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periodicity may sometimes not even be present. Therefore these known mechanisms would combine to give a resulting modulation of the geomagnetic response to the randomly generated source of storms. It was also found that an additional seasonal peak seems to exist in July, with an amplitude comparable to those of the equinoctial peaks, for the range of the most intense storms (Ap>-150 nT). A weak periodicity around 158 days, well correlated to that of about 155 days observed in the solar activity, has also been detected for some years during solar cycle 21.

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Periodic Variation in the Geomagnetic Activity: A Study Based on the Ap Index

ALICIA L. CLÚA DE GONZALEZ ,[1] WALTER D. GONZALEZ ,[1] AND SEVERINO L. G. DUTRA

Instituto Nacional de Pesquisas Espaciais, São José dos Campos, São Paulo, Brazil

BRUCE T. TSURUTANI

Jet Propulsion Laboratory, California Institute of Technology, Pasadena

The monthly and daily samples of the Ap geomagnetic index for 51 years, 1932–1982, were investigated by means of the power spectrum technique. In general, the results confirm previous findings about possible periodicities in the geomagnetic activity. However, in our opinion the following aspects are either new or they are being interpreted somewhat differently than other authors have done. The period around 4 years in the monthly Ap power spectrum is associated to the double peak structure observed in the geomagnetic activity variation [*Gonzalez et al.*, 1990]. Several of the peaks shown by the daily Ap spectrum are interpreted as harmonics of the 6-month period and other peaks as caused by the solar rotation periodicity, in such a way that the two series of Fourier sequences are consider to be juxtaposed. A strong solar cycle modulation is observed in these series, particularly in that related to the solar rotation period, which almost disappears for the solar maximum phase. The study of the seasonal variation was complemented by a superposed epoch analysis. The profiles resulting from this analysis seem to show a multiple origin of the 6-month periodicity, so that it does not seem realistic to search for a unique cause for this well-known seasonal variation. This conclusion is also supported by the histograms of the occurrence of storms above a given intensity level, taken over short duration intervals (i.e., 8 days). According to these histograms, for large data samples the dates with largest number of storms are spread out around those predicted by the different theoretical models, while for short intervals the semiannual periodicity may sometimes not even be present. Therefore these known mechanisms would combine to give a resulting modulation of the geomagnetic response to the randomly generated source of storms. It was also found that an additional seasonal peak seems to exist in July, with an amplitude comparable to those of the equinoctial peaks, for the range of the most intense storms (Ap $\geq$ 150 nT). A weak periodicity around 158 days, well correlated to that of about 155 days observed in the solar activity, has also been detected for some years during solar cycle 21.

1. INTRODUCTION

Due to its well-known implications in many applied areas in addition to the intrinsic interest caused by the involved physics, the periodic variation in the geomagnetic activity has been the object of a large number of studies in the past. These studies have been carried out either by a direct monitoring of the components of the geomagnetic field or through the analysis of the available series of geomagnetic indices. In the present paper we follow the latter type of approach. The reader interested in the direct study of the field variations is referred to the review article by *Courtillot and Le Mouel* [1988 and references therein]. In spite of the fact that many authors have already taken advantage of the recent advances in the spectral analysis techniques as well as of the availability of long series of geomagnetic indices to study the periodic variations of the geomagnetic activity [e.g., *Ward*, 1960; *Shapiro*, 1969; *Fraser-Smith*, 1972; *Delouis and Mayaud*, 1975; *Currie*, 1976; *Courtillot et al.*, 1977; *Kane*, 1986], there are still some unclear points in the understanding of these variations. Therefore we believe that new efforts in that direction, like the present one, are still valuable.

In the present paper we analyze the periodic variations in the daily values of the geomagnetic index Ap for the interval 1932 through 1982. The main statistical tool is the power spectrum analysis [*Jenkins and Watts*, 1968] in the way described by *Gonzalez and Gonzalez* [1987], but other techniques are also used as discussed below. The data were obtained on magnetic tape from the World Data Center.

In section 2 we present the general results of our power spectrum analysis and devote section 3 to make more detailed considerations on the results obtained for the Bartel's period (around 27 days), and section 4 for the semiannual period, the dual-peak solar cycle distribution of geomagnetic storms, and some other medium-scale periodicities, respectively. Finally, we present in the appendix the results of the cumulative occurrence number of storms per decade as a function of the Ap and Dst indices for the storm.

2. THE SPECTRUM OF THE GEOMAGNETIC INDEX AP

Fraser-Smith [1972] did a fast Fourier transform analysis of the geomagnetic index Ap for the years 1932 through 1970. In that exhaustive study the data were considered in two different ways, namely, daily and monthly averaged values. In the present paper we undertake a similar approach but using the power spectrum analysis technique and extending the data up to 1982. In subsections 2.1

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[1] On leave at NOAA Environmental Research Laboratories, Boulder, Colorado.

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and 2.2 we present the results of this analysis for both the monthly averages and the daily Ap samples. For the power spectrum smoothing, a Hanning-Tukey lag window was used. The window closing technique allowed for a reasonable choice of the window size (the so-called truncation point, M). The smoothed power spectrum density, PSD, was plotted in a logarithmic scale and the bandwidth and the confidence intervals, to a predetermined level, were also estimated [*Jenkins and Watts*, 1968; *Gonzalez and Gonzalez*, 1987].

2.1. *Long-Period Variations in the Ap Index*

Since the averaging process acts as a low-pass digital filter, the spectral analysis of the monthly averaged Ap indices, $\langle \mathrm{Ap} \rangle$, is suitable for the study of the long-period variations in the geomagnetic activity. In Figures 1*a* and 1*b* we show the respective power spectra for $\langle \mathrm{Ap} \rangle$ and for R, for the time interval 1932 through 1982. For both spectra the truncation point in the Hanning-Tukey lag window, M, is equal to 300 months and the sampling frequency interval 0.5/1000 cycles month^{-1}. The errors in the determination of the spectral peaks were calculated assuming that the uncertainty in the frequency is given by $0.5/(2M)$ cycles month^{-1}. The frequency interval shown by these figures, 0 to 0.4 cycles month^{-1}, corresponds to periods running from infinite down to 2.5 months.

From the comparison of the spectra on Figures 1*a* and 1*b* two well-known features of the geomagnetic activity variation become evident. They are, on one hand, the solar cycle modulation (see, e.g., the review article by *Gorney* [1990 and references therein]) and, on the other, the seasonal effect present in its annual behavior (see section 4 for references). In fact, the power spectrum of $\langle \mathrm{Ap} \rangle$ shows a peak at 10.3 (± 1.1) years, indeed associated with the solar cycle period, or Schawabe cycle. For the monthly sunspot number (Figure 1*b*) the Schawabe periodicity is shown to be 10.4 (± 1.1) years. With respect to this periodicity it should be said that since the power spectrum analysis responds for the recurrence in the shape of the cycles and not only for the positions of the solar minima, the result obtained from the power spectrum analysis is not surprising as compared to the well-known value around 11 years (e.g., *Fraser-Smith* [1972] found the periodicity of 10.2 years for the interval 1932–1969). Concerning the semiannual periodicity, it is remarkable the difference in the amplitudes of the respective peaks. In the $\langle \mathrm{Ap} \rangle$ spectrum (Figure 1*a*) the peak at 6.00 (± 0.06) months is by far the most outstanding one from the background while in the R spectrum (Figure 1*b*) the peak around 6-months is not a significant one.

Besides those peaks corresponding to the solar cycle and to the semiannual periodicities, there are others in the spectra of Figures 1*a* and 1*b* that although may be below the considered levels of confidence, we believe that they should be mentioned due to their probable physical meaning and as clues for eventual future more extensive analyses.

Let us start from the low-frequency extreme and mention the probable periodicities in the increasing frequency direction, regardless of the differences in their relative significance. Since the data under consideration refer only to 51 years, one can not expect to find any periodicity at or beyond this time scale, even though long-period (longer than 50 years) variations are suspected to exist in the geomagnetic activity [e.g., *Gleissberg*, 1965; *Currie*, 1973b, 1976; *Delouis and Mayaud*, 1975; *Feynman and Gu*, 1986; *Courtillot and Le Mouel*, 1988, *Borello Filisetti et al.*, 1990] as well as in the sunspot number [*Gleissberg*, 1958; *Cohen and Lintz*, 1974; *Currie*, 1976; *Wallenhorst*, 1982]. However, the $\langle \mathrm{Ap} \rangle$ and the R spectra show indications of a periodicity around 32 and 33 years, respectively, and since the resolution for this spectral region is not better than 11 years, both peaks are probably correlated. In the work by *Fraser-Smith* [1972] the corresponding line in the $\langle \mathrm{Ap} \rangle$ spectrum shows up at 35.6 years while *Delouis and Mayaud* [1975] found a peak at 36.0 years in their fast Fourier transform spectrum of the *aa* index. Furthermore, *Rotanova et al.* [1985] detected possible periods at 30–40 years in the components of the geomagnetic field. Concerning the R spectrum it should be noticed that the 33-years line is very unstable. Actually, it does not appear in the power spectrum for the interval 1920–1982, that includes the cycle 16. This instability explains the fact that this possible periodicity in the sunspot number is hardly mentioned in the literature. Further studies in this direction are necessary to confirm the existence of this periodicity.

No evidence is found in either the geomagnetic or sunspot spectrum for the so-called solar magnetic cycle around 22 years, or Hale cycle [e.g., *Babcock*, 1961; *Currie*, 1973a; *Sonett*, 1982]. Some doubt has been raised about the real existence of this periodicity [e.g., *Currie*, 1976; *Courtillot and Le Mouel*, 1976]. However, we can not draw any definite conclusion here due to the size of our data sample. We also do not see any peak around 16 years as would be expected from the works by *Fraser-Smith* [1972] and *Delouis and Mayaud* [1975].

