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What Causes Geomagnetic Activity During Sunspot Minimum?[1]

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Abstract—It is well known that the main drivers of geomagnetic disturbances are coronal mass ejections whose number and intensity are maximum in sunspot maximum, and high speed solar wind streams from low latitude solar coronal holes which maximize during sunspot declining phase. But even during sunspot minimum periods when there are no coronal mass ejections and no low latitude solar coronal holes, there is some "floor" below which geomagnetic activity never falls. Moreover, this floor changes from cycle to cycle. Here we analyze the factors determining geomagnetic activity during sunspot minimum. It is generally accepted that the main factor is the thickness of the heliospheric current sheet on which the portion of time depends which the Earth spends in the slow and dense heliospheric current sheet compared to the portion of time it spends in the fast solar wind from superradially expanding polar coronal holes. We find, however, that though the time with fast solar wind has been increasing in the last four sunspot minima, the geomagnetic activity in minima has been decreasing. The reason is that the parameters of the fast solar wind from solar coronal holes change from minimum to minimum, and the most important parameter for the fast solar wind's geoeffectivity—its dynamic pressure—has been decreasing since cycle 21. Additionally, we find that the parameters of the slow solar wind from the heliospheric current sheet which is an important driver of geomagnetic activity in sunspot minimum also change from cycle to cycle, and its magnetic field, velocity and dynamic pressure have been decreasing during the last four minima.

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1. INTRODUCTION

As early as in the middle of the 19th century, it was found that the minima and maxima in the average rate and size of magnetic disturbances at widely separated observatories coincide, and correspond to minima and maxima in sunspot numbers [Sabine 1852]. It is now known that there are two maxima in geomagnetic activity during the sunspot cycle. The major geomagnetic storms which follow the sunspot cycle are caused by coronal mass ejections [Gosling, 1993], and are the source of the maximum of geomagnetic activity in sunspot maximum. Another source of geomagnetic activity are the high speed solar wind streams (HSS), which originate from the coronal holes—open unipolar magnetic field areas [Sheeley Jr. et al., 1996]. Coronal holes are biggest and in most geoeffective position during the sunspots declining phase, causing a secondary maximum in geomagnetic activity.

[Feynman, 1982] showed that for every number of sunspots R, there is some minimum value below which the geomagnetic activity measured e.g. by the geomagnetic aa-index cannot fall. This minimum value depends linearly on the number of sunspots, and is determined by the equation $aa_R = a_0 + b.\ R$, where aa_R is the minimum geomagnetic activity for a given number of sunspots, R is the international sunspot number, and a_0 and b are constants. The values above this line, $aa_P = aa - aa_R$, are due to the contribution of HSS to geomagnetic activity. Therefore, geomagnetic activity can be divided into two parts: aa_R—sunspot-related and due to CMEs, and aa_P—non sunspot-related, due to HSS. [Kirov et al., 2013] noticed that a_0 and b calculated by different authors and for different periods differ, and found that this is not a result of the different computational methods used, but a_0 and b indeed vary from cycle to cycle and have cyclic long-term variations. Moreover, the geomagnetic activity should be divided into 3 rather than 2 components to better track its variations. The first component, equal to the a_0 coefficient, is the "floor" below which geomagnetic activity cannot fall even in the absence of sunspots, and is obviously not related to sunspots. a_0 is practically determined by the activity in the cycle minimum. The second component is the geomagnetic activity caused by sunspot-related solar activity which is described by the straight line $aa_T = b^*R$ so that $aa_R = a_0 + aa_T$. The slope b of this line also changes cyclically. The third component aa_P (the value above aa_R) is caused by high speed solar wind (Fig. 1).

The subject of the present study is to find what determines the height of the geomagnetic activity floor a_0 and, respectively, the geomagnetic activity in sunspot minimum.

