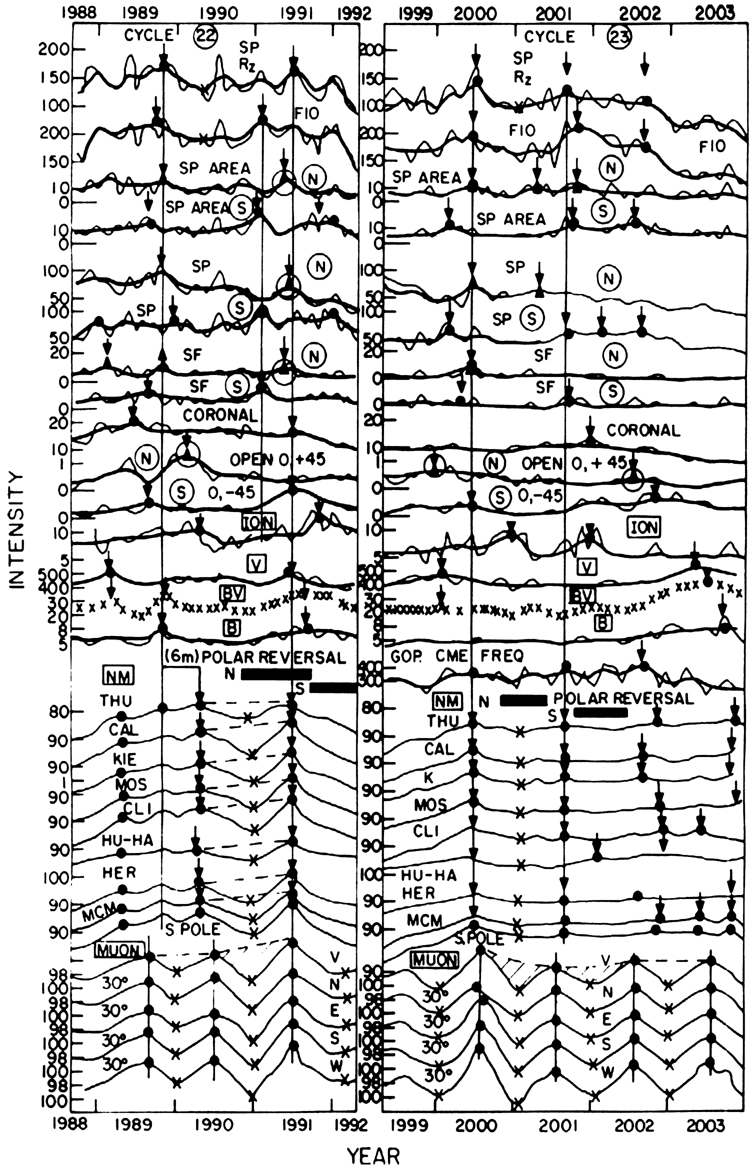

Figure 2. Plots of monthly means (*thin lines*) and 3-monthly means (*thick lines*) during the maxima of sunspot cycles 22 (*left half*, 1988 – 1992) and 23 (*right half*, 1999 – 2003) for sunspot numbers Rz, 2800 MHz solar radio emission F10, sunspot areas (SP AREA), sunspot numbers (SP), solar flare index (SF) in the northern N and southern S solar hemispheres, coronal green line index, solar magnetic open flux (OPEN) at low solar latitudes, northern N, 0 to +45° and southern S, 0 to −45°, interplanetary parameters ion density (ION), solar wind speed (V), total magnetic field (B) and the product BV, Coronal Mass Ejection (CME) occurrence frequency, cosmic ray neutron monitors at Thule, Calgary, Kiel, Moscow, Climax, Huancayo-Haleakala, Hermanus, McMurdo, South pole, and Nagoya muon telescopes for vertical, and inclined at 30°, N, E, S, W. Maxima are indicated by *full dots* and *arrows*, the prominent ones are connected by *vertical lines*.

(1999 – 2003) in the right half. Several more solar parameters are considered, for some of which data were available for the northern (N) and southern (S) solar hemispheres separately. The plots in the upper part of Figure 2 are now for: sunspot number Rz, radio flux F10, sunspot area for N and S, sunspot numbers for N and S separately, Solar Flare index (SF) for N and S separately, Coronal green line index, open solar magnetic low latitude fluxes for N and S separately, followed by interplanetary ion density ION, solar wind speed V, total magnetic field B and their product BV (crosses ×) and the occurrence frequency of CMEs (Coronal mass ejections, for cycle 23 only). Plots in the lower half are for CR neutron monitor and muon count rates in percentages.

2.1. RESULTS FOR YEARS NEAR MAXIMUM OF SOLAR CYCLE 22 (1988–1992)

For solar cycle maximum of cycle 22 (1988 – 1992) in the left half of Figure 2, the following is noteworthy:

