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COMPARISON OF THE VARIATIONS OF CMEs AND ICMEs WITH THOSE OF OTHER SOLAR AND INTERPLANETARY PARAMETERS DURING SOLAR CYCLE 23

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Abstract. This paper examines the variations of coronal mass ejections (CMEs) and interplanetary CMEs (ICMEs) during solar cycle 23 and compares these with those of several other indices. During cycle 23, solar and interplanetary parameters had an increase from 1996 (sunspot minimum) to ∼2000, but the interval 1998–2002 had short-term fluctuations. Sunspot numbers had peaks in 1998, 1999, 2000 (largest), 2001 (second largest), and 2002. Other solar indices had matching peaks, but the peak in 2000 was larger than the peak in 2001 only for a few indices, and smaller or equal for other solar indices. The solar open magnetic flux had very different characteristics for different solar latitudes. The high solar latitudes (45°–90°) in both N and S hemispheres had flux evolutions *anti-parallel* to sunspot activity. Fluxes in low solar latitudes (0°–45°) evolved roughly parallel to sunspot activity, but the finer structures (peaks etc. during sunspot maximum years) did not match with sunspot peaks. Also, the low latitude fluxes had considerable N–S asymmetry. For CMEs and ICMEs, there were increases similar to sunspots during 1996–2000, and during 2000–2002, there was good matching of peaks. But the peaks in 2000 and 2001 for CMEs and ICMEs had similar sizes, in contrast to the 2000 peak being greater than the 2001 peak for sunspots. Whereas ICMEs started decreasing from 2001 onwards, CMEs continued to remain high in 2002, probably due to extra contribution from high-latitude prominences, which had no equivalent interplanetary ICMEs or shocks. Cosmic ray intensity had features matching with those of sunspots during 2000–2001, with the 2000 peak (on a reverse scale, actually a cosmic ray decrease or trough) larger than the 2001 peak. However, cosmic ray decreases started with a delay and ended with a delay with respect to sunspot activity.

1. Introduction

Coronal mass ejections (CMEs) were identified more than 30 years ago by Tousey (1973) in the OSO-7 data. The phrase “coronal mass ejection” was initially coined to describe the detection of new, discrete, bright features appearing in the field of view of a white-light coronagraph and moving outward over a period of minutes to hours (e.g., Munro *et al.*, 1979). These episodic expulsions of mass and magnetic fields from the solar corona into the interplanetary medium may have masses of a few 10^{15} g and may liberate energies of 10^{30}–10^{32} ergs. During the most active phase of the solar cycle of ∼11 years (solar maximum), the solar activity is dominated by flares and disappearing filaments, and their concomitant CMEs. The fast CMEs coming from the Sun into the interplanetary space are the solar/coronal features that contain high magnetic fields. The interplanetary counterparts of solar CMEs are termed as ICMEs. Several review papers in the past have described CME characteristics; a recent one (Cliver and Hudson, 2002) describes the theoretical and observational aspects of CMEs in a "Q&A" style. Piecing together data from different spacecrafts, long-term behavior of CMEs has been examined (e.g., Webb and Howard, 1994).

A more copious data set for CMEs is now available from the Solar and Heliospheric Observatory (SOHO) mission's Large Angle and Spectrometric Coronagraph (LASCO), which images the corona continuously since 1996, covering a field from $1.5\,R_s$ to $32\,R_s$. Simultaneous data for ICMEs are available from Wind and ACE spacecrafts. St. Cyr *et al.* (2000) studied 841 CMEs during January 1996 through June 1998 and found CME characteristics similar to those found in previous observations by other similar instruments. Gopalswamy *et al.* (2000, 2001) developed an empirical model of the acceleration/deceleration of CMEs as they propagated through the solar wind. Gopalswamy *et al.* (2003a) found a close relationship between the solar polarity reversal and the cessation of solar high-latitude CMEs, for cycles 21 and 23. Gopalswamy *et al.* (2003b) studied the solar cycle variation of various properties of CMEs for cycle 23 (1996–2002) and reported an order of magnitude increase ($\sim$12 times) in CME rate from solar minimum (1996) to solar maximum (2002). Thus, CME increases were almost parallel to sunspot activity. However, they noted a phase shift also, namely whereas sunspots reached a maximum in July–August 2000, CMEs peaked about 2 years later, in August–September 2002.

