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Variations of solar indices during the sunspot maximum years (1999-2002) of cycle 23

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Comparison of the evolutions of daily and monthly values of several solar indices during 1999-2002 indicated that the daily values had large day-to-day fluctuations with peak spacings differing considerably from the 27-day solar rotation period. Plots of the percentage increases (trough-to-peak) versus temperature of the source regions of the various indices indicated a double-humped structure. The monthly values showed many peaks. The average spacing was ~3.5 months (~100 days). The 12-month moving averages showed considerable differences. Some indices reached a maximum near March 2000. Some of these decreased since then and continue to decrease at present; but some reached a minimum near January 2001 and remained steady there, or started increasing again to reach a probable maximum near June 2002. Some indices did not have a maximum in March 2000 and continued to increase till June 2002. Thus, the evolutions of the various solar indices during the sunspot maximum of cycle 23 (1999-2002) are substantially different from each other. Obviously, the dynamical upheavals in the photosphere reach upper levels of the solar atmosphere with varying intensities.

Key words: Solar indices, Sunspot maximum, Solar cycle 23.
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1 Introduction

The sun is a highly active star. There are many indices of solar activity currently in use. These indices indicate activities at various levels in the solar atmosphere, are produced by a number of different mechanisms, and have a strong relationship with solar magnetic activity, which is the engine driving all these indices. Based on the length of data record, the primary index of solar activity has been the Wolf (Zurich) sunspot number R_z, published by Wolf in the various issues of *Astron. Mitt.* (1858-1893) and by others[1,2]. Presently it is generated by the Solar Index Data Center, Brussels. It has a prominent 11-year cycle, named after Schwabe[3,4]. The cycles are numbered since 1750 (cycle 1=1755 minimum to 1766 minimum). The next most prominent index has been the 2800 MHz, 10.7 cm radio emission flux, recorded routinely by a radio telescope near Ottawa, Canada, since 14 Feb. 1947, which is presently operated by the National Research Council, using two fully automated radio telescopes at the Dominion Radio Astrophysical Observatory, Penticton, Canada. All solar indices show an 11-year cycle, except that during sunspot minimum when sunspot numbers almost reach zero, most of the other indices reach a minimum non-zero level, indicating the presence of magnetic activity even then. Solar activity occurs in complexes, which are localized areas having a number of active regions and can persist for several (up to a dozen) solar rotations[5].

In a recent communication[6], it was shown that the evolutions of the various indices during sunspot maxima and sunspot minima were not alike. In some cycles, the sunspot number (R_z) rose rapidly to a maximum and fell thereafter rapidly, giving the impression of a sharp peak, while in some other cycles, the rise of R_z from the sunspot minimum halted abruptly after a few years. The level remained almost steady for the next few years giving the impression of a plateau, and then there was a sharp fall up to the next sunspot minimum. Most of the other indices had coincided sharp maxima. In cases of duplicate peaks, their evolution was not similar to the sunspot numbers. The latest data examined were up to about the end of 2000, and most of the indices showed a maximum during March-April of 2000. However, it was noticed later that the solar activity did not decrease thereafter monotonically and many indices rose again to give a second maximum. In the present paper, the behaviours of various indices during 1999-2002 are compared in detail.

2 Data

All the data were obtained from NOAA websites *http://www.ngdc.noaa.gov/stp* and *www.sec.noaa.gov*. Table 1 lists the various radio emissions, line

Table 1—List of solar indices used in the present analysis

Solar indices	Percentage changes		Log *T*	% Amp 27-day	Ranges (%) during day numbers of 1999			
	Wavelength nm	Temp.*T* K		(Av 97-98)	22-35	46-35	212-230	240-230
Intpl.N,V,B	-	-	-	Obscure	Obscure	Obscure	Obscure	Obscure
X-rays	0.1-0.8	>2000000	>6	Abnormally large values				
Protons	>1Mev	~1000000	~6	Abnormally large values				
S.flares	-	~1000000	~6	Abnormally large values				
EUV	26-34	<1000000	<6	8.1	-	-	29	32
Sunspots	-	5000	3.7	Obscure	Abnormally large values			
Mag. F.Kitt	-	5000	3.7	-	138	138	74	70
UV lines								
He I	1083.0	5000	3.7	-	30	30	22	38
Mg II	280.0	6500	3.85	2.2	10	12	8	-
O I	130.4	7060	3.85	3.7	15	17	13	-
C I	165.6	7060	3.85	2.6	14	15	9	-
Si II	126.2	10000	4	6.8	27	28	22	-
Si II	153.0	10000	4	6.0	27	32	20	-
Si II	181.3	10000	4	3.8	17	18	17	-
C II	133.6	12600	4.1	6.5	21	27	15	-
Si III	120.6	17800	4.25	8.7	44	39	28	-
H I	121.6	40000	4.6	5.0	20	22	19	-
Si IV	139.8	56700	4.75	6.3	33	33	23	-
He II	164.0	56700	4.75	9.5	41	50	53	-
C IV	155.0	100000	5	3.7	23	24	20	-
N V	124.1	200000	5.3	4.0	30	28	26	-
Radio MHz								
15400	-	8800	4.95	1.9	16	21	16	22
8800	-	140000	5.15	4.5	22	23	30	21
4995	-	200000	5.3	10.1	52	64	73	65
2800	F10	300000	5.48	13.8	77	106	77	101
2695	-	315000	5.5	14.0	88	112	80	89
1415	-	415000	5.62	13.8	74	93	57	60
606	-	835000	5.92	9.2	41	58	28	27
410	-	1000000	6	9.4	40	109	27	27
245	-	1200000	6.08	8.8	79	203	56	69

