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Large-scale dynamical phenomena during solar activity cycles

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Abstract. The long-term behaviour of several solar-activity parameters (spots, flares, radio and X-ray fluxes) was investigated to identify essential characteristics of the 11-year cycle maximum. We confirm past findings suggesting that activity maxima occur at least twice during a cycle: first, near the end of the rising activity phase and then in the early years of the declining phase. However, we show that the double peak is more distinct when intense and/or long-lasting events are considered, because low-energy and short-duration events tend to follow a single-peaked 11-year cycle. Moreover, structured activity maxima are detected in all the solar atmospheric layers (photosphere, chromosphere and corona) up to interplanetary space, where several indices display a clear trace of the dual-peak maximum. Results based on some activity indices for cycle 21 support the effectiveness of the heliomagnetic cycle in producing the structured shape of the maximum phase of solar activity cycles.

Key words: Sun: activity; sunspots; radio radiation; flares; X-rays; magnetic fields

1. Introduction

Solar activity study has been developed in several ways over the years. Among them, the sunspot variability has been greatly investigated because data go back to the year 1610. The long-term spot series shows an average cycle length of 11.1 years (Schwabe cycle), with a standard deviation of 0.26 year. However, Maunder's Minimum (interval with quasi-suppressed spot appearance: 1645-1705; Ribes & Nesme-Ribes 1993; Hoyt, Schatten & Nesmes-Ribes 1993; Eddy 1976) and several ancient periods inferred from solar proxy-data suggest, from the reduced activity, that the Sun exhibits quasi-periodic or intermittent behaviour. The former interpretation allows us to ascribe activity cycle anomalies to a stochastic process, while the latter pertains to the deterministic chaos. The matter is still controversial (e.g., Weiss 1990; Price et al. 1992; Rozelot 1995, among others). Hence, investigation of solar activity phenomena in terms of stochastic behaviour cannot be rejected and offers useful clues for the understanding of solar-type stars.

Several aspects of the 11-year solar-activity cycle were examined in the past. Without reviewing this long series of works, we only notice that, by examining measurements of the green line (Fe XIV, 5303 Å) intensity of the solar corona ordered in heliographic latitudinal belts, Gnevyshev (1963) claimed the existence of a dual-peak structure for the coronal activity maximum of the 19^{th} cycle. The first peak was observed near the sunspot number maximum (1957) and involved the medium and high heliographic latitudes (maximum intensity at $\sim 25^o$); the second one occurred about two years later at low latitudes only (maximum at $\sim 10^o$). Similar results from other activity parameters (such as radio emission, sunspot areas, chromospheric and proton flares) and extended to past cycles reinforced the idea that, during each 11-year cycle, there is a splitting of the activity maximum in all the solar atmospheric layers. Two waves of activity, partly superimposed in time, were invoked (Gnevyshev 1967, 1977 and references therein) to explain this long-term trend.

In a review paper by Sýkora (1980) the isophote charts of the green corona brightness (derived from homogenized data of various coronal observatories) were published for cycles 18 to 20. It was easier to describe the outstanding coronal activity in terms of large well-isolated impulses (not necessarily in phase in both solar hemispheres) rather than in terms of two activity waves. The phenomenon was connected with the processes involved in the development of large and complex active regions (Bumba & Howard 1965). Moreover, Antalová & Gnevyshev (1983) published similar charts for sunspot areas (1874-1976 years), recognizing the possible existence of more peaks during a cycle (often a third peak). On the other hand, Mikhailutsa & Gnevyshev (1988) showed that for cycle 21 there exists a link between the double peak of the green corona activity cycle and the coronal magnetic energy maxima. The same cycle was investigated by Obridko & Shelting (1992), showing a relationship between the cyclic variation of the global heliomagnetic field (see also Sect. 5) and the one of several solar-geophysical parameters.

Moreover, recent studies on cosmic rays (Nagashima et al. 1991; Storini 1995; Storini & Pase 1995; Sýkora & Storini 1996;