To the right of the solar cycle peak we observe in the $\langle \mathrm{Ap} \rangle$ spectrum of Figure 1*a* two peaks, one very broad (particularly in the direction of increasing frequency) with a maximum at 4.4 (± 0.2) years, and the other at 2.90 (± 0.08) years. These possible periods do not seem to be related to those at 5.5 (± 0.3) and 3.2 (± 0.1) years seen in the R spectrum (Figure 1*b*), which are currently interpreted as the respective first and second harmonics of the solar cycle [e.g., *Currie*, 1976; *Sugiura*, 1980]. In our opinion, they could be originated by the dual-peak structure in geomagnetic activity reported in the article by *Gonzalez et al.* [1990]. It was shown in that paper that the yearly distribution of intense storms has two peaks around the solar maxima, with an average time separation of approximately 3 to 4 years. We shall consider this topic in more detail in section 5, but let us notice that the hypothesis connecting the periodicities around 3 and 4 years to the dual peak structure in geomagnetic activity would be further confirmed if the complementary periods (in one solar cycle) of approximately 8 and 7 years were found. This is not the case in the spectrum of Figure 1*a*, but probably as a consequence of the limited resolution of the $\langle \mathrm{Ap} \rangle$ spectrum at this spectral range, largely dominated by the solar cycle period. In fact, in the respective reports by *Fraser-Smith* [1972] and by *Delouis and Mayaud* [1975], a line around 4 years (more exactly 4.1 years) and another one around 7 years (7.0 years for Fraser-Smith and 7.2 years for Delouis and Mayaud) are given, without a definite interpretation. Possible periodicities in geomagnetic activity around 3, 4 and 7 years were also found by *Currie* [1973b, 1976], and about 4 years by *Kane* [1986]. Furthermore, a possible periodicity around 4 years in the polarity pattern of the

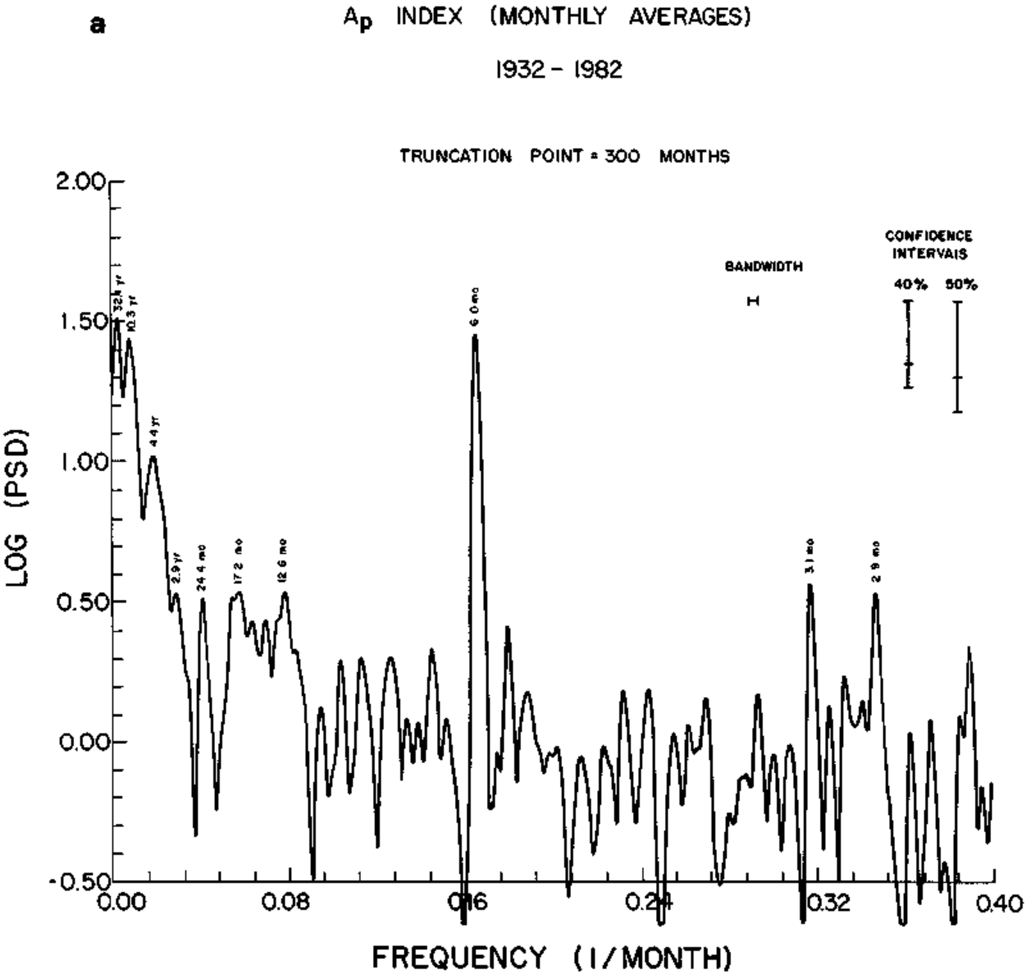

Fig. 1. Logarithm of the power spectrum density PSD of (a) the monthly averages of the Ap index (⟨Ap⟩), and (b) the monthly values of the Zurich sunspot number, for the years 1932 through 1982. A Hanning-Tukey lag window with a truncation point of 300 months was used to obtain these spectra. The sampling frequency interval is 0.5/1000 cycles month^{-1}. The bandwidth and confidence bars, at a 60 and 80 % confidence level, computed for this type of window, are given on the top of each figure.

interplanetary magnetic field was observed by *Gonzalez and Gonzalez* [1987]. In order to improve the resolution of our spectral analysis, a study similar to the present one but based on the longer series of monthly *aa* index is being presently undertaken.

As expected, the spectral region for periods between about 3 years to 1 year is very rich in lines in the geomagnetic as well as in the sunspot spectrum. For the latter, all the observed peaks in this region are well correlated with the solar cycle harmonics, starting from the fourth peak (around 2 years) down to the ninth (around 1 year). However, the ⟨Ap⟩ spectrum has its own peculiarities and we believe that not all the observed lines are necessarily identifiable with those harmonics. From left to right, we observe first a peak at 24.4 (± 0.5) months, comparable to the quasi-biennial periodicity in geomagnetic activity observed by *Currie* [1973b, 1976] and by *Kane* [1986] [see *Sugiura and Poros*, 1977, and references therein]. Then, we see a complex line around 17 months, peaking at 17.2 (± 0.3) months (or 1.43 ± 0.02 years), very close to the value of 1.4 years found by *Fraser-Smith* [1972] and *Delouis and Mayaud* [1975], as well as by *Kane* [1986]. It is worth noticing that *Gonzalez and Gonzalez* [1987] have claimed that the sector structure of the interplanetary magnetic field has a periodicity of about 1.5 years. Furthermore, *Silverman and Shapiro* [1983] also have devoted some attention to the 1.4-year peak found in their power spectral analysis of the auroral occurrence frequency. We observe also a peak at 12.6 (± 0.1) months, or 1.05 (± 0.01) years, with about the same amplitude than the former, in close agreement with the small line detected by *Fraser-Smith* [1972] at 1.09 years and that observed by *Delouis and Mayaud* [1975] at 1.086 years.

The region for periods between around 1 year to 4 months also presents differences in the respective ⟨Ap⟩ and *R* spectra. The latter also shows practically all the solar cycle period harmonics from the tenth (around 11 months) down to the 30th (around 4 months), with relative amplitudes varying according to a not too evident behavior. On the other hand, the ⟨Ap⟩ spectrum is dominated by the strong 6-month period peak and its side lobes, making it difficult to obtain any conclusion about any other possible periodicities. We will come back below to discuss the 6-month period,which is the most prominent one in the geomagnetic spectrum, but hardly appears in the sunspot spectrum (probably as the 20th solar cycle period harmonic). Below the 4-month period region the only

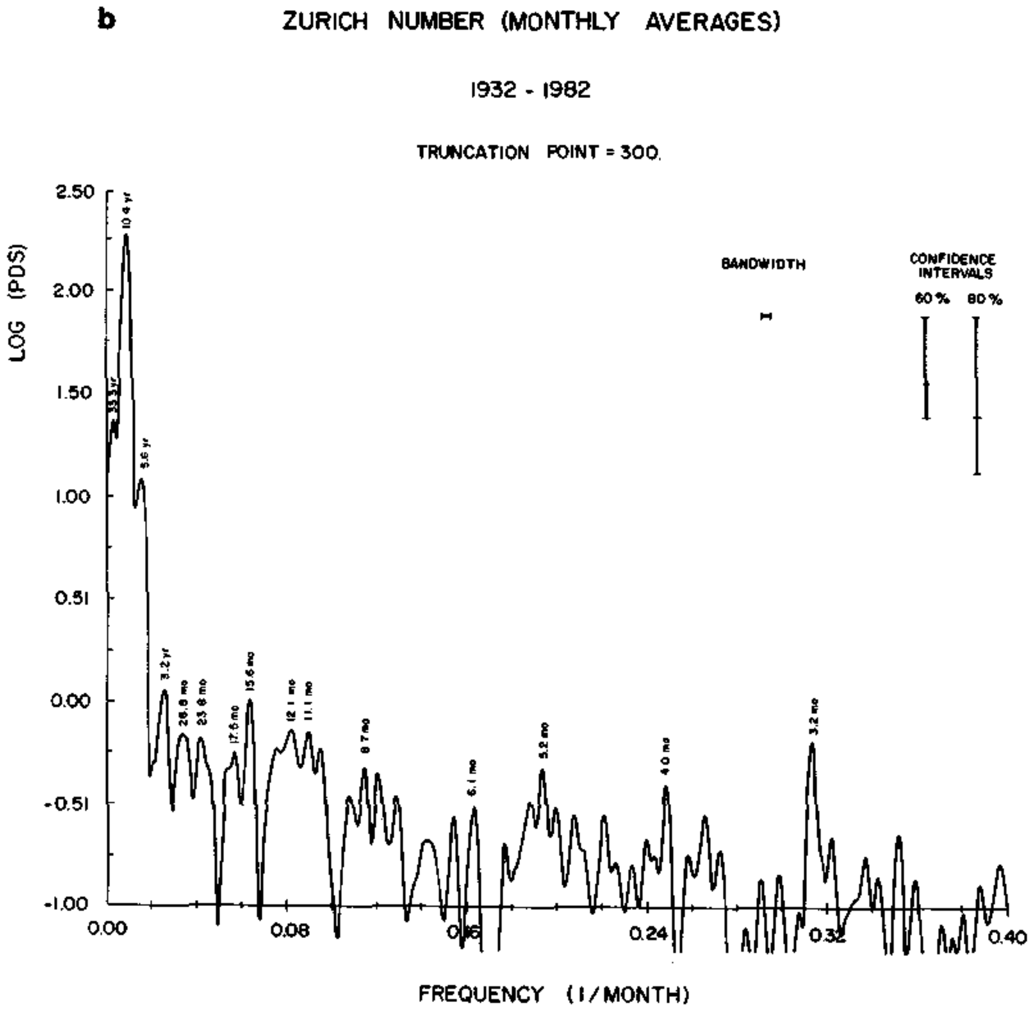

Fig. 1. (continued)

noticeable peaks seen in Figure 2*a* and Figure 2*b* are found around 3 months. In the case of the ⟨Ap⟩ spectrum, we have indeed in this region the first harmonic of the 6-month period. We discuss this in more detail in the next subsection.

