LONG-TERM AND MEDIUM-TERM VARIATIONS OF SOLAR RADIO EMISSIONS AT DIFFERENT FREQUENCIES

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Abstract. Plots of 12-month moving averages of the radio emission values for 1947 – 2002 indicated that the ratios (maximum/minimum) of the solar cycles 19 – 23 were low (~ 1.2) in the upper chromosphere and lower corona (frequencies near 15 000 MHz), rose to maximum levels of ~ 3.5 in the middle corona (frequencies $\sim 2000 \pm 500$ MHz), and dropped thereafter to ~ 2.5. In some cycles, there were two maxima separated by about 2 years. In cycles 20 and 23, mostly the second maximum was larger than the first maximum, but in cycles 21 and 22, some parameters showed the first maximum larger while others showed the second maximum larger. There was no systematic shift from first maximum to second maximum, with frequency or temperature (or altitude).

1. Introduction

The Sun emits radio energy with a slowly varying intensity. Radio flux originates from atmospheric layers high in the Sun's chromosphere and low in its corona, and changes gradually from day to day, in response to the number of spot groups on the disk. Radio intensity levels consist of emission from three sources: from the undisturbed solar surface, from developing active regions, and from short-lived enhancements above the daily level (NOAA website *ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SOLAR_RADIO/FLUX/read.me*).

Radio emissions can be due to several mechanisms, e.g., bremsstrahlung, gyrosynchrotron, Čerenkov. The radio emissions studied here (245 – 17 000 MHz) are mostly from the upper chromosphere to the solar corona due to the bremsstrahlung, and the frequency that is emitted depends upon the plasma density of the region of emission. Due to the highly dynamic nature of the solar atmosphere, the densities at any altitude are highly variable, particularly during severe solar activity periods. But models of plasma density and radio emissions give approximate heights for the various emissions. Aschwanden and Benz (1995) and Melendez *et al.* (1999) have discussed a model which sets the density at different heights above the solar surface. From this model, the plasma frequency at different heights can be calculated. Benz (1993) mentions that dynamic spectra (e.g., of type III bursts) sometimes show two similar features displaced in frequency by about a factor of two, which can be interpreted as the fundamental plasma frequency (first harmonic), and its second harmonic. However, due to collisional absorption, the low-frequency part

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(first harmonic) is mostly invisible and what is seen is the second harmonic, of about double the frequency. On the other hand, for bremsstrahlung, the emission would be in a range of frequencies. If it is assumed that it is the second harmonic that escapes from any region, the model proposed by Aschwanden and Benz (1995) and Melendez *et al.* (1999) indicates a height range from about 150 000 km (for 275 MHz flux), down to about 20 000 km (for 17 000 MHz flux). If the first harmonic is considered, the height range indicated is from about 90 000 km (for 275 MHz flux). The second harmonic is probably not relevant in case of bremsstrahlung. In any case, the range covers a very large portion of the corona. Also, even though the altitudes as given here are very approximate, in general, higher frequencies can be assumed to be able to emerge from deeper regions (lower solar altitudes). 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. Also, the solar corona is not always spherically symmetric. During solar minimum, only the equatorial corona is bright with streamers. During solar maximum, streamers can be seen all over, so the corona looks symmetric. The CMEs (coronal mass ejections) also come from low latitudes during solar minimum but from low and high latitudes during solar maximum (Gopalswamy *et al.*, 2003a, b). Hence, the same frequency may escape from different altitudes during solar maximum and solar minimum. The effect is more severe for solar maximum because the plasma levels fluctuate between streamer and non-streamer regions. In white light, the coronal brightness varies by a factor of 4 (MacQueen *et al.*, 2001, and references therein) due to an increase in electron density (Thompson scattering) and this affects plasma levels. Thus, the absolute altitude levels from which radio frequencies escape are uncertain and *all height estimates are very approximate*. However, we believe that in a relative way, higher frequencies would escape from lower depths (lower solar altitudes), so the relative comparison should be qualitatively valid.

