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The 22-year cycle in the geomagnetic 27-day recurrences reflecting on the F2-layer ionization

E. M. Apostolov[1], **D. Altadill**[1], **and M. Todorova**[2]

[1]Observatorio del Ebro, (URL-CSIC), Horta Alta 38, E43520 Roquetes, Spain
[2]Geophysical Institute, Bulgarian Academy of Sciences, Acad. G. Bonchev bl.3, 1113 Sofia, Bulgaria

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Abstract. Solar cycle variations of the amplitudes of the 27-day solar rotation period reflected in the geomagnetic activity index A_p, solar radio flux F10.7 cm and critical frequency *fo*F2 for mid-latitude ionosonde station Moscow from the maximum of sunspot cycle 18 to the maximum of cycle 23 are examined. The analysis shows that there are distinct enhancements of the 27-day amplitudes for *fo*F2 and A_p in the late declining phase of each solar cycle while the amplitudes for F10.7 cm decrease gradually, and the *fo*F2 and A_p amplitude peaks are much larger for even-numbered solar cycles than for the odd ones. Additionally, we found the same even-high and odd-low pattern of *fo*F2 for other mid-latitude ionosonde stations in Northern and Southern Hemispheres. This property suggests that there exists a 22-year cycle in the F2-layer variability coupled with the 22-year cycle in the 27-day recurrence of geomagnetic activity.

Key words. Ionosphere (mid-latitude ionosphere; ionosphere-magnetosphere interactions) – Magnetospheric physics (solar wind-magnetosphere interactions)

1 Introduction

The 22-year cycle of geomagnetic activity is the least well examined of the long-period geomagnetic variations which are longer than the solar cycle. The reality of the geomagnetic 22-year cycle has not gone unquestioned. There are some investigations based on spectral analysis of long-term series of geomagnetic indices or geomagnetic data of individual stations which have provided no evidence for a 22-year periodicity (Fraser-Smith, 1972; Delouis and Mayaud, 1975; Gonzalez et al., 1993), but, on the other hand, there are studies showing the strong 22-year periodicity, for instance, those of Currie (1973) and Courtillot et al. (1977). Moreover, some investigations reveal an important 22-year cycle in some properties of the geomagnetic activity variations as the vernal-autumnal asymmetry in the seasonal variation of geomagnetic activity (Triskova, 1989). The 22-year variation in the geomagnetic activity was clearly demonstrated by enhanced 27-day recurrent activity during the declining phase of even-numbered solar cycles (Ondoh and Nakamura, 1980; Hapgood, 1993) and also by transient activity in the rising phase of odd-numbered cycles (Cliver et al., 1996). The period of activations of strong geomagnetic 27-day recurrent activity is longer in the even-numbered cycles – nearly 4 years – than in the odd cycles, nearly 2 years (Ondoh and Nakamura, 1980). The significant peaks of occurrences are in the second half of the declining phase of each cycle, but the peaks are much higher for the even cycles than for the odd ones (Hapgood, 1993).

A large part of the F2-layer variability is linked to the geomagnetic activity (Forbes et al., 2000; Rishbeth and Mendillo, 2001) and, therefore, we would expect to observe a 22-year cycle in the F2-layer characteristics. The investigation of Feichter and Leitinger (1997) of two consecutive solar cycles, 21 and 22, show the existence of a 22-year period in the daytime total electron content (TEC) and over four solar cycles (19–22) for F-layer peak electron density (NmF2) over Europe. They found that the annual variation of TEC and NmF2 shows the change in the maximum from autumn in odd cycles to a spring maximum in even cycles in European mid-latitudes. The authors conclude that the observed annual asymmetry of F-layer ionization in European mid-latitudes is in anti-phase with the vernal-autumnal asymmetry of geomagnetic activity (Triskova, 1989) because of the ionization depression caused by "negative storm effects".