2.2. *Short-Period Variations in the Ap Index*

As already mentioned in the introduction section, we also applied the power spectrum analysis to the daily sample of the Ap values. For this set of approximately 18,600 points, values of the truncation point of 500, 1000 and 3000 days were tested. The resulting power spectrum for a truncation point of 1000 and 3000 days and sampling frequency intervals of 0.5/5000 and 0.5/10000 cycles day^{-1}, respectively, are shown in Figures 2*a* and 2*b*. One can see in these figures the great complexity of the Ap spectrum. It is, for instance, much more complex than a similar figure obtained for the sector structure of the interplanetary magnetic field (shown in Figure 1 of *Gonzalez and Gonzalez* [1987]). Again, the most noticeable peak is that at 6 months, or more precisely, at 181.8 (± 8.3) days. Furthermore, many of the harmonics of this period seem to be also present in this spectrum. In Table 1a the expected harmonics and their possibly associated observed peaks are listed together. As seen in this table, many of the observed peaks agree, within the predicted error, with the expected values of the harmonics of the 6-month periodicity (this error has been computed considering that the uncertainty in the frequency is given by $0.5/(2M)$ cycles day^{-1}). The hypothesis of this association between many of the observed peaks and the 6-month period harmonics applies particularly to the peaks around 37, 18 and 14 days whose origin has not been clearly established yet [*Fraser-Smith*, 1972].

The spectra of Figures 2*a* and 2*b* show some other peaks, not listed in Table 1a, that do not match with the expected harmonics of the 6-month period. The most important feature of this spectrum, after the semiannual period sequence, is the sequence originated by the solar rotation period of 27 days. Taken the observed value of 27.3 days as the fundamental period for this Fourier sequence, we obtain the harmonics shown in Table 1b. From the comparison of Tables 1a and 1b we conclude that neither this fundamental period or its first harmonic, 13.6 days, overlap with the sequence corresponding to the 6-month period, so that no doubt remains concerning the different causes of these peaks. On the other hand, the peaks are expected to mix with the 6-month sequence from the second harmonic on, and this is probably the cause of the broad profiles observed for such frequencies. No intent has been made in Tables 1a and 1b to resolve these lines.

The simultaneous presence of two strong periodicities and their corresponding series of harmonics explains the complexity observed in the Ap spectrum. Nevertheless, it

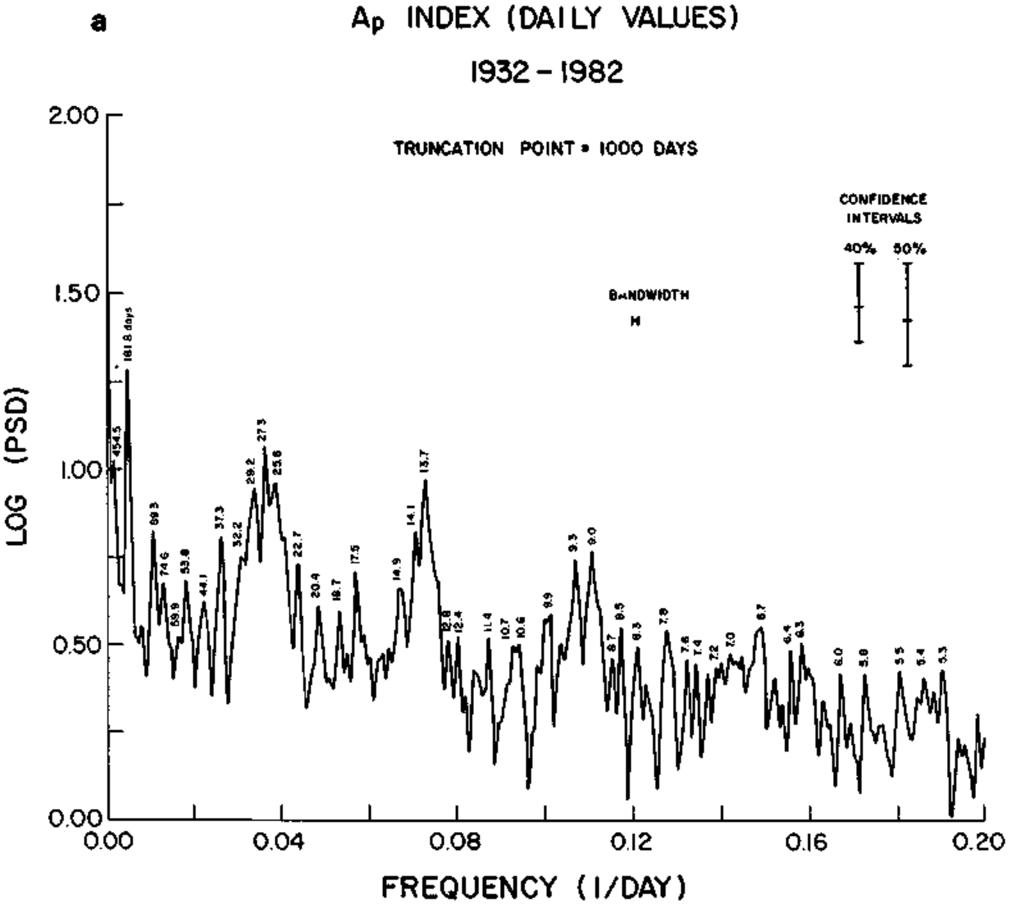

Fig. 2. Logarithm of the PSD for the daily Ap index for the years 1932 through 1982. The truncation point for the Hanning-Tukey window and the sampling frequency interval are respectively (a) 1000 days and 0.5/5000 cycles day^{-1}, (b) 3000 days and 0.5/10000 cycles day^{-1}. The spectral bandwidth and the confidence intervals to a 40 and 60 % level are given on the top.

can be seen that the relative amplitudes of the solar rotation period series is very similar to that observed by *Gonzalez and Gonzalez* [1987] for the polarity of the interplanetary magnetic field, for a similar time interval: 1926–1982. In that paper the decreasing in the amplitudes with increasing order of the harmonics of the Bartel's periodicity was related to the long-time predominance of the two-sector structure over more complex structures, particularly the four-sector one, sometimes observed in the interplanetary magnetic field. On the other hand, this resemblance between the geomagnetic activity and the sector structure of the interplanetary magnetic field has been already demonstrated to exist [e.g., *Francia and Villante*, 1986].

A few remaining significant peaks in the spectrum of Figure 2 do not match with either of the series shown in Tables 1a and 1b and have been listed separately in Table 1c. In this table we have also included the corresponding periodicities found by *Fraser-Smith* (third column) as well as some periodicities recently observed in the solar activity [i.e., *Delache et al.*, 1985]. For the confection of this table the improved resolution of the spectrum in Figure 2*b* (M = 3000 days) has been used. Considering the spectrum in the increasing frequency direction, we observe first a peak at 526 (± 23) days, or 1.44 (± 0.06) years which evidently corresponds to the possible periodicity around 1.4 years observed in the $\langle \mathrm{Ap} \rangle$ spectrum and discussed in the previous subsection. It is not clear whether this possible periodicity matches with that at 688 days observed in the daily Zurich sunspot number [*Delache et al.*, 1985]. Following this, we observe a peak of similar amplitude at 392 (± 13) days, or 1.07 (± 0.04) years, also mentioned in section 2.1, that has its close counterpart in the daily Zurich sunspot number spectrum [*Delache et al.*, 1985]. The much weaker peaks at 157.5 (± 2.1) days and at 51.7 (± 0.3) days seem to correspond, respectively, to that around 155 days and its possible harmonic at 51.7 days observed in the solar activity [*Rieger et al.*, 1984; *Delache et al.*, 1985; *Lean and Brueckner*, 1989; *Bai and Cliver*, 1990, and references therein]. We will come back to this correspondence in section 4. Among the remaining peaks, the most noticeable is that around 54 days (53.8 ± 0.9 days) that has been also reported by *Fraser-Smith* [1972], *Delouis and Mayaud* [1975] and by *Kane* [1986] and can not apparently be associated to any known periodicity in the Sun.

3. The Solar Rotation Period

From what it was seen in subsection 2.2, it can be inferred that the solar rotation period is one of the most important features in the geomagnetic activity variation, together with the semiannual and the solar cycle periodicities. Its existence is now well documented [e.g., *Ward*, 1960; *Shapiro and Ward*, 1966; *Fraser-Smith*, 1972; *Delouis and Mayaud*, 1975, *Kane*, 1986; Sargent, 1986]. As a matter of fact,

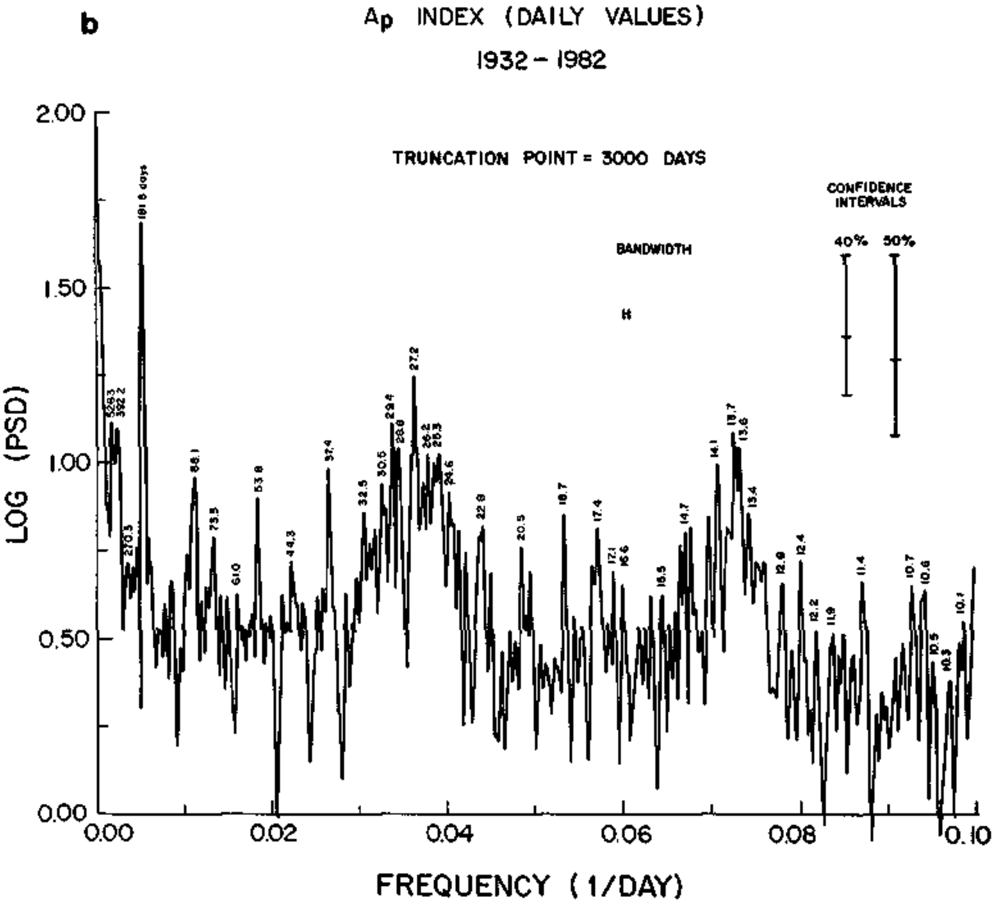

Fig. 2. (continued)

the geomagnetic activity spectrum looks in general quite complex in the region around 27 days (see the comments by *Coleman and Smith* [1966] and *Fraser-Smith* [1973]) as observed in the spectra of Figures 2*a* and 2*b*.

