Periodicities of a few months in solar indices

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Abstract

The periodic structure in the time series of a number of solar indices is examined for the interval 1992–2000. The de-trended values of the 27-day moving averages of various solar indices indicated substantial oscillations (ranges up to 35% or more), but the spacings in successive peaks varied considerably (100–600 days). A spectral analysis indicated prominent peaks at ∼360 and 670 days, with minor peaks at 120–230 days. The ranges (peak to trough) were large (15–20%) for solar indices sunspots and magnetic fields, but very small (1–3%) for lines in lower chromosphere, increasing to ∼10% in the middle and upper chromosphere, decreasing (∼5%) in the lower transition region, rising rapidly (up to 35%) in the middle corona, and decreasing thereafter to ∼20%. The peaks at different solar altitudes generally tallied, indicating that the structures spread above the photosphere into the chromosphere and corona in phase, though the magnitudes were different at different altitudes. © 2003 Elsevier Ltd. All rights reserved.

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1. Introduction

Solar activity indices show variations in a wide range of time scales, from a few days to several years. In short-term variations, the most striking is the 27-day oscillation (attributed to solar rotation), which has been examined in great details (e.g., Donnelly et al., 1983; Rottman, 1983; Simon et al., 1987; Lean and Brueckner, 1988; Tobiska and Bouwer, 1989), and is shown to be similar at all solar altitudes (Kane, 2002a). Long-term variations of ∼11 years are also reported in many solar indices and irradiances for which data over several solar cycles are available (notably, sunspot number itself, 10.7 cm 2800 MHz flux F10, and radio fluxes 1000, 2000, 3750, 9400 MHz observed at Toyokawa). Recently, Kane (2002b) examined the temperature (or solar altitude-) dependence of the percentage amplitudes of the 27-day oscillations and long-term trends of several solar irradiances originating in the solar chromosphere and the corona, and reported a double-humped structure (maxima in the middle chromosphere and middle corona and minima in between). However, there have been reports of solar variability at intermediate periodicities too, e.g., ∼155 days (Rieger et al., 1984; Lean and Brueckner, 1988) and ∼300 days (Delache et al., 1985; Lean and Brueckner, 1988; London et al., 1989). The reality of these periodicities has been doubted by Hudson (1987) mainly on the grounds of use of inadequate or inappropriate computational techniques, but Pap et al. (1990) used a standard FFT time series analysis and showed an 8–11 months periodicity in the solar total and UV irradiances, 10.7 cm radio flux, Ca K plage index, and sunspot blocking function. The data used were from the Nimbus-7 and Solar Maximum Mission (SMM) satellites during 1981–1989. In recent years (1990–2001), data are available for several chromospheric line emissions and coronal radio emissions. In the present communication, these data are examined for periodicities of a few months.

2. Data

Table 1 lists the various solar indices and irradiances for which data were used. For the UV spectral lines, data
<table>
<thead>
<tr>
<th>Wave. (nm)</th>
<th>Temp. $T$ (K)</th>
<th>Log $T$</th>
<th>Range (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-rays 0.1–0.8</td>
<td>&gt; 2 million.</td>
<td>~-6</td>
<td>16.9</td>
</tr>
<tr>
<td>Cor. Green 530.3</td>
<td>&gt; 1 million</td>
<td>~-6</td>
<td>16.9</td>
</tr>
<tr>
<td>Sunspots</td>
<td>5000</td>
<td>3.7</td>
<td>20.5</td>
</tr>
<tr>
<td>Ca PFIFX</td>
<td>5000</td>
<td>3.7</td>
<td>13.0</td>
</tr>
<tr>
<td>Mag. AR</td>
<td>5000</td>
<td>3.7</td>
<td>77.0</td>
</tr>
<tr>
<td>Mag. QS</td>
<td>5000</td>
<td>3.7</td>
<td>15.2</td>
</tr>
</tbody>
</table>