In this investigation we present another aspect of a 22-year cycle manifestation in upper ionosphere ionization based on the long-term variations of the 27-day amplitudes of the geomagnetic activity in even/odd numbered solar cycles.

2 Data and method

The following parameters have been used in our analysis. The hourly values of the F2-layer critical frequency (*fo*F2) for the period from 1947 to 2001 from Moscow (55.5° N, 37.3° E) are retrieved from the COST251 database for the

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Correspondence to: E. M. Apostolov
(ema@geophys.bas.bg)

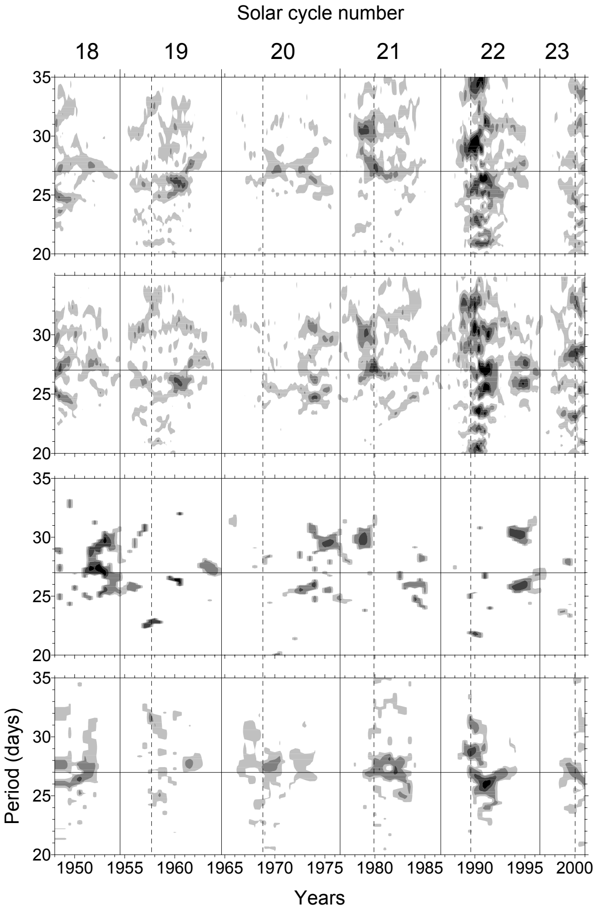

Fig. 1. Dynamic amplitude spectra in the period range from 20 to 35 days of solar radio flux F10.7 cm, geomagnetic activity index A_p and critical frequencies *fo*F2 for midday and midnight (Moscow) over the years 1947–2001. Solar cycle maxima and minima are marked with dashed and thin vertical lines, respectively. Highest amplitudes are painted in a black tone. The 27-day period is indicated by a horizontal line in each panel.

period 1947–1998 and for the period 1999–2001 from the World Data Centre for Solar-Terrestrial Physics, Boulder, via the http://ngdc.noaa.gov/spidr. This time series has been used as a base for the purpose of our investigation because it is very long – it covers the interval from the maximum of solar cycle 18 to the maximum of solar cycle 23 – and it is characterized by a scarcity of missing values. Two sequences of average hourly *fo*F2 for midday (10–14 LT) and midnight (22–02 LT) bins for each day have been retrieved for the analysis. Additionally, the *fo*F2 hourly data for some ionosonde stations in the mid-latitude belt of the Northern and Southern Hemisphere used in the present analysis are retrieved from WDC for STP, Chilton, via the http://wdc.rl.ac.uk. Because the F-layer ionization variability is linked to the geomagnetic activity and solar EUV variations, we also use daily values of the geomagnetic activity index A_p, and solar radio flux at 10.7 cm (F10.7 cm), as proxies of geomagnetic and solar EUV variations for the time interval being investigated. Note that the time series of F10.7 cm starts on 14 February 1947.

