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Periodicities in geomagnetic-activity indices and solar-wind parameters, and their possible solar origin

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Summary. — We have examined the average behaviors of the solar-wind parameters and the geomagnetic-activity indices. There is a good correlation between the increasing pressure at the magnetopause and the intense magnetospheric disturbances. The ultra-low frequency power spectra for the geomagnetic disturbances have been analyzed and tested. Although the spectrum shows remarkable and stable peaks at the wavelengths 0.5, 0.7, 1.0, 1.3 years, additional significant peaks of 73 d, 1.5 y, 5.1 y and 9.2 y for Ap and 73 d and 1.4 y for the product B_SV^2 are also found. However, the 73-d and 5.1-y variations correspond to a non-obvious physical process in the Sun. The Sun may reflect some irregular variations, basically not fundamental, which appear at different times. A comparison of both spectra for periods > 0.5 year suggests different solar origins. Both spectra have different power amplitudes and peaks at different locations. Our study confirmed 1.4–1.5 year oscillations in B_SV^2 measurements between 1987 and 2000, and located slightly higher than the Kp peaks (~ 1.3 y). Although many papers have discussed periodicities in the Ap index, a 9.2-year period has not been reported previously. There is some indication of an association with the coronal-hole variations in the southern hemisphere of the Sun. The conjunction of the Sun observations and SW measurements may be used to estimate the disturbances in the geomagnetic activity in the heliosphere.

PACS `96.50.Ci` – Solar wind plasma; sources of solar wind.
PACS `96.50.Bh` – Interplanetary magnetic fields.
PACS `94.30.-d` – Physics of the magnetosphere.

1. – Introduction

Solar-wind coupling is the name applied to the studies of the relation between phenomena on the Sun and in the solar wind to various measures of geomagnetic activity. This field of research often treats the earth's magnetosphere as a black box whose properties can be ascertained from records of its past behavior. These properties were then

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used in conjunction with measurements of the Sun and solar wind to predict future geomagnetic activities. The most popular geomagnetic indices are the planetary range, Kp, Ap and aa, the polar cap, PC, the auroral electro-jet, AE, and the ring current, Dst. Many important phenomena have been correlated with these indices to estimate or predict their development.

The solar wind (SW) is a continuous stream of ionized particles with highly variability on time scales. These different time scales can be associated with distinctly different physical processes (or changes) on the Sun. Many investigations on the solar-wind control of the magnetospheric activity have been performed to make clear the relationships occurring between some solar-wind parameters and the occurrence of geomagnetic disturbances in the short term (*e.g.*, [1]). In addition, there is some evidence for a relationship between the increasing pressure of SW at the magnetopause and the triggering of intense geomagnetic activity [2].

The measurements of the solar-wind speed (V) confirmed periodicities with the solar rotation period (roughly 26 days) and the solar cycle [3-7]. Other [8] showed that the average V was higher during the solar minimum and lower during the solar maximum. Previous investigations, using data collected between 1973 and 2000, have reported variations with a 1.3-year period in V in the inner and outer heliosphere [2, 6, 9-12]. More recently, a 9.6-year periodicity in V was identified. These observations are due to the observed variations in the southern coronal-hole areas [7]. Other parameters showed the same oscillations ($\sim 1.3\,\mathrm{y}$) in studies of geomagnetic disturbances [2], in the north-south (GSE) component of the magnetic field at 1 AU [13], in the sunspot number [14], and in the rotation rate near the bottom of the solar convective zone [15], providing insight into the nature of these oscillations. The one-year oscillations have occurred between 1965 and 1985 in V variations [6, 16]. The products $V^2\,B_{zsm}$ and $V^2\,B_S$ also displayed this periodicity during the years 1986-1994 [2]. However, the 1-y and 1.3-y variations have corresponded to no obvious physical process in the Sun [11]. They suggested that these enhancements in SW velocity were associated with some fundamental variations whose period was irregular, varied between solar cycles, or was some sort of resonant period that appeared different at different times.

Previous analysis [6, 17, 18] of both solar-wind ion density (n) and speed (V) had indicated the existence of periodicities of 1 y during the solar cycles 20 and 21, and 1.3 y during the cycle 22. Our results presented, for the first time, evidence of peaks at ~ 1.9 year in field magnitude $|B|$, and 8.25 ± 0.4 year in Ap, a measure of the geomagnetic activity. Earlier results [19] displayed a high correlation between the geomagnetic activity index Ap and V during the solar cycle 20 but not during the cycle 21. Moreover, the solar cycle variation of nV^2 was remarkably regular. The product (the dynamic pressure) had a smoother repeatable solar cycle variations, with a minimum just prior to the middle of the cycle and a maximum just prior to the end of the cycle. Other showed that the 22-year average of geomagnetic activity, the aa index, remained fairly constant [20].

In this study, we have used data up to the year 2000 to examine the long-term enhancements in various geomagnetic indices and the SW plasma measurements. The analysis of power spectra density (PSD) of Ap has been yielded in the frequency range from $1.1\,\mathrm{nHz}$ to $1.1\,\mu\mathrm{Hz}$ for an integrated data set, which covers the period 1961-2000. The power spectrum analysis is the most common method for studying the variations existing in the time-series and one can obtain a synthetic and comparative view of the sinusoidal components in which the series can be decomposed. We analyze the magnitude and the time changes of the PSD. The results are presented, tested, and discussed.