Lines

- O I 130.4 7060 3.85 1.9
- C I 165.6 7060 3.85 1.5
- Si II 126.2 10,000 4 3.2
- Si II 153.0 10,000 4 4.0
- Si II 181.3 10,000 4 2.6
- C II 133.6 12,600 4.1 4.5
- Si III 120.6 17,800 4.25 5.3
- H I 121.6 40,000 4.6 2.5
- Si IV 139.8 56,700 4.75 5.4
- He II 164.0 56,700 4.75 9.0
- C IV 155.0 100,000 5 3.5
- N V 124.1 200,000 5.3 3.4
- Mg II 280.0 6500 3.85 1.3
- He I 1083.0 6500 3.85 15.1

Radio (MHz)

- 2800 F 10 300,000 5.48 13.8
- 15400 SGMR 88,000 4.95 1.9
- 8800 SGMR 140,000 5.15 13.4
- 4995 SGMR 200,000 5.3 25.5
- 2695 SGMR 315,000 5.5 34.7
- 1415 SGMR 415,000 5.62 31.5
- 606 SGMR 835,000 5.92 18.8
- 410 SGMR 1,000,000 6 22.6
- 245 SGMR 1,200,000 6.08 32.8

(daily values of intensities) were the UARS SOLSTICE observations of 12 lines, namely, Hydrogen I (Lyman $\alpha$), 121.6 nm Helium II, 164.0 nm; Nitrogen V, 124.1 nm; Oxygen I, 130.4 nm; Carbon I, 165.6 nm; II, 133.6 nm; IV, 155.0 nm; Silicon II, 126.2 nm; II, 153.0 nm; II, 181.3 nm; III, 120.6 nm; IV, 139.8 nm, kindly supplied by Dr. Thomas Woods of the University of Colorado. These UV emission lines are from a special UARS data product 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. The excitation temperatures of these line emissions have been determined (Vernazza et al., 1981; Woods et al., 2000) by taking the ratio of excitation rates for two doublets of the same super-multiplet (Zirin, 1988) 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 temperature–height profiles are taken from Fontenla et al. (1999), where the temperature drops from ~6000 K at the solar surface to 4800 K at ~500 km and then rises to 6000 K at 900 km, 8000 K at 1900 km, 10,000 K at ~2100 km, increases rapidly to ~500,000 K in a narrow transition region around 2100 km, reaches 900,000 K at 2800 km, and a million degrees or more in the corona. However, these are quiet-sun values and may change considerably (lower altitudes for the same temperatures) over active regions. Spatially-resolved observations in the UV and X-rays have shown material of a given temperature extending tens to thousands of km in the corona. Radio emissions in the 1000 –10,000 MHz range can arise from the chromosphere at the high end, corona at the low end, or a combination of both. Hence, all height estimates are very, very approximate and uncertain. Variations with respect to temperatures are more reliable.
Data were available for Mg II 280.0 nm (NOAA website) and SEM/SOHO EUV (26–34 nm) for 1996 onwards. However, the region in which the EUV data originate is not unique (private communications from Karen Harvey and Don McMullin). The 26–34 nm wavelength range is produced at three levels: upper chromosphere, transition region and corona. The temperature of the 28.4 nm Fe XII line is 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.

For radio emissions, the data are from the WDC-A Archive, Boulder, average calculated for data from Sagamore Hill, Massachusetts; Pahelua, Hawaii; San Vito, Italy; Learmonth, Australia (245, 410, 606, 1415, 2695, 4995, 8800, 15, 400 MHz, noon-time values). The temperatures of the regions of origin of these radio emissions are obtained as discussed in Kane et al. (2001). Besides, data for some other parameters were obtained from the NOAA website.