In order to investigate the spectral composition of the solar rotation period reflected in the geomagnetic, ionospheric and solar radio flux variations, we use the Lomb-Scargle periodogram method. The periodogram algorithm given by Scargle (1982) for the general case is for an unevenly sampled time series. The application of this periodogram method is very convenient in the case of ionospheric sounding time series which are characterized by data gaps. The probability that a given periodicity is a true signal can be estimated when the periodogram power is normalized by the total variance of the data (Horne and Baliunas, 1986; Press et al., 1992). Hocke (1998) has extended the methodology for calculating the amplitude and phase spectra.

3 Results

To investigate the temporal variations of the spectral power or amplitude of solar rotation period reflected in the investigated time series, dynamic spectra were calculated. The Lomb-Scargle periodogram was applied to a 2-year window within each time series and the window is then slid through the series in 73-day (0.2-year) increments. The 2-year window length was selected to reveal the dominant characteristics of temporal variations of the 27-day period amplitude by diminishing the seasonal variations and emphasizing the intervals with long-lived structures. The periodograms for A_p and F10.7 cm are computed in the frequency interval 0.05–0.0285 day^{-1} and for *fo*F2 in the interval 0.002–0.0012 hour^{-1}, both corresponding to the period range between 20 and 35 days, with an over sampling factor of four.

Figure 1 depicts the dynamic amplitude spectra for F10.7 cm, A_p and *fo*F2 for Moscow. The amplitudes which exceed 95% confidence level are taken for spectrograms only. Three features of the dynamic amplitude spectra of interest of the present study should be immediately noted: (1) The figure reveals a distinct 22-year cycle of the geomagnetic activity around 27-day period. The highest A_p-amplitudes occur strongly in the late declining phase of the even cycles 18, 20 and 22. (2) The highest amplitudes of F10.7 cm are near solar cycle maxima and negligible in the declining phases before solar cycle minima. (3) There are significant activations of *fo*F2-amplitudes in both midday and midnight during the declining phases of each solar cycle. These activations coincide in time, near 4-years intervals before sunspot minimum, with those of the geomagnetic activity for the even cycles (18, 20 and 22). This is an indication of the expected manifestation of a 22-year cycle in F2-layer ionization due to the 22-year cycle of geomagnetic 27-day period.

The spectral behaviour of the investigated parameters in the late declining phase of solar cycles is more clearly seen in Fig. 2. This figure depicts the amplitude spectra in the period range from 20 to 35 days for *fo*F2, A_p and F10.7 cm over 4-year intervals before sunspot minimum of the cycles 18 to 22. First of all, we see a clear double cycle variation in A_p- and *fo*F2-spectra with higher amplitudes near the solar rotation period for solar cycles 18, 20 and 22 in comparison with