2. – Results and discussion

2·1. *The occurrence of magnetospheric disturbances and the solar-wind plasma.* – The first observations of interplanetary plasma data began in late1964. Since then coverage has been continuous enough such that it is now possible to obtain a time series of the plasma data that is more than 40 years long. These data are measurements from different spacecrafts in the near-Earth solar wind inter-calibrated by a linear regression analysis (*e.g.*, [21]). The instruments measure solar-wind parameters and properties of the interplanetary magnetic field (IMF). We have used the hourly-averaged measurements of solar-wind bulk speed (V), ion density (n), and field magnitude (B) for the period 1986-2000, which were provided by the National Space Science and Data Center (`http://nssdc.gsfc.nasa.gov/omniweb/form/` (2005)). These are the largest data sets without significant gaps in time ($\approx$ 4% of the total length of the interval). In addition, we have analyzed the long series of the geomagnetic activity sums Kp, Ap throughout 1961-2000 (provided by the National Geophysical Data Center NGDC (`http://www.ngdc.noaa.gov/ngdc.html` (2005))) in order to ascertain whether some characteristics of the spectral peaks (the ultra-low frequency from 1.1 nHz to 1.1 μHz) occurring at periods approximately ranging between 6-day to $>$ 22-year may be related, in statistical sense, to external solar-wind features. The interval of that kind of data spans the three solar cycles 20-22, and more than 3 years in both cycles 19 and 23. This paper is restricted to a discussion of solar-wind density, velocity, field magnitude, and geomagnetic activity indices (Kp, Ap).

In order to look for periodicities, especially in the last few years, daily averages of the data were computed. Following the established analysis reported before [7,9-11]. Figure 1 shows the 81-day running averages (every three-Carrington-rotations) of geomagnetic index Kp and the product B_SV^2 throughout the period 1987-2000. The parameter B_S is the southward component of the interplanetary magnetic field. The choice of an 81-day interval for the running averages was made to emphasize variations with long duration while suppressing fluctuations on time scales of a solar rotation or less. Significant gaps in measures were treated. Thus, the data set is smoothed with all the data gaps filled in and the dominant $\sim$ 27-day synodic solar rotation period removed from the data. In the two panels of fig. 1, the vertical dashed line represents the solar minimum epoch and the upper arrows correspond to the solar maximum periods. Carrington rotation numbers (CRs) are noted in panel a. This figure demonstrates that the period can easily be observed visually when present.

The variations of Kp show some good correlation with the product B_SV^2 on short-time scales. Until the end of 1996, the two parameters track each other quite well, but after 1996 the tracking is poor. Generally, just after the solar maximum in mid-1989, the Kp magnitudes decrease to low values over a few years, then gradually increase to a maximum. Solar cycle variations in Kp are not observed [19]. Feynman [4] compared *aa* index variations with sunspot numbers and he concluded that the 11-y solar cycle as represented by the sunspot numbers was very different from the 11-y cycles of the solar wind or the geomagnetic index. Moreover, there are four remarkable decreases in Kp labeled from A to D in the upper panel. These events occurred, respectively, at the mid-1987 (CR 1790), end-1990 (CR 1837), mid-1996 (CR 1912), and end-1997 (CR 1932) implying that the variations in Kp is nearly cyclic. It seems to perform a cyclic variation of 9 y. We find twenty enhancements in Kp, centered near 1987.7, 1988.2, 1989.3, 1990.2, 1990.7, 1991.5, 1992.8, 1993.2, 1994.2, 1994.8, 1995.3, 1995.7, 1996.2, 1996.7, 1997.2, 1997.8, 1998.8, 1999.3, 1999.8, and 2000.5. The peak-to-peak amplitude