(1) The maxima solar activity interval has a structure, with Rz having two major maxima (marked by arrows and two vertical lines) near November 1989 and July 1991 (separation 20 months), but there are several smaller peaks before, in between, and after. The F10 has the first major maximum almost coinciding with the first major maximum of Rz, but the second major maximum of F10 occurred ~5 months earlier (marked by another vertical line). In the next six plots (three for solar parameters in the northern, N, hemisphere, interspersed with three for the southern, S, hemisphere), both N and S have the first maxima almost coincident with the first maximum of Rz and F10, but the second maximum of N coincides with the second maximum of Rz, while the second maximum of S coincides with the second maximum of F10, which occurred ~5 months earlier than the second maximum of Rz. Thus, the Gnevyshev gap GG was shorter (15 months) for F10 and the S plots, compared to the GG of Rz and the N plots (20 months). The coronal green line index had one major maximum *~4 months before the first maximum of Rz*, and a second minor maximum coinciding with the second maximum of Rz. The open flux N had only one major maximum, which occurred ~4 months later than the first maximum of Rz, while open flux S also had only one major maximum but it coincided with the second maximum of Rz. Thus, open flux was not bimodal and had considerable phase difference between N and S (N – S asymmetry). Since cosmic rays are affected by heliospheric conditions (magnetic structures) which receive solar imprints probably mostly through the solar magnetic open flux, a GG structure for open flux different from that of sunspots would imply that CR modulation may have a gap more like the GG of open flux than like the GG of sunspots. (This did not happen, as shown later).

(2) The interplanetary parameters also show peaks and gaps. The ion density ION is known to have an uncertain long-term relationship with sunspot activity (correlation was −0.23 during 1970 – 2003, see Table I in Kane, 2005b). Hence, the appearance of a fine structure like the solar GG in interplanetary ion density may have doubtful meaning. There are two peaks in ion density, but these are delayed by ∼4 – 6 months with respect to the first and second peaks of Rz. The solar wind speed V also has two peaks. The first peak occurred ∼9 months *earlier* than the first peak of Rz, and the second peak occurred two months later than the second peak of Rz. Thus, there was a mismatch. The interplanetary B has two peaks, the first one coinciding with the first peak of Rz, and the second peak slightly delayed (∼2 months) with respect to the second peak of Rz. In contrast to interplanetary ion density and V, the variation of B seems to have a better correlation with sunspot cycle (correlation was +0.68 during 1970 – 2003, see Table I in Kane, 2005b). Hence, the double-peaked structure of B may have some meaning (discussed further later).

(3) The GG phenomenon in solar indices is often reported to be related to the solar polar magnetic field reversals. These intervals are available in Makarov and Makarova (1996), Harvey and Recely (2002) and Vernova *et al.* (2002) and the years (in decimal) for north and south pole reversals are: cycle 22, 1990.8, 1991.8; cycle 23, 2000.9, 2001.8. These are shown as rectangles below the plots for B. As can be seen, the reversals occurred much later than the first peak of Rz in November 1989 (∼September 1990 for North pole and ∼September 1991 for South pole). Thus, polar reversal is only one of the features of the turmoil during sunspot maximum, and not an *initiator* of any dynamic process.

(4) The lower part of Figure 2 shows plots of CR counting rates (%). The CR neutron monitors are at latitudes right from high North (Thule) to high South (South pole), but the variations are almost alike. The plots are upside down so that maxima are actually minima (large depressions of CR counts). After a minor peak in November 1989 (coinciding with the first major peak of sunspots), the first CR peak occurred in May 1990, *6 months later* than the first peak of Rz in November 1989 (for Huancayo-Haleakala, it was 5 months later). This delay is most probably due to the transit time of solar emissions from the solar surface through the heliosphere, for which the boundary is roughly placed at about 100 AU. However, whereas the CR gap starts ∼6 months later than the first maximum of Rz (which we interpret as delay of solar emissions reaching the heliosphere), the CR gap ends exactly at the second maximum of Rz, so no delay is involved. This means that the CR gap is narrower than the Rz GG by about 6 months.

(5) Incidentally, the interplanetary V and B could have physical significance for heliospheric modulation of cosmic rays. Ahluwalia (2003, 2005) and Ahluwalia and Kamide (2005) emphasize that it is not just V or just B, but

their product BV representing the 'electric field carried by the solar wind', which should play a significant role in causing cosmic ray modulation, and may be important for the cosmic ray gap also. To check this, values of the product BV were calculated and are plotted in between the V and B plots in Figure 2 (left half), as crosses (×). There are three peaks, with gaps of 8 and 22 months. The latter gap almost coincides with the Rz gap of 20 months, but both these are larger than the CR gap of 14 months. Thus, association of BV gaps with CR gaps is dubious.

(6) Table I (left half) gives the months of the first and second maxima, the time interval between them (in months) and depths of the gap, defined as the difference between the minimum and the average of the first and second maxima for the various parameters for cycle 22. For example, for Rz, the first and second maxima (3-monthly values) were 171.9 in November 1989 and 173.2 in July 1991, the average of the two was 172.6, the minimum between these two maxima was 126.0 in May 1990, and hence, the depth was $100(172.6 - 126.0)/(172.6) = 27\%$. As can be seen, the second peak was higher than the first peak (positive values) for almost all parameters but in different percentages (for CR neutron monitors, in a range of $\sim 3-5\%$), except for sunspot numbers in the northern hemisphere (SP N), and for the coronal green line index, where the first peak was higher. The depths also varied in a wide range, but for CR neutron monitors, the range was $9-15\%$ except for CR of higher energies at Huancayo-Haleakala ($\sim 6\%$). For muons, all these quantities are smaller as compared to the neutron monitors, and the peaks for neutron monitors and muons are not alike. There are phase differences of $2-3$ months, some positive (leads), some negative (lags). However, since we have used 3-monthly values of muon intensities, *large seasonal temperature effects (uncorrected) are expected to be present.* The peak separation of 12 months clearly indicates that these peaks have a seasonal origin and may have no relationship with the external GG phenomena. Thus, the depths in the muon plots are not solar GG effects but, uncorrected atmospheric seasonal temperature effects on muon intensities. If we use 12-monthly means, the seasonal effects are minimized but the troughs become shallower and the gap depths become smaller as shown in the bottom part of Figure 1.