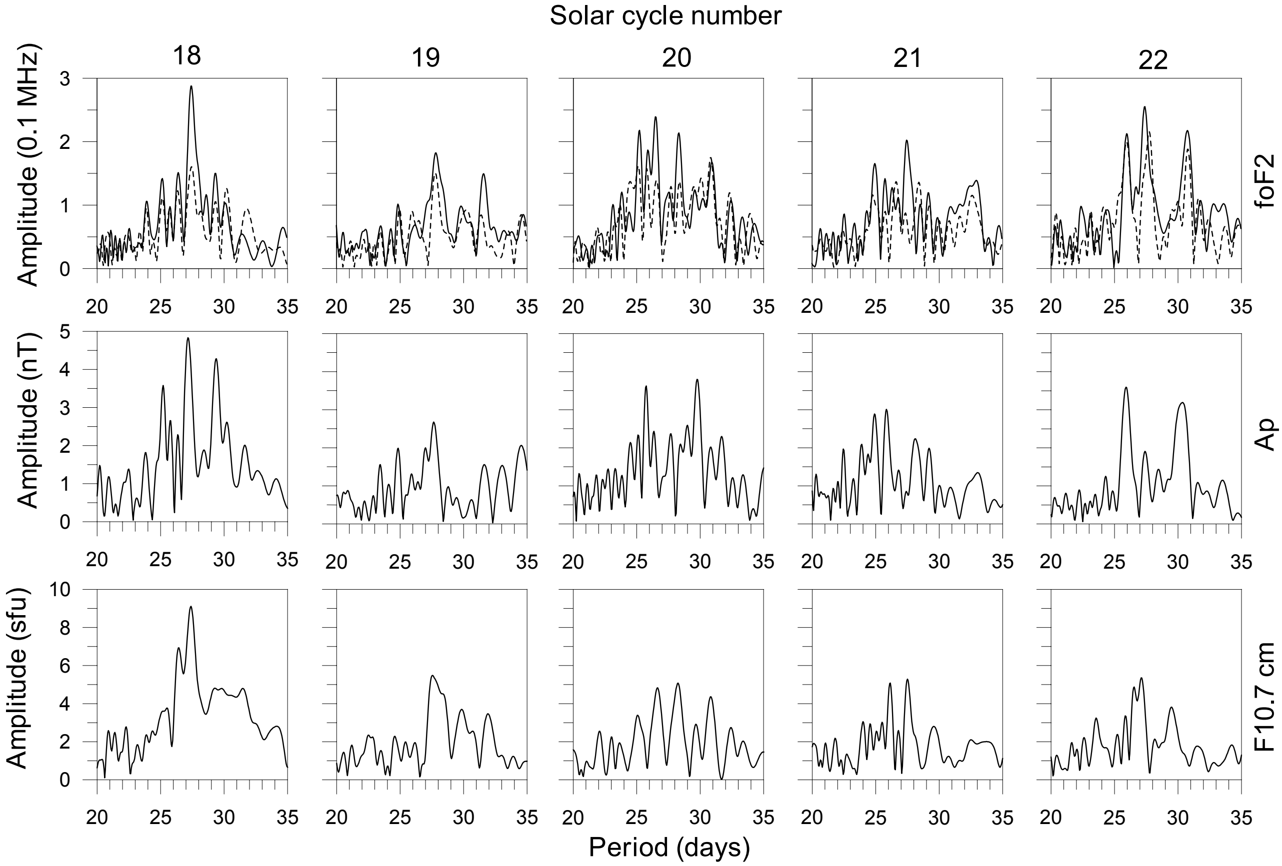

Fig. 2. Amplitude spectra of *fo*F2 (Moscow), A_p and F10.7cm in the period range from 20 to 35 days over 4-year intervals in the late declining phase of solar cycles 18–22 before sunspot minima. The thick and dashed lines mean midday and midnight *fo*F2 spectra, respectively.

those for solar cycles 19 and 21. For F10.7 cm-amplitudes there is no such variation, they are nearly equal in the cycles 19 to 22. The amplitude spectra of the three parameters have similar features including a significant band of sharply defined peaks around the 27-day solar rotation period, between 25 and 31 days. The causes of the appearance of this multi-peaked structure were analyzed mainly for solar and geomagnetic parameters. According to the studies of Fenimore et al. (1978), Letfus and Apostolov (1980), and Bouwer (1992), the combined effects of solar rotation and active region evolution, or its longitudinal distribution, may produce this structure. The power (or amplitude) spectra over long-time intervals of geomagnetic activity indices performed in many studies show dominant subsidiary peaks at 25.2 and 29.5 days around the peak of 27–27.4 days. Coleman and Smith (1966) argued that these subsidiary peaks result from amplitude modulation of the 27.4-day period by the period of 1 year. However, the power of the solar rotation period reflected in the three parameters is distributed in a series of spectral lines mainly between 25 and 31 days. This is why we have calculated the period-averaged amplitude as an integrated measure of the amplitude distributed within the periods from 25 to 31 days for the three parameters, over 2-year windows sliding by 73 days (Fig. 3). To some extent, Fig. 3 represents a section of the results in Fig. 1 for the limited periodic band of interest. Figure 3 shows that there are enhancements of the period-averaged amplitudes in the declining phase of each solar cycle for both *fo*F2 and A_p. These enhancements are better expressed and they coincide in time during the even cycles 20 and 22.