3. Methodology

Since the 27-day oscillation is substantial (several tens of percent), it had to be eliminated. This was achieved by calculating moving averages over 27 consecutive daily values. Fig. 1 illustrates the procedure for the 10.7 cm 2800 MHz flux (termed here as F10). In Fig. 1a, the 27-day moving averages of F10 are plotted, not for every day but for every seventh day (52 values per year). As can be seen, the major variation now is the long-term (solar cycle variation), as the declining phase of cycle 22 (1992–1996) and the ascending phase of cycle 23 (1996 onwards). The 8–11 month oscillation is not evident in this plot because of its comparatively small magnitude. To eliminate the long-term variation, the 27-day averages spaced at 7 days (1 week) were moving averaged over 52 (weekly) values and these (yearly) averages were subtracted from the weekly values of the 27-day moving averages. Fig. 1b shows the plots. As can be seen, there are oscillations with spacings in a very wide range, 18–68 weeks, indicated by numbers, or 126–476 days, indicated by numbers in parentheses. Since some numbers are very near a year (365 days), the subtraction of yearly (52 week) averages may not be appropriate. Hence, moving averages over 103 weeks (~720 days, almost 2 years) were calculated and subtracted (with proper care for centering) from the weekly values of the 27-day moving averages. Fig. 1c shows the plots. The spacings are almost the same as in Fig. 1b, indicating that the use of 1-year or 2-year moving averages for determining the long-term trend is not very critical. Nevertheless, to be on the safe side to ensure that fluctuations of even up to ~600 days would be retained, the 2-year moving averages were used, even though this meant losing almost a year’s data at each end. Further, for comparative examination of different indices, these deviations were expressed as percentages of the 2-year moving averages at appropriate centering. Fig. 1d shows the plots of Fig. 1b in percentages and Fig. 1e shows the plots of Fig. 1c in percentages. As can be seen, oscillation ranges (trough to peak) can be as large as 35%, but only in years of high solar activity. In low solar activity, the ranges are less than 10%. In subsequent figures, only plots like Fig. 1e are shown.


Fig. 2 shows the plots for 1991–1995, starting with highest solar altitudes (approximate) at the top, for radio emissions 245, 410, 606, 1415, 2695, 4995, 8800, 15, 400 MHz, with F10 (2800 MHz) sandwiched in between (near 2695 MHz) and shown by a thicker line. The maxima are shown with full dots and minima with crosses. As can be seen, during 1991, there were many maxima at short spacings (~10 weeks, i.e., 35–70 days, more in the 245 MHz, but some also present in other radio fluxes) but thereafter, clear peaks are seen at longer spacings, though the spacings are not constant. The second thick line is the average for all radio emissions (excluding 2800 MHz) and shows major spacings of 400, 308, 336, 308 days, almost the same as for F10 (the accuracy of these numbers is only ~ ± 7 days, also, some minor shorter spacings in the average plot are mainly due to their presence in 245 MHz). The plots for X-rays and coronal green line index show prominent peaks but the spacings are different. The middle part of Fig. 2 shows plots for the various emission lines. These start only by the end of 1992 (the daily values were available from the end of 1991 only) and the plots are similar. Their average (thick line) shows spacings of 350 and 330 days, somewhat different from the 308 and 336 days of the radio emissions. Plots further down below are for the Helium I absorption line 1083 nm (ground-based measurements), magnetic fields from the Kitt Peak Observatory (for Active Regions AR and Quiet Sun QS, data sent privately by K. Harvey), Calcium SFO K line Facular data PFIX (Chapman et al., 1996), and sunspot numbers. The daily values of the Helium I data are very intermittent and 27-day averages may not be reliable, but for the common period 1993–1995, the peaks are similar to those of the line emission average. The magnetic fields, both AR and QS also show similar peaks, though in 1991–1992, the two differ considerably. The PFIX data and the sunspots seem to show peak positions slightly different from those of the other indices, indicating a lack of spatial or temporal correlation between sunspots and flux indices.