emissions and other parameters for which data were used. The UV emissions lines are from a special UARS data product (solstice L2 lines) that is created by extracting the emission lines from the 0.1 nm spectral data by fitting Gaussian functions to the lines and accounting for a continuum background spectrum as a second degree polynomial. Therefore, these 'solstice' emission line fluxes are free of the underlying continuum, but some of these lines do have blends with other emission lines within the 0.15 nm spectral resolution. These 'solstice' data are available only up to the middle of 2001. Data were available for SEM/SOHO EUV (26-34 nm) for 1996 onwards. However, the solar region in which these originate is not unique (private communications from Karen Harvey and Don McMullin). The 26-34 nm wavelength range is produced at three levels: namely, upper chromosphere, transition region and corona. The temperature of the 28.4 nm Fe XII line is about 2 MK, while that of 30.4 He II emission line is about 55,000 K. Thus, no single temperature can be attributed to this band, but an average value of ~200,000 K is assumed for illustration.

The excitation temperatures of these line emissions have been determined[7,8] by taking the ratio of excitation rates for two doublets of the same super-multiplet[9] at 0.15 nm resolution, but the absolute temperature values may not be very accurate. (Emission temperatures are based on measurements and theory, and different results can arise from different sets of data or different atomic theory/coefficients). The solar atmosphere, particularly over active regions and complexes of activity, is highly inhomogeneous. There is a chromosphere overlaid by a corona with a transition layer in between, but often there are intrusions of material from the chromosphere into the corona and *vice versa* with the transition region acting as an adaptive skin between the chromospheric and the coronal plasmas. However, for indices integrated over the whole sun (full disc averages) and over long time intervals, marked differences in the height dependence of various parameters between active regions are expected to cancel out. Figure 1 shows an example of the temperature-height profiles as derived by Fontenla *et al.*[10], for the quiet sun. In these profiles, the temperature drops from about 6,000 K at the photosphere to 4,800 K at the temperature minimum, which lies roughly 500 km above the photosphere. The temperature then rises again to about 10^4 K at an altitude of about ~2000 km, where the transition region is located. In the thin transition layer (a few kilometres thick), the temperature rises to about 5×10^5 K. As height increases further, the temperature rises to a typical coronal value of about 10^6 K (assumed in the present example to have reached at about 3000 km above the photosphere). These heights are significantly lower over active regions, as indicated in Fig. 1 by the dashed (broken) line. In any case, these heights are only approximate ones and will be considered only in a relative way, i.e., in general, higher the altitude, larger the temperature. The dots in