2.2. RESULTS FOR YEARS NEAR MAXIMUM OF SOLAR CYCLE 23 (1999–2003)

For solar cycle maximum of cycle 23 ($1999-2003$), results are shown as plots in the right half of Figure 2 and values in the right half of Table I. The following is noteworthy:

(1) In Figure 2 right half, the maxima interval has a structure, with Rz having three major maxima (marked by arrows and the first two marked by vertical lines) near July 2000 and September 2001 (separation 14 months)

TABLE I

Months of the first and second maxima and the relative strength of the second maxima (in 1991 in cycle 22 and in 2001 in cycle 23) with respect to the first maximum (in 1989 in cycle 22 and in 2000 in cycle 23) (II minus I in percent), and the depths of the in-between gaps, for various parameters.

	1989 – 1991	1989 – 1991	Int.	1989 – 1991	1989 – 1991	2000 – 2001	2000 – 2001	Int.	2000 – 2001	2000 – 2001
Parameter	1st max	2nd max	Mon.	II minus I (%)	Depth (%)	1st max	2nd max	Mon.	II minus I (%)	Depth (%)
					Solar					
Rz	November 1989	July 1991	20	0.8	27	July 2000	October 2001	15	−10.0	31
F10	October 1989	February 1991	16	3.2	20	June 2000	December 2001	18	12.1	25
SP Area N	November 1989	June 1991	19	21.8	59	June 2000	November 2001	17	−1.5	52
SP Area S	September 1989	February 1991	17	41.1	62	April 2000	October 2001	18	13.4	67
SP N	October 1989	July 1991	21	−17.1	53	July 2000	May 2001	10	−17.1	33
SP S	February 1990	February 1991	12	25.8	36	March 2000	January 2002	22	−11.1	44
SF N	October 1989	June 1991	20	1.9	69	June 2000	November 2001	17	−54.9	88
SF S	September 1989	February 1991	17	25.2	65	April 2000	October 2001	18	53.2	74
Coronal	July 1989	July 1991	24	−14.8	17		January 2002			
Open Mag N	March 1990					January 2000	July 2002	30	−43.7	64
Open Mag S	October 1989	October 1991	24	96.6	69	June 2000	November 2002	29	69.4	70
					Interplanetary					
Inter. Ion	April 1990	October 1991	18	19.3	37	December 2000	January 2002	11	−1.0	46
Inter. V	March 1989	July 1991	28	2.6	27	January 2000	June 2003	41	16.9	28
Inter. B				7.2	37		July 2003			
CME				No data		July 2000	September 2001	14	4.9	35

TABLE I

(Continued)

	1989 – 1991	1989 – 1991	Int.	1989 – 1991	1989 – 1991	2000 – 2001	2000 – 2001	Int.	2000 – 2001	2000 – 2001
Parameter	1st max	2nd max	Mon.	II minus I (%)	Depth (%)	1st max	2nd max	Mon.	II minus I (%)	Depth (%)
					CR Neutrons					
Thule	May 1990	July 1991	14	2.8	9	July 2000	September 2001	14	−1.3	4
Calgary	May 1990	July 1991	14	5.0	14	July 2000	September 2001	14	2.9	6
Kiel	May 1990	July 1991	14	4.3	12	July 2000	September 2001	14	1.1	5
Moscow	May 1990	July 1991	14	5.1	12	July 2000	September 2001	14	−0.2	6
Climax	May 1990	July 1991	14	4.8	15	July 2000	September 2001	14	0.7	7
Huan.Halea.	April 1990	July 1991	15	2.9	6	July 2000	January 2002	14	−0.2	3
Hermanus	May 1990	July 1991	14	4.3	10	July 2000	September 2001	14	1.9	4
McMurdo	May 1990	July 1991	14	4.0	12	July 2000	September 2001	14	0.1	5
South Pole	May 1990	July 1991	14	5.2	15	July 2000	September 2001	14	1.3	6
					CR Muons					
Muon Vertical	July 1990	July 1991	12	3.3	6.2	August 2000	August 2001	12	−1.8	5.9
Muon 30 N	July 1990	July 1991	12	3.0	6.0	August 2000	August 2001	12	0.2	5.0
Muon 30 E	July 1990	July 1991	12	2.8	5.7	August 2000	August 2001	12	−2.4	5.7
Muon 30 S	July 1990	July 1991	12	3.1	6.1	August 2000	August 2001	12	−2.3	6.4
Muon 30 W	July 1990	July 1991	12	3.2	6.3	August 2000	August 2001	12	−2.3	7.1

and September 2002 (further separation 12 months). F10 has almost similar maxima. Further plots for other parameters show maxima not necessarily near about these, in some cases only the first one and in some cases, only the second one. The open flux N had only one major maximum, which occurred ~6 months earlier than the first maximum of Rz, while open flux S also had only one major maximum much later than the second maximum of Rz, and coinciding with the third maximum of Rz. Thus, open flux was not bimodal and had considerable phase difference between N and S.

(2) The interplanetary parameters ION and V also show two peaks, but very different from those of Rz and F10.