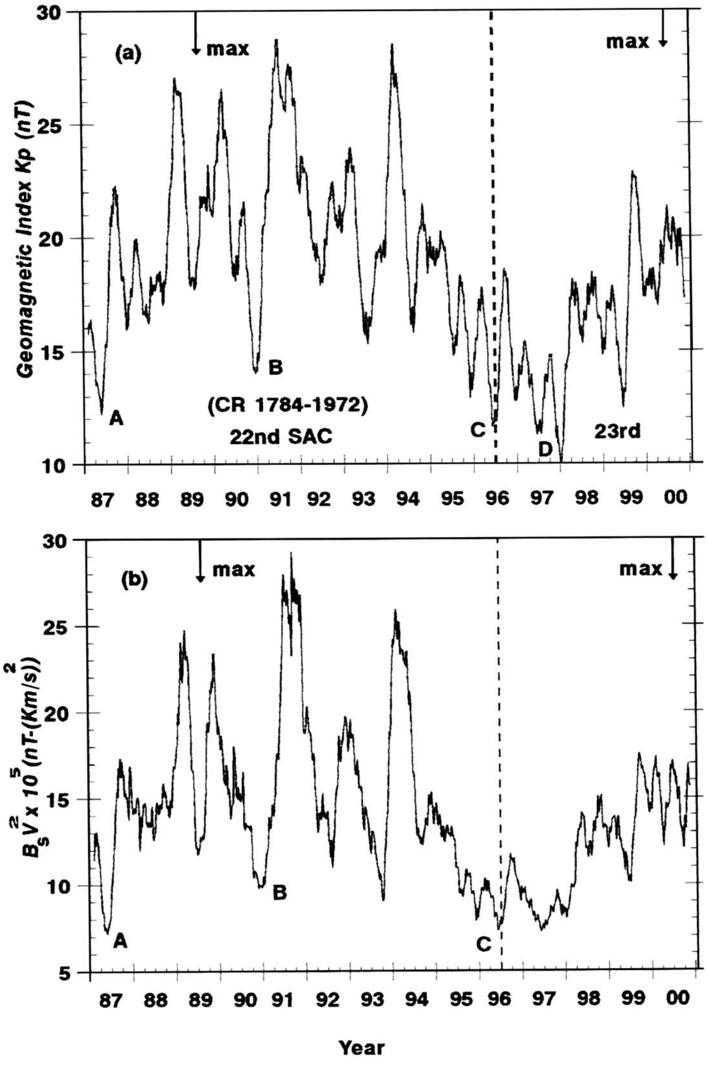

Fig. 1. – Three-Carrington-rotations running averages of the geomagnetic activity index Kp (top panel) and the product $B_S V^2$ (bottom panel) between 1987 and 2000 (from CR 1784 to CR 1972). Minimum and maximum solar activity periods are represented by the vertical dash line and arrows, respectively.

of Kp changes from 0.5 to 0.6 y, and 1.1–1.35 y. The annual and semiannual peaks in geomagnetic activity are well established in geomagnetic data. On the other hand, the amplitude of the Kp peaks changes considerably each solar cycle: six larger peaks, on averaged, occurred in the 22nd solar activity cycle, and one in the mid-23rd SAC. This behavior exists also around the minimum year of cycle 23 (in 1996) with lesser magnitudes than the other cycle.

Figure 1b shows the 81-day running averages of $B_S V^2$ between 1987 and 2000. Generally, the solar cycle variation of $B_S V^2$ is unclear. The recent work of [7] has displayed enhancements in solar-wind parameters of periods 0.7 y, 1.0 y, 1.3 y that occurred between 1987 and 2000. The $B_S V^2$ enhancements shown in fig. 1b are consistent with the results obtained before. There are sixteen enhancements in the product measurements at intervals in: 1987.7, 1989.2, 1989.9, 1991.6, 1993.0, 1994.2, 1994.7, 1996.2, 1996.7, 1998.4, 1998.8, 1999.2, 1999.7, 2000.1, 2000.5, and 2000.8. The approximately 1.4–1.5 year period is very evident between 1987 and 2000, although it is located slightly higher than the Kp peaks (~ 1.3 y). Inspection of the plasma parameters shows that the flux modulation is due mainly to density rather than velocity variations, whereas both density and velocity contribute substantially to pressure change. Note that there are almost no oscillations in the averages of $B_S V^2$ after mid-1997. The last eight peaks during the cycle 23 (from June 1996) are less distinct and intermixed with smaller peaks (double-peak structures). Thus, stable variations of 0.5, 1.0, and 1.4-1.5 year still appear and maintain their periodicities during the period 1994-2000 indicating that a common feature in the heliosphere existed continuously. Some fundamental variations on the Sun cause these periodicities to persist during the considered periods. However, during the 22nd SAC, when the geomagnetic activity is high (and double peaks obtained) around the sunspots maximum, a strong coupling between B_S and V^2 has been found. The opposite is true for cycle 23 with less magnitude and the contribution of B_S clearer. The various solar cycles differ considerably from each other. The Kp index minima do occur at or near (within 1–2 y) of the sunspot minima (low geomagnetic activity during sunspot minimum), the Kp maxima have an irregular pattern. Generally, two Kp maxima are observed (double-peaked modulations). The major Kp peak is reported as occurring during the declining phase of the sunspot cycle and a secondary peak occurring near the sunspot maximum.

Figure 2 shows the scatter plots of Kp against the three commonly used products, $B_S V$, $B_S V^2$, and nV^2, respectively, for each CR number (from 1784 to 1972) between 1987 and 2000. The plots display the magnetic disturbances relate to the solar-wind dynamic pressure. The $B_S V$ averages show linearity and the correlation coefficient is good (0.8), indicating that there is a good relation between Kp and $B_S V$. A value of $R = 0.8$ is considered a good correlation, whereas we have examined 189 pairs of data points during the noted period. The plot of $B_S V^2$ against Kp in fig. 2b shows far less scatter and more correlation than the other plots. The geomagnetic activity seems to be nearly controlled by the product $B_S V^2$. The linear fits of fig. 2 yield

$$Kp = 4.6 \times 10^{-3} B_S V + 4.6; \quad \text{and} \quad (R = 0.8), \tag{1}$$

$$Kp = 7.9 \times 10^{-6} B_S V^2 + 8; \quad \text{and} \quad (R = 0.85), \tag{2}$$

$$Kp = 5.9 \times 10^{-6} nV^2 + 7.7; \quad \text{and} \quad (R = 0.66), \tag{3}$$

where R is the correlation coefficient. The correlation between Kp averages and nV^2 can probably be ascribed to the role of solar-wind dynamic, proportional to nV^2. The correlation between Kp and nV^2 is nearly significant with less magnitude. Thus, all fluctuations in Kp seem to be caused by a similar fluctuation in both V and B. Many important phenomena can be correlated with these indices and if the values of the indices are known, the correlations can be used to estimate or predict their development. Therefore, the conjunction of the Sun observations and SW measurements may be used to estimate the geomagnetic activity in the heliosphere.

