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INFLUENCE OF THE β SOLAR WIND PARAMETER ON STATISTICAL CHARACTERISTICS OF THE A_p INDEX IN SOLAR ACTIVITY CYCLE

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Abstract. We have studied the effect of the β solar wind parameter (equal to the ratio of the plasma pressure to the magnetic pressure) on statistical characteristics of the A_p index reflecting the triggering behavior of the activity of Earth's magnetosphere. The trigger effect of the dynamics of magnetospheric activity consists in the abrupt transition from the periodic mode to the chaotic mode in the solar activity cycle. It is shown that cumulative amplitude distribution functions and power spectra of the A_p index of both the periodic and chaotic modes are well approximated by power and exponential functions respectively. At the same time, the indices of power functions and the indices characterizing the slope of the A_p index spectrum differ significantly in magnitude for the periodic and chaotic modes. We have found that A_p nonlinearly depends on β for both the modes of magnetospheric dynamics. The maximum of the A_p index amplitude for periodic modes is observed when β>1; and for chaotic ones, when β<1. In almost every cycle of solar activity, the energy of the A_p index fluctuations of chaotic modes is higher than that of periodic ones. The results indicate intermittency and its associated turbulence of magnetospheric activity. The exponential character of the spectral density of the A_p index suggests that the behavior of magnetospheric activity is determined by its internal dynamics, which can be described by a finite number of deterministic equations. The trigger effect of magnetospheric activity is assumed to be due to the angle of inclination of the axis of the solar magnetic dipole to the ecliptic plane, on which the dynamics of the β parameter in the solar activity cycle depends.

Keywords: magnetosphere, solar activity, A_p index, trigger mode, intermittency.

INTRODUCTION

The magnetosphere is a complex dynamic system constantly exposed to plasma of the solar wind (SW) and interplanetary magnetic field (IMF). Numerous studies such as [Burlaga, 1991; Marsch, Tu, 1997; Ryazantseva, Zastenker, 2008; Yordanova et al., 2009] have shown that SW plasma stream parameters are intermittent in nature. Thus, SW velocity and magnetic field distribution functions demonstrate the non-Gaussian nature [Marsch, Tu, 1997]. Intermittent solar wind fluctuations have a significant effect on geomagnetic activity [Vörös et al., 2002; D'Amicis et al., 2010]. Yordanova et al. [2009] have shown that SW plasma has turbulent characteristics. According to [Borovsky, Funsten, 2003], turbulence is a characteristic feature not only of plasma streams but also of the magnetic field in the plasma sheet of Earth's magnetosphere. Thus, the magnetosphere, whose activity is determined by the interaction with SW, features intermittency and turbulence.

Magnetospheric activity is usually characterized using planetary geomagnetic indices, for example, the A_p index. It is believed that A_p reflects the influence of solar activity and interplanetary medium on the magnetosphere. The 11-year geomagnetic activity periodicity strictly follows the 11-year solar cycle [Schreiber, 1998]. Unlike the solar cycle, the geomagnetic activity periodicity has two peaks, one of which occurs near solar maximum; the other, during its decay phase [Schreiber, 1998]. The first maximum in the annual dynamics of A_p is associated with sporadic solar activity, which includes, inter alia, coronal mass ejections. The second maximum is attributed to recurrent solar activity determined by the 27-day synodic period of solar rotation. Sources of recurrent geomagnetic activity are high-speed streams from coronal holes [Webb et al., 2001].

The spectral analysis of the A_p index carried out in [Zotov, Klain, 2017] has revealed intermittency of two modes in the magnetospheric dynamics in each 11-year solar cycles. One of the modes, conventionally called by the authors "periodic", features a weak broadband noise with predominant 27-day periodicity and its several harmonics. The other mode — "chaotic" — features the predominant intense broadband noise and the virtual absence of the 27-day periodicity. Note that transitions from one mode in the magnetospheric dynamics to the other are quite abrupt. This behavior of magnetospheric activity with abrupt transitions from one mode to the other has been called "the trigger mode in the magnetospheric dynamics" [Zotov, Klain, 2017].