(3) The interplanetary B has only one peak in September 2003, much later than even the third peak of Rz (September 2002).

(4) Data for CME occurrence frequency were available for cycle 23 (Gopalswamy *et al.*, 2003a,b; Kane, 2006) and show peaks similar to Rz.

(5) The plots of CR neutron monitor counting rates (%) show a first peak coinciding with the first peak of Rz. *Thus, there was no lag between the two, in contrast to the 6 months lag in cycle 22*, indicating that the explanation of the lag as due to delay of solar characteristics reaching deep into the heliosphere may not always be true. However, later, there are virtually no further peaks. All neutron monitors show a very shallow gap and remained almost steady at the high modulation level for a very long time, almost up to the end of 2003 when a second maximum (maximum CR depression or modulation) occurred at about November 2003, though by that time, Rz had decreased considerably. Table I (right half) gives the depths of the gaps for the various parameters. For solar and interplanetary parameters, the depths were in similar wide ranges in cycles 22 (20 – 69%) and 23 (25 – 88%). But for CR neutron monitors, the range was only 4 – 7% in cycle 23, in contrast to 9 – 15% in cycle 22 (excluding Huancayo-Halekala for which the depths were 6% in cycle 22 and 3% in cycle 23, both lower than the depths at other locations, due to higher energy response). Thus, the gap in neutron monitor count rates was shallower in cycle 23 as compared to cycle 22. The plot for the product BV, shown by crosses (×) in between the plots of V and B, shows a monotonic increase ending finally as one strong peak in July 2003, and the BV plot has no resemblace whatsoever with the CR neutron monitor plots.

(6) The muon plots show strong peaks and gaps throughout the interval 1999 – 2003. There are four peaks and three gaps, but for comparison with neutron monitors, only the second gap (shown hatched on the vertical muon plot) is considered. However, the muon peaks are not of solar origin. Peak separations of exactly 12 months indicate that these are uncorrected temperature effects, mostly unrelated to the GG phenomenon. The 12-monthly running means shown at the bottom of Figure 1 indicate very shallow trough depths (<1%).

Delays and hysteresis effects in CR modulation have been known earlier and have been explained as due to drift mechanisms which give opposite effects with the changing sign of the solar magnetic field (Jokipii and Thomas, 1981; Kóta and Jokipii, 1983), but there are other superposed effects due to a convection-diffusion mechanism, which do not depend on the sign of the solar magnetic field (details in Dorman, 2001; Dorman, Iucii, and Villoresi, 2001; Dorman, Iucii, and Villoresi, 2001). If so, is the reduction in gap depth in cycle 23 (as compared to cycle 22) due to the enhanced hyteresis effect (CR depression continuing even when sunspot number have started reducing) in odd cycles, or is the gap depth variation due to other causes? This could be checked by examining the gap depths in earlier odd cycles 19 and 21, and comparing with the depths in even cycles 20 and 22. For all these five cycles 19 – 23, CR data are available for the neutron monitors at Kiel, Moscow, Climax and Huancayo. Figure 3 shows the plots of 3-monthly values of the solar parameters Rz, F10 and solar magnetic open flux, and of CR intensity at Climax only (for other neutron monitors, variations were similar and are not shown here), for the few years around the sunspot maxima in cycles 19 – 23 on the left side and the corresponding hysteresis loops (Rz versus CR% at Climax) on the right side. The following may be noted:

(1) In Kane (2005a), the sunspots near maxima were examined for all cycles 1 – 23 and it was noted that all had more than one maxima. Cycles 1, 9 – 11, 19, 23 had only two major maxima, while all others had more than two prominent maxima. Here in Figure 3 left half, the top plot for cycle 19 shows two prominent maxima in Rz and F10, and the gap depth for Rz is 17%. The Climax CR also has two maxima with a small gap depth of ∼6%, but the first CR maximum is 5 months later as compared to the first maximum of Rz, and the second CR maximum is 12 months later as compared to the second maximum of Rz. Thus, apart from the shifts, the separation between the first and second maxima is 9 months for Rz but 16 months for CR. A complete association between Rz and CR is therefore doubtful, though it could be given the benefit of a distorted association. The rectangle at the bottom indicates the interval during which the solar polar magnetic field reversed, first at the solar northern pole and a few months later at the solar southern pole (dates from Makarov and Makarova, 1996; Harvey and Recely, 2002; Vernova *et al.*, 2002). As can be seen, for cycle 19, the reversal started soon after the first maximum of Rz, and the CR peak occurred soon after the starting of the magnetic field reversal.

(2) In the next plot for cycle 20, Rz and F10 have three prominent peaks (peak values marked, 120, 121, 116 for Rz; 170, 160, 165 for F10), but the values in between (troughs) are lower only by a few units, so that the Gnevyshev gaps GGs are of negligible depths (∼1%). Thus, there are virtually no prominent GGs in Rz and F10 in this cycle 20. Data for solar open magnetic flux are available for this cycle for 1967 onwards and show peaks similar to Rz for