2˙2. *Spectral analysis of Ap and* $B_S V^2$. – It is well now known that most of the disturbances in geomagnetic activity are of solar-wind origins, which have their seeds in solar-physical processes. Some peaks in Ap spectra located at long periods (> 2.1 y)

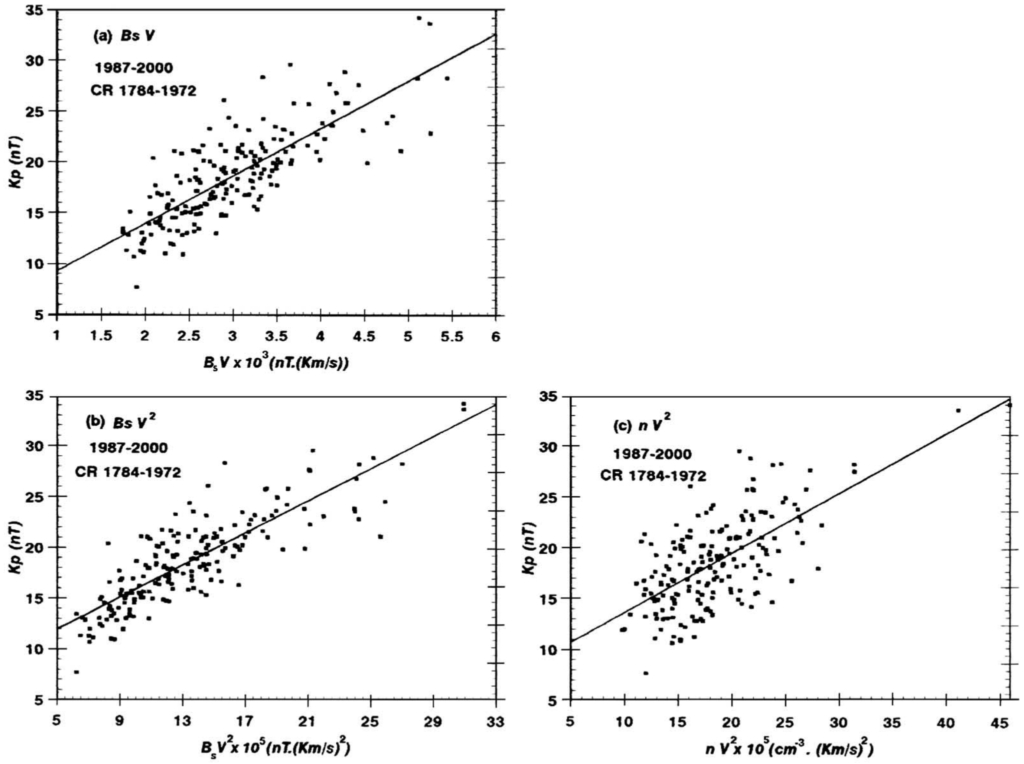

Fig. 2. – Scatter plots of $B_S V$, $B_S V^2$, and nV^2 against Kp for the 1987-2000 epoch, with linear regression fits. The corresponding coefficients are (a) 0.8, (b) 0.85, and (c) 0.66.

were found [6, 7]. The periodicity of 8.25 ± 0.4 year has been observed in the running averages (100-day measures) of *Ap*. Because the plasma speed and the magnetic field affect geomagnetic activity, so that using the *Ap* data would show a similar periodicity. The *Ap* index values for the time period from 1961 to 2000 have been examined.

Over the past years, substantial interest has been developed in the possible existence of periodicities in solar-wind parameters and *Ap* measurements greater than a few years [6, 7, 22-24]. In addition, the near-Earth variations in the solar wind, measured by the geomagnetic *aa* index have been displayed good correlations with the global surface temperature [25, 26].

In order to determine the dominant periodicities of *Ap*, we have performed a series of power spectral analyses on daily averages for the period 1961-2000. Significant gaps in data have been treated [27]. To remove any instrumental long-term variations from the *Ap* measurements, a technique of the linear-trend removal was applied. Then, Fourier transformations were used to yield the power spectral density and the results were smoothed using the Hanning window weighting function. This is necessary since most of the distributed features will completely disappear, while the significant peaks are clearly defined. Nevertheless, the particular window chosen does not shift the positions of the spectral peak. Next, each spectrum is independently normalized to the largest peak in the complete spectrum, which had a period shorter than 3/4 of the record-time.