Further studies [Zotov et al., 2018] have shown that the most probable parameter responsible for intermittency of the periodic and chaotic modes of magnetospheric activity is likely to be the SW parameter β equal to the ratio of the thermal pressure to the magnetic pressure: $\beta = NkT/(B^2/(8\pi))$, where N and T are the density [cm^{-3}] and temperature [K] of SW proton plasma, B is the interplanetary magnetic field [nT]. The dynamic spectrum of β as well as the spectrum of A_p are characterized by the intermittency of the two modes differing in signal noise intensity. Moreover, we drew attention to the fact that the change of mode in the magnetospheric dynamics depends on the β parameter. At $\beta \sim 1$, the chaotic mode is observed in the magnetosphere; at $\beta > 1$, the periodic one. Zotov et al. [2018] did not, however, analyze the effect of the β parameter on geomagnetic activity characteristics (A_p index) for the periodic and chaotic modes of the magnetosphere.

This paper is a sequel to [Zotov, Klain, 2017; Zotov et al., 2018] and examines the influence of the SW parameter β on statistical characteristics of the A_p index reflecting the previously observed effect of the triggering behavior of magnetospheric activity.

EXPERIMENTAL DATA

In this paper, as characteristics of solar and magnetospheric activity we have utilized daily average Wolf numbers (W) and A_p index obtained respectively from the World Data Center on Solar-Terrestrial Physics (Moscow) [www.wdcb.ru] and from the World Data Center in Kyoto [http://swdcwww. kugi.kyoto-u.ac.jp/the index.html] for the period from 1932 to 2018. In addition, we have used daily and 27-day data on SW and IMF plasma parameters for 1964–2018 from the OMNI database [https://omniweb.gsfc.nasa.gov/ow.html].

RESULTS

Before analyzing the effect of the SW parameter β on statistical characteristics of the A_p index, it is necessary to briefly describe the previously detected features of magnetospheric activity in the solar cycle. Let us present two Figures [Zotov et al., 2018] that reflect the essence of the trigger effect in the magnetospheric dynamics. Compared with [Zotov et al., 2018], this paper uses much greater amount of data (to 2018 inclusive). For example, Figure 1 shows the annual average variation in the sunspot number W, the dynamics of the annual average amplitude, and the spectral density of the A_p index from the end of solar cycle 16 to solar cycle 24. The dynamics of the A_p amplitude reflects the known regularities of geomagnetic activity, namely, in each solar cycle there are two peaks one of which occurs during the growth or maximum phase; the other, during the decay phase (Figure 1, *a*). In the dynamic spectrum of A_p (Figure 1, *b*) there are pronounced abrupt transitions of magnetospheric activity from the periodic mode to the chaotic one. Such transitions have first been identified in [Zotov, Klain, 2017] for 1932–2000. They were called "the trigger mode in the magnetospheric dynamics".

Figure 2, which displays dynamic spectra of the sunspot number W, A_p, and β from solar cycle 20 to 24, demonstrates that one of the factors responsible for the effect of mode switching in the magnetospheric dynamics may be the SW parameter β. The spectral density of Wolf numbers has a maximum intensity and exhibits the 27-day periodicity at the maximum of each solar cycle (Figure 2, *a*), which clearly does not coincide in time with periodic modes in A_p dynamics (Figure 2, *b*). Hence, the sunspot number dynamics is unrelated to the trigger mode of magnetospheric activity. The β dynamic spectrum is characterized by the intermittency of the broadband noise of different intensity (Figure 2, *c*). In other words, the β spectrum clearly exhibits abrupt changes of intensity of the chaotic mode, which mainly coincide in time with the transitions from the periodic mode to the chaotic one in the A_p spectrum (Figure 2, *b*). Note that such features have not been found in dynamic spectra of other SW and IMF parameters. The time coincidence of change of the nature of the A_p and β spectra in the solar cycle allows us to assume that the trigger mode in A_p variations and accordingly magnetospheric activity are controlled by the β dynamics [Zotov et al., 2018]. The comparison between the A_p dynamic spectrum and the annual average dynamics of β (Figure 2, *d*) shows that at $\beta \sim 1$ in the magnetosphere there is mainly the chaotic mode; at $\beta >> 1$, the periodic one.

Zotov et al. [2008] have shown for 1932– 2000 that the distribution of the A_p index has a non-Gaussian shape and a long tail. Such distributions are called distributions with heavy tails or fat tails [Malinetsky, Potapov, 2000]. Consequently, the A_p index has features of intermittent processes. Due to the fact that in magnetospheric activity there are at least two modes — periodic and chaotic, the questions arise: 1) whether the intermittency is characteristic of the A_p behavior in each of the above modes in the magnetospheric dynamics or not; 2) whether the SW parameter β affects statistical characteristics of A_p for the periodic and chaotic modes or not.