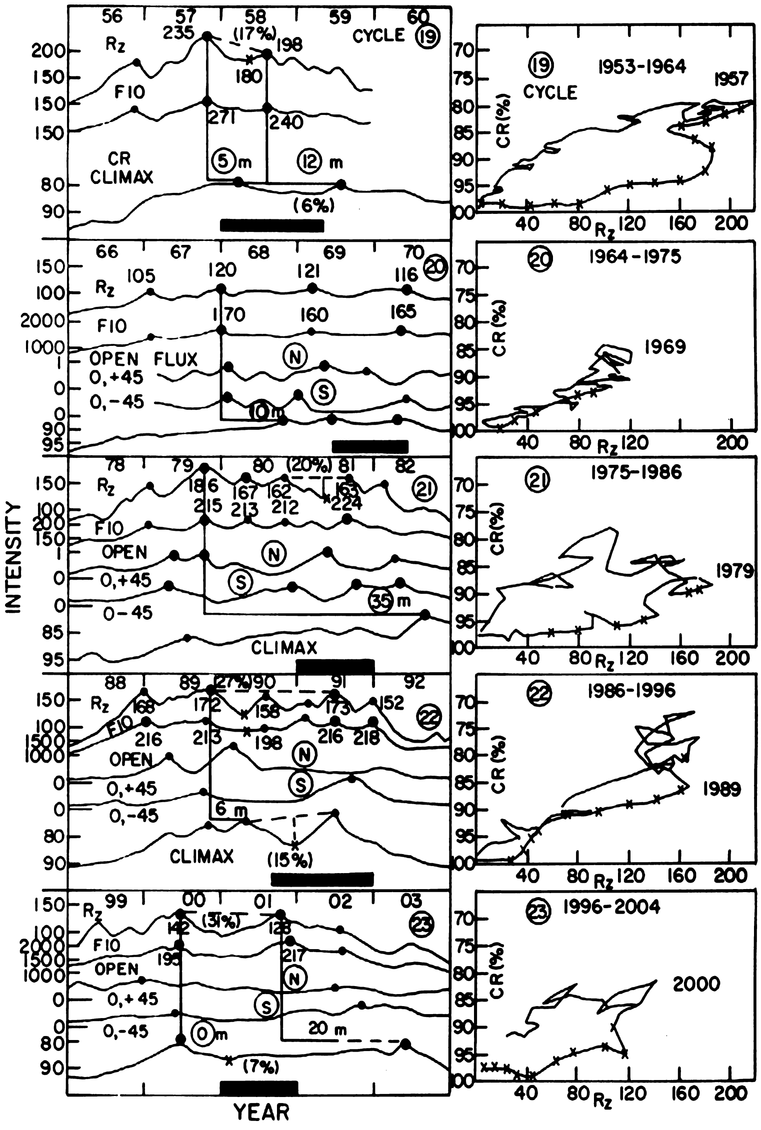

Figure 3. Left half, plots of 3-monthly means for Rz, F10, solar magnetic field open fluxes N and S, and cosmic ray (CR) neutron monitor at Climax, for cycles 19 – 23 in successive panels. The *full rectangles* in each, below the CR plots, indicate the solar polar magnetic field reversals. *Right half*, hysteresis plots of CR (%) at Climax versus sunspot number Rz, for cycles 19 – 23 in successive panels.

the northern flux N (0 to +45°) but dissimilar to Rz for the southern flux S (0 to −45°). The CR at climax shows three peaks, but the first CR peak is later by 10 months with respect to the first major peak of Rz, while the other two CR peaks coincide with the second and third peaks of Rz. Thus, the association of Rz with CR is partial. Incidentally, the depths of the gaps in between the CR peaks are also very small ($\sim$1%). Hence, in cycle 20, one can conclude that the peaking is almost as a plateau, with negligible GGs. The solar polar *magnetic field reversal occurred later* than the first peak of CR and coincided with the interval between the latter two CR peaks.

(3) In the next plot for cycle 21, there are four prominent peaks in Rz and F10 of almost the same magnitudes (peak values marked, 186, 167, 162, 163 for Rz; 215, 213, 212, 224 for F10), so there are more than one (actually three) GGs, with the largest GG depth of $\sim$20% between the third and fourth peaks of Rz. The open fluxes have 3 – 4 peaks but only the first one of each N and S tallies with the first peak of Rz. Other peaks do not tally. In the Climax CR plots, there is no gap at all. The modulation continued monotonically far beyond all the Rz peaks and CR had only one maximum much later, in September 1982 (with no prominent maximum thereafter either, plot not shown here) when Rz activity was on the decline. The CR peak was 35 months later than the first Rz peak, and since there was no second maximum, there was no CR gap. Thus, in this cycle 21, though Rz and F10 had multiple peaks and substantial GG depths, CR had no dips. The solar polar magnetic field reversal occurred during the third and fourth peaks of Rz, but much earlier (20 months) than the CR peak.

(4) The next plot for cycle 22 has been depicted earlier in the left half of Figure 2, and here too, though two prominent peaks are marked prominently in Rz and F10, there are many in between peaks of comparable magnitudes (peak values marked, 168, 172, 158, 173, 152 for Rz; 216, 213, 198, 216, 218 for F10), and there are many GGs. The largest gap depth in Rz is $\sim$27%. The open fluxes N and S have each a major peak and a minor peak, not tallying with the Rz peaks. In CR, there is only one prominent peak in July 1991, tallying with a prominent peak in Rz, but there are two earlier minor peaks in CR, the first CR peak tallying with the first major peak of Rz, and the second CR peaks occurring 6 months later. There is a big gap between the second (minor) and the third (major) peak of CR and the gap depth is $\sim$15%, the largest CR gap in any cycle. Whether this gap corresponds to any of the several Rz GGs is a moot question. The CR gap started about 6 months later than a Rz GG. Matching is not perfect, though some association cannot be ruled out. The solar polar magnetic field reversal occurred during the third and fourth peaks of Rz, and almost coincided with the CR gap.