Whereas solar activity increases almost monotonically from minimum to maximum, there are superposed fluctuations, particularly near the sunspot maximum years. Gnevyshev (1967) showed that in solar cycle 19 (1954–1965), the coronal line half-yearly average intensity at 5303 Å (green line) had actually two maxima, the first one in 1957 and the second in 1959–1960. On shorter time scales, peaks are seen during sunspot maximum years with irregular spacings of 5–15 months, and a spectral analysis indicates periodicities in the ranges (months): 5.1–5.7, 6.2–7.0, 7.6–7.9, 8.9–9.6, 10.4–12.0, 12.8–13.4, 14.5–17.5, 22–25, 28, 31–36, 41–47 (e.g., Kane, 2005a). In the present communication, CME and ICME frequencies are compared with solar indices to see whether the short-term peaks in both are similar near the maximum of solar cycle 23 (1998 onwards up to date).

2. Data

All data were obtained from the websites *http://www.ngdc.noaa.gov/stp/SOLAR/solintro.html* and *http://cdaw.gsfc.nasa.gov/geomag_cdaw/Data.html*.

3. Plots

Figure 1 shows in the two top plots, the annual values of two solar indices, namely, sunspot number Rz (full lines) and 2800 MHz radio flux F10 (crosses and dashes). Next follow the annual values of three interplanetary features, namely, ICME events from Cane, Richardson, and von Rosenvinge (1996, updated by private communication with Richardson in 2002), the annual CME count (SOHO LASCO CME catalogue at *http://cdaw.gsfc.nasa.gov/CME_list/UNIVERSAL/*) (triangles and dashes), and Kasper's list of IP shocks seen at WIND (crosses and dashes). The next plot is for interplanetary total magnetic field B. The next four plots are for the solar open magnetic fluxes (Wang and Sheeley, 2002 and further private communication from Wang in 2004) for different solar latitude ranges, namely, 90–45N, 45–0N, 0–45S, 45–90S. The following may be noted:

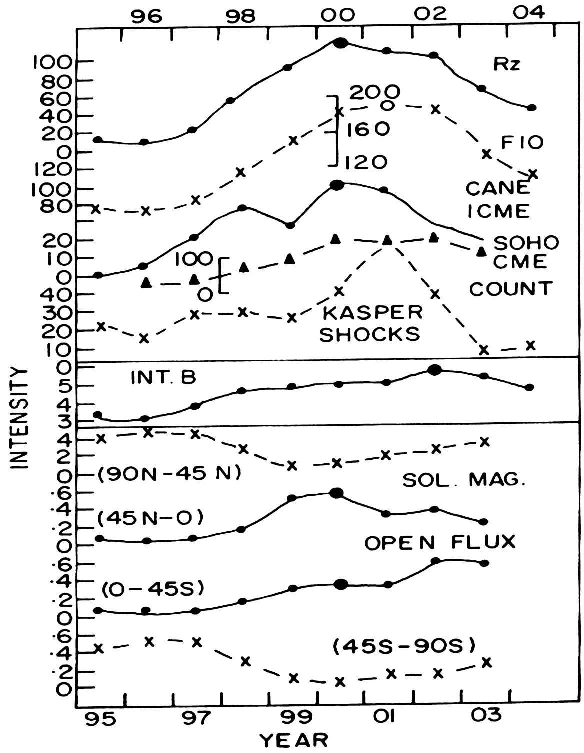

Figure 1. Plots of annual values (1995–2004) of sunspot number Rz and 2800 MHz radio flux F10; Cane and Richardson's ICME events (1996–2002), the annual CME count (SOHO LASCO CME catalogue, *triangles* and *dashes*), and Kasper's IP shock events seen at WIND (*crosses* and *dashes*); interplanetary total magnetic field B (*full lines*); solar open magnetic fluxes for different solar latitude ranges 90°–45°N (*crosses*), 45°–0°N (*full lines*), 0°–45°S (*full lines*), 45°–90°S (*crosses*).