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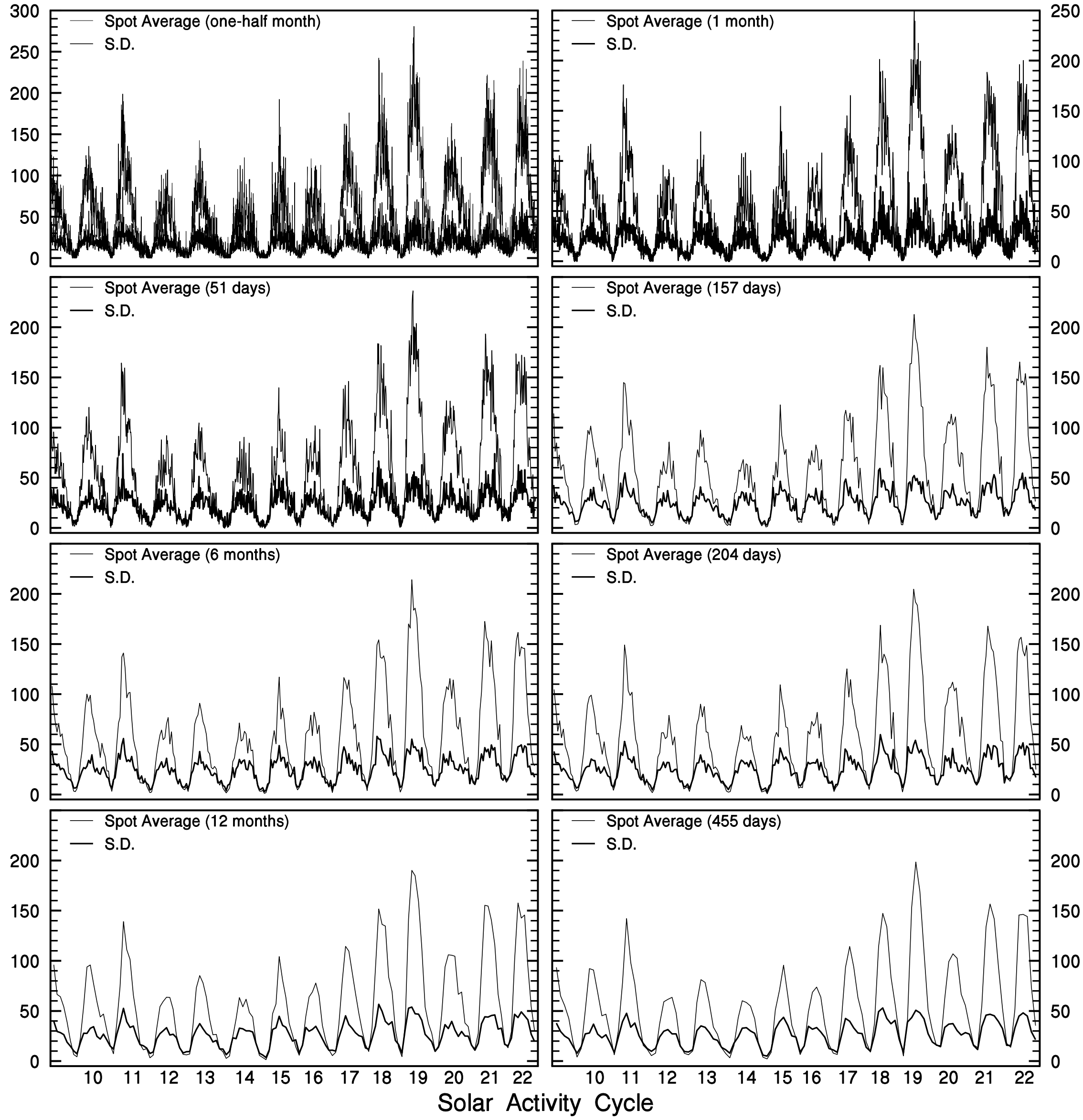

Fig. 1. Rz averages (thin lines) on several time-scales together with the corresponding standard deviations (S.D., thick lines). Numbers on the abscissa axis represent the activity cycle enumeration (10 to 22, according to the Zürich one).

Storini et al. 1996) and geomagnetic activity (Gonzalez et al. 1990; Clúa de Gonzalez et al. 1994) recall the reliability of Gnevyshev's dual-peak in the heliospheric parameters.

Hence, the necessity for a better understanding of the 11-year cycles is emerging not only for solar and stellar structure studies but also for solar-terrestrial physics. This paper describes part of an ongoing investigation into the subject looking at the Sun as a star, i.e. neglecting the latitudinal distribution of activity centers (see Feminella & Storini 1996 for preliminary results).

2. Dataset used

To investigate the activity maximum shape during 11-year cycles, a set of four parameters related to different solar layers has been used. It is composed of:

1. the relative (or Zürich) sunspot number Rz (McKinnon 1987), updated with the international sunspot number (Solar Geophysical Data - Monthly Reports), as photospheric activity index. The analysis was restricted to the epoch 1849-1994 to avoid daily gaps existing prior to 1849;
2. the daily 10.7-cm (2800 MHz) radio flux integrated on the whole solar disk, mainly as parameter of chromospheric activity (because of its sensitivity to the magnetic complexity of active regions; see: Wilson et al. 1987; Tapping & DeTracey 1990). Our dataset includes daily observations from February 14, 1947 to December 31, 1994 (Algonquin and Penticton radiotelescopes, Canada), corrected by the antenna gain, atmospheric absorption, burst in progress and the background sky temperature; moreover, each measure-

ment is multiplied by the antenna efficiency (η = 0.9) and corrected by the variations in Sun-Earth distance;

3. the daily flux of the 1-8 Å solar X-ray background, integrated on the whole solar disk, as a density parameter of the quiet corona structure. Data from the **SOL**ar **RAD**iation (SOLRAD) satellites cover the period March 14, 1968 - February 28, 1973 (i.e. the maximum phase of cycle 20; Solar Geophysical Data 1994a). Data from the **G**eostationary **O**perational **E**nvironmental **S**atellites (GOES) only cover the period January 1, 1987 - December 31, 1993 (the most part of cycle 22; Solar Geophysical Data 1994b), to avoid periods in which data have a high relative error induced by low-flux instrumental problems. Data for the maximum phase of cycle 21 are not available to us;
4. the monthly counts of grouped chromospheric flares from January, 1965 to December, 1994 (Solar Geophysical Data 1995; observations of the same event by different solar observatories were lumped together and counted as one). The released energy during flare events is connected to the presence of enhanced magnetic-field intensities in the involved regions.

3. Data processing and results

Due to the observational evidence of a complex shape of the solar activity cycles, our study started by computing the average trends on several time-scales and the corresponding standard deviations. Data averages allow to examine maximum shape variability in the 11-year quasi-stationary trends while standard deviation values reveal dynamical phenomena along the cycle.