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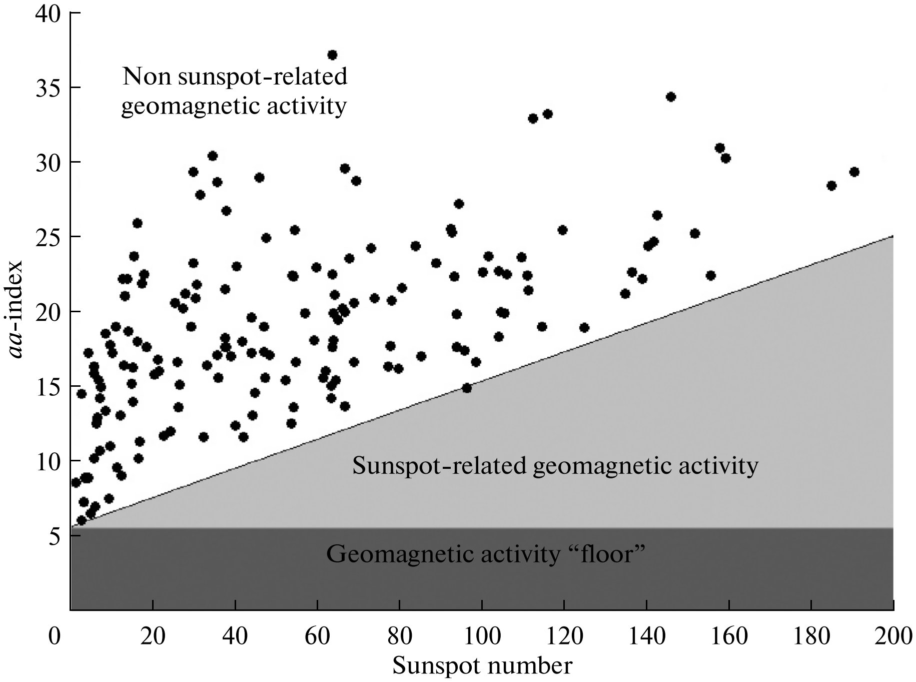

Fig. 1. Dependence of the geomagnetic activity on the sunspot number.

2. DATA

We study the periods of sunspot minima in the last four solar cycles for which there are direct instrumental measurements of the solar wind parameters. Time intervals of 24 months around the sunspot minimum for each of the last four minima are used in our investigation. They cover: 06.1975–06.1977 (min 20/21 cycle); 09.1985–09.1987 (min 21/22 cycle); 05.1995–05.1997 (min 22/23 cycle); 01.2007–01.2009 (min 23/24 cycle).

Next, the periods when the Earth is under the influence of CME and HSS are determined. We categorized a CME using the following properties of the interplanetary space plasma [Richardson and Cane, 1995]:

1. Proton temperature $Tp < 0.5T_{ex}$, where T_{ex} is the expected temperature for the observed solar wind speed, $T_{ex} = 3(0.0106V_{sw} - 0.287)$ if $V_{sw} < 500$ km/s and $T_{ex} = (0.77V_{sw} - 265)$ if $V_{sw} > 500$ km/s (V_{sw} = Flow Speed).

2. Magnetic field magnitude $B \geq 10$ nT.

3. Plasma Beta ≤ 0.8 for at least 5 hours.

The periods of HSS are taken from several catalogues: [Lindblad and Lundstedt, 1981]; [Mavromichalaki and Vassilaki, 1988]; http://www.spacescience.ro/new1/HSS_Cat. For periods not covered by the catalogues, we apply criteria which include an increase of the solar wind velocity by at least 100 km/s in no more than one day to at least 500 km/s for at least 5 hours, accompanied by high temperature and low density [Georgieva et al., 2008].

As a result of this differentiation, three groups of solar wind affecting the Earth during sunspot minima were defined:

1. The Earth is under the influence of CME

2. The Earth is under the influence of HSS

3. The Earth is under the influence of the background solar wind, undisturbed by CME and HSS.

3. CME AND HSS INFLUENCE

There are two main hypotheses which explain the differences in geomagnetic field disturbances during different solar minima:

1. Variations of the number and/or parameters of CME and/or HSS

2. Variations of the thickness of the heliospheric current sheet [Simon and Legrand, 1989] as a result of which the portions of time vary when the Earth is inside the slow, dense and with low geoeffectivity wind of the heliospheric current sheet, and when it is outside the current sheet and is exposed to the fast solar wind from super-radially expanding polar coronal holes.