For 2800 MHz flux (and probably for many other frequencies), there are two major components, namely, rotationally modulated, and unmodulated. The unmodulated emission comes from outside active regions, is mostly thermal bremsstrahlung, and dominates the Sun during solar minimum. The rotationally-modulated 2800 MHz solar radio emission is mostly a thermal gyro-resonance emission from the strong magnetic fields above sunspots (though some non-thermal emission is also indicated and thermal free–free emission from active regions cannot be ruled out), and may come from a wide range of altitudes, say 10 000−40 000 km above the solar surface (Schmahl and Kundu, 1994, 1995). In any case, the flux range 275−17 000 MHz is most probably from the upper corona down to the upper chromosphere.

In this communication, long-term (solar cycle) and medium-term (1–3 year) variations are examined and compared at different radio frequencies for solar cycles 18–23.

2. Data

Solar flux density at 2800 MHz (10.7 cm) has been recorded routinely by the radio telescope near Ottawa, Canada since 14 February 1947. Each day, levels are determined at local noon (1700 GMT) and then corrected to within a few percent for factors such as antenna gain, atmospheric absorption, bursts in progress, and background sky temperature. Beginning in June 1991, the solar flux density measurement source is Penticton, B.C., Canada. The tables in the above website contain fluxes from the entire solar disk at a frequency of 2800 MHz in units of 10^{-22} J $s^{-1}sm^{-1}$ Hz^{-1}. Three sets of fluxes – the observed, the adjusted, and the absolute – are available. In the present communication, adjusted fluxes have been used.

Besides the 2800 MHz flux recorded in Canada since 1947, data are available for several frequencies recorded at other locations (data in the above NOAA website). Data from May 1966 through December 1987 are from Sagamore Hill (SGMR) in Massachusetts only. These data have been quality-controlled. From 1988 onwards, data are available from Palehua (PALE) Hawaii, San Vito (SVTO) Italy, Learmonth (LEAR) Australia, and Sagamore Hill. However, these data have not been quality-controlled and we have used only SGMR data for 1988 onwards. The following frequencies are available: ~245, 410, ~609, 1415, 2695, 4995, 8800, and 15 400 MHz. In Japan, data are available from Toyokawa and Nobeyama from 1951 onwards for frequencies 1000, 2000, 3750, 9400, and 17 000 MHz.

3. Plots

Radio emissions have contributions from short-lived bursts (minutes to hours) as well as day-to-day variations. As the purpose was to study medium- and long-term variations (one year and more), monthly means were calculated and smoothed by calculating 12-month moving averages. Figure 1 shows the plots of 12-month moving averages. The first (top) plot is for sunspot number Rz and the second plot is for 2800 MHz radio emission, for sunspot cycles 18–23 (1947–2002). The dashed lines connect the cycle maxima and indicate large cycle-to-cycle variations. The other plots are for radio emissions at ~245, 410, ~609, 1000, 2000, 1415, 2695, 3750, 4995, 8800, 15 400, and 17 000 MHz. Two major features are evident in all the plots, namely, (a) the ~11-year cycle and (b) double peaks at the maxima of cycles 20, 21, 22, 23 (larger peak indicated by a full square, and the smaller peak by a dot).