The observed vernal-autumnal asymmetry of the annual variation of the F-layer ionization, coupled with the 22-year cycle in geomagnetic activity (Feichter and Leitinger, 1997) has been obtained for European mid-latitudes but not for the Southern Hemisphere because of the lack of difference between vernal and autumnal maxima (Titheridge et al., 1996). However, the solar rotation period in the EUV and geomagnetic variations is reflected strongly in the components of the F-layer variability in both hemispheres. We have reason to believe that the long-term variations of 27-day period characteristics on the F-layer variability should show a 22-year variation in the Southern Hemisphere as well. Figure 4 shows the amplitude spectra of midday and midnight *fo*F2 for southern station Canberra (35.3° S, 149° E) for the late declining phases of solar cycles 18 to 21, obtained by the same method as for *fo*F2 (Moscow) in Fig. 2. Again, the amplitudes for the even cycles are higher than for the odd ones.

Analogous results are also obtained for some mid-latitude sounding stations in Northern Hemisphere and for Southern Hemisphere in the Australian sector (Table 1). The values of

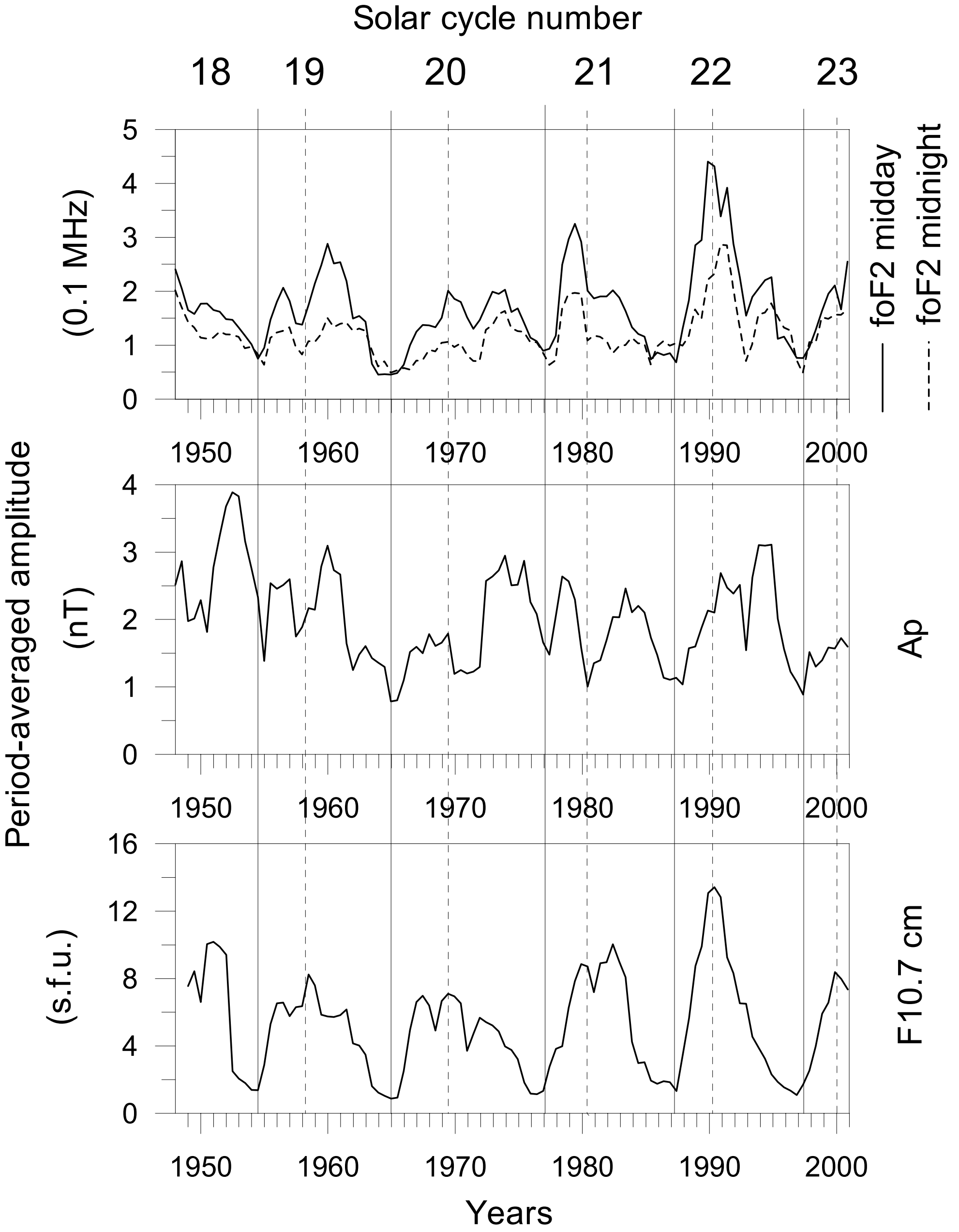

Fig. 3. Behaviour of the period averaged amplitude of the period band 25–31 days for *fo*F2 (Moscow) for midday and midnight, A_p and F10.7 cm for the interval 1947–2001. The solar cycle maxima and minima are marked as in Fig. 1.

the period-averaged amplitude from the 25- to 31-day period of *fo*F2, using all the hourly data, over 4-year intervals, before sunspot minima for all stations, show that the amplitudes for even cycles are greater than for the odd ones.

4 Conclusions