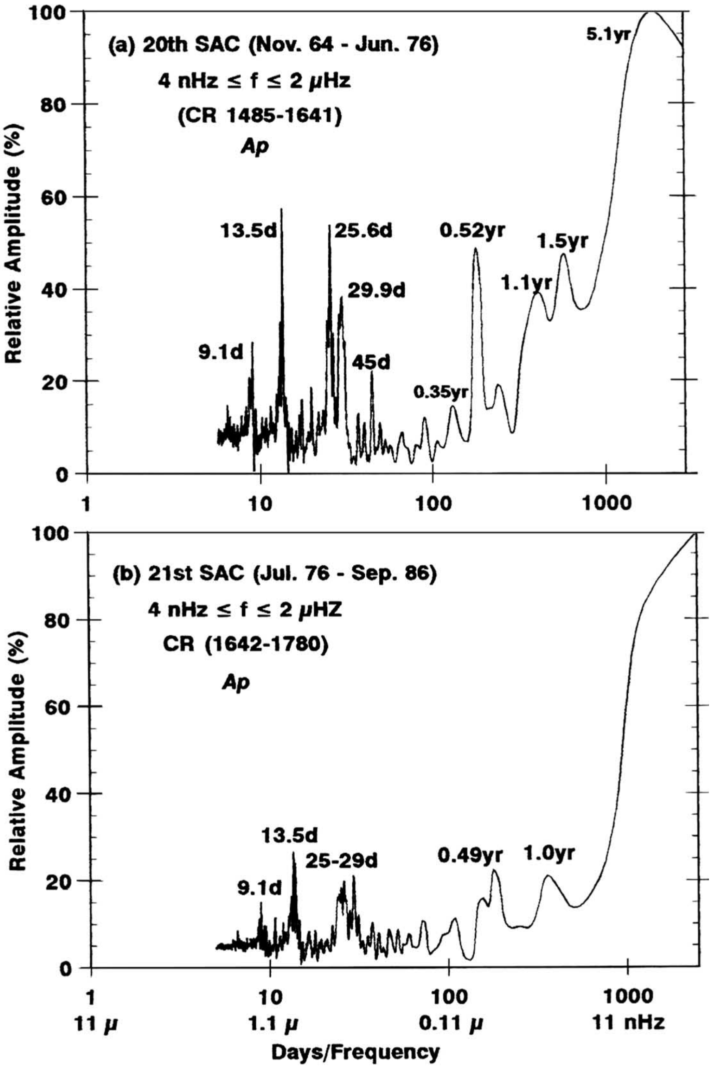

Fig. 3. – The power spectra of *Ap* (panels a and b) for the two solar activity cycles. The actual frequency ranges are indicated in the panels. Values are normalized to the maximum spectral density.

This restriction was chosen in order to avoid spurious strengths often associated with peaks near the start and end of the data set. This normalization does not introduce any errors into our identification of the peaks because it changes only the relative amplitude and not the position of the peak spectrum.

Figure 3 shows the relative power spectral density (PSD) for the *Ap* (panels a and b), for the two solar activity cycles (SACs) 20 (from November 1964 to June 1976) and 21 (from July 1976 to September 1986), respectively. The actual frequency ranges are indicated in the two plots. We can easily see that the various peaks along the spectra toward high frequencies are due to the Earth and Sun rotation effects. Significant peaks in the two plots exist at 9.1 d, 13.5 d, 25–30 d, 45 d, 0.35 y, 0.5 y, 1.0–1.1 y, and 1.5 y and 5.1 y in plot 3a. We note that a one-year period in *Ap* is clearly evident in cycles 20 and 21, which was at a slightly longer period for the period 1987-2000 as reported before. In addition, there is a 1.5-year period in earlier *Ap* data. The spectrum variations observed during the 20th SAC period are more pronounced than those of the 21st SAC, indicating two different mechanisms of the particles modulation between the two cycles [23, 24]. There exists a difference in the peak amplitude by a factor of about two. The cycle 21 reflected minor peaks than the cycle 20. In addition, one maximum peak has been observed (5.1 y). The *Ap* peak with this period has been unreported previously and it will be discussed later. However, the spectra for the two periods show some differences: some of the peaks (at 45 d, 0.35 y, 1.5 y and 1.5 y in plot 3a) do not exist in plot 3b. Other peaks have the same PS with the same locations, indicating the same effect of the solar origin.

Figure 4 (plots a and b) shows the relative power spectra of the daily average of the geomagnetic index *Ap*, and the product $B_S V^2$ for the 22nd SAC and a major part of the 23rd SAC. In each plot we have added the corresponding frequency to assist in determining the relative location of the peaks. The actual frequency range is from 2.6×10^{-4} to 0.16 day^{-1}, which corresponds to a range of periods from 6-day to 10.6-y (from 1.9 μHz to 3 nHz). It can be seen in plot 4a that there are significant peaks at wavelengths of 9 d, 13.5 d, 26 d, 73 d, 0.52 y, and 1.2 y. Some of these peaks were reported previously and their causes were identified. However, our results show the existence of a 73-d periodicity in *Ap*. To our knowledge this peak has not been reported elsewhere and the possible causes will be discussed later. On the other hand, several periods are evident in the $B_S V^2$ data set (plot 4b): narrow peaks at 27-d and its harmonics, longer periodicities at 73-d, 0.7-y, and 1.4-y oscillations. Periodicities of around one year and a harmonic at ~ 0.5 y are not unexpected since the satellite follows Earth's orbit around the Sun and samples different ranges of solar magnetic latitudes [16]. The spectrum of *Ap* and $B_S V^2$ indicate significant peaks at the solar rotation period (~ 27 d) and its two harmonics (13.5 d and 9 d). Equal amplitude of the 13.5-d peak with respect to the 27-d peak is seen in the two plots. Note the bands of power at 27 d, 13.5 d and 9 d in the plots. The band of power near 27-d extends from about 23 to 28.5-d and contains a number of sharp peaks. The overall increases in power near 27 and 13.5 days are certainly significant and a result of solar rotation. In addition, there is considerable similarity between both *Ap* and $B_S V^2$ spectra for the short-time scales (from 6 d to 73 d). The power of both solar parameters shows a broad band with low amplitudes between the frequency range 30 d and 100 d (from 0.4 μHz to 0.11 μHz). Then, the power increases with decreasing frequency.