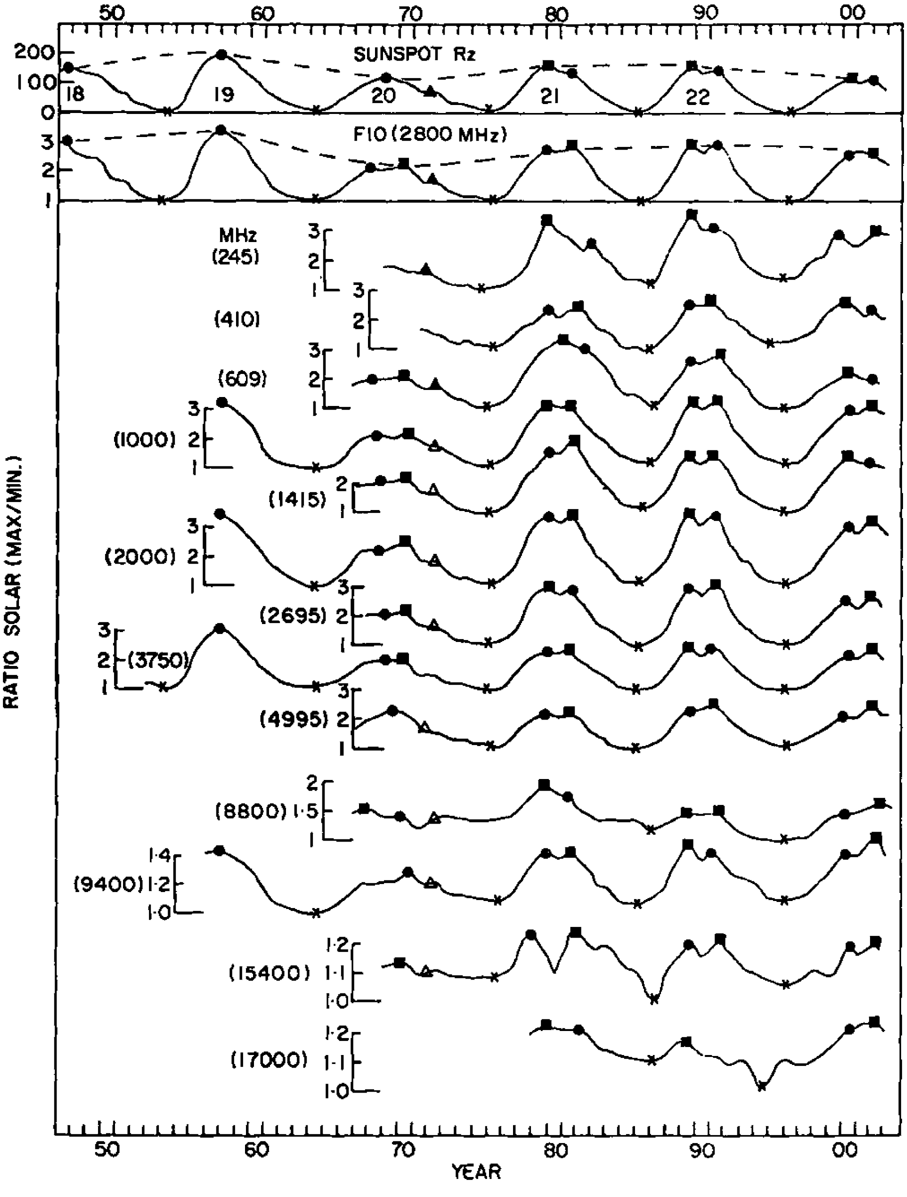

Figure 1. Plots of the 12-month moving averages (1947–2002) of sunspot number Rz (*top plot*), 2800 MHz solar radio flux *F*10 (*second plot*) (the *dashed lines* connect the cycle maxima), and 13 solar radio frequencies (245–17 000 MHz) in *succeeding plots*. In cycles 21–23 where two peaks occurred near sunspot maxima, the larger peak is denoted by a *full square* and the smaller peak by a *dot*. Minima are indicated by *crosses*. During the declining phase 1970–1976 of cycle 20, values for 1972 showed an inflection (values same as or larger than the previous year 1971), shown by a *triangle*.