To answer these questions, A_p data has been divided into two groups in accordance with the periodic and chaotic modes of magnetospheric activity. Figure 3 shows the distribution of A_p amplitudes $N(A_p)$ separately for intervals of "periodicity" (*a*) and "chaos" (*b*). We can see that both the distributions exhibit a smooth decrease in the number of daily A_p values with increasing amplitude, i.e. they have a typical shape of heavy-tailed distributions. According to [Malinetsky, Potapov, 2000], such distributions are satisfactorily approximated by power-law functions of the form of $f(x) = x^{-\alpha}$ at x exceeding a certain threshold value x_0. It is not necessary here that the entire distribution is approximated by the power-law function — it is sufficient that this condition holds for $x > x_0$. This Figure also shows cumulative functions of A_p distributions $P(A_p)$ and approximations of their tails by power-law functions of the form of $P(A_p) = (A_p)^{-\alpha}$. The method of deriving the cumulative function of distribution of signal amplitudes and exponent α characterizing the slope of the cumulative function of A_p distribution is described in detail in [Kurazhkovskaya, Klain, 2015]. Figure 3 suggests that regardless of the type of the mode of magnetospheric activity tails of cumulative functions of A_p amplitude distributions are quite well approximated by power-law functions, but α values differ significantly for

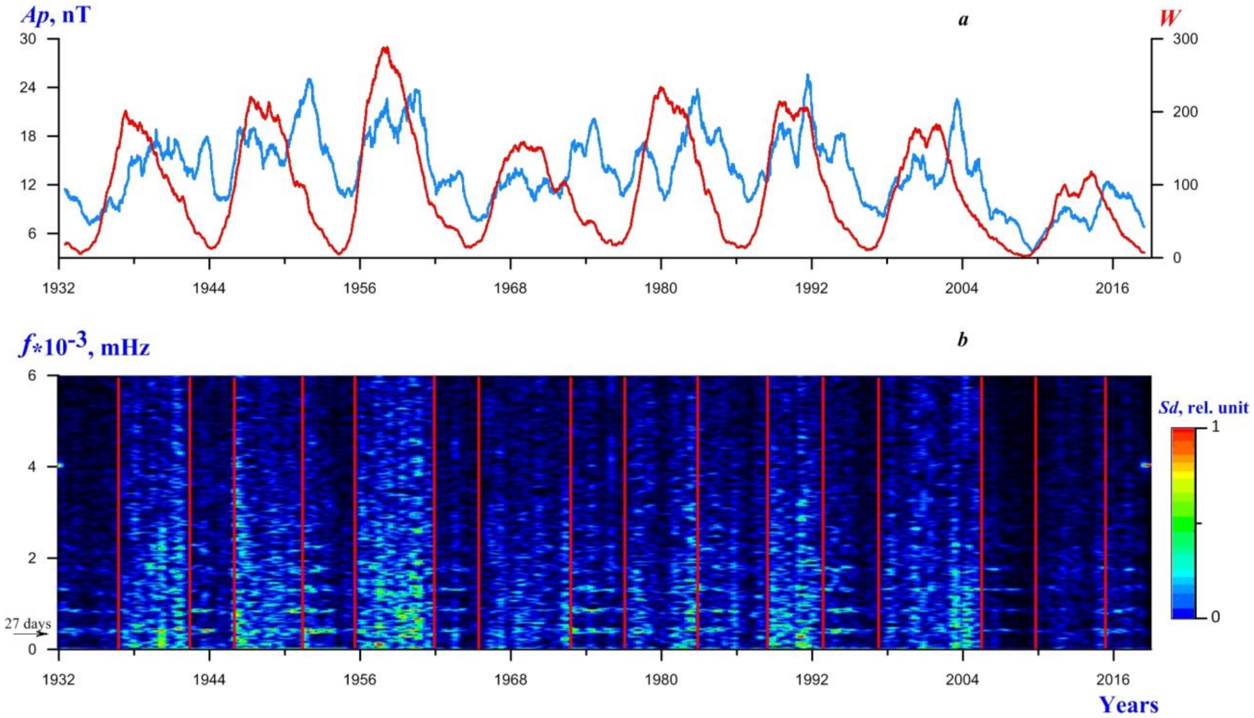

Figure 1. Annual average variations in sunspot number *W* (red curve), and A_p index (blue curve) (*a*), and A_p dynamic spectrum from the end of solar cycle 16 to solar cycle 24 (*b*). Vertical lines mark boundaries of the periodic and chaotic modes