On the other hand, a comparison of the two plots on the long-time scales shows that the two parameters have greatly different power spectra at periods > 0.5 year, indicating a non-stationarity origin of the spectrum. The 1.4-y variation in the $B_S V^2$ measurements is probably due to different paths of ion particles into the heliosphere for epoch of different solar magnetic cycles. One should suggest that the observed periodicity of 0.7 ± 0.06 year in $B_S V^2$ spectrum is a harmonic of the 1.4-year oscillation. Similar periods of 0.63 ± 0.04 year in the North-South component of the IMF were found [13]. The connection between the observations of $B_S V^2$ and the $\boldsymbol{B_Z}$ of the IMF shed some light on the nature of these oscillations. Other [22, 28] found a broad peak near 250–280 days (0.68–0.77 year) in the cosmic-ray power spectrum during the epoch 1964-1995. The spectrum analysis was carried out over a wide range of the particle rigidities. These periodicities were attributed to changes in the coronal holes and to solar active regions

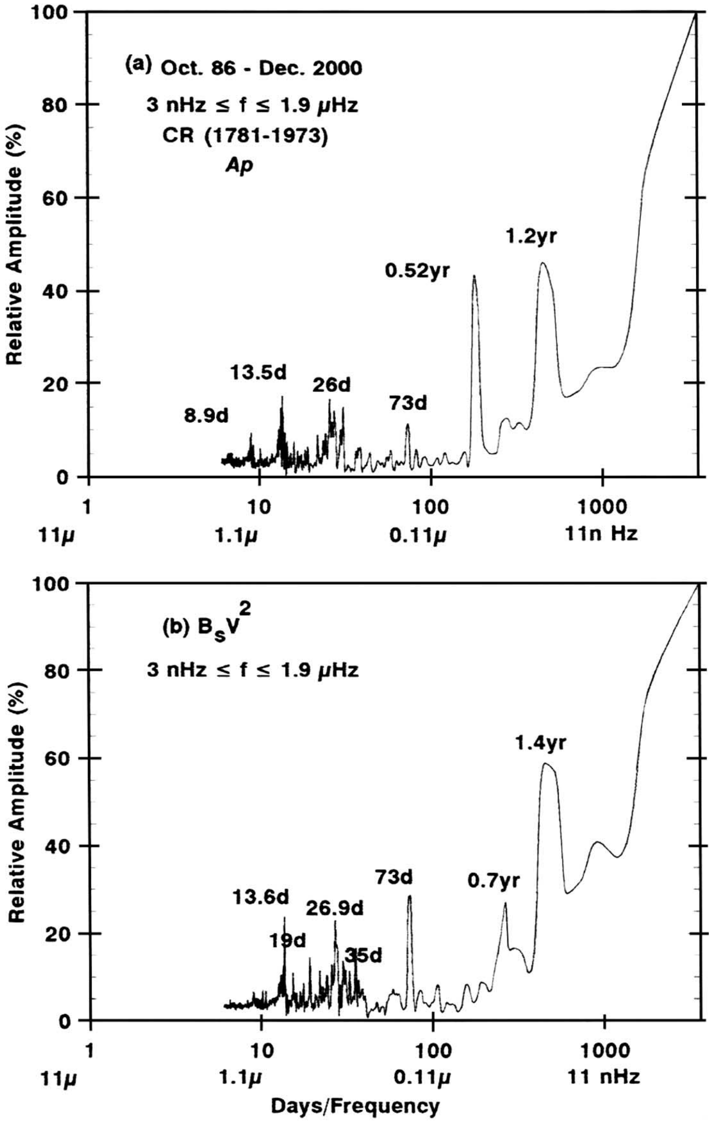

Fig. 4. – Comparison of spectrum of *Ap* (top panel) and $B_S V^2$ (bottom panel) for the period 1986-2000 (CR 1781-1973). The actual frequency range is from 1.9 μHz to 3 nHz.

near coronal-hole boundaries [29].

The most important feature is that corresponding to periods of 73 d, 0.35 y, 1.5 y, and 5.1 y in the *Ap* spectra (see plots 3a, 3b). We think these peaks are due to true modulation effects. Most interplanetary plasma and solar parameters are highly variable on time scales. Coronal holes, high-speed solar-wind streams (corotating or flare-associated streams), variations in the interplanetary magnetic field, sudden storm commencements, solar flares, etc. Furthermore, the Sun's northern hemisphere was geomagnetically more active, on average about 20%, than the southern hemisphere [22]. Any enhanced varia-