(1) Almost all indices show a minimum in 1996 and a maximum during 2000–2002.
(2) A glaring exception is for solar open magnetic fluxes. Whereas the low latitude (0°–45°) fluxes run parallel to solar activity, the high-latitude (45°–90°) fluxes run just opposite, minimum at sunspot maximum, maximum at sunspot minimum.
(3) Whereas Rz and F10, have an almost smooth rise and fall, some other indices show fluctuations.

Short-term fluctuations can be illustrated better on detailed plots. Figure 2 shows the 3-monthly means (DJF, MAM, JJA, SON, centered at January, April, July, October) for several indices. The upper part shows some solar indices, namely, sunspot number Rz, magnetic fields observed at Kitt Peak Observatory, Lyman-α (Woods *et al.*, 2000, updated), Solar flare Index SF (Kandilli Observatory, Istanbul, Turkey; Ataç and Ozguç, 1998 and further private communication from them in 2004), 2800 MHz flux F10, X-ray background, protons >1 MeV, coronal green line index (Rybansky, Rusin, and Minarovjech, 1998 and further private communication from Minarovjech in 2004), and 606 MHz solar radio flux. This is followed by two open solar magnetic fluxes (low latitudes only, 0°–45°), three interplanetary structures (Cane ICMEs, Kasper shocks, SOHO all CME count), three interplanetary parameters (number density N, flow speed V, total magnetic field B), and finally, CR (cosmic ray) neutron monitor counts at Climax. The following may be noted:

(1) The sunspot number Rz increased steadily up to the end of 1997 and then showed fluctuations during 1998–2002, with distinct peaks (marked with big dots) near July 1998, July 1999, July 2000 (largest), October 2001 (second largest) and October 2002. Among the two largest peaks of July 2000 and October 2001, *the first (July 2000) peak is larger for sunspots.*
(2) All other solar indices also show these two peaks as the most prominent ones. For total solar flare index (SF), the first peak is larger. (Here, there is a north–south asymmetry. The northern hemisphere plot N shows the first peak in 2000 very much larger than the second peak in 2001, but for the southern hemisphere plot S, the first peak in 2000 is smaller than the second peak in 2001). For all others, including 2800 MHz F10, the *second peak is larger*. Even for Kitt Peak magnetic field, which is a photospheric phenomenon like sunspots, the second peak is larger. On the other hand, for higher solar altitudes where coronal green line and 606 MHz originate, the two peaks are of the *same size*. Almost all these indices show decreases from the beginning of 2002 onwards, but for X-ray background, there is a strong peak in 2002, and for protons, in 2003 (probably because of the Halloween events of October–November 2003).
(3) The solar open magnetic flux at low northern solar latitudes (0–45N) remains low up to the middle of 1998 end and then increases rapidly and oscillates