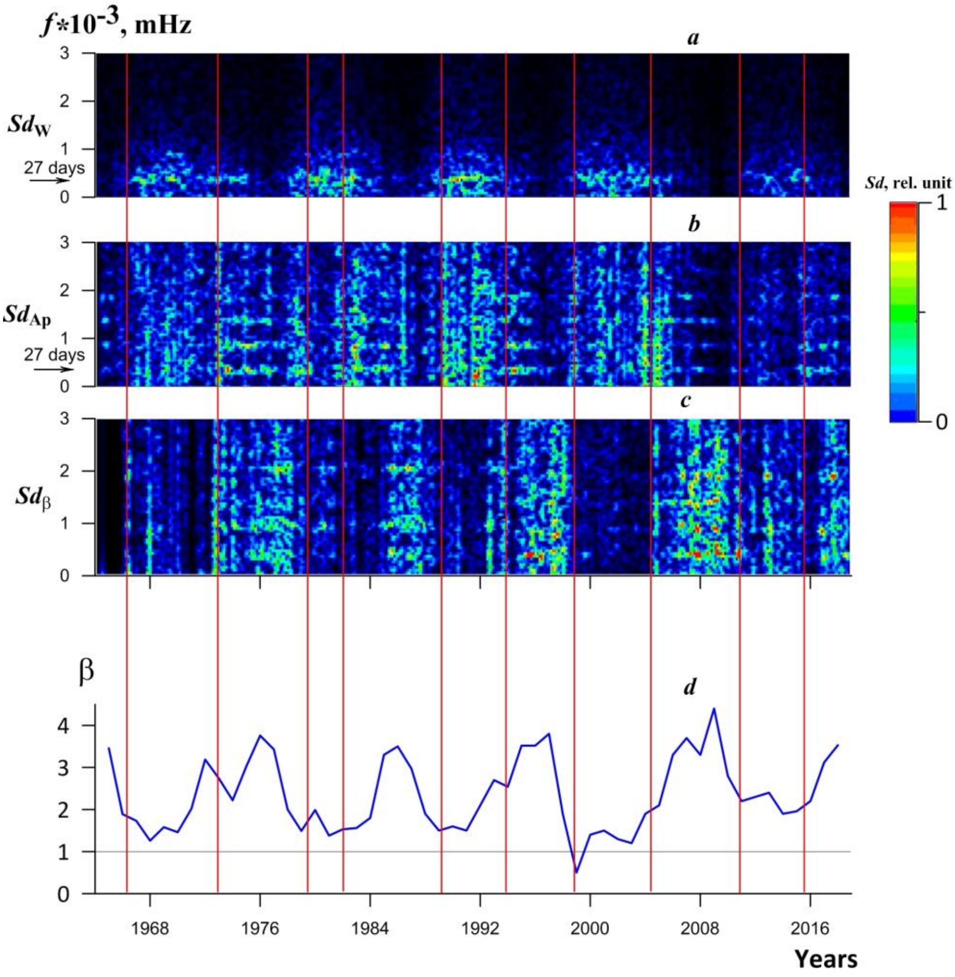

Figure 2. Dynamic spectra of: sunspot number W — Sd_W (*a*); A_p index — Sd_{A_p} (*b*); β parameter — Sd_β (*c*); and also annual average dynamics of β (*d*) in solar cycles 20–24. Vertical lines mark boundaries of the periodic and chaotic modes