Fig. 1 (thin lines) illustrates the Rz averages on one-half, 1, 6 and 12 months, together with the ones for 51, 157, 204 and 455 days (periodicities obtained by Pap et al. 1990, and Bouwer 1992).

On a short time-scale ($\tau \leq 51$ days) the cycle shape (in particular, the maximum phase) is dominated by large fluctuations; conversely, on a large time-scale ($\tau > 12$ months) only the quasi-stationary 11-year trend appears. Finally, on an intermediate time-scale (see panels for $157 \leq \tau \leq 204$ days), two or more peaks emerge during the maximum phase of each solar cycle. In a similar way, the average trends of the 10.7-cm radio flux have been computed (Fig. 2, thin lines). Again, on intermediate time-scales (see panels for $155 \leq \tau \leq 237$ days) more than one peak occurs in the maximum activity phases; for example, the dataset for 155-day averages shows many peaks in cycle 20 and double-structured maximum phases in cycles 19, 21 and 22.

The average datasets seen as a whole (thin lines in Figs. 1 and 2) suggest that:

1. the shape of the maximum phase is double- or multi-structured (i.e., composed of several peaks);
2. only averages on intermediate time-scales highlight the maximum shape by performing a compromise between fluctuations of data and long-term 11-year behaviour of activity cycles;

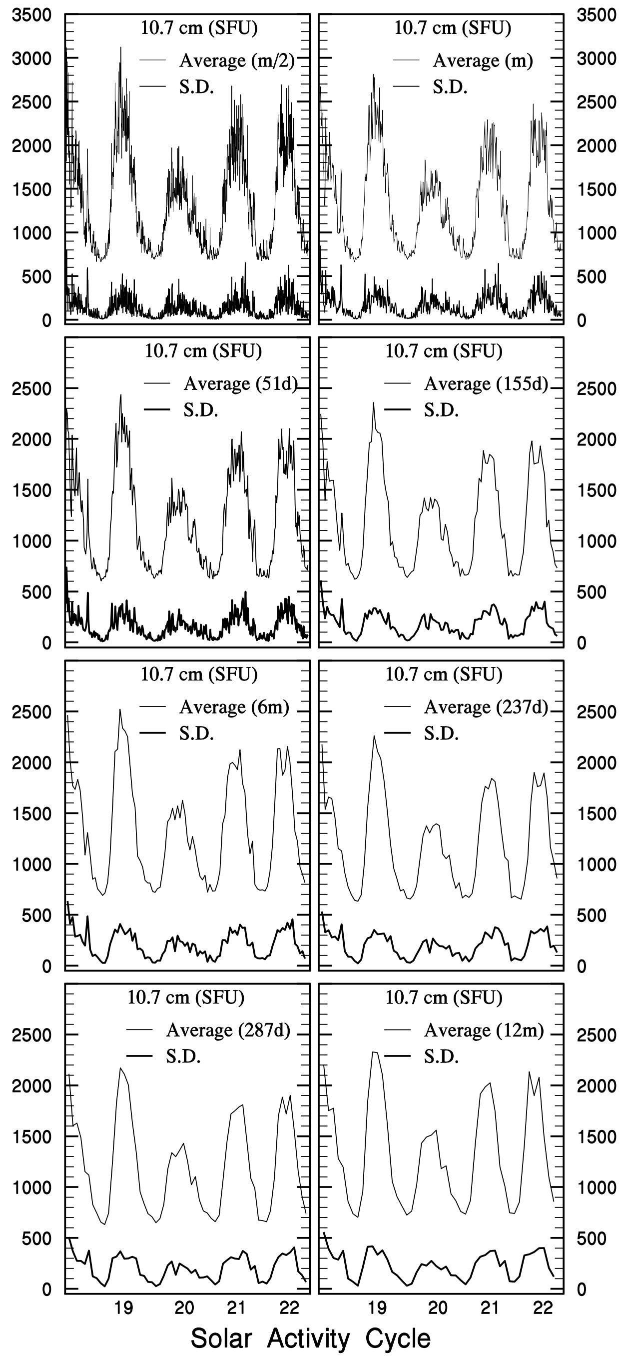

Fig. 2. As for Fig. 1 but for the 10.7-cm flux (1 S.F.U. = 10^{-22} W m^{-2} Hz^{-1}).

3. double- or multi-structured maxima seem to be a common feature at all the atmospheric layers.

With this aim in mind, we looked at the standard deviation results (thick lines in Fig. 1 and 2) but we found that the standard deviation of monthly means with respect to the annual mean (denoted m/y in Fig. 3) reveals the presence of double-peak structures better. In fact double sharped peaks are found in the majority of the cycles (11, 16, 19, 21 and 22 for Rz; 19 and