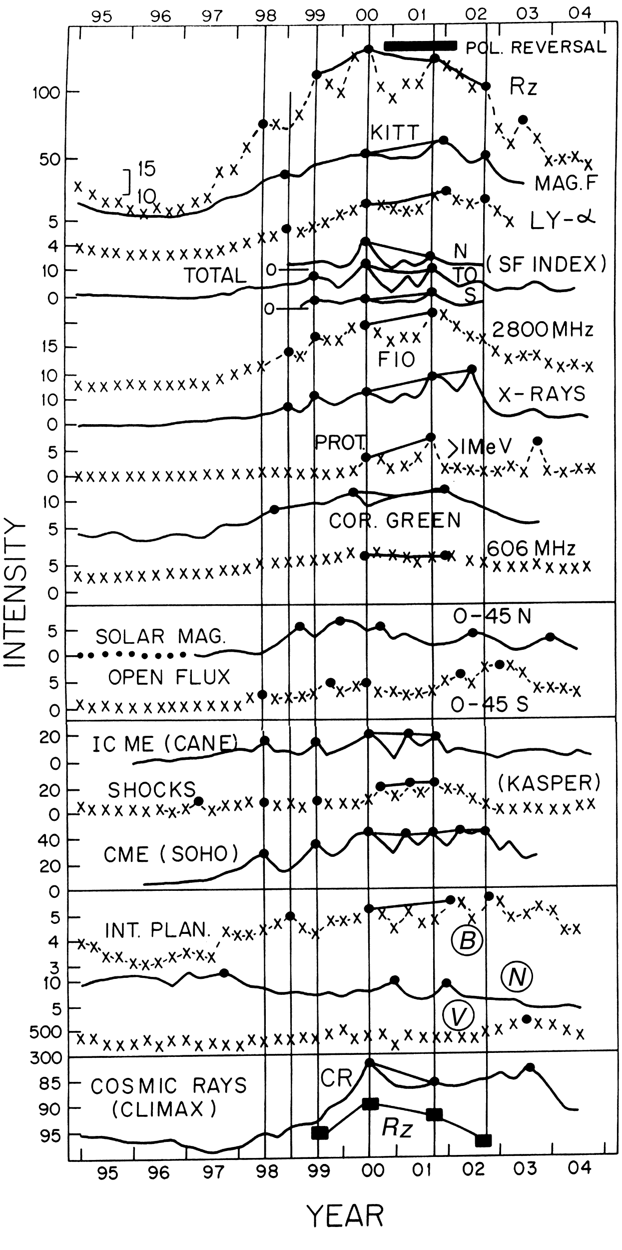

Figure 2. Plots of 3-monthly values (1995–2004) of sunspot number Rz, solar magnetic field observed at Kitt Peak Observatory, Lyman-α, solar flare index SF, 2800 MHz radio flux F10, X-ray background, solar protons >1 MeV, coronal green line index, 606 MHz radio flux, solar open magnetic fields for low solar latitudes, Cane and Richardson's ICME events (1996–2002), Kasper's IP shock events seen at WIND, the annual CME count (SOHO LASCO CME catalogue), interplanetary total magnetic field B, number density N, flow speed V, and cosmic ray (CR) intensity at Climax. At the *top* (above Rz), the *rectangle* marks the solar polar magnetic field reversal (north pole, last quarter of 2000 to south pole, first quarter of 2002).

until 2003, but the peaks do not match with other solar indices. For low southern latitudes (0–45S), the flux rises more slowly but increases considerably in 2002–2003. Matching with peaks of other solar indices is not good. Thus, the low latitude solar magnetic open fluxes are not matching the other solar indices and in addition, there is considerable *north–south asymmetry*. Gopalswamy *et al.* (2003b) point out a north–south asymmetry for high-latitude CMEs, roughly related to solar polar magnetic field reversal. (In Figure 2, the reversal is marked by a rectangle above the *R*z plot, from last quarter of 2000 for the north pole to the first quarter of 2002 for the south pole). A relationship of N–S asymmetries with solar polar magnetic field reversals was reported by Vernova *et al.* (2002) and some discrepancies in the same are discussed in Kane (2005b). This needs further scrutiny.

(4) The ICMEs and CMEs show peaks similar to those of other solar indices, but the two major peaks of 2000 and 2001 are of almost the *same size*, similar to coronal green line and 606 MHz radio flux. Thus, it is tempting to speculate that CMEs may have sources in the upper atmosphere of the Sun also, though Gopalswamy *et al.* (2003b) mention that the correlation of sunspots with at least some CMEs is good to the extent that both arise in (photospheric) active regions. The total CME count has still larger peaks in 2002 (just like X-rays). Thus, CME count continues to be high for about 2 years more after sunspot number started declining (pointed out by Gopalswamy *et al.*, 2003b). However, ICME (Cane) and Shocks (Kasper) do not have the third maximum in 2002 and start decreasing by the end of 2001 (just like other solar indices) Thus, the lingering of CME total count should be due to a contribution from sources not relevant to interplanetary space. Gopalswamy *et al.* (2003b) attribute it to high-latitude CMEs, associated with prominences not related to sunspot activity in active regions.

(5) In interplanetary parameters, the total magnetic field B has peaks matching with sunspots and, not only the second peak is larger, but there is a further third peak still larger. Thus, high values of B lingered on in 2002–2003 when sunspot activity had declined. The number density N was high in 1996–1997 and declined thereafter almost steadily and had a few peaks unrelated to sunspots. The flow speed V was almost constant and had a substantial increase only in 2003. Thus, interplanetary N and V (near Earth) do not have variations parallel to sunspot activity.