(5) The next plot for cycle 23 has also been depicted earlier in the right half of Figure 2. Here, things are much simpler than in any of the previous cycles. Rz and F10 have only two major peaks (142, 128 for Rz; 195, 217 for F10) and the 16-month GG depth is 31% for Rz, again largest in any cycle (cycle 19, 17%; cycle 20, nil; cycle 21, 20%; cycle 22, 27%). The open fluxes N and S have each a major peak and a minor peak, not tallying with the Rz peaks. In CR, there are two peaks, the first CR peak tallying with the first peak of

Rz, but the second CR peak occurring 20 months later than the second peak of Rz. Thus again, matching is not perfect (Rz GG lasted 16 months, CR gap lasted 35 months). The solar polar magnetic field reversed a little after the GG of Rz, and was within the long-lasting CR gap.

(6) The right half of Figure 3 shows the hysteresis loops in the various cycles. An obvious feature is that the loops are broader during odd cycles 19, 21, 23 as compared to the even cycles 20, 22. This feature is well known (confirmed here for cycle 23 which is about to end) and is explained as due to drift mechanisms which give opposite effects with the changing sign of the solar magnetic field (Jokipii and Thomas, 1981; Kota and Jokipii, 1983). However, at both ends of the sunspot cycle (solar minimum at the left side bottom, solar maximum at the right side top of each panel), there are small loops indicating dephasing between the evolution of sunspots and CR modulation. Notably, the loops in cycles 19, 21, 23, though all broad, are not exactly alike, indicating considerable differences in successive odd cycles. Similarly, the narrow loops in cycles 20 and 22 are not alike. In cycle 20, the points are almost along a straight line, indicating very little dephasing between Rz and CR, while in cycle 22, there is considerable dephasing during the rising and declining phases, and a wider loop is obtained.

For CR, data are available only for five cycles (19 – 23) and the GG relationship with sunspots or even with polar field reversals seems to be dubious. Briefly, the results are as follows:

In cycle 19, sunspots had two peaks with a GG of 17% lasting 9 months, CR had a gap of 6% five months later, lasting 16 months, and the polar field reversal occurred in between. So, this could be an example of a rough association between all the three.

In cycle 20, sunspots had three flat peaks and no worthwhile GGs, CR had three flat peaks ten months later and no worthwhile gaps, and the *polar field reversal occurred later* than the first peaks of Rz and CR. Thus, the reversal phenomenon could not be the cause of any CR gap.

In cycle 21, sunspots had four major peaks and one GG of 20% between the third and fourth peaks, lasting 10 months. CR had only one major peak much later than all the sunspot peaks (hence no gap at all in CR), and the polar field reversal occurred during the later peaks of sunspots but much before the only major peak of CR.

In cycle 22, sunspots had four major peaks and one GG of 27% between the first and second peaks, lasting 9 months. CR had three peaks and one GG of 15% between the second and third peaks (lasting 14 months), about six months later than sunspot GG, and the polar field reversal occurred much after the sunspot GG and started 4 months *after* the start of the CR gap.

In cycle 23, sunspots had two peaks (separation 16 months) with a GG of 33%. CR also had two peaks (but with a separation of 34 months, double that of sunspot separation), and a gap of 7% starting simultaneously with the sunspot GG (but ending much later), and the polar field reversal occurred *six months later* than the first peaks of sunspots and CR

Thus, taking a broad view, one would claim a rough overall association between sunspot and CR gaps and the solar polar magnetic field reversal intervals, ignoring completely the phase differences. However, examining critically, the CR gaps do not match perfectly with sunspot GGs. Durations are different and/or there are variable delays, and magnitudes of the depths of the suspot GGs and CR gaps are loosely proportional (Cycle 19, Rz 17%, CR 6%; Cycle 20, no GGs; Cycle 21, Rz 20%, no CR GG; Cycle 22, Rz 27%, CR 15%; Cycle 23, Rz 33%, CR 7%). Magnetic field reversal intervals do not coincide exactly with either sunspot GGs or CR gaps. More embarrassing, some magnetic field reversals started *later* than the starting of the CR gaps. Hence, the field reversal could not be a cause of the CR gaps (causes must precede effects, not succeed). The field reversals occur at the maximum of all solar cycles, but CR gaps occurred only in three cycles (one even cycle 22, and two odd cycles 19, 23) out of five. With only five CR cycles with characteristics so different from each other, any general conclusion would be unreliable.

3. Conclusions and discussion

After rising almost monotonically from sunspot minimum, sunspot activity falters and remains in a narrow grove for several tens of months (2 – 3 years) and later, decreases almost monotonically up to the next sunspot minimum. During the 2 – 3 years near sunspot maximum (let us term it Turmoil Interval TI), sunspots may depict several peaks (Gnevyshev peaks) and several gaps (spaces between successive peaks, termed as Gnevyshev Gaps GG). An examination (present paper and also Kane, 2005a,b,c, 2006) revealed the following:

(1) In all the cycles 1 – 23 so far, there have been two or more Gnevyshev peaks in the TI near solar maxima and correspondingly, one or more GGs. However, the *depths* of the troughs are variable from one GG to the next in the same cycle and the magnitudes may vary in a wide range ($<$1% to $\sim$20%).