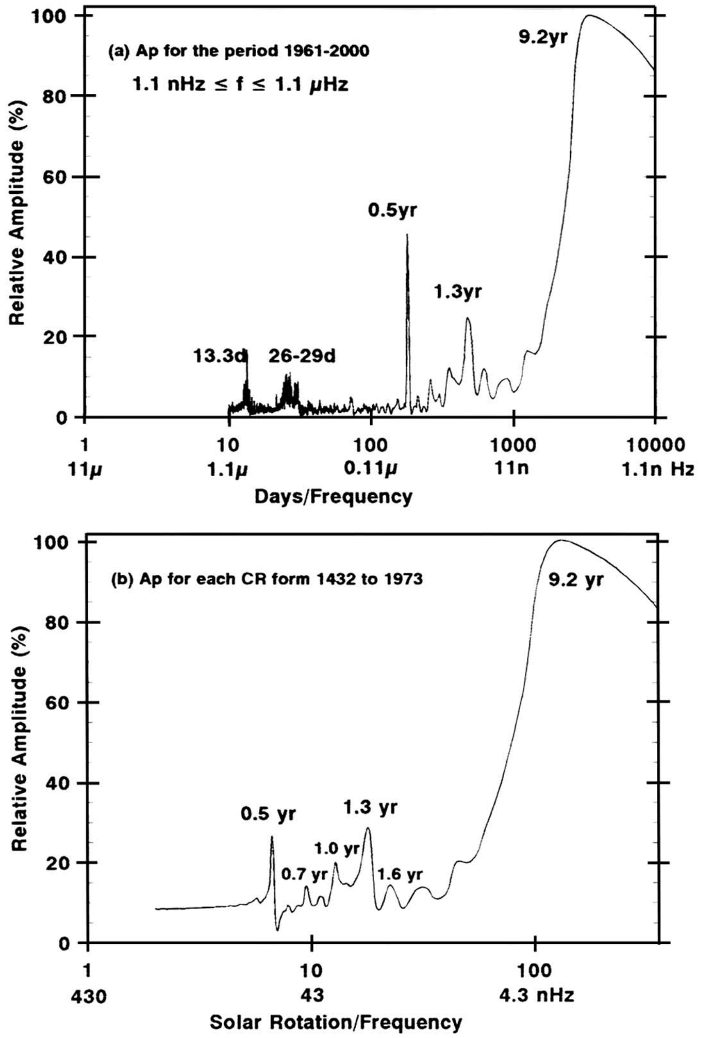

Fig. 5. – The ultra-low frequency power spectra of the daily averages of *Ap* for the period 1961-2000 (above) and for the mean value of each Carrington rotation number (below). The magnitudes are normalized to the largest peak of the spectrum band. The actual frequency range is noted.

tion in these factors may be attributed to disturbances (or periodicities) in geomagnetic activity. Therefore, we must look in the Sun variations for its causes. In order to more closely study the observed periodic variations of *Ap*, we have re-examined and extended the PSDs. The reality of these peaks can be confirmed in fig. 5. Plot 5a shows the resulting spectra derived from the daily averages of *Ap* for the period 1961-2000. The frequencies are from $9.5 \times 10^{-2}\,\mathrm{d}^{-1}$ to $9.5 \times 10^{-5}\,\mathrm{d}^{-1}$, which corresponds to 10.5 day-28.8 year (from $1.1\,\mu$Hz to 1.1 nHz). Significant peaks are found at wavelengths 13.3-d, 26-29-d, 0.5-y, 1.3-y, and 9.2-y. Plot 5b shows the resulting spectra derived from the mean values each Carrington rotation (from CR 1432 to 1973). The frequency range is from

$1.85 \times 10^{-2}\,\mathrm{d}^{-1}$ to $1.03 \times 10^{-4}\,\mathrm{d}^{-1}$, which corresponds to 54 day–26.6 year (from $0.2\,\mu$Hz to 1.19 nHz). Strong periodicities have been found at wavelengths 0.5 y, 1.3 y, and 9.2 y. Less significant, but still statistical meaningful, are hints of 0.7 y and 1.0 y. There is also some indication of the presence of a 1.6-year periodicity. The 1.3-year periodicity is consistent with the observed variation in the radial component of the solar-wind plasma velocity and density [7]. So, we can say that the connection between the observed periodicities of the 0.5 y, 0.7 y, 1.0 y, 1.3 y, and 1.4–1.5 y variations in the solar-wind plasma measures, the north-south component of the IMF and magnetospheric disturbances further strengthens the hypothesis of a solar origin for these periodicities. Thus, by using different periods and different way of calculating the mean (daily average or average over a CR period) of the same database, we find the same peaks, slightly shifted in location, but well defined and definitely not spurious.

Other peaks are disappeared (45 d, 73 d, 0.35 y, and 5.1 y). Some peaks were found according to the size of modulation region for each solar cycle [7, 23, 24]. Although the solar activity cycles 21 and 22 have nearly the same pattern, the particle modulation of cycle 22 is quite different in shape and magnitude than observed before, depicting the different modulation for odd and even cycle [28]. The obvious question is whether these periods are related to a fundamental oscillation related to structural changes on the Sun. Correlations of the $B_S V^2$ power spectra with solar observations may provide more important features on the origin of such long-periods in Ap oscillations.