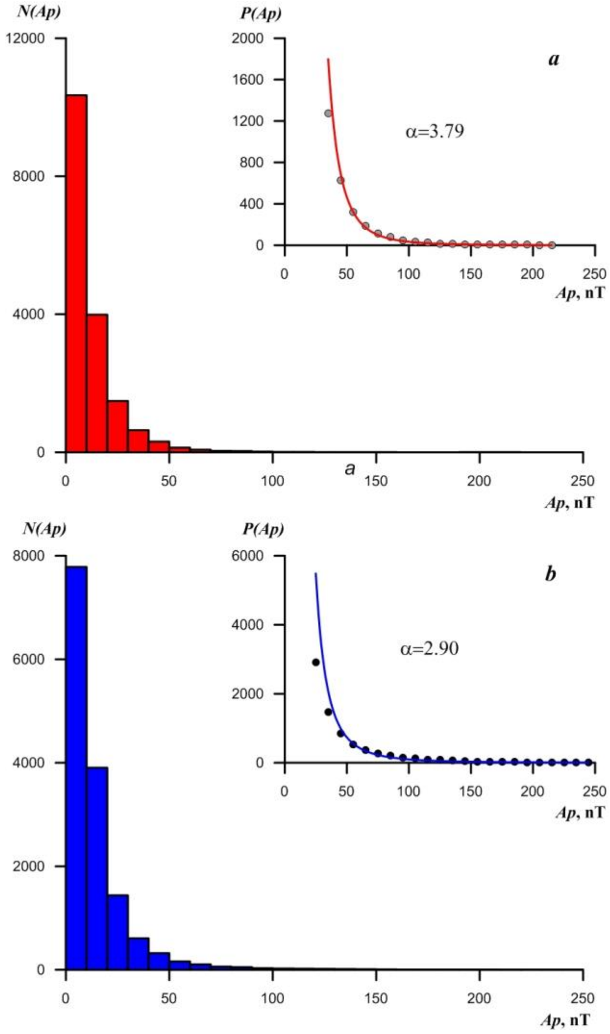

Figure 3. Distributions $N(A_p)$ of daily A_p amplitudes for the periodic (*a*) and chaotic (*b*) modes in the magnetospheric dynamics in 1932–2018. On the right are approximations of tails of cumulative distribution functions $P(A_p)$ of A_p amplitudes (circles) by power-law functions (solid line)

the periodic and chaotic modes: α=3.79 and α=2.90 respectively. The power law of A_p amplitude distribution for both the modes in magnetospheric dynamics indicates the intermittency and its associated turbulence of magnetospheric activity. From the exponent α we can qualitatively estimate the degree of turbulence of the magnetosphere in the periodic and chaotic modes.

Figure 4 shows averaged power spectra of daily A_p for the periodic and chaotic modes. Construction of the power spectra are based on the Fourier transform. The A_p values were separated into time intervals (according to the division into periodic and chaotic modes), for each of which we constructed a power spectrum. Then, all the A_p spectra for modes of each type were averaged. The spectra obtained for both the modes are well approximated by exponential functions:

$$S(f) \sim \exp(-\gamma f),$$

where S is the spectral density; f is the frequency; γ is the exponent characterizing the slope of the spectrum. Exponents of the A_p spectrum slope differ for different

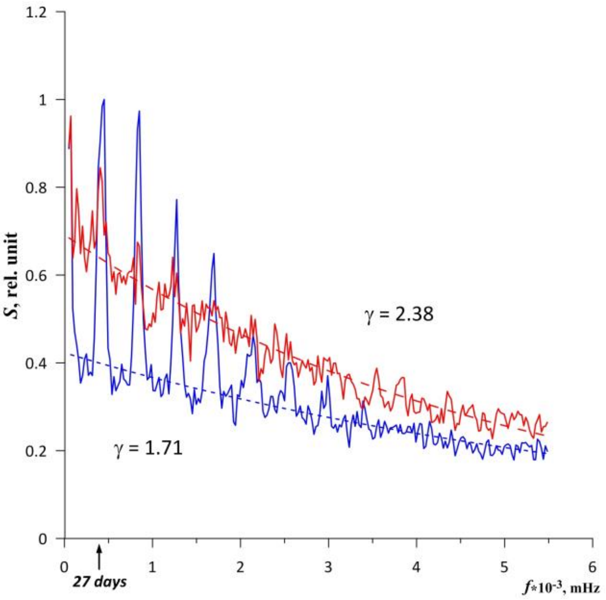

*Figure 4.*Power spectra of daily A_p for the periodic (red curve) and chaotic (blue curve) modes in the magnetospheric dynamics in 1932–2018. Dashed lines indicate approximations of A_p spectra by exponential functions

modes: γ=1.71 and γ=2.38 for the periodic and chaotic modes respectively.