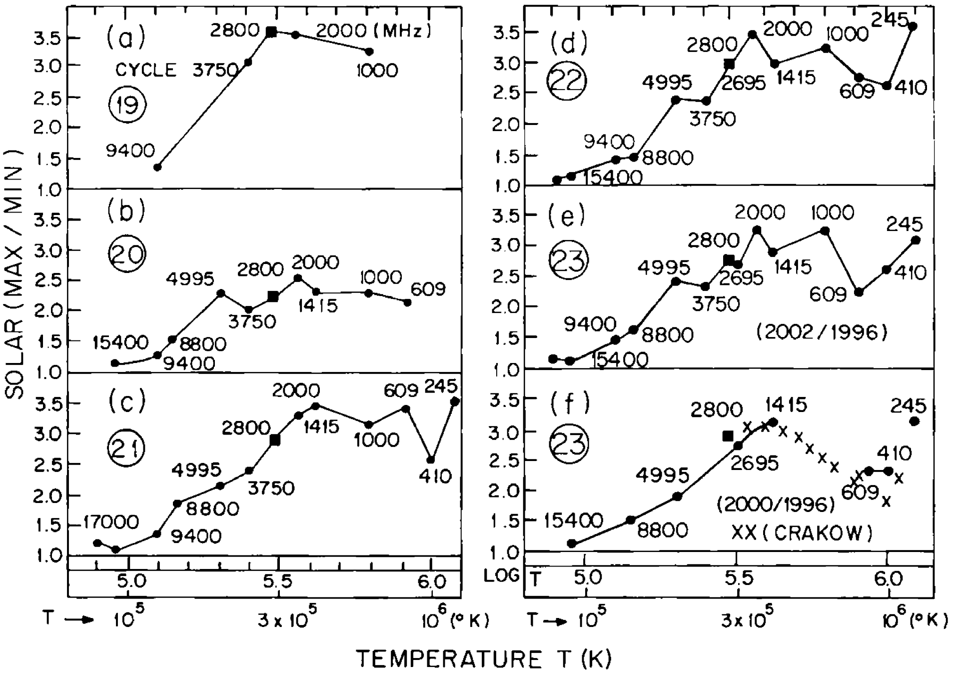

Figure 2. Plots of magnitudes of the ratio solar max/min if there were two maxima, the higher one) versus temperatures T, for (a) cycle 19, (b) cycle 20, (c) cycle 21, (d) cycle 22, and (e) cycle 23. The radio frequencies involved are indicated. (f) is also for cycle 23, but shows ratio for data up to year 2000 only and additional data (*crosses*) observed at Krakow, Poland are used as in Kane (2002). The *full square* is for 2800 MHz and *dots* are for other frequencies.

3.1. LONG-TERM VARIATION

As is already known, the peak values in different cycles are different, with cycle 19 having the largest values and cycle 20 having the lowest values. For sunspots, the minimum values were very near zero and hence, actual sunspot numbers are plotted. For radio emissions, the minimum values for every frequency were nonzero and were almost the same for all sunspot minima. Hence, the actual values are divided by the minimum value of each frequency, and the plotted values are ratios, relative to 1.00 at solar minimum. Table I lists the ratios (relative values) at the maximum of each of the cycles 19–23, for which data for five or more indices were available. Figure 2 shows the plots of magnitudes versus frequencies. The abscissa scale is log T, to cover adequately the wide range of temperatures T. As can be seen, the magnitudes are very different for the different temperatures or frequencies. The values are very low (~ 1.2) for frequencies near 17 000 MHz (upper chromosphere?) but rise to ~ 3.0 for frequencies around 3000 MHz, after which there is a decrease to ~ 2.5 for frequencies near 600 MHz. In Figure 2 for cycles 21, 22, 23, there seems to be an increase thereafter (particularly for 245 MHz) to values of ~ 3.5. However, *this is not reliable*, for the following reason. In the original data of daily values, we noticed that for 200–500 MHz, there were often sequences of several continuous days (generally two or three but in rare cases, even seven days) when effects of individual flare bursts persisted, with values double or more than the average level. We tried to eliminate such extreme values but during solar maximum, the pollution from this source seems to persist. Hence, this increase of the ratio for 245 MHz is most probably spurious and should be ignored at present, though this needs further investigation.