Concerning the Ap spectral peaks, three studies over long-time periods showed similar oscillations. A remarkable 9.5-year variation in the spectrum of the sunspot numbers for the 1700-1981 epoch was found [30]. Their analysis showed also the 11.1-y peak in sunspot number and it was nearly three times higher than 9.5-y peak. The 11-year periodicity was the only statistically significant one. We should note that peaks in the power spectra of the sunspot number at periodicities other than 11 y are found to appear and disappear in a random way [31]. The only real feature in the solar PS is the 11 y, the standard solar cycle. One possible explanation is the fact that the sunspot number shape itself is not sinusoidal. More intense cycles have shorter times [22, 32]. A simple alternative explanation for the 9.2 y peak is that it results from the fact that not all the solar cycles have 11-year lengths. However, the sunspot PS contained the 11-y peak with smaller peaks at 10 y and 12 y. The solar cycles which are not sinusoidal were not responsible for the presence of peaks other than 11 y in the spectrum [33]. Therefore, we can say that the observed peak of 9.2 year in the Kp spectra is not related to such 11-year variations. There is no available evidence for their correlation. A second study [34] showed that the solar southern coronal-hole areas power spectra had a distinct peak at 3490 days (9.5 y). The geomagnetic activity structure is closely related to the magnetic topology of coronal holes area, in particular to the divergence rate of magnetic flux in the solar corona. Therefore, one possibility is that our observed (9.2 y) period for Ap is related to the formation rate and the magnetic structure of active regions in the solar southern hemisphere. A third study [7] confirmed the existence of periodicities 9.6 y in SW velocity and 5.6 y in ion density measurements. The averages of solar-wind ion density showed a periodic variation at intervals of 5.1 ± 0.2 y. The long-term enhancements in solar-wind parameters reflected nearly stable variations, unknown, and a continuously existing feature in the heliosphere. Thus, the observed periodicities in n, V, and Ap spectra may be strongly related to, or organized by, the observed variations in the coronal-hole areas between the northern and southern hemispheres of the Sun. This observation sheds new light on the nature of these unusual oscillations.

3. – Conclusion

The importance of the solar-wind pressure has been examined and there are well evidence for a relationship between the increasing pressure at magnetopause and the intense geomagnetic activity. We have examined the long-term periodicity in the geomagnetic disturbances and solar-wind plasma observations. The ultra-low frequency power spectra for the geomagnetic disturbances have been analyzed and tested. Although the spectrum shows remarkable and stable peaks at the wavelengths 0.5, 0.7, 1.0, 1.3 years, additional significant peaks of 73 d, 1.5 y, 5.1 y, and 9.2 y for Ap and 73 d, and 1.4 y for the product $B_S V^2$ are also found. However, the 73-d and 5.1-y variations correspond to no obvious physical process in the Sun. Since the region of particles modulation in the heliosphere is changed according to the solar cycle, even or odd cycle (*e.g.*, [22, 35]), some irregular variations may appear at different times. Such variations may be associated with different physical processes (or changes) on the Sun. The fundamental variations on the Sun cause some periodicities to persist (*e.g.*, 27-day, 11-year, 22-year variations).

A large number of physical phenomena is occurring in the heliosphere following the changes associated with various solar origins, over a period of solar rotation every 27 day, 11 or 22 years, etc. Small variations in the dynamics, ionization, density, and magnetic field strength of the interstellar medium surrounding the Sun yield pronounced changes in the heliosphere. The study of [30] found a remarkable 9.5 y in the sunspot spectra. The long-term enhancements in solar-wind parameters reflected nearly stable variations, unknown, and a continuously existing feature in the heliosphere [7]. On the other hand, the solar southern coronal-hole areas showed a distinct peak at 9.5 y [34].Moreover, the geomagnetic activity structure is closely related to the magnetic topology of coronal holes area, in particular to the divergence rate of magnetic flux in the solar corona. Therefore, we think that the observed (9.2 y) period for Ap is related to the formation rate and the magnetic structure of active regions in the solar southern hemisphere.

Our study confirmed 1.4–1.5 year oscillations in $B_S V^2$ measurements between 1987 and 2000, and located at a slightly longer than the Kp peaks (~ 1.3 y). The variations of Kp showed well correlation with the product $B_S V^2$ on short-time scales. The peak-to-peak amplitude of Kp changes from 0.5 to 0.6 y, and 1.1–1.35 y. The amplitude of the Kp peaks changes considerably each solar cycle: six larger peaks, on averaged, occurred in the 22nd solar activity cycle, and one in the mid-23rd SAC. This behavior exists also around the minimum year of cycle 23 (in 1996) with lesser magnitudes than the other cycle. The conjunction of the Sun observations and SW measurements may be used to estimate the disturbances in the geomagnetic activity in the heliosphere.

The results emphasized that there are three remarkable features in the power spectrum: its periodicities, the non-stationarity of the corresponding solar origin, and its long-life time. The measurements of both solar parameters confirmed periodicities associated with the solar rotation period (27 day and its harmonics), the position in Earth's orbit (0.5 y, 1.0 y), and the changes in the coronal holes (0.7 y). Other periodicities are existing in Ap spectra. The second remarkable feature of the spectra is the differences in periodicities resulting from the non-stationary nature of the solar origin.

A comparison of both spectra for periods > 0.5 year suggests different solar origins. Both spectra have different power amplitudes and peaks at different locations. The third, long-lived features have been reported [6, 17, 36, 35, 37] in the inferred interplanetary magnetic field sector structure deduced from geomagnetic disturbances. Clearly there are multiple peaks in the Kp, Ap analysis located at wavelengths of the semiannual, annual variations, 1.2–1.3 year, and 9.2 year.

Although many papers have discussed periodicities in the *Ap* index, a 9.2-year period has not been reported previously. We believe that the *Ap* periodicity we report here is a solar effect. The 9.2-y period *Ap* is not related to the period of the solar activity cycle, but there is some indication of an association with the coronal-hole variations in the southern hemisphere of the Sun. The long-term enhancements in *Kp* and the three products of SW plasma reflect nearly stable variations and a continuously existing feature in the heliosphere.

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