(2) This pattern of multiple sunspot peaks in the TI of each cycle is not the same for all other solar parameters. The months of commencement and ending and the magnitudes of the depths differ from those of sunspot GGs, and from parameter to parameter. Thus, whereas there is a general turbulence interval TI superimposed on a quasi-stationary 11-year trend, its patterns are different for different solar parameters, qualitatively as well as quantitatively. Large north – south asymmetries are seen in the patterns.

(3) The solar open magnetic flux emerging from the Sun (estimated roughly at $\sim$20 solar radii above the photosphere) also shows gaps, but their patterns

are different in the northern and southern low solar latitudes, and unlike the pattern of any other solar parameter.

(4) A connection with the reversal of solar polar magnetic field is often claimed in the literature, and it is surmised that in the course of the Sun's polar magnetic field reversal, a part of the Sun's energy is used up for this reversal process, implying that during such periods the interaction between "local magnetic fields" (particularly those connected with the processes involved in the development of large and complex active regions) and the "background magnetic field" is suppressed, and large-scale dynamical phenomena cannot reach the solar corona and hence they are not able to affect the interplanetary medium. However, we find a mismatch between the GGs of sunspots and other parameters and the commencement of the polar magnetic field reversal. *The reversal occurs several months after the first sunspot maximum*. Thus, the field reversal is only one of the features occurring some time during the TI, but could not be the *initiator* of the turmoil.

(5) Interplanerary parameters also show gaps but these are dissimilar to the gaps of all other parameters.

(6) For cosmic ray (CR) modulation which occurs deep in the heliosphere, what matters is the state of the heliosphere. This state should be affected by the solar emissions (plasma as well as magnetic field structures) reaching way out in the heliosphere with some delay. For CR, data are available only for five cycles (19 – 23) and in some cycles (not all), gaps are seen during TI, but the CR gaps, when they occur, do not match with sunspot GGs or with gaps in any other parameter. Durations are different and/or there are variable delays, and magnitudes of the suspot GGs and CR gaps are not proportional (Cycle 19, 17%, 6%; Cycle 20, no GGs; Cycle 21, 20%, no CR GG; Cycle 22, 27%, 15%; Cycle 23, 33%, 7%).

(7) Long-term variations of CR are roughly anti-parallel to sunspot activity but the plots of CR versus sunspot number show hysteresis loops which are broader in odd cycles 19, 21, 23 as compared to the loops in the even cycles 20, 22. This is well-known and is explained as due to drift mechanisms some of which give opposite effects with the changing sign of the solar magnetic field.

Since none of the solar and near-Earth interplanetary parameters show gaps qualitatively and quantitatively similar to the gaps in CR, the exact cause of CR gaps remains obscure. None of the solar and near-Earth interplanetary parameters seem to reflect the heliospheric conditions that dictate CR modulation. One would have thought that solar open magnetic field flux would be an appropriate parameter for such a connection, but it does not seem to be so. Or, its pattern may be getting largely modified by the time the effects reach the middle heliosphere. The same argument applies to interplanetary partameters. CRs are affected by diverse structures of the solar wind (*e.g.*, interplanetary transients, corotating regions, current sheet, etc.) in different ways. Various physical processes (diffusion, drift, convection, focusing, adiabatic deceleration, wave-particle interactions, etc.) are involved in the modulation, and each of them has its own characteristic time. As a result, different delays could occur between various solar wind features and the CR response.

For the solar open magnetic flux, Wang and Sheeley (2003) performed ad hoc numerical simulations exploring the nature of the source regions of the solar magnetic field. They stimulated the evolution of the Sun's equatorial dipole strength and total open flux under the assumption that the active region sources are distributed randomly in longitude and interpreted the results with the help of a simple random walk model including dissipation. They found that the equatorial dipole and open flux exhibited multiple peaks during each 11-year cycle, with the highest peak occurring during sunspot maximum and/or later in the declining phase. They attribute the Gnevyshev gaps (GGs) to random fluctuations in the rate of emergence of major active regions and their longitude distribution, and the widths of the peaks are determined by the time scale for the equatorial dipole to decay through the combined action of meridional flow, differential rotation and super granular diffusion. How these patterns are transmitted to regions deep in the heliosphere is a moot question.

Acknowledgments

Thanks are due to the various workers who recorded the neutron monitor data at the various locations and to Zenjiro Fujii and his colleagues at the Cosmic Ray Section, Solar-Terrestrial Environment Laboratory, Nagoya University for the muon data. Neutron monitors of the Bartol Research Institute are supported by a NSF grant ATM-0527878. Thanks are due to the referee for valuable suggestions. The present work was partially supported by FNDCT, Brazil under contract FINEP-537/CT.

References

Ahluwalia, H.S.: 2003, *Geophys. Res. Lett.* **30**(3), 1133, doi:10.1029/2002GL016017.
Ahluwalia, H.S.: 2005, *J. Geophys. Res.* **110**, A10106, doi:10.1029/2005JA011106.
Ahluwalia, H.S. and Kamide, Y.: 2005, *Adv. Space Res.* **35**, 2119.
Alania, M.V., Baranov, D.G., Tyasto, M.I., and Vernova, E.S.: 1999, *Proc. 26th ICRC* **7**, 13 l.
Ataç, T. and Özguç, A.: 1998, *Solar Phys.* **180**, 397.
Bao, S.D. and Zhang, H.Q.: 1998, in A. Antalova and A. Kucera (eds.), *JOSO Annual Report'97*, Astronomical Institute, Tatranská Lomnica, p. 132.
Bazilevskaya, G.A., Krainev, M.B., Makhmutov, V.S., and Sladkova, A.I.: 1995, *24th ICRC* **4**, 572.
Bazilevskaya, G.A., Krainev, M.B., Makhmutov, V.S., Fltickiger, E.O., Sladkova, A.I., and Storini, M.: 2000, *Solar Phys.* **197**, 157.
Bieber, J.W. and Rust, D.M.: 1995, *Astrophys. J.* **453**, 911.
Bumba, V. and Howard, R.: 1965, *Astrophys. J.* **141**, 1502.