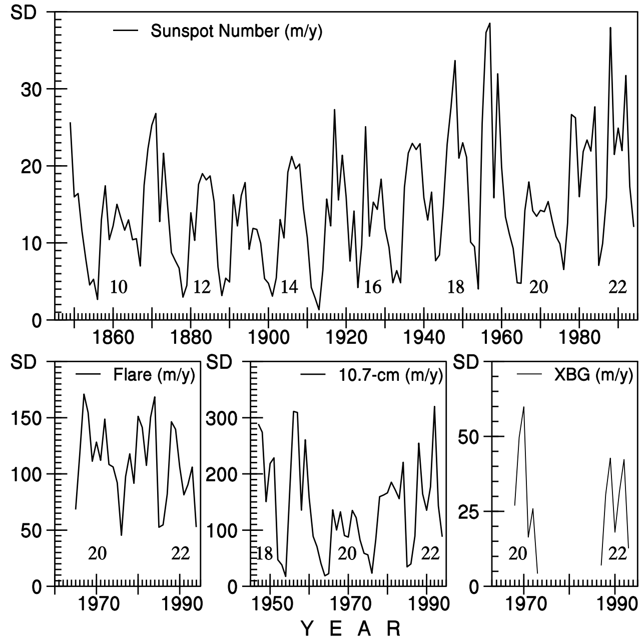

Fig. 3. Standard deviation (SD) of monthly averages with respect to the annual average (m/y) for Rz, grouped H_α flare number, 10.7-cm radio and 1-8 Å X-ray background fluxes (in units of 10^{-8} W m^{-2}).

22 for 10.7-cm radio flux; 22 for 1-8 Å X-ray flux and H_α flux). On the contrary, multi-structured maxima appear in cycles 10, 13 and 15 for Rz; in cycle 20 for the radio flux index and in cycles 20 and 21 for the grouped H_α flares. Large unresolved peaks appear in cycles 12, 14 and 17 for Rz and in cycle 21 for the radio flux. Multi-structured peaks during the maximum phase of solar activity indicates that a search for only two peaks, according to Gnevyshev's first results, could be misleading with regard to the causes of the phenomenon. Moreover, pure statistical artefacts (appearing in the form of minor peaks) cannot be excluded. On the other hand, the quasi-repetitivity of a dual pattern represents a valid indicator for the existence of dynamical variations overlapped on the long-term trend. On the ground of the previous observations we will pay attention to remove causes of its scarce evidence.

4. Looking for intense dynamical phenomena on the Sun

Past researches have indicated (without emphasizing the fact) that the double-peaked maxima are easier to find considering the growing importance of the examined solar events. Among them we recall:

1. Gnevyshev (1977), in which Fig. 5 shows the progressive emergence of a double peak in the yearly number of sunspots, with areas increasing from 200 to more than 500 area units;
2. Roy (1977), taking into account all the major flares meeting Dodson's and Hedeman's criteria, found a double peak in the flare occurrence for cycles 19 and 20.

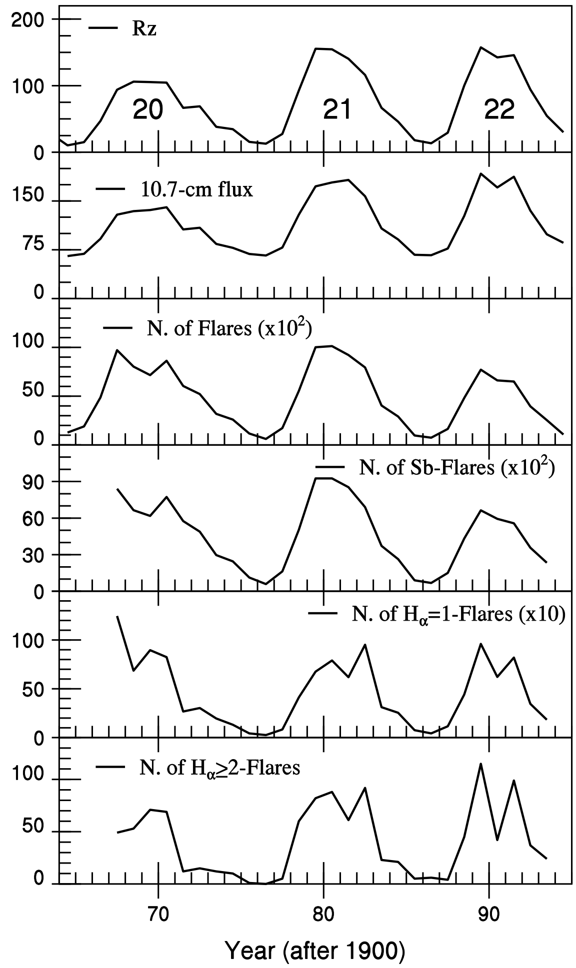

Fig. 4. H_α flare events arranged by importance for activity cycles 20 to 22. *Panels 1-3, from the top*: sunspot number Rz, 10.7-cm radio flux, total number of flares. *Panels 4-6*: number of subflares (Sb), of flares with H_α importance = 1 and $\geq$ 2 (data obtained from Mouradian & Soru-Escaut 1995).

Hence, we re-examined the annual counts of grouped solar flares according to their H_α importance, i.e. subflares (Sb), = 1, $\geq$ 2, as reported by Mouradian & Soru-Escaut (1995). They were plotted in Fig. 4 together with Rz, the 10.7-cm radio flux and the total number of flares.

A double-peaked structure emerges by moving from subflares (low energy events; fourth panel from the top of Fig. 4) to flares with H_α importance $\geq$ 2 (high energy events; sixth panel). On the contrary, activity indices accumulating events whatever their importance, as for example the total number of flares (third panel), Rz or the 10.7-cm radio flux (first and second panels, respectively), do not always display structured maxima. Remarkable similarities between their profiles and those obtained for indices of little importance (such as the subflares) suggest that the former activity parameters are dominated by non energetic events.