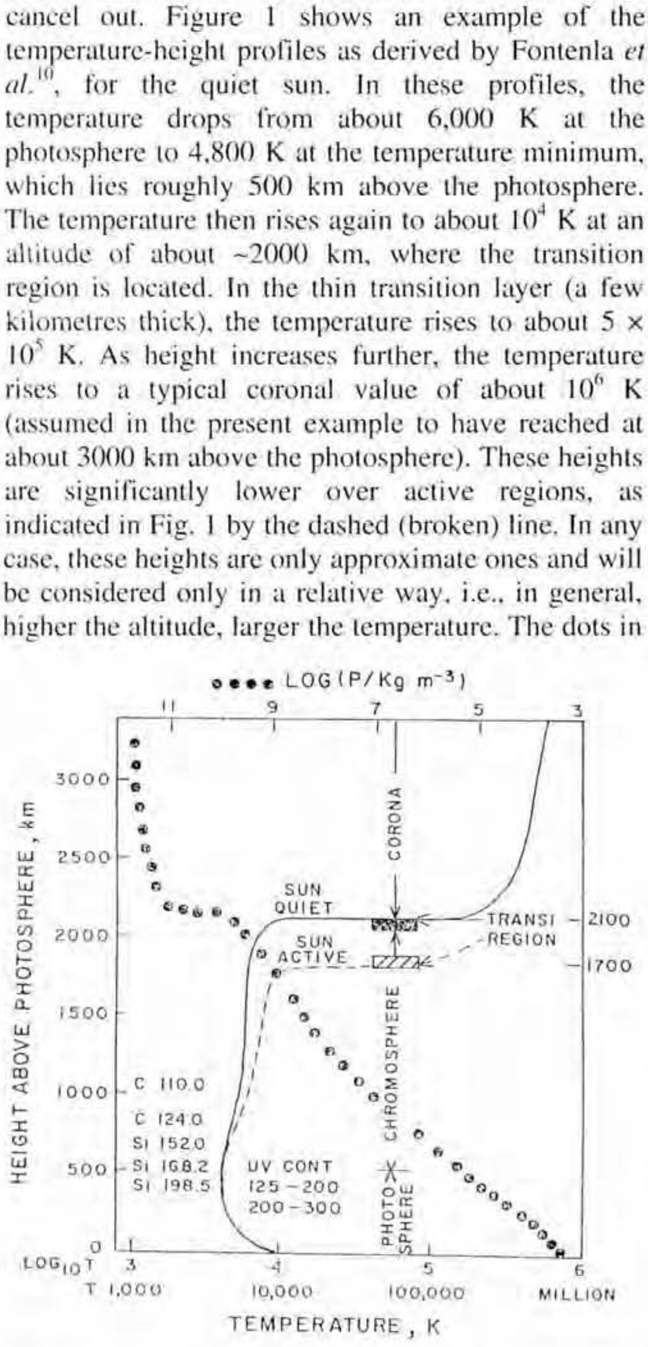

Fig. 1—Temperature (full line) and density (dots) distribution of the average quiet sun, indicating approximate depths of various solar emissions [10,13,20] [The dashed line shows the temperature profile above solar active regions (higher temperatures at similar heights).]

Fig. 1 show the density ρ, which decreases rapidly with altitude.

For radio emissions, data are obtained from the WDC-A Archive, Boulder, and the average was calculated for the data from Sagamore Hill, Massachusetts (SGMR); Palehua, Hawaii (PALE); San Vito, Italy (SVTO); Learmonth, Australia (LEAR), for noon-time values at frequencies 245, 410, 606, 1415, 2695, 4995, 8800 and 15400 MHz. The temperatures of the regions of origin of these radio emissions are obtained as discussed earlier by Kane *et al*[11].

3 Plots of daily values

Table 2 represents the sample of daily values of radio frequency (average for LEAR, PALE, SGMR, SVTO) for 17-30 Jan. 2001.

As can be seen in Table 2, the day-to-day variation is abnormally large at 245 and 410 MHz. This is because, in high solar activity, there is frequent burst emission, which lasts for several hours and the effect may be seen even in daily values for several continuous days, notably at low frequencies. We have tried to omit such abnormally high values from the analysis of monthly values, but the procedure is obviously subjective and values, especially for 245 MHz, may still have considerable pollution from burst emissions. Also, it may be noted that thermal radio emission has two components, i.e. thermal gyro-resonance from thermal plasma trapped in the magnetic fields over sunspots, and thermal free-free emission from active regions elsewhere. At very high frequencies like 15 GHz, the emission would be largely free-free, as the ambient magnetic fields are too weak for gyro-resonance. At low frequencies such as 1 GHz, the emission would be optically-thick thermal emission, as gyro-resonant contributions would be screened out. At intermediate frequencies, both the processes would contribute. At very low frequencies like 200 MHz, important plasma processes would complicate the relationship between brightness temperature of the emission and the ambient physical temperature. Thus, interpretation and comparison of results at different radio frequencies is not straightforward. Nevertheless, an attempt is made to get a rough idea about the frequency dependence of radio emission, but results at low frequencies, notably at 245 MHz and, to some extent, 410 MHz would be unreliable.

Figure 2 shows plots of the daily values of 2800 MHz (10.7 cm) solar radio emission flux (henceforth

Table 2—Daily values of radio frequency intensities for 245-15400 MHz during 17-30 Jan. 2001

Dates	Radio frequency intensity (arbitrary units) at frequency (MHz)							
January	245	410	606	1415	2695	4995	8800	15400
17	24	52	68	128	140	183	289	541
18	23	54	75	137	156	197	295	541
19	21	48	71	140	155	199	303	549
20	25	48	71	145	156	200	300	546
21	41	55	73	148	155	199	310	552
22	60	67	77	159	164	209	320	556
23	52	66	80	167	175	223	327	571
24	89	154	91	164	185	223	331	552
25	82	88	96	169	188	239	345	580
26	24	57	72	166	175	216	340	574
27	51	57	82	162	177	217	322	534
28	40	59	85	165	195	216	316	559
29	26	58	81	158	169	208	317	557
30	28	62	78	162	178	209	314	531
Mean	42	66	79	155	169	210	316	553
Std.dev	22	27	8	13	15	14	16	15
SD %	54	41	10	8	9	7	5	3