Fig. 3 shows plots for 1996–2000. Here, the plots for different indices differ considerably. The F10 (first thick line) shows virtually no variation in 1996–1997 and two waves (spacings 336, 266 days) in 1998–2000. On the other hand, the average of other radio emissions (and even individual
Fig. 1. Plots for the 10.7 cm 2800 MHz radio flux (F10) for 1992–1996 and 1996–2000, (a) 27-day moving averages at intervals of 7 days, 52 values per year, (b) 27-day moving averages from which 52-week moving averages are subtracted (to remove long-term variations), (c) 27-day moving averages from which 103-week moving averages are subtracted (to remove long-term variations), (d) Values of (b) expressed as percentage deviations, (e) Values of (c) expressed as percentage deviations. The numbers indicate spacings in weeks and the numbers in parentheses indicate the same spacings in days. Maxima are marked by dots and minima by crosses.

emissions) show several peaks in 1997–2000, with spacings in a wide range 112–350 days, but mostly in the range 112–147 days, much shorter than the range in 1991–1995. These peaks are very prominent in 245 MHz and dominate in the average, but the peaks are there in all frequencies (except perhaps 15,400 MHz where all effects are very small). The X-rays show very few peaks. (Data for coronal green line index are not yet available to us beyond 1997). For solar chromospheric line emissions, there are virtually no peaks during 1996–1997, and the average plot shows two short-spaced (∼150 days) peaks in early 1999. The radio emissions data seem to show many short-spaced peaks in 2000. Surprisingly, the He I line, magnetic field, and sunspot data seem to show peaks even in 1996–1997 (PIFX data are insufficient), and the spacings are dissimilar for the different indices.

6. Spectra

The irregular spacings could be because the activity occurs irregularly or because more than one (but not too many) periodicities are involved. In the latter case, a spectral
analysis could give some clue. For the three longest series namely, F10 (2800 MHz), average of radio flux 245–15, 400 MHz and sunspots, spectral analysis was done for 1991–1995 and 1996–2000 separately, using Maximum Entropy Spectral Analysis (MESA, Burg, 1967; Ulrych and Bishop, 1975). However, in MESA, the amplitude (or power) estimates are unreliable (Kane, 1977; Kane and Trivedi, 1982). Hence, MESA was used only for detecting the peaks $T_k$ ($k = 1–n$) and the various $T_k$ for every series were used in a multiple regression analysis (Bevington, 1969) to estimate $A_0$, $(a_l, b_l)$ and their standard errors (by a least-squares fit) for that series (see also Kane et al., 2001). From these, $r_k$ and their standard error $\sigma_r$ (common to all $r_k$, in this methodology) were estimated and $r_k$ exceeding $2\sigma_r$ were accepted as significant at a 95% (a priori) confidence level.

Fig. 4 shows the spectra, for (a) 1991–1995 in the left half and for (b) 1996–2000 in the right half. The hatched portion shows the $2\sigma$ limits. As can be seen, the strongest periodicity is near 325–365 days, but there are other minor periodicities, often barely significant, near 120–230 days, different in different solar indices. To check whether these were mainly due to 245 MHz, the analysis was repeated for an average of 410–15, 400 MHz (i.e., excluding 245 MHz). It was noticed that the amplitudes for 120–130-day range were reduced considerably (but were not zero) and fell
inside the $2\sigma$ limit, while the other periodicities remained unaltered. A striking feature is a periodicity near 615–680 days (21–22 months) seen in all the three indices. It could be a distorted form (due to the methodology of subtracting 2-year averages) of the $\sim$25-month periodicity reported by Shapiro and Ward (1962) and Westcott (1964) for sunspot series.