Besides the fact that several different phenomena can contribute to periodicities around 27 days, there is an intrinsic temporal variation in the period values that can not be separated from the persistent contributions in a global analysis such as that shown in Figures 1*a*, 2*a* and 2*b*, referent to 51 years of data. Thus due to the existing evidence of a dynamic behavior of the geomagnetic activity, particularly related to the solar rotation period, we have also applied the power spectrum analysis to the daily data divided into smaller subsets. A first intent was done by considering separately intervals corresponding to different phases of the solar cycle, that correspond, respectively, to years of solar maximum and to years involving the late descending phase and minimum (called here solar minimum for short) of the solar cycle. The resulting samples consist of sets of daily values of ⟨Ap⟩ for 4 or 5 years, which were submitted to a power spectrum analysis with truncation points varying between 100 and 300 days. The resulting spectra were grouped according to the corresponding solar cycle phase in Figures 3*a* and 3*b*. In these figures the selected truncation point is equal to 200 days and the sampling frequency interval equal to 0.5/500 cycles day^{-1}. In both figures the frequencies corresponding to the Bartel's period of 27 days and its first three harmonics have been indicated by dashed lines.

Figure 3*a* refers to the solar minimum intervals. It is seen that the spectra in this figure are characterized by a very regular behavior, showing as its main feature the solar rotation sequence. The relative amplitudes of the peaks in this sequence vary from one interval to another. While for the first two intervals (between cycles 17 and 18, and 18 and 19, respectively) the predominant peak is that corresponding to the fundamental period around 27 days, for the third interval (between cycles 19 and 20) the predominant peak is that for the second harmonic while for the fourth interval (between cycles 20 and 21) it is that for the first harmonic. Referring to the interplanetary magnetic field polarity, *Gonzalez and Gonzalez* [1987] have interpreted the spectra with a predominant peak at the fundamental solar rotation period as due to a dominant two-sector structure, and those with a predominant peak at its first harmonic as due to a dominant four-sector structure. On the other hand, as already mentioned, there seems to exist a correlation between the sector structure and the geomagnetic activity [e.g., *Hirshberg and Colburn*, 1973; *Lundstedt et al.*, 1981; *Francia and Villante*, 1986; *Villante and Francia*,, 1988], and one seems to be led to conclude that the first two solar minimum intervals are dominated by a two-sector structure while for the last two intervals more complex structures become relevant. The result presented

TABLE 1*a*. Semiannual Harmonics Sequence

n	Observed Period,* day	Predicted Period,† day	Estimated Error, day	Amplitude, day nT^2
0	181.8		8.3	19.4
1	89.3	90.9	2.0	6.7
2	59.9	60.6	0.9	3.3
3	44.1	45.5	0.5	4.2
4	36.4	37.3	0.4	6.4
5	29.2	30.3	0.2	8.8
6	25.6	26.0	0.2	9.2
7	22.7	22.7	0.2	5.4
8	20.4	20.2	0.1	4.1
9	18.1	18.2	0.08	9.0
10	17.5	16.5	0.06	5.2
11	14.9	15.2	0.06	4.6
12	14.1	14.0	0.05	6.7
13	12.8	13.0	0.04	3.2
14	12.4	12.1	0.04	3.4
15	11.4	11.4	0.04	3.0
16	10.6–10.7	10.7	0.03	3.2
17	10.1	10.1	0.03	2.7
18	9.6	9.6	0.03	3.2
19	9.0–9.3	9.1	0.03	5.9–5.6
20	8.7	8.7	0.03	2.9
21	8.3	8.3	0.02	3.1
22	7.8	7.9	0.02	3.5
23	7.6	7.6	0.02	2.9
24	7.4	7.3	0.02	2.8
25	7.0	7.0	0.02	3.0
26	6.7	6.7	0.02	3.6
27	6.4	6.5	0.02	3.1
28	6.3	6.3	0.02	3.2
29	6.1	6.1	0.01	2.2
30	6.0	5.9	0.01	2.6
31	5.8	5.7	0.01	2.6
32	5.5	5.5	0.01	2.7
33	5.3	5.3	0.01	2.7
34	5.2	5.2	0.01	1.7
35	5.1	5.1	0.01	1.6

Main peaks observed in the power spectrum analysis of the daily Ap index in the interval 1932–1982. Sequence of the semiannual peak, from a power spectrum with truncation point, M, equal to 1000 days. The first column gives the order of each harmonic, starting from the fundamental ($n = 0$). The second column gives the values of the peaks as observed in the spectrum. In the third column, the observed period of 181.2 days is taken as the fundamental of the predicted sequence. The error, fourth column, is derived assuming that the uncertainty in the frequency is given by $0.5/(2M)$ cycles month^{-1}.The amplitude, fifth column, refers to the observed peaks of the first column.

* Present analysis with a truncation point, $M = 1000$ days.

† The nth harmonic derived from the first value of the first column.

in Figure 3*a* is based, however, on a large-scale subdivision of the data and might change if a finer scanning (1 or 2 years) were done, as shown below and also as concluded from the sector structure variations illustrated by Figure 4 of *Gonzalez and Gonzalez* [1987]. A further reason to avoid this simple interpretation of the relative amplitude of the peaks is the presence of the 6-month sequence that gets mixed with the solar rotation sequence altering the weight of the higher harmonics.

In Figure 3*b* we show the spectra corresponding to intervals of solar maximum. The spectra in this figure look much more complex than those for the solar minimum intervals and the solar rotation period sequence seems to be less important for this phase of the solar cycle.

A more detailed picture of the dynamic behavior of the geomagnetic activity pattern is given in Figure 4, which shows the power spectrum contour lines for 2-years running subintervals of the daily Ap sample. The selected truncation point is equal to 200 days and the sampling frequency interval is $0.5/500$ cycles day^{-1}. The intervals of late descending phase and solar minimum (the same as in Figure 3*a*) are limited by the vertical dashed lines. It can be seen in this figure that the regions of higher spectral power for the 27-days line are practically restricted to these solar minimum intervals. Although not shown in Figure 4, a similar behavior is observed for the first harmonic of this period (around 13.5 days).

A yearly subdivision of the data, not shown here, was also considered in order to compare with a similar running power spectrum done on the interplanetary magnetic field polarity by *Gonzalez and Gonzalez* [1987]. It was observed that periodicities between approximately 26.5 and 28.5 days correlated well with the corresponding values found in the field polarity analysis and could be associated to the same solar cause. Outside this range the correlation drops, and the observed values seem to be more related to the harmonics of the semiannual period shown in Table 1a.

4. MEDIUM-SCALE PERIODICITIES

4.1. *Semiannual Periodicity*

Although the seasonal variation of the geomagnetic activity is known from long ago [e.g., *Sabine*, 1856; *Cortie*, 1912; *Chapman and it Bartels*, 1940; *Silverman*, 1986; *Crooker and Siscoe*, 1986], theories regarding its origin are still controversial. Therefore it is interesting to consider here the 6-month period in more detail. There are basically two mechanisms through which the seasonal variation can be explained. One of them, historically the first, is the so-called axial mechanism [*Cortie*, 1912, 1915; *Priester and Cattani*, 1962]. It is based on the fact that the Earth reaches its maximum heliographic latitude of +7.2° and −7.2° on approximately September 6 and March 5, respectively, which are close to the epochs of the observed maximum geomagnetic activity. According to this model, the reception by the Earth of flares and other outburst of plasma from the Sun is favored at these positions due to its larger latitudinal approximation with the active solar region (located between 10° and 20° of solar latitude).

The other alternative mechanism is based on the variation

TABLE 1*b*. Solar Rotation Period Harmonic Sequence

n	Observed Period,* day	Predicted Period,† day	Estimated Error, day	Amplitude, day nT^2
0	27.3		0.2	11.7
1	13.7	13.7	0.4	9.4
2	9.0–9.3	9.1	0.03	5.9–5.6
3	6.7	6.8	0.02	3.6
4	5.5	5.5	0.01	2.7

Similar to Table 1*a*, but for the sequence of the solar rotation period (around 27.3 days).

* Present analysis with a truncation point, $M = 1000$ days.

† The nth harmonic derived from the first value of the first column.