Nevertheless, we observe that, only for cycle 22, the annual averages of Rz and 10.7-cm flux present a double-structured

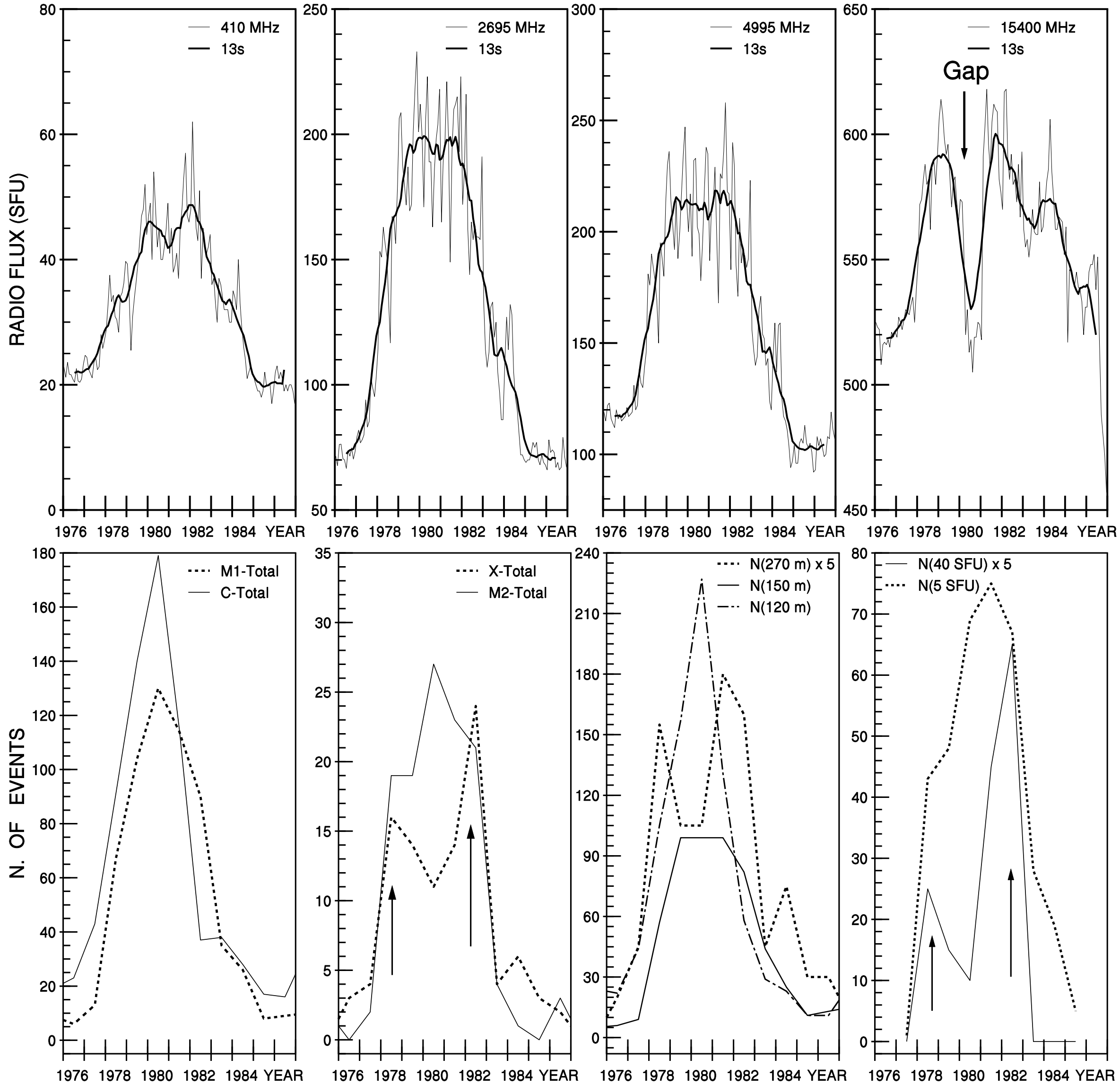

Fig. 5. Several parameters for cycle 21. *Upper panels*: monthly averages (thin lines) of radio flux and the corresponding 13-running averages (denoted by 13s, thick lines). *First and second lower panels*: total annual number of LDE-type flares of C, M1, M2 and X class (Antalová 1990). *Third lower panel*: annual number of LDE-type flares with life-time ranging from 120 to 270 minutes (Antalová 1990). *Fourth lower panel*: annual number of 10.7-cm bursts of long duration, with flux $\geq$ 5 and $\geq$ 40 SFU (Kahler & Cliver 1988). Arrows indicate the double peak emergence.

maximum, suggesting that this cycle contains a major number of events of large importance with respect to the previous ones. In this case double peaks clearly arise without the use of "filtering criteria" (such as the classification of events on the ground of the event's importance). We recall that Gnevyshev's maxima are not easy to find in Rz (Fig. 1) because it counts together sunspots and sunspot groups irrespectively of their importance (i.e. the sunspot area).