For cycle 23, there are two plots, namely, (e) and (f). Plot (e) is just like plots a–d (cycles 19–22). Plot (f) is reproduced from the earlier publication Kane (2002), where data for some more radio frequencies observed at Krakow, Poland (275, 405, 670, 810, 925, 1080, 1215, 1350, 1620, 1755 MHz) were used, but only for 1996 to July 2000 (first maximum of cycle 23). Since more data points were used, the plot is more specific and shows a maximum clearly near ~ 2000 MHz. In general, plots (a–e) are in agreement with plot (f).

It may be remembered that at frequencies above about 15 000 MHz, coronal holes are bright in radio wavelengths (Gopalswamy *et al.*, 1999). During solar minimum, this would have a large effect because almost 15% of the solar surface is covered by coronal holes. This would reduce the solar minimum to solar maximum variability at the highest frequencies and may contribute to the smaller ratio at higher frequencies. Thus, the contrast between frequencies near 15 000 MHz and 2800 MHz may not be so large as shown in Figure 2. Nevertheless, the qualitative picture (maximum ratios near 2800 MHz) should still be valid.

3.2. MEDIUM-TERM VARIATION

In Figure 1, apart from the 11-year cycle, a curious feature seems to have occurred in 1972. Whereas the rises and falls are smooth for almost all cycles, in the declining phase of cycle 20 (1970–1976), the 1972 values show an inflection point (values same as or more than the previous year 1971, indicated by a triangle). This feature, seen even in 12-month moving averages, is unusual but is only pointed out here and will not be discussed further. A more prominent feature is the double-peaked structure at sunspot maxima. In cycles 18, 19, and 20, the sunspots had only one prominent maximum, while in cycles 21, 22, 23, sunspots had two maxima, separated by about 2 years. In radio emissions, cycles 20, 21, 22, 23 had two maxima. For sunspots, the first maxima were larger than the second maxima, but for radio emissions, the second maxima were often larger. (The larger maxima are shown by full squares and the smaller maxima by dots.) In Table I, the magnitudes of the larger maxima are indicated in the appropriate columns (I maximum or II maximum) for each cycle. The following may be noted:

(1) In cycles 20 and 23, mostly the second maximum was larger, but in cycles 21 and 22, some parameters had the first maximum larger while other parameters had the second maximum larger.

TABLE I

Magnitudes of the larger maxima for different frequencies of radio emissions in cycles 19–23.

MHz	Ratio solar Max/Min T(K)	log T	Cycle 19 I Max. Jan. 1958	Cycle 19 II Max none	Cycle 20 I Max. May 1968	Cycle 20 II Max Jun. 1970	Cycle 21 I Max. Jan. 1980	Cycle 21 II Max Mar. 1981	Cycle 22 I Max. Jun. 1989	Cycle 22 II Max Jul. 1991	Cycle 23 I Max. Jul. 2000	Cycle 23 II Max Feb. 2002
17 000	80 000	4.9	x		x		1.22		1.18			1.24
15 400	88 000	4.95	x			1.13		1.25		1.22		1.19
9400	130 000	5.1	1.44			1.29		1.43	1.49			1.51
8800	140 000	5.15	x		1.52		1.91		1.50			1.71
4995	200 000	5.3	x			2.34		2.16		2.52		2.46
3750	250 000	5.4	3.01			2.02		2.38	2.48			2.39
2800	300 000	5.48	3.51			2.23		2.92	3.04			2.82
2695	315 000	5.5	x			2.16	2.96			3.10		2.75
2000	365 000	5.56	3.54			2.56		3.39	3.57			3.33
1415	415 000	5.62	x			2.29		3.50	3.01	2.97	2.94	
1000	625 000	5.8	3.27			2.33	3.18	3.17	3.35	3.35		3.29
609	835 000	5.92	x			2.12	3.72			2.82	2.27	
410	1 000 000	6	x			x		2.55		2.62	2.68	
245	1 200 000	6.08	x			x	3.53		3.69			3.05
X rays	2 000 000	>6.0				*		*	*			*
Group SF	∼50 000				*			*	*		*	
Mag. field	∼5000					*		*		*		*
Ca index	∼5000		*			*	*		*			*
Sunspots	∼5000		*		*		*		*		*	

(2) There is no systematic shift from first maximum to second maximum (or vice versa) with frequency in cycles 21 and 22.