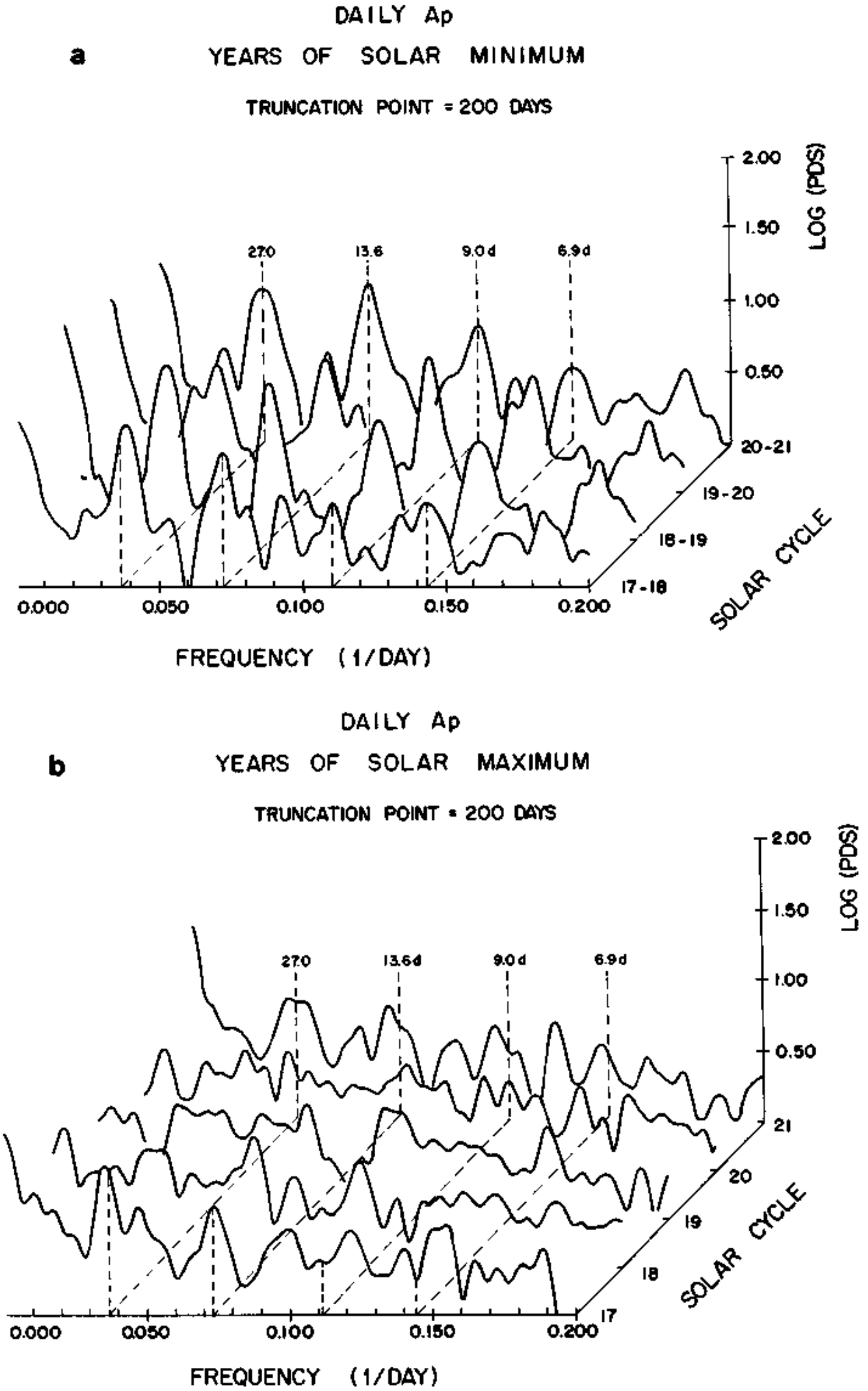

Fig. 3. Logarithm of the PSD for years of (a) descending phase and solar minimum (1941–1944, 1950–1954, 1961–1965, 1972–1975), and (b) solar maximum (1936–1939, 1946–1949, 1956–1960, 1967–1970, 1978–1982). The truncation point for the Hanning-Tukey lag window is 200 days and the sampling frequency interval 0.5/500 cycles day^{-1}. The dashed lines show the frequency of the solar rotation peak and its main harmonics.

of the effectiveness of the interaction between the solar wind and the Earth's magnetosphere with the orientation of the Earth's magnetic dipole relative to the Earth-Sun line. In one of its versions, first suggested by *McIntosh* [1959], this effectiveness depends on the angle between the Earth's dipole and the solar wind velocity, and the model predicts geomagnetic activity maxima to occur at the Earth equinoxes (March 21 and September 23) and is known as the equinoctial mechanism. Another version, that takes also into account the inclination of the solar magnetic equator with respect to the ecliptic plane, has been developed by *Russell and McPherron* [1973]. In the Russell-McPherron model the predicted maxima, that correspond to dates with largest southward component of the interplanetary magnetic

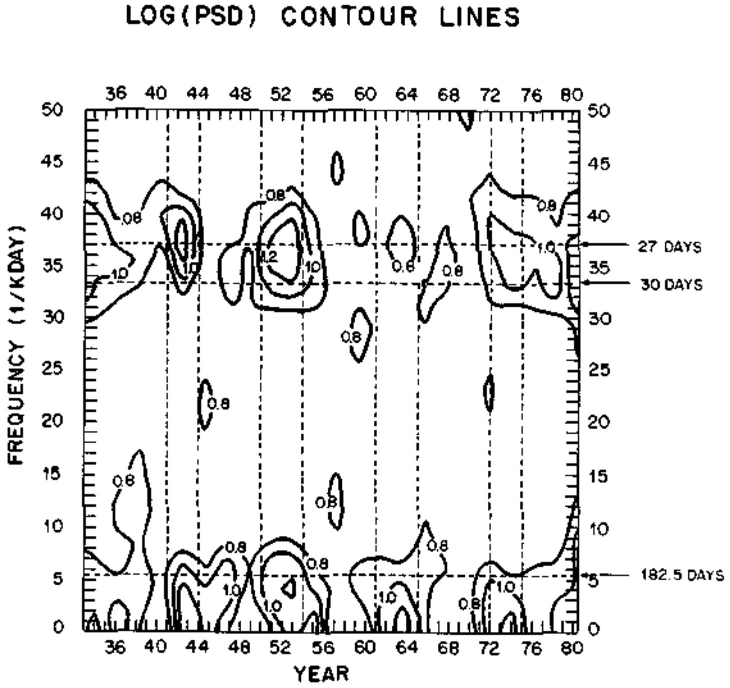

Fig. 4. Logarithm of the PSD of 2-year running intervals of the daily Ap values. The truncation point in the Hamming-Tukey window is 200 days. The shaded intervals correspond to the descending phase and solar minimum years of Figure 3*a*. The horizontal dashed lines show the frequencies corresponding to periods of, from bottom to top, 182.5 (0.5 year), 30 and 27 days.

TABLE 1*c*. Other Observed Periodicities

Present Analysis*		Fraser-Smith	Solar Activity
Period, day	Amplitude, day-nT^2	Period,† day	Period,‡ day
526. (±23.)	13.0	536	688.
392. (±13.)	12.6	398	392.
157.5 (± 2.1)	5.1		157.
73.5 (± 0.5)	6.1	—	74.6
53.8 (± 0.3)	7.9	54	—
51.0 (± 0.3)	3.5	—	51.6

Some remaining peaks, with no agreement either with the semiannual or the solar rotation sequences, are listed on the first column according with the periodicities obtained with a truncation point equal to 3000 days, together with their amplitude (second column). The corresponding values obtained by *Fraser-Smith* [1972] for the daily Ap index and some of those found for the solar activity [*Delache et al.*, 1985] are given in the third and fourth columns, respectively.

* Present analysis with a truncation point, $M = 3000$ days.

† From *Fraser-Smith* [1972].

‡ From *Delache et al.* [1985].

field as seen in the GSM coordinate system, are shifted to April 5 and to October 5 [*Russell and McPherron*, 1973; *Crooker and Siscoe*, 1986].

Due to the proximity predicted by the different models for the dates of maximum geomagnetic activity and also to the intrinsic variations observed from year to year in the seasonal variation pattern, it is not a simple task to determine which of these models is the most appropriate one. *Fraser-Smith* [1972] sees in his analysis evidence for supporting the equinoctial mechanism. *Green* [1984] has carried out a complex demodulation analysis on the geomagnetic *aa* index for 1868–1980 and the Ap index for 1932–1980. He found a yearly variation in the amplitude and phase of the semiannual variation as well as a solar cycle modulation but concluded anyway that the mean value of the phases would be in agreement with the equinoctial model. On the other hand, some authors see evidence for a combination of effects leading to the seasonal variation [see *Silverman*, 1986, and references therein]. *Murayama* [1974] has shown that the semiannual variation of the Kp index can be interpreted as the combined effect of the semiannual variation of the southward component of the interplanetary magnetic field according to the model of Russell and McPherron and the heliographic latitude dependence proposed by the axial mechanism, so that the closeness of the semiannual peaks to the equinoxes would be a mere coincidence. *Berthelier* [1976] concluded that the influence of the interplanetary magnetic field polarity on the

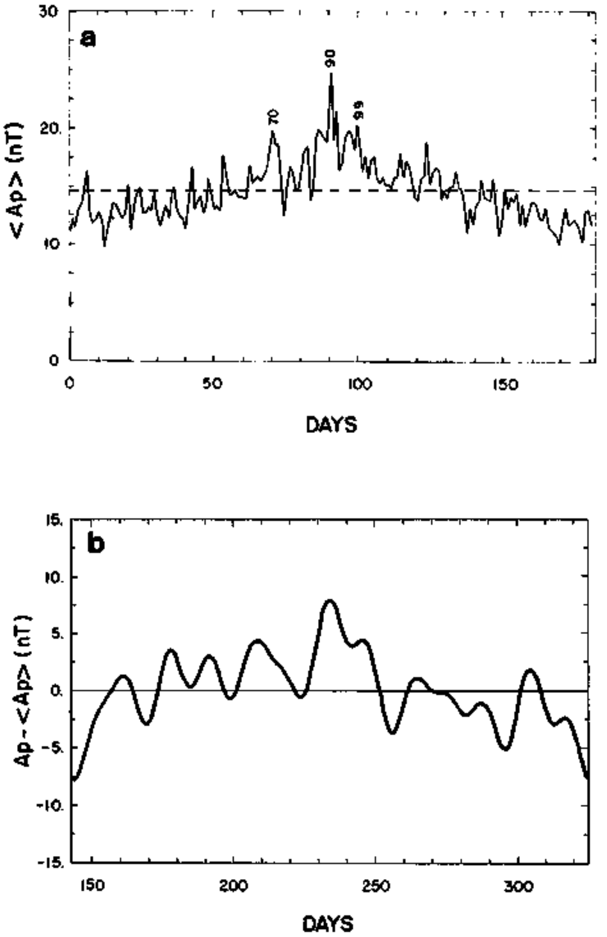

Fig. 5. (a) Superposed epoch analysis of the Ap values, for a period of 182.5 days (0.5 year), starting on January 1 (July 2). The total average of 14.55 nT is shown by the dashed horizontal line. The main peaks are at days: 70, corresponding to March 12 and September 10; 90, corresponding to April 1 and September 30; and 99, corresponding to April 10 and October 9. (b) Fourier-generated function with a period of 182.5 days, according to the fundamental and harmonics amplitudes and phases given by *Fraser-Smith* [1972].