Thus, in terms of statistical properties of the A_p index, the modes of magnetospheric activity exhibit both similarities and differences. Similarities are that the intermittency of magnetospheric activity is characteristic of both periodic and chaotic modes. Differences between power exponents of approximating functions imply different levels of magnetospheric turbulence in each of the modes, the appearance of which depends on the β parameter.

Figure 5 shows average A_p as a function of β for the periodic and chaotic modes. For these plots, we have used daily A_p and β. From the analysis we excluded values of the A_p index that had gaps in data on the β parameter. Note that β varies largely from ~0.1 to ~4.0. According to [Veselovsky et al., 2010], this range of β variation includes ~90 % of all observed values. We therefore show average A_p as a function of β for $0 < \beta < 4$ for both the modes of magnetospheric activity (Figure 5). Average values of the A_p index were determined as follows. Initially, source data was used to calculated running means from 50 points. Then, we made spline approximation of the obtained data. Figure 5 shows that A_p is the highest at β~1 in the case of both periodic and chaotic modes. Moreover, the maximum A_p for the chaotic mode occurs when β<1; whereas for the periodic one, when β>1. The resulting differences in $A_p(\beta)$ are statistically significant. When β>>1, A_p gradually decreases with increasing β. The $A_p(\beta)$ dependencies for the periodic and chaotic modes are clearly nonlinear, indicating the nonlinear behavior of magnetospheric activity, characterized by the A_p index.

Figure 6 displays histograms representing the energy of A_p fluctuations for the periodic and chaotic modes of magnetospheric activity from late solar cycle 16 to solar cycle 24. The energy of A_p fluctuations was calculated

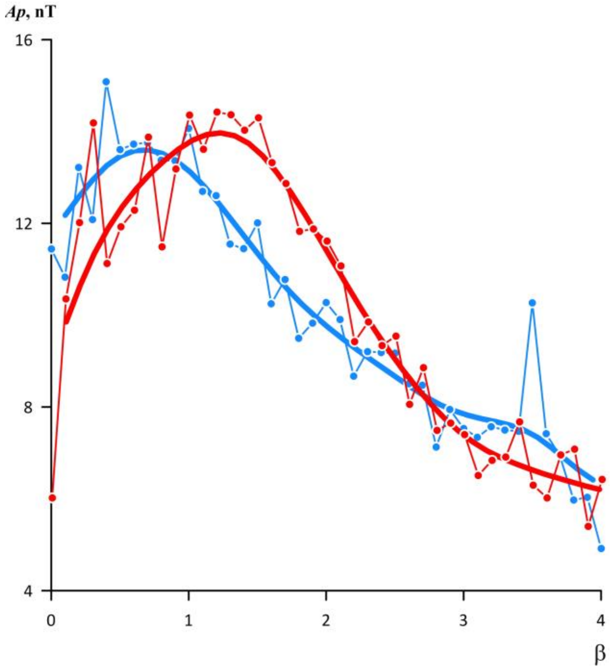

Figure 5. A_p versus β for periodic (red circles) and chaotic (blue circles) modes for 1965–2018. Spline approximations of experimental data for the periodic and chaotic modes (red and blue curves respectively)

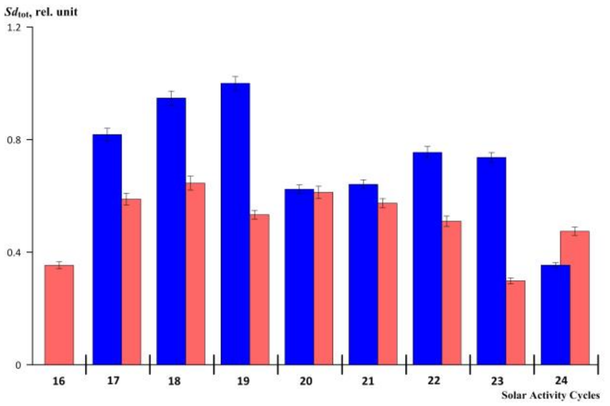

Figure 6. Energy of A_p fluctuations (Sd_{tot}) for periodic (red) and chaotic (blue) modes from late solar cycle 16 to solar cycle 24

by multiplying the mean spectral density amplitude by the spectral band width. We can see that in almost each solar cycle the energy of A_p fluctuations for the chaotic mode is higher than for the periodic one. An exception is solar cycle 20 in which energies of A_p fluctuations for the periodic and chaotic modes are comparable in magnitude, and solar cycle 24. The difference between energies of A_p fluctuations for the periodic and chaotic modes is statistically significant. This follows from estimated errors in determining the energy at the level of 95 % (vertical lines in Figure 6). Since the A_p index reflects magnetospheric dynamics in the solar cycle, from the data presented in Figure 6 we can estimate the change in the energy of the magnetosphere.