The present investigation indicates the existence of 22-year cycle in the F2-layer ionization at mid-latitudes for both Northern and Southern Hemisphere. The midday and midnight *fo*F2 variations that reflect the 27-day solar rotation period, more precisely in the period range from 25 to 31 days, show distinct enhancements in the late declining phases before sunspot minima of the investigated solar cycles 18–22. These *fo*F2 enhancements coincide strongly in time with the significant peaks of 27-day geomagnetic activity in the second half of the declining phase of each cycle. The even-high and odd-low pattern of the 27-day geomagnetic activity in the late declining phase of solar cycles is one of the main characteristics of the 22-year cycle in geomagnetic activity (Hapgood, 1993; Cliver et al., 1996), and the same pattern is well developed for the investigated *fo*F2 time series (Figs. 1–4). Such behaviour is not typical for solar radio flux F10.7 cm variations as a proxy of ionizing EUV-radiation. There are

Table 1. Period-averaged amplitudes from 25- to 31-day periods of *fo*F2 (all the hourly data, 0.1 MHz) over 4-year intervals before sunspot minima. Note that time intervals are in a fraction of years. The last two rows show the period-averaged amplitudes for daily A_p and F10.7 cm, respectively.

Solar cycle Time interval	18 1950.3–1954.3	19 1960.9–1964.9	20 1972.5–1976.5	21 1982.8–1986.8	22 1992.4–1996.4
Slough (51.5° N, 359.4° E)		0.67	0.97	0.55	0.75
Moscow (55° N, 37.3° E)	0.88	0.68	1.05	0.71	0.88
Alma Ata (43.2° N, 77° E)		0.60	0.75	0.50	
Tomsk (56.5° N, 84.9° E)		0.70	0.92	0.57	0.68
Irkutsk (52.5° N, 104° E)		0.72	0.92	0.50	
Akita (39.7° N, 140° E)		0.75	0.82	0.68	
Boulder (40° N, 256.7° E)		0.75	0.87	0.56	0.70
Mundaring (32° S, 116.2° E)		0.66	1.02	0.51	
Hobart (42.9° S, 147.3° E)	0.90	0.50	1.10	0.49	
Canberra (35.3° S, 149° E)	0.87	0.68	1.05	0.51	
Christchurch (43.4° S, 172.3° E)		0.90	1.16	0.58	
A_p (nT)	2.38	0.98	1.95	1.13	1.75
F10.7 cm (s.f.u.)	4.92	2.30	2.50	2.45	2.50