To investigate better the link between double-peak shape and the event's importance, we analyse several activity parameters available for cycle 21 (Fig. 5) and their hemispherical distribution on the Sun (Fig. 6):

1. the annual number of long-duration events (LDE-type flares) in the soft X-ray flux, according to their importance: X (10^{-4} W m^{-2}), M2 ($6-9\ 10^{-5}$ W m^{-2}), M1 ($1-5\ 10^{-5}$ W m^{-2}) and C ($1-9\ 10^{-6}$ W m^{-2}) as computed from Antalová (1990); the flare life-time ranges from 120 to 270 minutes;
2. the annual number of long duration ($\geq$ 4 hours) 10.7-cm bursts with flux $\geq$ 5 and $\geq$ 40 SFU (Kahler & Cliver 1988);
3. the monthly radio flux at 410, 2695, 4995 and 15400 MHz (73.17, 11.13, 6.01, and 1.95 cm; Sagamore Hill Observatory - Massachusetts);

4. the monthly sunspot areas separately for northern and southern hemispheres (Makarov & Makarova 1996);
5. the semi-annual hemispherical flare index, derived from Ataç (1987), which roughly gives a measure of the total energy emitted by a chromospheric flare;
6. the semi-annual hemispherical distribution of solar LDE-type flares for M-X classes (computed from Antalová 1990).

The double peak structure is clearly seen in the radio flux trends with increasing energy from 410 to 15400 MHz (73.17 to 1.95 cm; Fig. 5, upper panels). Alternatively to the double peak, it is possible to speak in terms of the "Gnevyshev gap" (as called by Storini & Pase, 1995; it is defined as a relative decrease in the strength of solar activity indices connected with the maximum phase) whose depth increases with the energy of the events (see Sects. 5.1 and 5.2).

The lower panels of Fig. 5 show the number of LDE-type flares separated into energy (classes X, M1, M2 and C), the number of LDE-type flares of increasing life-time (from 120 to 270 minutes) and the radio burst number. Data of LDE-flares lasting 270 minutes are multiplied by a factor of 5 to compare them with trends of LDE-flares of minor importance. The same occurred for 10.7-cm burst numbers of energy $\geq$ 40 SFU. The dependence of the double-peak occurrence with the increasing energy of single events is confirmed, as for previous data (Fig. 5, upper panels).

Fig. 6 shows another aspect of the problem: the double peak structure emergence on sunspot areas (upper panels), the total energy emitted by chromospheric flares (middle panels) and the M-X LDE-flares (lower panels) related to their hemispherical distribution. The figure shows that the bimodal data distribution is not a north-south anisotropic effect (see also the time sequence of the sunspot-area variability from 1874 to 1971 reported by White & Trotter 1977).

5. Discussion

5.1. General aspects of double-peaked activity maxima

The above results indicate that dynamical activity phenomena (revealed from S.D. datasets) are superimposed on the quasi-stationary 11-year trend (long-term average datasets) and can be identified on intermediate time-scales (about 5 to 12 months). The dual pattern is also evident in the standard deviation plots of Fig. 3. It follows that the formation of the activity maximum as dual- or multi-peaked pattern concerns all the solar atmospheric layers. In this paper we have not attempted to make a fine analysis of the exact time occurrence of peaks. Consequently, even though underlining their existence from lower to upper atmospheric layers, we are not able to examine their synchronism which, of course, plays a key-role in the analysis of the dual pattern propagation through the solar atmosphere up to interplanetary space and the terrestrial magnetosphere. In particular, from Figs. 2 (10.7-cm flux averages), 4 and 5 (flares and radio bursts) we observe that, for activity indices related to layers higher than the photosphere, double-peaked structures clearly appear in the average profiles (i.e., not only in the S.D. plots).