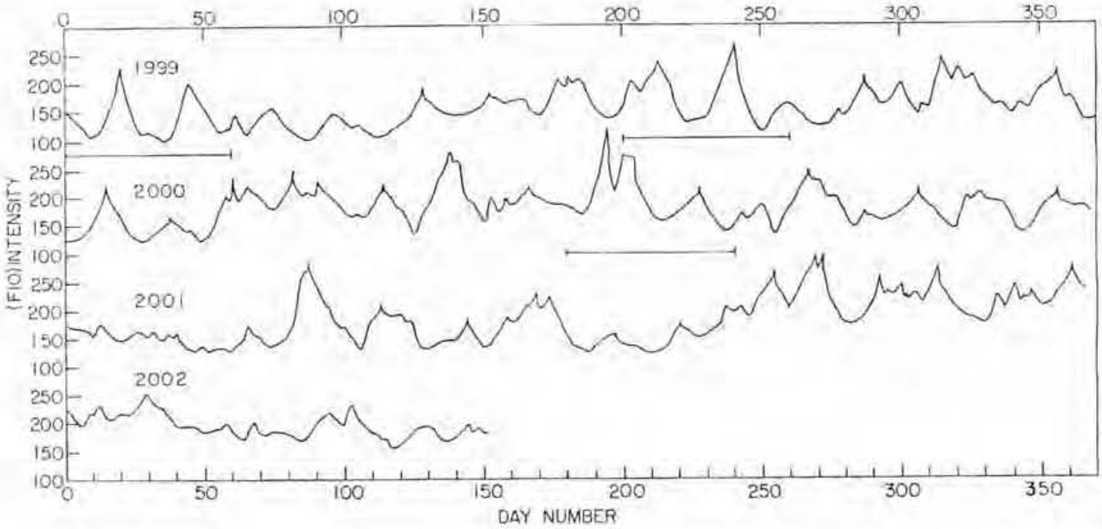

Fig. 2—Plots of the daily values of the 2800 MHz (F10) solar radio emission flux for 1999, 2000, 2001 and 2002 (unit 10^{-22} joules/sec/sq.m/hertz [Each number has been multiplied by 10 to suppress the decimal point). The events marked by horizontal lines were selected for detailed studies.]

referred to as F10) for 1999, 2000, 2001 and a part of 2002 (in unit of 10^{-22} joules/sec/sq.m/hertz. Each number has been multiplied by 10 to suppress the decimal point.). There are considerable day-to-day fluctuations, mostly of solar rotation origin, though the peak spacings deviated considerably from 27 days. For examination, three events were chosen (marked by horizontal lines), each of 60 continuous days (day numbers 1-60 of 1999; 200-260 of 1999; 180-240 of 2000) and each having two prominent peaks. (Many other events could also be chosen as having two prominent peaks, but only these three are chosen as a reasonable sample). Figure 3 shows the plots of daily values for each event for all the solar indices included in Table 1.

In the first event [Fig. 3(a), day numbers 1-60 of 1999], there were two prominent peaks (average locations day 22 and day 46, indicated by vertical lines) with a spacing of 24 days. All indices had peaks within a day or two of these positions. However, the relative heights of these two peaks were different for different indices. For radio emissions, the second peak was higher. A glaring exception was F10 (2800 MHz), which had the second peak smaller, in contrast to even the nearby radio frequency 2695 MHz, which had the second peak higher. This is because the value