(6) The cosmic ray intensity (CR) is modulated by solar activity and hence, on an upside down scale, should look parallel to sunspot activity. Whereas sunspots started increasing in the beginning of 1997, CR level started changing only in the beginning of 1998, i.e., with a delay of about 1 year. The two peaks of sunspots are seen in CR also, with the second peak lesser for both. However, CR level continued high (reverse scale, implying that CR decrease continued) even up to the middle of 2003 when sunspot activity had decreased considerably. Thus, except at the peaks where matching was very good, the

CR lagged behind sunspots in other phases of the sunspot cycle. In odd cycles (19, 21, 23), such a lag (hysteresis effect) is expected. Jokipii and Thomas (1981) and Kota and Jokipii (1983) attributed it to the alternating direction of the gradient and curvature drifts of GCR as interplanetary magnetic field (IMF) changes sign at successive sunspot maxima (22-year cycle).

4. Conclusions and Discussion

During cycle 23, almost all solar and interplanetary parameters had an almost monotonic increase from 1996 (sunspot minimum) to ∼2000, but the interval 1998–2002 had short-term fluctuations as follows:

(1) Sunspots had peaks in 1998, 1999, 2000 (largest), 2001 (second largest), and 2002.

(2) Other solar indices had peaks matching in time with sunspot peaks, but the peak in 2000 was larger than the peak in 2001 only for sunspots and total SF (total solar flare index). (Here, there was a N–S asymmetry. For SF-N, the peak in 2000 was much larger than the peak in 2001. For SF-S, the peak in 2000 was smaller). For other indices (Kitt Peak magnetic field, Lyman-α, 2800 MHz flux, X-rays, protons >1 MeV), the peak in 2000 was smaller than the peak in 2001. For coronal green line index and for 606 MHz radio flux, which originate in the upper atmosphere of the Sun, the peaks in 2000 and 2001 were almost of the same size.

(3) The solar open magnetic flux had very different characteristics for different solar latitudes. The high latitudes (45°–90°) in both N and S hemispheres had flux evolutions *anti-parallel* to sunspot activity. Fluxes in low latitudes evolved parallel to sunspot activity, but the finer structures (peaks etc. during sunspot maximum years) did not match in time with sunspot peaks. In addition, the low latitude fluxes in the northern and southern hemispheres (0°–45°N and 0°–45°S) did not evolve in a similar way, and considerable N–S asymmetry was observed.

(4) CMEs and ICMEs showed increases similar to sunspots during 1996–2000, and during 1998–2002, there was good matching of peaks in time. But for both CMEs and ICMEs, the peaks in 2000 and 2001 had similar sizes, in contrast to the 2000 peak being greater than the 2001 peak for sunspots.

(5) Whereas ICMEs started decreasing from 2001 onwards, CMEs continued to remain high in 2002, indicating contribution from sources other than the active regions where sunspots evolve. These other sources were probably high-latitude prominences, and these extra CMEs had no equivalent interplanetary ICMEs or shocks (Gopalswamy *et al.*, 2003b).

(6) Cosmic ray intensity had features matching with those of sunspots during 2000–2001, with the 2000 peak (on a reverse scale, actually a cosmic ray

decrease or trough) larger than the 2001 peak. However, cosmic ray decreases started with a delay and ended with a delay with respect to sunspot activity.

These observations could be indicative of origins of different indices at different altitudes in the solar atmosphere but for the fact that Kitt Peak magnetic field, a surface phenomenon, had an evolution pattern different from that of sunspots (a surface or photospheric phenomenon), while solar flare index originating certainly above the photosphere and probably in lower corona, showed evolutions similar to sunspots. High above, the coronal green line and low-frequency radio emissions showed still more different patterns. CMEs and ICMEs too show evolutions of patterns not exactly similar to those of sunspots. Thus, the dynamics of all these parameters in solar atmosphere seems to be fairly complicated and needs further detailed scrutiny.

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