(3) The bottom part of Table I shows the locations of the larger maximum (by an $*$) for some other solar parameters, namely sunspot number, Ca K index, magnetic field (Mt. Wilson), group solar flare index (all in the photosphere and chromosphere) and X-ray background (corona). Whereas sunspot numbers had invariably the first maximum larger, other indices (even near photosphere) had sometimes the second maximum larger. Thus, no systematic relationship with solar temperatures (or altitudes) is indicated.

4. Conclusions and discussion

Plots of 12-month moving averages of the radio emission values for 1947–2002 indicated the following:

(1) Data for five solar cycles (18–23) indicated different maximum levels in different cycles, with cycle 19 having the largest values and the next cycle 20 having the lowest values.

(2) The ratios maximum to minimum for each cycle were plotted versus the temperatures of the region of origin of the various radio frequencies. The ratios were low (~ 1.2) in the upper chromosphere and lower corona (frequencies near 15 000 MHz), rose to maximum levels of ~ 3.5 in the middle corona (frequencies $\sim 2000 \pm 500$ MHz), and dropped thereafter to ~ 2.5 in the upper corona.

(3) In some cycles, there were two maxima separated by about 2 years. In cycles 20 and 23, mostly the second maximum was larger than the first maximum, but in cycles 21 and 22, some parameters showed the first maximum larger while others showed the second maximum larger. There was no systematic shift from first maximum to second maximum, with frequency or temperature (or altitude).

The max/min ratios for high frequencies escaping from the lower corona may not be as low as indicated in our Figure 2, as the effects of coronal holes differ in solar maxima and minima. Also, the same frequency may escape from different altitudes in solar maxima and minima, and the temperature levels indicated in Figure 2 may be erroneous, but we expect that the error would be systematic for all levels, and the plots may shift towards higher temperatures *bodily*. The *qualitative* maximum magnitude near ~ 2000 MHz is expected to remain as it is, and may have a physical significance from the point of view of plasma physics. This needs further exploration. For individual flare events, a spectral dependence has been reported by many workers (e.g., Kundu *et al.*, 1994). The same may be true for the slowly varying background radio emissions. On the other hand, the effect might be related to chaotic conditions in the transient regions between chromosphere and corona, which obliterate or minimize large magnitudes, and magnitudes increase in regions further up where conditions may be more stable, till in the outer corona, the solar influence diminishes and magnitudes decrease. This viewpoint is based completely on the assumption that the radio emissions at different frequencies escape from different temperature environments or altitudes (approximately, larger frequencies from deeper layers in the solar atmosphere). If the same frequency escapes from different altitudes, the interpretation becomes ambiguous.

A difference between the first and second maxima for sunspots on the one hand and radio flux on the other is intriguing. If the radio emission is associated with sunspots, the relative values of the first and second maximum should be similar, at least qualitatively, for both. However, decimetric frequencies would be from bremsstrahlung and may not follow sunspots. Between the radio emissions themselves, there is no consistency. A scrutiny showed that during 2000 –2002, whereas frequencies 245–1415 MHz had the first maximum (near July 2000) higher (just like sunspots) than the second maximum (February 2002), frequencies 2695–8800 MHz had the second maximum higher (unlike sunspots), but 15 000 MHz had the first maximum higher (like sunspots). Thus, the 2695–8800 MHz (decimetric) range should have a origin mostly unrelated to sunspots.

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