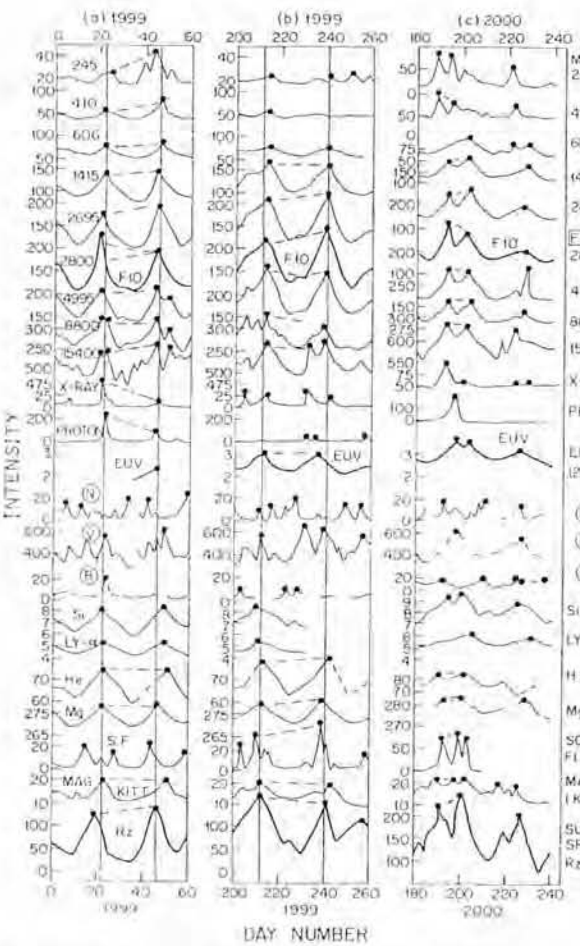

Fig. 3—Plots of the daily values (arbitrary units) of various solar indices for 60-day intervals [(a) Day numbers 1-60, 1999, (b) Day numbers 200-260, 1999 and (c) Day numbers 180-240, 2000.]

of F10 on a single day, namely 20 Jan. 1999 was abnormally high (231). The nearby values were only 170, and if this value is used, the second peak becomes higher (marked by an additional dashed line), just as for 2695 MHz. However, a pollution from burst emissions in 2695 MHz is not ruled out completely. For chromospheric parameters, the two peaks were almost equal, though for sunspot number, the second peak was slightly higher. Different indices had different relative proportions of the first and second peaks with the corona and photosphere having the second peak larger, and in between chromosphere having equal peaks. For an earlier example in the AE-E data, Donnelly *et al.*[12] had reported that the ratios of the first peak near 9 Nov. 1979 to the second peak near 13 Dec. 1979 were 0.95, 1.04, 1.11, 1.22, 1.36 and 1.54 for Ly-α, Ly-β, 304 Å, 284 Å, 335 Å and F10. The interplanetary parameters N (number density), V (wind speed) and B (total magnetic field) near earth had peaks different from the solar indices. No data were available for EUV.

In the second event [Fig. 3(b), day numbers 200-260 of 1999], there were two prominent peaks (average locations day 212 and day 240, indicated by vertical lines, average spacing 28 days), but only for higher radio frequencies (1415 MHz and higher), and the second peak was lower for 1415 MHz, higher for 2695, 2800 MHz only and then lower for 4995 and 8800 MHz. The EUV (26-34 nm) had both peaks equal. There were no complete data for Si III and Ly-α , but He I, Mg II and the solar flare index (*SF*) had the second peak higher, while magnetic field and sunspots had both peaks almost equal. Thus, in contrast to the first event, results were not similar for all parameters in corona or in chromosphere.

In the third event [Fig. 3(c), day numbers 180-240 of 2000], there were three prominent peaks, near day numbers 201 and 227. The third peak was mostly lower than the first two. But for some indices, the first peak was higher than the second peak ,while for some other parameters, it was the other way round.

Thus, the juxtapositions of the second peak with respect to the first peak differed from parameter to parameter with no clear-cut relationship with any solar region (corona, chromosphere, etc.). The systematic ratios reported by Donnelly *et al.*[12] are not seen in all events.

4 Day-to-day changes with temperature in solar atmosphere

Lean[13] mentioned that emissions at the shortest UV wavelengths typically originate mostly from the solar atmosphere. Woods *et al.*[14] mentioned that, in general, there is a decrease in variability with increasing wavelength, because the larger wavelengths emerge from deeper layers in the solar atmosphere where thermal effects of sunspots and plages are relatively small. Thus, the variability should be larger for lower wavelengths. However, such a pattern is valid only for the 'background continuum'. For the various individual emission lines superposed on the continuum, the fluxes and their variabilities are known to be very different from those of the background continuum. Different wavelengths could originate in the same altitude (or temperature) region of the solar atmosphere and may show similar magnitudes of percentage variabilities. Or, similar wavelengths could originate from different parts (chromosphere, corona , etc.) and may have different variabilities. There is also another complication.

Many wavelengths originate from more than one region. For example, the Ly-α radiation is formed in the chromosphere and transition region[7]. The peak emission also depends upon the state of solar activity. For quiet sun, the peak Ly-α emission is near 40,000 K in the lower transition region, while for the plage model, it is near 70,000 K in the higher transition region[10]. Thus, wavelength may not necessarily be a good criterion to judge the depth in solar atmosphere. On the other hand, temperature would probably be a fairly satisfactory indicator of the altitudes as in Fig. 1, at least, in a relative way.