Thus, the two modes we have identified in magnetospheric dynamics differ not only in intermittency, but also in energy characteristics.

DISCUSSION

Earth's magnetosphere features a continuous distributed SW energy and its subsequent dissipation. In such systems, a distributed active medium is formed in which stationary or time-dependent spatial structures arise. As is known [Horsthemke, Lefever, 1984], even weak external noise affecting such nonlinear systems can change them. If the input of a simple nonlinear system is acted upon by external noise, at the output there is a signal with heavy-tailed distribution of its amplitudes. The magnetosphere is likely to belong to the class of such systems. Zotov et al. [2008] have shown that the experimental function of distributions of daily A_p is well approximated by the product of power-law and exponential functions. This heavy-tailed distribution and hence the statistics of magnetospheric dynamics can be described using the above model.

Results of the analysis of cumulative functions of A_p amplitude distributions and its power spectra indicate that regardless of the division of modes of magnetospheric activity into periodic and chaotic the behavior of A_p exhibits the intermittency. However, intermittency indices for the two modes differ significantly. In other words, the stochastic behavior of the magnetosphere is described by different indices in the periodic and chaotic modes. Since the exponent of the power-law function reflects the state of a medium [Malinetsky, Potapov, 2000], we can qualitatively estimate the level of turbulence of the magnetosphere. For example, from the exponent of intermittency α characterizing the slope of cumulative functions of A_p amplitude distribution (Figure 3) we can see that the level of A_p turbulence is significantly higher in the periodic mode than in the chaotic one. In this regard, the magnetosphere is more turbulent in the periodic mode than in the chaotic one. The comparison between spectral densities of the A_p index and γ indices characterizing the slope of the power spectrum (Figure 4) indicates that the intensity of the broadband noise for the periodic mode is lower than for the chaotic one.

Such stochastic behavior of the magnetosphere may be due to external factors (magnetospheric response to variations in SW and IMF parameters) and internal dynamics associated with energy storage and release during magnetic storms and substorms [Johnson, Wing, 2005]. The effect of external sources on the A_p dynamics in the solar cycle has been discussed in detail, for example, in [Holappa et al., 2014]. According to the results obtained by the authors, during the growth and maximum phases of solar activity geomagnetic activity is largely driven by coronal mass ejections, whereas during the decay phase of solar cycle geomagnetic activity is determined mainly by high-speed SW streams from coronal holes. The chaotic mode with predominant intense broadband noise must be associated with coronal mass ejections. The periodic mode, characterized by a significant predominance of the 27-day periodicity as compared to the noise, is determined by recurrent high-speed streams related to the 27-day period of solar rotation.

The resulting dependence of A_p on β confirms the influence of external factors on the magnetospheric dynamics. Referring to Figure 5, in the case of the chaotic mode the A_p index is maximum when the plasma pressure does not exceed the magnetic pressure (β<1). For the periodic mode the situation is reverse, namely, A_p is maximum when the plasma pressure predominates over the magnetic pressure (β>1).

Note that in the statistical distribution of the SW parameter β the observation frequency is maximum when β<1 [Veselovsky et al., 2010]. According to [Xu, Borovsky, 2015], β varies from 0.13 to 0.98 with a mean of 0.71 depending on the type of SW plasma source. According to [Chernyshev et al., 2014], the level of space plasma turbulence depends greatly on β. The obtained statistical characteristics of the A_p index and the fact of observations of the periodic and chaotic modes in the magnetospheric dynamics at various ranges of β variation indicate that the degree of magnetospheric turbulence at β>1 is higher than at β<1. This conclusion seems very surprising at first. In other words, in the case of the chaotic mode (β<1) the external noise (SW turbulence) suppresses the transition of the magnetosphere to the turbulent mode. Horsthemke, Lefever [1984], examining the influence of external noise characteristics on the transition of nonlinear systems to turbulence, have, however, shown that the external noise stabilizes chaos. There is likely to be a similar situation in the magnetosphere, i.e. for the chaotic mode, the external action of the turbulent SW stabilizes the chaos.