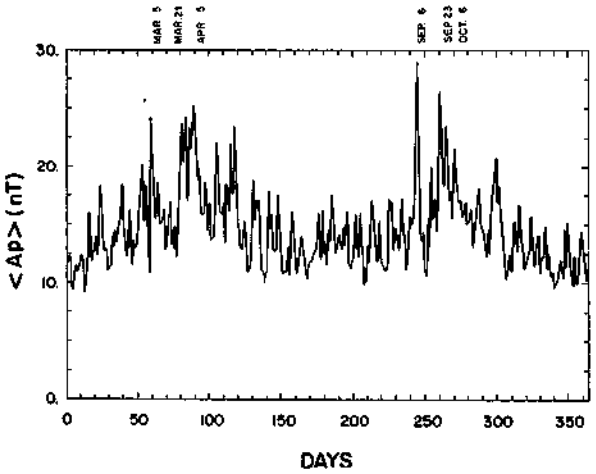

Fig. 6. Superposed epoch analysis of the Ap values for a period of 365.35 days, starting on January 1. The main peaks and corresponding amplitudes are given at column 5 of Table 2.

annual variation of the Am index for 1964–1969 would be responsible for a part of the observed variation but that the McIntosh, or equinoctial, mechanism would remain valid. *Holzer and Slavin* [1982] demonstrated that the mechanism of Russell and McPherron could account for a significant fraction of the semiannual variation but that some modifying factor, like a variation of the merging efficiency at the sunward magnetopause modulating the geographical axis inclination to the Earth-Sun line, would also be present.

In order to understand more about the annual and semiannual periodic variations we have used the superposed epoch analysis, of the daily Ap data. This classical statistical technique [e.g., *Chapman and Bartels*, 1940; *Meyer*, 1966; *Forbush et al.*, 1982] has the advantage of showing at once the average behavior of a given temporal series through a known period. In this analysis we have varied the folding period by small fractional amounts around the expected values, looking for that value able to minimize the total variance. The effect of considering a period compound of an integer number of days (T) plus a fraction d/h days (where T, d, and h are integers) is that the averaging sample of T days will shift T days for the first $h-1$ intervals, $T+d$ days for the hth interval, T days for the following $h-1$ days and so on.

In Figure 5*a* we show the superposed epoch analysis for a period of 182.5 days, or 0.5 year, which is a value that minimizes the total variance in an interval around 6 months. January 1 and July 2 are taken as the starting dates. The peaks indicated by 70, 90 and 99 correspond to the dates March 12 and September 10, April 1 and September 30, and April 10 and October 9, respectively, which are not too far from the values predicted by the different models. However, it should be mentioned that a small change in the chosen folding period produces a drastic change in the resulting profile, probably due to the random occurrence of the storm sources. In order to have a better idea of how this profile should look, we have constructed a function generating the Fourier series of 6-month harmonics. Since in the present analysis the harmonics phases have not been computed, we have taken the amplitudes and phases given by *Fraser-Smith* [1972] for this simulation. The resulting profile, with the constant term ⟨Ap⟩ (= 14.55 nT) being already subtracted and with a proper phase constant added, is shown in Figure 5*b*. As it can be seen, this curve gives the gross variation of the curve in Figure 5*a*, so that the period of 182.5 days seems to be a reasonable choice. As compared to the value 181.8 (±8.3) days found by means of the power spectrum analysis, this is also an acceptable figure.

The superposed epoch analysis was also carried out for periods around 1 year. In this case the minimum variance was obtained for a period of 365.35 days which is close to the mean year duration of 365.25 days. Figure 6 shows the resulting profile for this folding period, with January 1 as starting date. Although, as mentioned before, small variations in the tested folding periods produce large variations in the resulting profiles, a common observed feature is the presence of several peaks instead of the expected two seasonal maxima. For the chosen period of 365.35 days the largest peaks in the average Ap values appear at days March 1, March 25, March 31, April 16, April 29, September 2, September 18, September 22 and October 27. These results are summarized in Table 2 in which the dates predicted by the different models are also

TABLE 2. Dates for Maximum Geomagnetic Activity

Model			$T = 365.25$, $\sigma_u = 0.717$, T in day	$T = 365.35$, $\sigma_u = 0.713$, σ_u in nT^2/day
Axial Mechanism	Equinoctial Mechanism	Russell-McPherron		
				March 1 (24)
			March 3 (21)	
March 5				
	March 21			
			March 25 (23)	March 25 (24)
			March 29 (23)	
				March 31 (25)
			April 2 (25)	
		April 5		
				April 16 (22)
				April 29 (23)
				Sept. 2 (29)
			Sept. 5 (24)	
Sept. 6				
				Sept. 18 (26)
				Sept. 22 (23)
	Sept. 23		Sept. 23 (26)	
				Sept. 28 (22)
		Oct. 5		
				Oct. 27 (21)
			Oct. 29 (21)	

The two dates predicted for the seasonal variation according to each of the different models (given at the heading) are given in the three first columns, respectively. The dates and amplitudes (nanotesla) of the peaks obtained by the superposed epoch analysis for different folding periods, that lead to minimum variance per day of period (given by σ_u at the heading), are given in columns four and five.

given. Besides the results obtained for the period of 365.35 days those for 365.25 days are included because it also leads to relatively small values in the variance. These variances, normalized to a 1-day period (σ_u), are shown in parentheses in the heading of both columns. Together with the date corresponding to each of the main peaks, the resulting averages for the Ap indices (in nanotesla) are indicated in parentheses.

As Figure 6 and Table 2 show, there is a large spreading of the peaks around the activity maxima predicted by each model, independently of the values of the folding period. Therefore one can conclude from this analysis that it is not possible to draw a definite conclusion concerning a unique mechanism responsible for the seasonal geomagnetic activity variation. More than that, it seems to support the multiple origin nature of this variation as suggested by *Murayama* [1974], *Berthelier* [1976] and *Holzer and Slavin* [1982].

As it has been found by several authors [e.g., *Meyer*, 1966; *Russell and McPherron*, 1973; *Green*, 1984] and as seen in Figure 4, the dynamical behavior of the seasonal periodicity is also noticeable. Furthermore, it is seen in Figure 4 that the contour lines around the 6-month period show a better definition during years corresponding to the descending phase and minimum of the solar cycle (shaded intervals in this figure). Therefore we have also conducted the superposed epoch analysis for shorter data subsets. The results, not presented here, show that there is a large variability in the period as well as in the resulting profiles of the geomagnetic activity pattern.

The dynamical aspects of the seasonal pattern have also been observed through the power spectrum analysis of the Ap data for each solar cycle. The daily Ap data were divided in subsets corresponding to cycles 17 through 21, samples that consisted of about 2200 to 4400 points. For this purpose, the data for cycle 21 were updated to 1986 and samples consisting of about 3600 to 4400 points were submitted to power spectrum analysis with truncation points up to 1000 days and sampling frequency intervals of 0.5/3000 cycles day^{-1} with reasonably good results (see Figure 13). The results show that the 6-month period is a clear feature for all the complete cycles but that for smaller subsets this periodicity can not be completely developed. One example of this is the interval 1977–1982 discussed in subsection 4.3).

We have also focused on the seasonal variation from the point of view of the statistics of geomagnetic storms including the data for 1983 through 1986. In Figure 7 the numbers of geomagnetic storms in each month of the interval, 1932–1986, are displayed for three different thresholds. As seen in this figure, the total number of storms, considering those with maximum Ap equal or larger than 50 nT, show a clear seasonal distribution. Similarly, the more intense storms, with maximum Ap equal or larger than 75 nT, seem to show the seasonal variation. For the super intense storms, considered as those with maximum Ap equal or larger than 150 nT, one observes from this figure that the seasonal variation is also present but that there is a further peak distribution in July, of comparable amplitude, as discussed in subsection 4.3.

Since 1-month duration intervals are too long to allow a distinction among the possible causes of the seasonal variation, we have also conducted the storm occurrence analysis dividing the data in shorter intervals. In Figure 8*a* we show a histogram for which the data have been subdivided in 8-day intervals (except at the beginning and the end of the year), for the years 1932 through 1986, and for events above the Ap = 25 nT threshold. This relatively small threshold was taken in order to keep reasonable

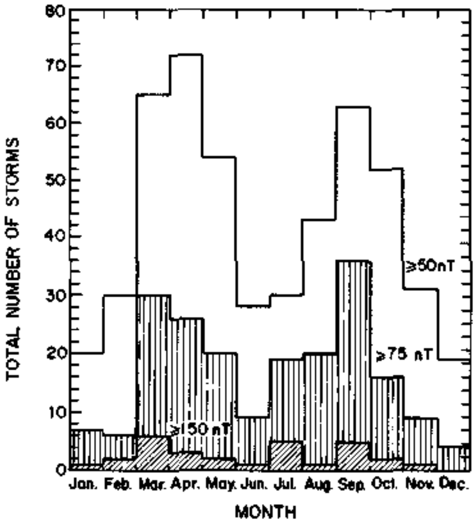

Fig. 7. Monthly distribution of storms according to their peak Ap value, in the interval 1932 through 1986.

statistics for these short intervals.

Similarly to the superposed epoch analysis shown in Figure 6 and Table 2, the histogram of Figure 8*a* seems to suggest that the peak occurrence dates are spread in time between the middle of February and the middle of April and through September and October. Particularly, the maxima labeled from 1 through 4 correspond to the intervals February 16 – February 23, March 28 – April 4, September 20 – September 27 and October 14 – October 21, respectively. However, the occurrence pattern may be different for different sample sizes. For instance, if the samples are as short as 1 year, the semiannual periodicity may not be present at all, as occurs for the year 1977 (Figure 8*b*). Different storm level threshold can also change the dates of the peak occurrences as seen for instance in the histograms corresponding to storms with Ap greater than 50 nT and for storms with Ap greater than 75 nT (not shown here). For these, the storm occurrence distribution shows also several peaks around the first equinox although centered by the end of March. For the second equinox, the occurrence peaks are crowded around September 12 – September 27 and show smaller amplitude that those for first equinox.

Figure 9 gives a simplified model of a possible interpretation of the seasonal variation. Assuming that solar causes of the geomagnetic storms are randomly distributed during the year, the different mechanism would act as modulating factors on the geomagnetic response, as is tried to be pictured by the smooth windows plotted in this figure. The resulting total window would be centered around the equinoxes that besides being the dates predicted the by one of the models (equinoctial) have the peculiarity of being almost equidistant to those predicted by the other two models (axial and Russell-McPherron). Of course, the larger the samples are the more they will follow this parent distribution pattern. Actually, we do not know either the shapes and the relative amplitude of each of the windows, and how they can change with the intensity level of the storms, so that the resulting modulation can not be predicted at present.