The daily values of solar indices as obtained by Kane[15] during the 26-month interval (June 1997-August 1999) were subjected to spectral analysis and the average amplitudes of the 27-day oscillation were estimated. A plot against solar temperature indicated a peculiar two-humped structure. Here, a different approach is adopted. Thus, in Fig. 3(a), there is a peak near day number 22, another near day number 46, and a trough in between, near day number 35. The two peak values were expressed as percentage increases over the trough value in between and these two were considered as events I and II. Similarly, in Fig. 3(b), the two peaks near day numbers 212 and 240 were expressed as percentage increases over the trough in between, near the day number 230. These two were considered as events III and IV. The plots of the percentage values for the various solar indices versus the solar temperatures at their origin (*T* values shown in Table 1) are shown in Fig. 4. No error bars are shown, as these are very small. The following may be noted:

(i) The plots in Fig. 4(a) is for the average amplitudes of the 27-day wave during 1997-1999, as described earlier by Kane[15]. The dots are for chromospheric UV and the crosses for coronal radio emissions. As mentioned there, the amplitudes have a two-humped structure with minima near the photosphere (5,000 K) and transition region (~100,000 K), and maxima near upper chromosphere (~10,000 K) and lower corona (~300,000 K). (The full lines are rough averages, estimated visually).

(ii) The plots in Fig. 4(b) is for event I (day numbers 22-35, 1999). The percentage values are much larger than those in Fig. 4(a), because the range of an individual event is considered, instead of the average amplitude in Fig. 4(a). However, the pattern (two-humped structure) is almost the same as in Fig. 4(a) .

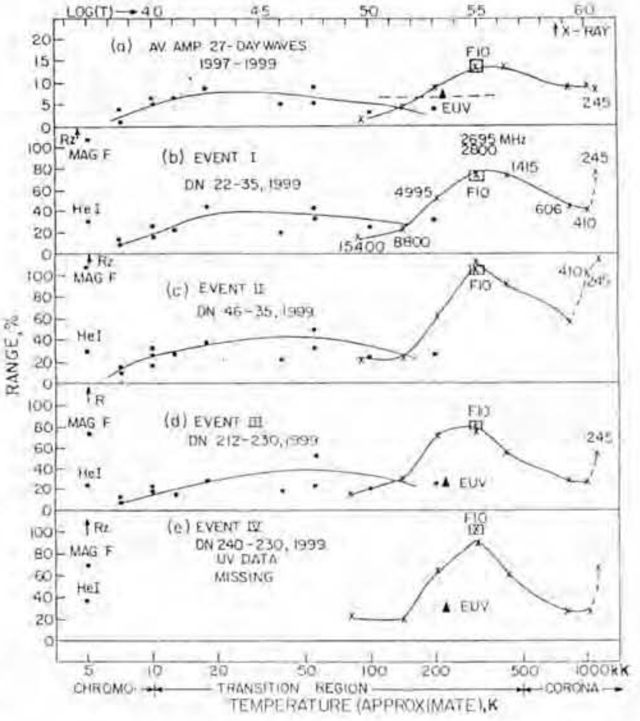

Fig. 4—(a) Percentage amplitudes of the 27-day oscillation during 1997-1999 (Kane[6]), and percentage increases (trough-to-peak) of the daily values during (b) Event I: Day numbers 22-35, 1999, (c) Event II: Day numbers 46-35, 1999, (d) Event III: Day numbers 212-230, 1999, and (e) Event IV: Day numbers 240-230, 1999 [Dots are for chromospheric UV and crosses are for coronal radio emissions.]

(iii) Plots in Fig. 4[(c) and (d)] are for the events II and III and show similar patterns (two-humped structure).

(iv) Plots in Fig. 4(e) is for event IV. Here, chromospheric UV data were missing, but the coronal radio emissions show the maximum near 300,000 K region, as in Fig. 4[(a)-(d)].

(v) Some parameters have abnormally large ranges (several hundred percent), notably sunspot numbers, X-rays and proton events, which rise sharply from very low trough values (see R_z in Fig. 3). Even solar magnetic fields (Kitt Peak observations) have large values. Some of these are shown in the left part of Fig. 4 as largely deviating from the general pattern.

(vi) The percentage values of 2695 MHz and 2800 MHz (F10, shown by rectangles) are almost the same, as expected.

(vii) The EUV values are shown by solid triangles at ~200,000 K [data missing in Fig. 4(b) and Fig.4(c)]. These are mostly away from the general pattern, indicating that a single temperature value is inappropriate. The values would fit well if shifted towards smaller temperatures (~60,000 K) or larger temperatures (~1,000,000 K) (dashed line).

(viii) The values for 245 MHz (and even 410 MHz in event II) are far above the general pattern. This may have a physical implication, but it was noticed that many daily values were abnormally large and were probably polluted by individual bursts. Some weeding has been done, but was probably not enough.