It is also possible that the intermittent behavior of the A_p is determined by the magnetospheric dynamics and can be described by a small number of deterministic equations. A simple criterion that allows us to distinguish systems exhibiting a deterministic chaos from systems affected by the external noise is that power spectra of time series describing the systems with deterministic chaos should decrease faster, for example, exponentially [Sigeti, Horsthemke, 1987]. Although a general theoretical solution to the problem of the behavior of power spectra of deterministic or stochastic systems have not been found yet, numerical experiments confirm this conclusion [Sigeti, 1995; Ohtomo et al., 1995; Valsakumar et al., 1997]. The exponential behavior of A_p power spectra we have identified (Figure 4) suggests that Earth's magnetosphere has its own dynamics, which can be considered in models of deterministic chaos. Thus, the exponential nature of the A_p power spectra (Figure 4) and the dependence of A_p on β (Figure 5) show that magnetospheric activity of the solar cycle generally depends on its own dynamics and an external factor such as the ratio of the plasma pressure to the magnetic one.

In addition to the above differences between statistical characteristics of the A_p index for the periodic and chaotic modes, we should pay attention to the differences between the two modes of magnetospheric activity, which manifest themselves in the energy of A_p fluctuations (Figure 6). In some solar cycles, the energy of A_p fluctuations in the chaotic mode is much greater than that in the periodic one. This regularity becomes clear if we look at the results obtained in [Yermolaev et al., 2009]. Indeed, the maximum frequency of observation of geoeffective large-scale SW streams determining geomagnetic activity corresponds to β~ 1 [Yermolaev et al., 2009]. It is at β~ 1 that the A_p index reaches maximum in the chaotic mode (Figure 5). Thus, we can assume that the chaotic mode in the magnetospheric dynamics is connected with input of a larger amount of SW energy in each solar cycle as compared to the periodic mode.

In conclusion, let us pay attention to the following regularity. Livshits, Obridko [2006] present a cyclic variation in the angle θ of inclination of the axis of the solar magnetic dipole, measured from the solar equatorial plane (latitude). If we compare it with the β cyclic variation shown in Figure 2, *d*, it is easy to see that β~1 when the angle θ~0–30°. When θ>30°, β>>1. Hence, the chaotic mode in the magnetospheric dynamics is observed when θ<30°; and the periodic one, when θ>30°. On the other hand, according to [Sokolov et al., 2013] in Earth's orbit the plasma and magnetic pressures are comparable in magnitude (β~1) at nearly zero angles of inclination of the axis of the solar magnetic dipole. Thus, the value of the β parameter in the solar cycle depends on the angle of inclination of the solar magnetic dipole to the ecliptic plane. Founding on the above and our results, we can assume that the global factor determining the trigger effect of magnetospheric activity is the cyclic variation in the angle of inclination of the axis of the solar magnetic dipole to the ecliptic plane.

CONCLUSION

In this paper, we have demonstrated that the ratio of the thermal pressure to the magnetic pressure of the solar wind is a key parameter determining not only trigger modes in the magnetospheric dynamics in the solar cycle, but also affecting the statistical properties of the A_p index. The cumulative functions of distribution of amplitudes and power spectra of the A_p index for both periodic and chaotic modes are well approximated by power-law and exponential functions respectively. The exponents of power-law functions and the exponents characterizing the slope of the A_p spectrum differ significantly in magnitude for the periodic and chaotic modes. We have found that A_p depends on β, and this dependence is nonlinear for both the modes in the magnetospheric dynamics. The A_p index is maximum in the periodic mode when β>1, and in the chaotic mode when β<1. We have established that in most solar cycles the energy of A_p fluctuations for the chaotic mode is higher than for the periodic one. The results indicate intermittency and its associated turbulence observed in magnetospheric activity during abrupt transition from the periodic mode to the chaotic one in the solar cycle. The exponential dependence of the spectral density of the A_p index suggests that the behavior of the magnetosphere is determined by its internal dynamics, which can be described by a small number of deterministic equations. On the basis of the relationship between the A_p index and the β parameter and between β and the angle θ, we can assume that the change to the angle of inclination of the axis of the solar magnetic dipole to the ecliptic plane is a global factor determining mode change or trigger effect of the magnetospheric dynamics in the solar cycle.

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