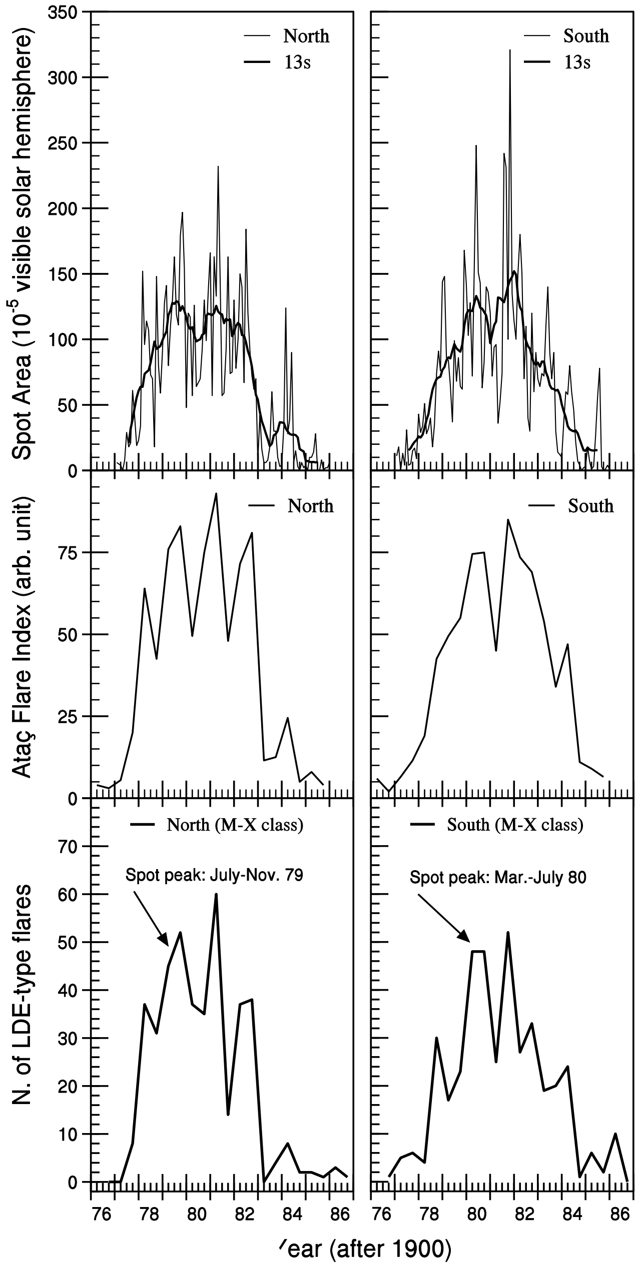

Fig. 6. Indices of northern (*left*) and southern (*right*) activity for cycle 21. *Upper panels*: monthly spot area (thin line) and 13-point running average (thick line; data derived from Makarov & Makarova 1996). *Middle panels*: Ataç semi-annual flare index (Ataç 1987). *Lower panels*: number of solar LDE-type flares of M-X classes on half-yearly basis (data from Antalová 1990).

We believe that only intense events have the right energy to emerge in the upper solar layers. These considerations open the way to the discussion of the energy role in the double peak appearance. First, we observe that, using solar activity parameters of low energy events (e.g., subflares) or cumulative indices of activity (e.g., Rz), the evidence of a dual activity shape abruptly degrades towards a single-peaked cycle. Analysing the percentage of energetic flare events (those with H_α importance ≥ 2)

with respect to the global ones for the three years centered on sunspot maxima, we found an increasing factor of about 1.4 from cycle 20 to 22. In other words, as only energetic phenomena (probably associated to the interaction between global and local magnetic fields; see Sect. 5.2) are involved in the double-peak structure, their relative increase leads to the shape in question. On the contrary, enhanced low-energy phenomena (relating mostly to local magnetic field variability and with their typical single-peaked cycle) mask the contribution of intense events to the sunspot maximum shape. A relevant dip in the outstanding events should occur during the inversion of the general heliomagnetic field (see also Nagashima et al. 1991). We underline the gap's role: in the bimodal behaviour of solar activity maxima the gap gives a net separation between the two peaks. As seen in Figs. 1, 2 and 3, peaks can appear well separated, or partially or completely merged; the use of the gap to individualize the double-peak appearance can be a less ambiguous method than looking for single peaks. As shown in Fig. 5, the gap's depth increases with the growing energy (and the importance) of the activity events. It should be noticed that the gap's depth increases abruptly at 15400 MHz (with respect to that of 410, 2695 and 4995 MHz radio flux trends); we suspect the existence of an energy threshold in the gap's generation but we underline the need for further studies on this subject.

5.2. Double-peak cycle structure and solar magnetic field

As pointed out above, we believe that the origin and evolution of dual-peak behaviour in solar activity cycles are related to the space-time variability of the heliomagnetic field. Looking for its role, we concentrated our attention on cycle 21, for which Obridko & Shelting (1992) introduced a magnetic energy index: $i(B_r) = \langle B_r^2 \rangle$, where the average of the radial field component is computed over two solar surfaces of radius r = R$_\odot$ (photosphere: i(B_p)) and r = 2.5 R$_\odot$ (source surface: i(B_s)) for each Carrington rotation.

Fig. 7 (obtained from a point-reading of parts of Figs. 1 and 2 reported by those authors) illustrates in the upper panel the i(B_p) trend. Connecting relative minima of i(B_p) we notice a "background cycle" which peaks at Rotation 1691 (1979.9), the maximum of sunspot cycle 21. If we hypothesize that the "field background" is made up of integrated small-scale (local) fields we can explain why the occurrence of low-energy phenomena tends to follow a single-peaked activity cycle, particularly those associated with deeper atmospheric layers. We observe six peaks (denoted by A, B, C, D, E and F) emerging over the background trend, with two absolute maxima occurring on Rotation 1680 (about 1979.3) and Rotation 1712 (1981.8). Moreover, an extended relative minimum is present around the sunspot cycle maximum (Rotation 1691).

Looking at the background of i(B_s) (Fig. 7, bottom panel) we learn that its lower envelop at the source surface practically disappeared. This reinforces the idea that, at this atmospheric height, effects of small-scale fields and low-energy phenomena are irrelevant. Only peak features dominate the temporal trend. We notice the strong stability of peak A (entity, average life-time and atmospheric depth involved). On the contrary, peaks B and C seem to combine together and lose in magnitude. Probably there is a damping of the magnetic energy transmission from the lower to the upper atmosphere. Peak D appears as the outstanding impulse, i.e. the absolute maximum (1982.5). Peaks E and F appear as for the B + C couple.

Because of the high stability of peak A (indicated by dashed arrows in the upper and lower panels of Fig. 7) we expect its strong connection with the high energy phenomena on the Sun. In fact, there is a very good relationship between this peak and the first one remarked in our figures. Good synchronic activation is presumed in all the atmospheric layers. This explains why it was easier for Kopecký (1973) to find the first Gnevyshev maximum on sunspot groups rather than the second one.