7. Temperature (solar altitude) dependence of the magnitudes of the fluctuations

The largest percentage fluctuation in Figs. 1 and 2 is in the beginning of 1992. However, there are no data for line emissions for that event. Hence, the next largest event was chosen namely, the decrease from the maximum near the 10th week of 1993 to the minimum near the 35th week of 1993. Table 1 lists the percentage ranges (peak to trough) for various parameters and Fig. 5 shows the plot of the ranges versus solar temperature. The percentages are small in the chromosphere (1–10%, shown by dots) and large in the corona (up to 35%, shown by crosses). There is a slight indication that the percentages are very small (1–3%) near the photosphere, have a maximum (up to 10%) in the upper chromosphere (see the probable trend indicated by the superposed full line), lower values ($\sim$5% or lower) in the lower transition region, rising thereafter up to 35% for the region where 2695 MHz radio emission occurs, and decreasing thereafter. Values for 410 and 245 MHz show a rise but, these are probably polluted by noise storms which per-

Fig. 3. Same as Fig. 2, for 1996–2000.
sist for days (though some obvious ones were eliminated from the data before analysis) and are not fully reliable, particularly for 245 MHz. A similar double-humped structure was noticed for the amplitudes of the 27-day oscillations (Kane, 2002b). The Coronal green line index had a range of \( \sim 15\% \) (roughly similar to the ranges of the radio emissions) and is tentatively put in the million K temperature region, though it may originate in a wide range of altitudes. The same is true for X-rays, which are indicated tentatively in the corona and had a range of 23\%, roughly the same as for the radio emissions.

It may be noted that the magnetic field of active region (AR) had an abnormally large range (77\%), while Magnetic field (quiet sun), sunspots, Calcium K line index PF1FX and the He I absorption line 1083 nm (big full circles), all originating at or near the photosphere, had large ranges of \( \sim 15\% \). However, these variations of solar indices do not have any specific emission temperature as such, and their variations are not directly comparable to the variations of solar irradiances. Hence, in Fig. 5, these are indicated by big full circles far above the smaller dots for solar irradiances at temperatures near the photosphere (\( \sim 5000 \) K).

8. Conclusions and discussion

To examine intermediate time-scales (few months), the daily values of several solar indices were subjected to 27-day
moving averages (to eliminate the 27-day oscillations) and from these, 2-year moving averages were subtracted (to eliminate long-term trends), and the deviations were expressed as percentage deviations of the 2-year averages. An analysis of the daily values and the moving averages of several solar indices and irradiances indicated the following:

(1) The deviations indicated substantial oscillations (ranges up to 35% or more), but the spacings in successive peaks varied considerably (100–600 days). A spectral analysis indicated prominent peaks at ~360 and 670 days, with minor peaks at 120–230 days. The possibility of the ~360-day periodicity being an artifact of weather (bad seeing conditions in summer or winter?) cannot be ruled out.

(2) The ranges (peak to trough) were large (15–20%) for solar indices (sunspots and magnetic fields) but these are not directly comparable to solar irradiances, for which the ranges were very small (1–3%) for lines in lower chromosphere, increasing to ~10% in the middle and upper chromosphere, decreasing (~5%) in the lower transition region, rising rapidly (up to 35%) in the middle corona, and decreasing thereafter to ~20%. This decrease could be an artifact, because of systematic errors in temperatures, or due to sunspot-associated gyroresonance emissions in the 2000–7000 MHz range.

(3) The peaks at different solar altitudes generally tallied, indicating that the structures spread above the photosphere into the chromosphere and corona in phase, though the magnitudes were different at different altitudes.

Since the magnetic fields, particularly those of active regions also show the intermediate scale periodicities, one may surmise that the sources of all this activity are probably the magnetic field structures. Pap et al. (1990) mentioned that 8–11-month periodicities were seen mainly during the declining phase of solar cycle 21. The same thing seems to be true for the declining phase of cycle 22. Pap et al. (1990) speculated that these periodicities seen in the Ca-plage indicated the evolutions of active regions on the various parts of the solar surface could result in more precise information. The dip in amplitudes in the region of ~100, 000 K is reminiscent of a similar dip in the "emission measure" reported by Warren et al. (1998, 2001) in their new model of EUV irradiance variability, and the two effects may be inter-related.

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References