Thus, the two-humped structure seems to be valid for all events, though the percentage magnitudes may differ from event to event. As an explanation, two possibilities need examination. Can a simple model of a chromosphere of a uniform temperature of about 10^4 K and an overlaid corona of temperature 10^6 K, with fixed but different scale heights in the two regions and a pressure balance across the transition region, lead to a double-humped structure? This needs further exploration. Alternatively, at frequencies near about 3 GHz, there will be increasing contribution by gyro-resonance which correlates well with sunspot numbers. This could result into a double-humped structure. This too needs further exploration.

5 Plots of monthly values

Figure 5(a) shows a plot of the monthly values for 1999- 2002 (a few of these are not mentioned in Table 1 as their daily values were not available). There are several peaks (shown by dots) in roughly the same months for all indices, indicating that these fluctuations are genuine. With 8-9 peaks in ~28 months, an average spacing of 3-3.5 months (~100 days) is indicated which is smaller than the ~155-day periodicity reported by Rieger *et al.*[16] and Lean and Brueckner[17]. A correlation analysis indicated the following:

The radio emissions at 1415, 2695, 2800, 4995 and 8800 MHz were well correlated with each other as well as with X-rays, EUV, Mg II, surface magnetic fields (Kitt Peak as well as Mt. Wilson), Ca K index and even sunspots, indicating that the peak-matching was quite good.

However, the correlations hardly exceeded 0.85, indicating some dissimilarities.

Figure 5(b) shows plots of the 12-month moving averages (6 months of monthly data of Fig. 5(a) are lost at each end). All values are fractions with respect to the average level of 2000-2001 (the vertical bar on the EMDX plot is the scale for EMDX, which could

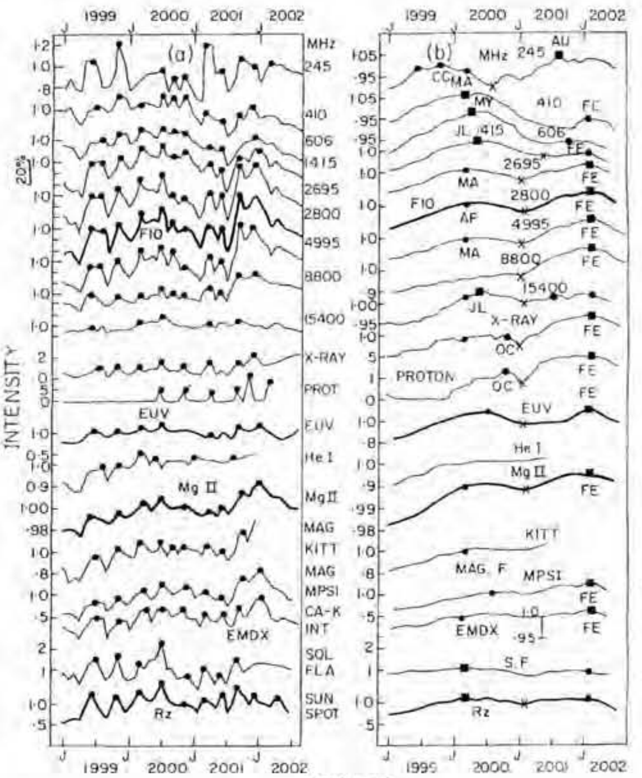

Fig. 5—Plots of (a) Monthly values and (b) 12-month moving averages of various solar indices for 1999-2002 (fractional units with respect to the average of 2000-2001).

not be indicated on the y-axis). The following are noteworthy:

(i) Most of the indices had a maximum near March 2000.

(ii) Some indices decreased monotonically thereafter, but some had a minimum near January 2001 and either stayed there or started rising again thereafter.

(iii) Some indices did not have a maximum near March 2000 and continued to rise till 2001 end. For these, the 12-month moving averages did not yet show a decline, but monthly values showed considerable declines, indicating that the 12-month moving averages might have reached a maximum. Data for the next few months should settle this issue.

(iv) A correlation analysis indicated that some indices were very well intercorrelated (410, 606, 1415 MHz with each other; 2695, 2800, 4995 MHz, Mg II with each other; EUV with Rz), but poorly correlated with some others (2800 MHz with EUV or R_z). This is strange, since R_z and 2800 MHZ are usually reported as having correlation exceeding 0.98. These dissimilarities are illustrated in detail by Kane[18].

6 Discussion and conclusions

Comparison of the evolutions of daily and monthly values of several solar indices during 1999-2002 reveals the following:

Daily values:

(i) The daily values indicated large day-to-day fluctuations with peak spacings differing considerably from the 27-day solar rotation period.