The large variability of the seasonal geomagnetic activity pattern has been associated by *Russell and McPherron*

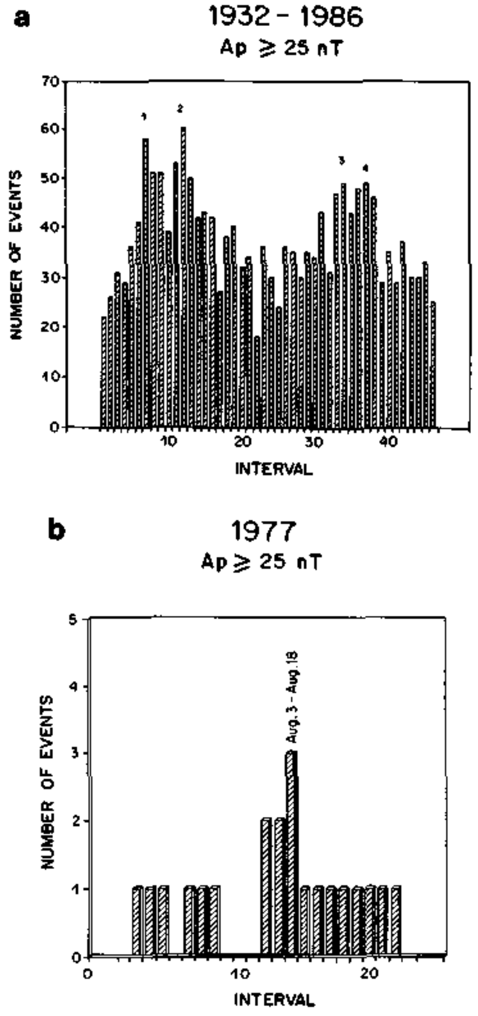

Fig. 8. (a) Number of geomagnetic storms between 1932 and 1986, with maximum Ap equal or larger than 25 nT, in each of the 46 8-day intervals in which the year was divided (the intervals at both extremes have less than 8 days). The peaks labeled as 1, 2, 3 and 4 correspond, respectively, to February 16 – February 23, March 28 – April 4, September 20 – September 27 and October 14 – October 21. (b) Idem for 1977 and a subdivision of the year in 16-day intervals.

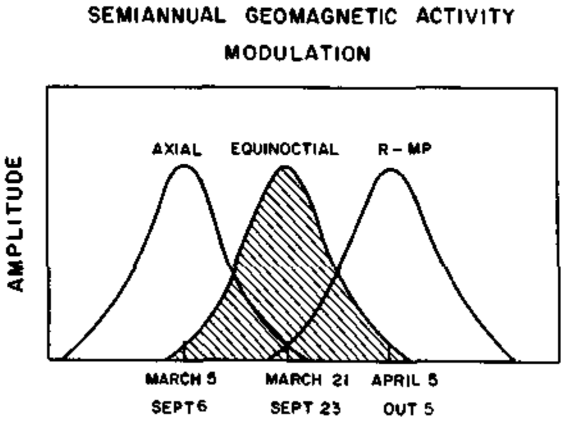

Fig. 9. A possible model for the seasonal variation. The three well-known mechanisms, axial, equinoctial and Russell-McPherron, act as a composed band-pass filter that modulates the random input responsible for the generation of the geomagnetic storms.

[1973] to the changes in the polarity of the interplanetary magnetic field. In order to check this dependence, the occurrence of storms during the equinoctial months has been related to that polarity for the years 1947 through 1982 used in the study by *Gonzalez and Gonzalez* [1987] and based on the data given by *Svalgaard* [1975, 1976] and *Scherrer et al.* [1977]. The results are shown in Figure 10, where March equinox is defined as the interval February-April and September equinox as the interval August-October. The histogram refers to the number of storms with maximum Ap equal or larger than 50 nT and with a well-defined polarity, during those months for that interval. The bars are labeled by A or T according to the corresponding away or toward interplanetary magnetic field polarity observed during each considered storm. As seen in this figure, the number of storms with toward polarity is more than twice the number corresponding to away polarity for the March equinox. Conversely, the number of storms with away polarity is almost twice the number of storms corresponding to toward polarity for the September equinox. Therefore for a class of around 60% of all storms the prediction of the model of Russell and McPherron seems to be confirmed, in the sense that the geomagnetic activity is favored by a toward polarity during the March equinox and by an away polarity during the September equinox. An inspection of the prevailing polarities for the equinoctial months for the interval 1947 through 1982 does not show the tendency observed by *Rosenberg and Coleman* [1969] for the years 1962 through 1968. For this subinterval there is an actual predominance of the away (toward) polarity for the March (September) equinox but this predominance seems to alternate from one solar cycle to the next one. Therefore the seasonal bias in the interplanetary magnetic field polarity shown by Figure 10 seems to be related to a enlarged effectiveness of solar wind-magnetosphere coupling for one of the polarities as established by the model of Russell and McPherron [see *Sheeley et al.*, 1977]. Note, however, that this A/T polarity behavior, shown in Figure 10, only confirms that the Russell-McPherron hypothesis participates in the modulation of the semiannual variability of storms but that such behavior does not necessarily mean that this hypothesis should predominate among the others mentioned above.

4.2. *The Dual-Peak Distribution Structure*

As mentioned in subsection 2.1, there is a possible periodicity around 4 years in the (Ap) power spectrum, and it could be associated to the existence of dual-peak distribution observed in the occurrence of the yearly distribution of intense storms. As shown by *Gonzalez et al.* [1990], this distribution has two peaks around the solar maxima, one occurring near solar maximum and the other at the early descending phase, with an average time separation of approximately 3 to 4 years [see *Hirshberg*, 1973; *Crooker et al.*, 1977; *Gosling et al.*, 1977; *Legrand and Simon*, 1985, 1989; *Constantin*, 1989; *Gorney*, 1989, 1990 and references therein]. This type of dual-peak distribution seems to be present also in the intensity of certain coronal processes, as shown in an early article by *Gnevyshev* [1967].

In the present analysis we have reproduced the statistics of *Gonzalez et al.* [1990], but considering storms with Ap equal or larger than 50 nT. The resulting histogram is shown in Figure 11, where the yearly number of those storms is displayed as a function of the year (solid line) together with the yearly sunspot number (dashed line). This plot leads to conclusions analogous to those drawn by Gonzalez et al., whose criterion was of considering storms with maximum *aa* index equal or larger than 100 nT for cycles 12 through 19 and minimum Dst index less or equal -100 nT for cycles 20 and 21.

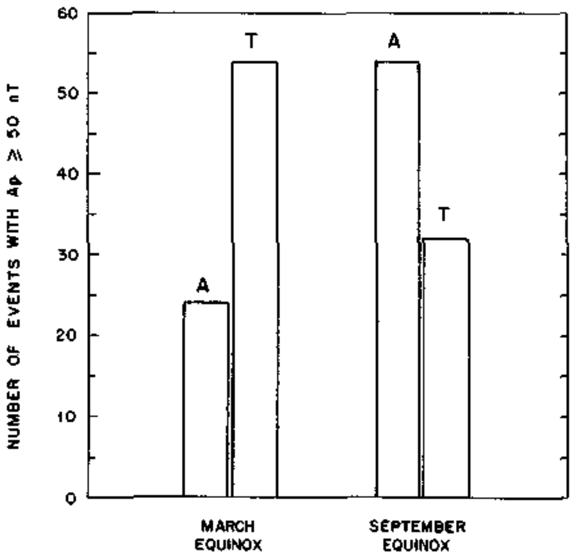

Fig. 10. Distribution of storms with maximum Ap equal or larger than 50 nT around the equinoxes, according to the associated polarity of the interplanetary magnetic field for the interval 1947–1982, as given by *Svalgaard* [1975, 1976] and *Scherrer et al.* [1977]. March equinox refers to the interval February–April, and September equinox to the interval August–October.

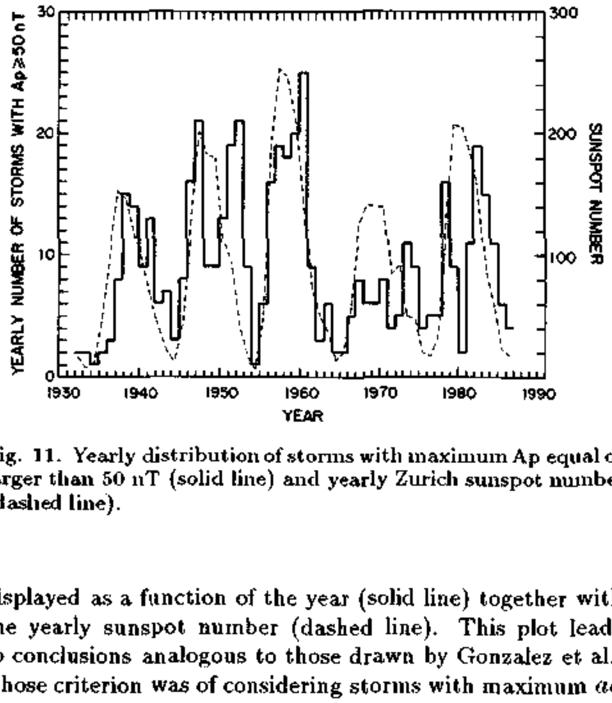

Fig. 11. Yearly distribution of storms with maximum Ap equal or larger than 50 nT (solid line) and yearly Zurich sunspot number (dashed line).

4.3. *Other Medium-Scale Periodicities*

As was mentioned in subsection 4.1, for the distribution of intense geomagnetic storms, above an Ap level of around 150 nT, there seems to be a peak in July (some of these memorable [Bartels, 1963]). Although the statistics for this storm threshold may be considered as poor, this possible peak for July shows up with a one-sigma significance level, that is similar to that of the equinoctial peaks.

In order to see if this July peak is due to a particular temporal contribution or to a long-scale effect, in Figure 12 we have broken the histogram corresponding to storms with maximum Ap equal or 150 nT in solar cycle subintervals. The lower panel of this figure reproduces the distribution for the whole time interval (dashed area of Figure 7, while the rest correspond to solar cycles 17 through 21, respectively.