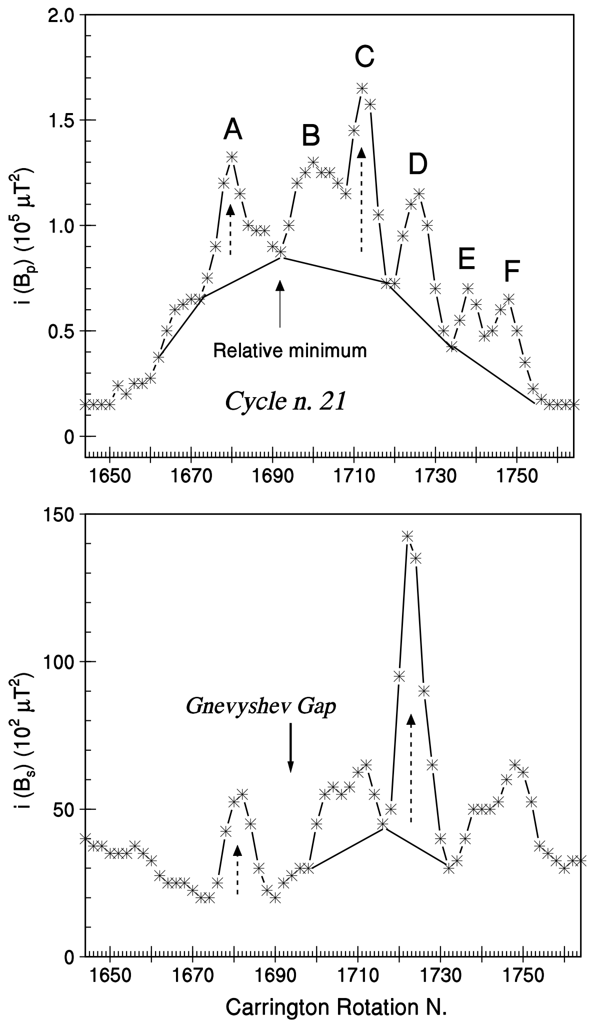

Fig. 7. *Upper panel*: the magnetic solar field index, i(B_r), at r = R$_\odot$ (photosphere). Horizontal axes indicate the Carrington rotation number. Letters A, B, ..., F indicate the peaks emerging over the background trend of cycle 21. *Lower panel*: i(B_r) at the source surface (r = 2.5 R$_\odot$). Data are derived from Obridko & Shelting (1992). The thick line joins up local minima to illustrate the "field background" (see the text).

As far as the B + C couple is concerned, we explain the damping effect with the contemporary inversion of the general magnetic field. In this cycle the earliest time for switched polarity occurs above 70^o heliographic latitude on Rotations 1692-93 (March 1980) at the North Pole and on Rotation 1699 (September 1980) at the southern one, but the reversal at the northern pole was not stable enough until Rotation 1719 (February-March 1982), as reported by Webb et al. (1984). The time interval between Rotation 1699 and 1719 corresponds very well with the B + C epoch. Hence, during this period the emergence of high energy phenomena in the outer solar atmosphere is unlikely. We believe that this is not the case for peak D, which occurs at the source surface level when the general magnetic field has reinforced its strength. This is the epoch for Gnevyshev's second maximum in the coronal layer. Its evidence should be clearly found in the upper solar atmosphere together with relevant effects in the interplanetary medium. On this ground even the role of Gnevyshev's gap is clarified: according to the inversion of the general magnetic field, a decrease (or a gap) in the number of high energy events occurs; consequently, two main peaks emerge on both sides of the gap. Previous considerations also throw light on what we call "large-scale dynamical phenomena": they are clusters of solar events originating in strong magnetic fields with the necessary energy to affect the heliospheric environment. We suggest that intense local fields strongly interacting with the global heliomagnetic field cause the large-scale restructuration of the solar corona; hence, they are deeply involved in the maximum shape of activity cycles.

6. Remarks and conclusions

The research of double peaks in solar activity maxima, starting from Gnevyshev's results, has been extended on a global scale (the photosphere, chromosphere and corona) to the on-going solar activity cycle. Results of our preliminary work on the subject suggest that:

1. structured maxima (with two or more peaks) generally occur in each activity cycle and are to be considered the result of dynamical effects superimposed on the quasi-periodic 11-year trend. The standard deviation of monthly averages with respect to the yearly averages is a good tool to stress the activity peaks in time series of data; in particular, the first intense peak is detected in the ascending phase of the cycle and the second one in the early years of the descending phase (Gnevyshev 1977).
2. The duration of each peak ($\leq$ 1 year) suggests that it can not be seen as the result of impulsive activity effects due to localised centers but a phenomenon which arises from a large-scale restructuration of the solar magnetic field and associated effects. We notice that Bieber & Rust (1995), evaluating the magnetic flux escape from the Sun, found that its characteristic time-scale is typically $\sim$6 months (with annual averages included between 0.3 and 1.1 year).
3. The double-peak appearance concerns each solar layer, even if an analysis on a finer time scale is necessary to evaluate the synchronic or delayed occurrence of each peak, when moving from the lower to the upper atmosphere.
4. The bimodal behaviour of solar activity occurs separately in each solar hemisphere, i.e. double peaks can not be considered a result of anisotropic solar activity.
5. The double peak appearance is strongly related to the growing event importance (i.e. clusters of high energy and long-lived events) while low energy phenomena tend to follow an 11-year cycle.
6. An evident link between the occurrence of major solar events and the strength of the heliomagnetic field energy seems to exist.

The Gnevyshev gap has great importance, because a reduction of large-scale and intense dynamical phenomena are expected in such a period. Its role in solar activity forecasting could be very important and future studies must concentrate on clarifying its origin and time-length occurrence.

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