(ii) Some individual events with large peak-to-trough ranges were examined. Plots of the percentage increases (trough-to-peak) versus temperature of the source regions of the various indices indicate a double-humped structure (low amplitudes in lower chromosphere, transition region and upper corona; high amplitudes in upper chromosphere and lower corona), similar to that reported by Kane[15].

Monthly values:

(i) The monthly values show many peaks. The average spacing is ~3.5 months (~100 days).

(ii) In the 12-month moving averages, some indices reached a maximum near March 2000. Some of these decreased since then and continue to decrease at present, but some reached a minimum near January 2001 and remained steady there, or started increasing again to reach a probable maximum near June 2002. Some indices did not have a maximum in March 2000 and continue to increase till June 2002. Thus, the evolutions of the various solar indices during the sunspot maximum of cycle 23 (1999-2002) are substantially different from each other. Obviously, the dynamical upheavals in the photosphere reach upper levels of the solar atmosphere with varying intensities.

These differences have an important implication for proxy purposes. Since the publication of solar UV and EUV data from AE-E (1977-1981), efforts have been made to model the EUV using 2800 MHz flux as a proxy. Later, Ly-α, X-rays and Mg II were also incorporated as proxies (Ref. 19 and references therein). During 2001-2002 [Fig. 5(b)], F10 and Mg II continued to rise considerably from January 2001 onwards up to June 2002, but EUV and smoothed sunspot number have remained steady since January 2001. Thus, neither F10 nor Mg II have evolved parallel to EUV, turning them unsatisfactory as proxies for EUV. Some of the correlations for the 12-monthly values for 1999-2001 are as follows : F10 with Mg II is 0.94; EUV with sunspots is 0.92; but EUV with F10 is only 0.57, and EUV with Mg II is only 0.49. Variations of solar radiations in the UV and EUV bands have important implications for day-to-day and long-term variabilities in the terrestrial atmosphere[21-23] and hence need to be estimated accurately.

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References

1 Waldmeier M, *The sunspot activity in the years 1610-1960* (Schulthess & Company AG, Zurich), 1961.

2 McKinnon J A, *Sunspot numbers 1610-1985* in *UAG Report*, NOAA Boulder, Colorado, USA, Vol. 95, 1987, p. 112.

3 Schwabe S H, *Astron Nachr (Germany)*, 20 Nr. 473 (1843) 283.

4 Schwabe S H, *Astron Nachr (Germany,)* 21 Nr. 495 (1844) 234.

5 Gaizauskas V, Zwaan C, Harvey K L & Harvey J W, *Astrophys J (USA)*, 265 (1983) 1056.

6 Kane R P, *Ann Geophys (France)*, 20 (2002) 741.

7 Vernazza J E, Avrett E H & Loeser R, *Astrophys J (USA)*, Suppl. Ser. 45 (1981) 635.

8 Woods T N, Tobiska W K, Rottman G J & Worden J R, *J Geophys Res (USA)*, 105 (2000) 27195.

9 Zirin H,. *The Chromosphere* in *Astrophysics of the Sun* (Cambridge University Press), 1988, Ch. 7

10 Fontenla J M, White O R, Fox P A, Avrett E H & Kuruez R L, *Astrophys J (USA)*, 518 (1999) 48.

11 Kane R P, Vats Hari Om & Sawant H S, *Sol Phys (Netherlands)*, 201 (2001) 181.

12 Donnelly R F, Hinteregger H E & Sheath D F, *J Geophys Res (USA)*, 91 (1986) 5567.

13 Lean J, *J Geophys Res (USA)*, 92 (1987) 839.

14 Woods T N *et al.*, *J Geophys Res (USA)*, 101 (1996) 9541.

15 Kane R P, *J Geophys Res (USA)*, 107 (A10) (2002) 1298.

16 Rieger E, Share G H, Forrest D J, Kanbach G, Reppin C & Chupp E L, *Nature (UK)*, 312 (1984) 623.
17 Lean J L & Brueckner G E, *Astrophys J (USA)*, 337 (1989) 568.
18 Kane R P, *J Geophys Res (USA)*, 108 (A12) (2003) 1455.
19 Tobiska W K, Woods T, Eparvier F, Viereck R, Flyod L, Bouwer D, Rottman G & White O R, *J Atmos & Sol Terr Phys (UK)*, 62 (2000) 1233.
20 Vernazza J E, Avrett E H & Loeser R, *Astrophys J (USA)*, Suppl. Ser. 30 (1976) 1.
21 Kane R P, Trivedi N B, Tanaka Y, Hajime Y & Pathan B M, *Indian J Radio & Space Phys*, 32 (2003) 251.
22 Kane R P, *Indian J Radio & Space Phys*, 32 (2003) 344.
23 Chandra H, Kovalam S & Vincent R A, *Indian J Radio & Space Phys*, 31 (2002) 237.