From Figure 12 the July peak for the monthly distribution of storms above the 150 nT threshold seems to be present in each of the cycles. Year to year statistics, not presented here, shows that the July occurrence of intense storms is sometimes observed simultaneously with that for September so that a peak shifting from September to July [e.g., *Lincoln*, 1967] is not much evident. Although a seasonal bias due to the uneven north-south geomagnetic station distribution should not be disregarded [e.g., *Campbell*, 1979], it would be interesting to know more about the nature of the July peak, as a possible manifestation of an annual cycle in the geomagnetic activity [see *Coleman and Smith*, 1966]. *Joselyn* [1991] has observed a peak in July for the monthly distribution of sudden storm commencements, and a peak in July seems to be also present in the distribution of the solar proton events obtained by satellites that are free from any seasonal bias [see *Smart and Shea*, 1989, and references therein].

Another possible medium-scale periodicity that was observed in the present analysis is that around 158 days, already mentioned in subsections 2.2 and 4.1. A periodicity of this order was first observed by *Rieger et al.* [1984] in the occurrence rate of gamma ray flares and since then in different aspects of the solar activity study [e.g., *Delache et al.*, 1985; *Lean and Brueckner*, 1989; *Bai and Cliver*, 1990], as well as in the auroral occurrence data [*Silverman*, 1990]. A noticeable feature of this solar activity recurrence is its sporadic nature. During the last three solar cycles it seems to have been present basically during two intervals, 1958–1972 and 1978–1983, with particular intensity in the latter. Although some tentative explanation have been given, the exact origin of this periodicity is not well understood as yet [*Bai and Cliver*, 1990].

Due to its sporadic nature, we can not expect that the periodicity around 158 days will be clearly manifested in the geomagnetic activity. In fact, we see that its contribution to the spectrum of the Ap index in the interval 1932–1982 (Figures 2*a* and 2*b*) is very small. However, for the power spectrum of the interval 1977–1982 this peak shows up at 157.5 (±2.1) days with a 50% level of significance, as shown in the top panel of Figure 13. For comparison, the Ap spectrum for the whole cycle 19 is given in the bottom panel (the truncation point, M, is equal to 1000 days, for both spectra). The fact that, coincidentally, for the interval 1977–1982 the seasonal variation has been poorly defined has indeed contributed to making the peak around 155 days more noticeable for this interval. Furthermore, for this same interval a peak at 51.7 (±0.3) days, probably a harmonic of the 155-day peak [*Lean and Brueckner*, 1989], is also observed. When the whole cycle 21 is considered, the Ap spectrum shows a broad profile around the normal 6-month period. On the other hand, for cycle 19 the 155-day peak, if present, becomes hidden by the semiannual peak but that at 51.7 days is observed with more intensity. For the rest of the analyzed cycles neither the 155 nor the 51.7-day period are evident. This periodicity seems to refer to a recurrence

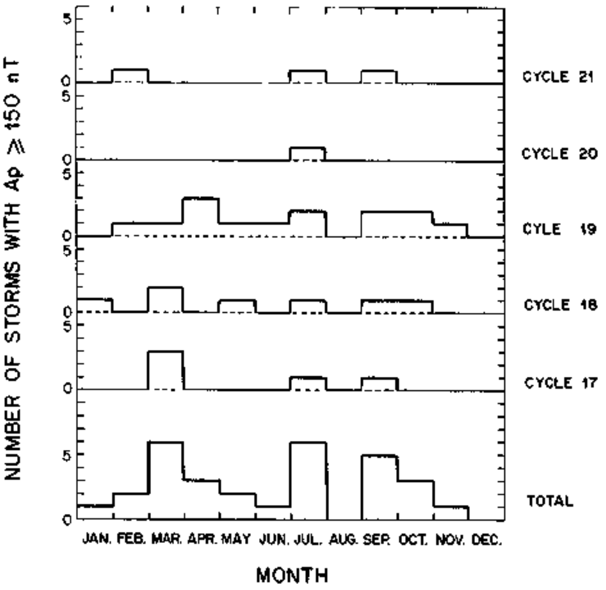

Fig. 12. Monthly distribution of storms with maximum Ap equal or larger than 150 nT for cycles 17 through 21 (1933–1986).

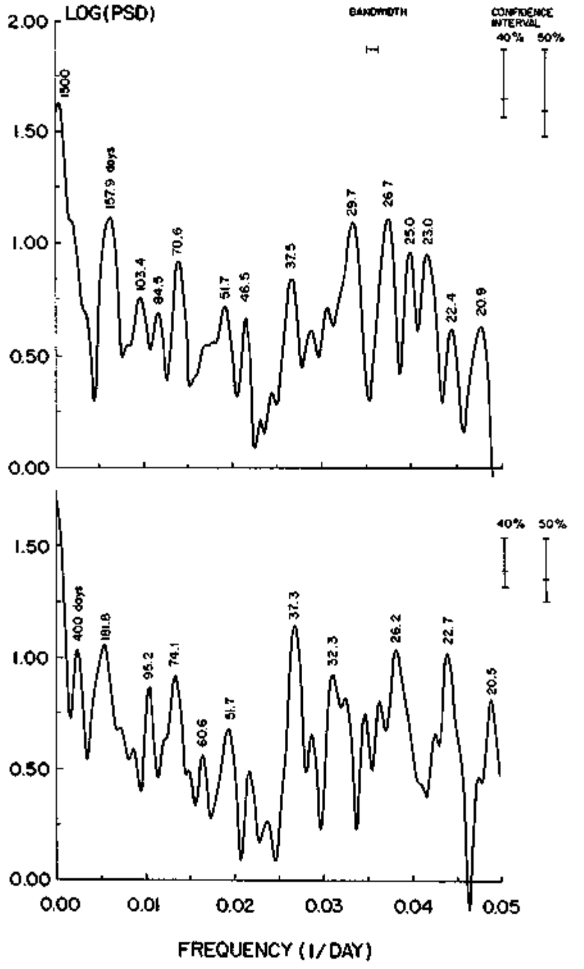

Fig. 13. Logarithm of the PSD of the daily Ap index for the intervals: (top) 1977–1982, (bottom) 1954–1963 (cycle 19). The truncation point for the Hanning-Tukey lag window is 1000 days and the sampling frequency interval 0.5/3000 cycles day^{-1}

of moderate storms with an enhancement of the Ap index of about 130% over the mean value (average Ap peak of about 35 nT).

5. SUMMARY AND CONCLUSIONS

The power spectrum analysis of the daily geomagnetic index Ap and of its monthly average ⟨Ap⟩ for the years 1932 through 1982 has led to the following conclusions.

The solar cycle periodicity presented by this index shows the well-known and strong solar cycle modulation of geomagnetic activity. Other remarkable periodicities are the also well-known 6-month, or seasonal, variation and the 27-day solar rotation modulation. The combination of all these components leads to a complex spectrum in which, besides the fundamental periods, many of the associated Fourier harmonics are also present. Furthermore, there is a noticeable dynamic behavior in time scales of one solar cycle that also contributes to the observed complexity of the spectrum. The solar rotation period shows a better definition during years in the descending and solar minimum phases and similar conclusion seems to be true for the seasonal variation. In addition to the above, the observed periodicity around 4 years has been associated to the dual-peak structure in the solar cycle distribution of storms observed by *Gonzalez et al.* [1990]. Concerning the origin of the seasonal variation, it is shown that it does not seem realistic to search for a unique mechanism but instead that the known models seem to work together to produce the observed variation. Therefore it is proposed that the axial, the Russell-McPherron and also the equinoctial mechanisms act as modulating factors in the geomagnetic response to the random activity sources.

It is also found that an additional seasonal peak seems to exist in July, with an amplitude comparable to those of the equinoctial peaks for a range of the most severe storms ($Ap \geq 150$ nT). No apparent explanation can be used at present for this seasonal peak.

The study has also shown a probable periodicity around 158 days, well correlated to that about 155 days observed in the solar activity, which seems to involve a recurrence of moderate storms and appears very sporadically along the studied interval.

APPENDIX

A further type of statistics carried out in this paper for the solar cycle time scale concerns the number of storms occurring per decade. The interval 1932–1981 was divided in five 10-year subintervals and the number of storms above thresholds running from 50 to 275 nT, with steps of 25 nT, were counted. For each range the average occurrence numbers and their respective standard deviation were computed based on these five-point samples. The results are shown in Figure 14, which displays this number in a logarithmic scale as a function of the Ap threshold. The best fit line was computed using the standard deviation as error bars [*Bevington*, 1969] and is given by $\log(N) = 2.67 - 0.0124\,\mathrm{Ap}$. The upper axis of this plot shows the corresponding values of $\log(-\mathrm{Dst})$ as determined by a similar adjust for the two last decades (1962 through 1971, and 1972 through 1981), for which this index is also available. *Russell and McPherron* [1973] did a similar fit also using the Dst index but for the more reduced time interval 1958 and 1961 through 1969. The plot in Figure 11 gives a sort of calibration between $\log(-\mathrm{Dst})$ and Ap based on their cumulative occurrence number per decade. It should be added that this relationship is not too different from the direct Ap versus $\log(-\mathrm{Dst})$ correlation (under present study).

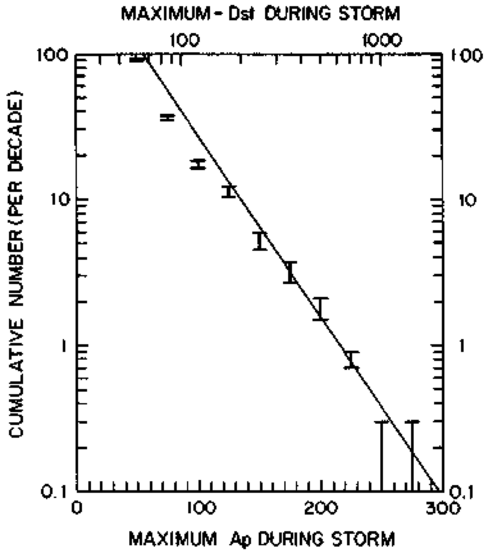

Fig. 14. Mean number of storms per decade according to their maximum Ap value. The mean and the error bars are obtained from the five 10-years subintervals between 1932 and 1981. The top axis is adjusted to the corresponding maximum values in $\log(-\mathrm{Dst})$, averaged in the two decades 1962–1971 and 1972–1981. The best fit line is given by $\log(N) = 2.67346 - 0.0124\,\mathrm{Ap}$, and $\log(N) = 6.17757 - 2.2220\,\mathrm{Dst}$.

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A. L. Clúa de Gonzalez, W. D. Gonzalez and S. L. G. Dutra, Instituto Nacional de Pesquisas Espaciais (INPE), CP 515, 12201-970, São José dos Campos, SP, Brazil.

B. T. Tsurutani, Jet Propulsion Laboratory, 4800 Oak Grove Drive, California Institute of Technology, Pasadena, CA 91109.

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