Cane, H.V., Wibberenz, G., Richardson, I.G., and von Rosenvinge, T.T.: 1999, *Geophys. Res. Lett.* **26**, 565.

Dorman, L.I.: 2001, *Adv. Space Res.* **27**(3), 601.

Dorman, L.I., Iucii, N., and Villoresi, G.: 2001, *Adv. Space Res.* **27**(3), 595.

Dorman, L.I., Dorman, I.V., Iucii, N., Parisi, M., and Villoresi, G.: 2001, *Adv. Space Res.* **27**(3), 589.

Feminella, F. and Storini, M.: 1997, *Astron. Astrophys.* **322**, 311.

Gnevyshev, M.N.: 1963, *Sov. Astron.* **A.I** (7), 311.

Gnevyshev, M.N.: 1967, *Solar Phys.* **1**, 109.

Gnevyshev, M.N.: 1977, *Solar Phys.* **51**, 175.

Gopalswamy, N., Lara, A., Yashiro, S., and Howard, R.A.: 2003a, *Astrophys. J.* **598**, L63.

Gopalswamy, N., Lara, A., Yashiro, S., Nunes, S., and Howard, R.A.: 2003b, Proceedings of the ISCS 2003 Symposium, Solar Variability as an Input to the Earth's Environment 1. Tatranská Lomnica, Slovakia, ESA. SP-535, (ed. Wilson) ESTEC, Noordwijk, The Netherlands, September, p. 403.

Harvey, K.L. and Recely, F.: 2002, *Solar Phys.* **211**, 31.

Jokipii, J.R. and Thomas, B.: 1981, *Astrophys. J.* **243**, 1115.

Kane, R.P.: 2005a, *Solar Phys.* **229**, 387.

Kane, R.P.: 2005b, *Solar Phys.* **227**, 155.

Kane, R.P.: 2005c, *J. Geophys. Res.* **110**, A01108, doi:10.1029/2004JA010606.

Kane, R.P.: 2006, *Solar Phys.* **233**, 107.

Kóta, J. and Jokipii, J.R.: 1983, *Astrophys. J.* **265**, 573.

Krainev, M.B., Bazilevskaya, G.A., Fltickiger, E.O., Makhmutov, V.S., Sladkova, A.I., and Storini, M.: 1998, Proceedings of the Conference on 50th Anniversary of the Kislovodsk Astronomical Observatox-v, Pulkovo, St. Petersburg, p. 95.

Makarov, V.I. and Makarova, V.V.: 1996, *Solar Phys.* **163**, 267.

Nagashima, K., Sakakibara, S., and Morishita, I.: 1991, *Geomag. Geoelectr.* **43**, 685.

Obridko, V.N. and Shelting, B.D.: 1992, *Solar Phys.* **137**, l67.

Sabbah, I., Helmi, M., Bishara, A., and Borie, M.: 1995, *Proc. 24th ICRC* **4**, 560.

Simpson, J.A., Fonger, W., and Trieman, S.B.: 1953, *Phys. Rev.* **90**, 934.

Storini, M.: 1995, *Adv. Space Res.* **16**(9), 51.

Storini, M. and Laurenza, M.: 2003, *Mem. S. A. It.* (*Memoirs Societa Astronomica Italiana*) **74**, 774.

Storini, M. and Pase, S.: 1995, *STEP GBRSC News* **5**(Special Issue), 255.

Storini, M., Massetti, S., and Antalova, A.: 1997, *Proc. 25th ICRC* **1**, 409.

Storini, M., Pase, S., Sykora, J., and Parisi, M.: 1997, *Solar Phys.* **172**, 317.

Storini, M., Feminella, F., Antalova, A., and Massetti, S.: 1999a, in A. Antalova, H. Balthasar, and A. Kucera (eds.), *Joso Annual Report'98*, Astronomical Institute, Tatranská Lomnica, p. 153.

Storini, M., Jakimiec, M., Antalova, A., and Sykora, J.: 1999b, *Proc. 26th ICRC* **7**, 151.

Storini, M., Bazilevskaya, G.A., Fluckiger, E.O., Krainev, M.B., Makhmutov, V.S., and Sladkova, A.I.: 2003, *Adv. Space Res.* **31**(4), 895.

Vernova, E.S., Tyasto, M.I., Baranov, D.G., and Grigorian, M.S.: 1995, *Proc. 24th ICRC* **4**, 564.

Vernova, E. S., Mursula, K., Tyasto, M. I., and Baranov, D. G.: 2002, *Solar Phys.* **205**, 371.

Wang, Y.M. and Sheeley, N.R.: 2002, *J. Geophys. Res.* **107**(A10), 1302, doi:10.1029/2001JA000500, SSH 10, 1.

Wang, Y.M. and Sheeley, N.R.: 2003, *Astrophys. J.* **590**, 1111.