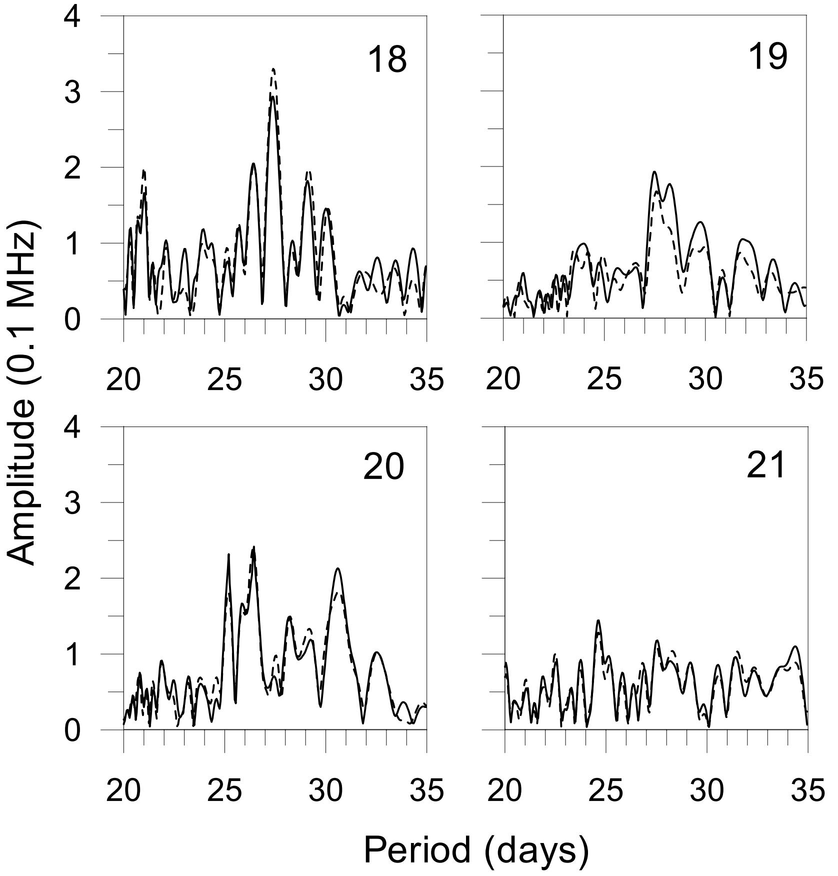

Fig. 4. The same as Fig. 2, but for *fo*F2 from Canberra for solar cycles 18–21.

no peaks of 27-day amplitudes in F10.7 cm during the second half of the declining phases of solar cycles, particularly in the even cycles 20 and 22. Instead of that, the amplitudes of F10.7 cm decrease gradually, while for those of the geomagnetic index A_p there are strong peaks also reflected in the *fo*F2 (Fig. 3). As an exception, the peak of the 27-day amplitude of F10.7 cm coincides in time with that of A_p for solar cycle 18, but this coincidence does not contradict the existence of a 22-year variation in *fo*F2 caused by geomagnetic activity, clearly expressed in the behaviour of A_p and *fo*F2 during solar cycles 19–22 (Fig. 2).

The obtained results are not surprising. A large part of F2-layer variability is linked to the geomagnetic activity (Forbes et al., 2000; Rishbeth and Mendillo, 2001). The possible causes of F2-layer variability related to the geomagnetic activity by means of Joule heating and energetic particle precipitation, are linked with the substorms, magnetic storms, and interplanetary magnetic field/solar wind structures that depict strong solar rotation and a 22-year cycle variation.

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