Our investigation shows that during the periods of minima, the time during which the Earth is under the influence of CMEs is very short: from 0.6% for the last minimum (23–24) to 1.1% in the minimum (20–21). Respectively, the time in which the geomagnetic *Ap* index is over 27 does not exceed 8% during the whole two year period around each minimum, and is slightly over 2% during the minimum (23–24)—Fig. 2. It is

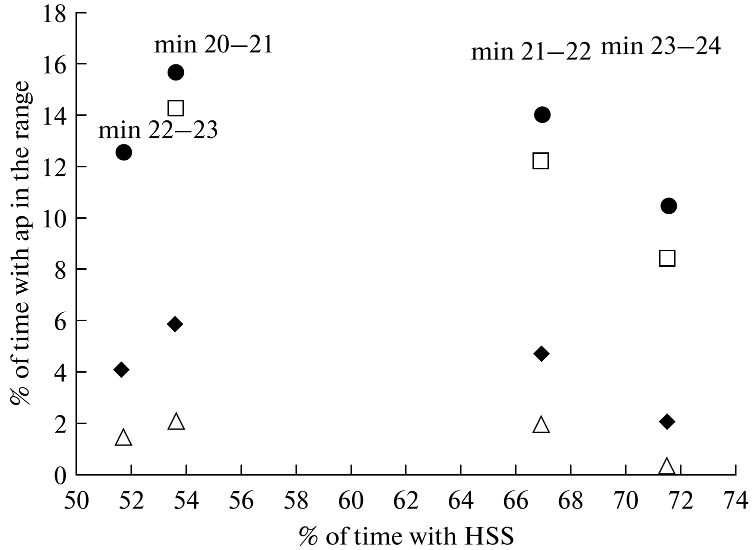

Fig. 2. *Ap* index (*Ap* in the range (10–15)—●, (15–27)—□; (27–50)—◇; (>50)—△) under the influence of HSS during last four solar minima.

clear that with such a short time of impact, CMEs cannot contribute to the average geomagnetic activity at solar minima.

The time during which the Earth is under the influence of HSS in the last four minima is always over 50% (Richardson et al., 2002), and this time has been increasing from 50 to 72%, with one exception (the 22–23 minimum). From these four minima it appears that the time under HSS influences depends on the cycle parity (greater for minima between odd and even than for minima between even and odd cycles)—Fig. 2, however more statistics is needed for a firmer conclusion.

It can be seen that the increased time in which the Earth is under the influence of HSS does not lead to an increase in the average geomagnetic activity in terms of *Ap* index for the two year period of the solar minimum. During the last 23/24 cycle minimum, when over 70% of the time the Earth was under the influence of HSS and the number of HSS reaching the Earth's orbit was greater than those of the previous cycles (due to several long living coronal holes at low latitudes), the time with high geomagnetic activity decreased, while the time with $Ap < 10$ was almost 80% of the whole two years period. [Kirov et al., 2012] showed that the geomagnetic activity with $10 < aa < 30$ for the last four minima has been decreasing from cycle to cycle. On the other hand it is known that these disturbances ($10 < aa < 30$) are caused by HSS (Shel'ting and Obridko, 2011). Therefore, a clear decrease of the geomagnetic activity in consecutive cycles inside the time intervals during which the Earth is under the influence of HSS is observed for the last four solar minima—Fig. 3.

The fact that the time during which the Earth is influenced by HSS at solar minimum is not directly related to the average geomagnetic activity, contradicts the concept that the variations of the heliospheric current sheet thickness leading to variations of the time when the Earth is under HSS influence, lead to variations of the averaged geomagnetic activity. We see that the geomagnetic activity caused by HSS at solar minima is determined not by the HSS number and total duration but by the internal properties of HSS—Fig. 4.

In Fig. 4 it can be seen that the main factor determining the HSS geoeffectiveness is the structure's pressure, because the changes in geomagnetic activity during HSS dominated intervals follow the changes in the pressure of HSS.

3. BACKGROUND SOLAR WIND

Between 30 and 50% of the time during the two year period around each solar minimum, the Earth is not influenced by either CMEs or HSS, and is only affected by the background solar wind (BSW). Even in the absence of CMEs and HSS, the geomagnetic activity is above zero, therefore BSW is in itself also a driver of geomagnetic disturbances. In order to understand how BSW affects the geomagnetic field, we study the time intervals in which the Earth is not influenced by HSS and CMEs.

Surprisingly, we find that the way the BSW affects the Earth's magnetic field, smoothly changes with increasing speed of the BSW. The geomagnetic activity increases with increasing speed of the BSW below 450 km/s and decreases with increasing speed of the BSW above 490 km/s—Fig. 5 and Fig. 6, with a transition region in-between.

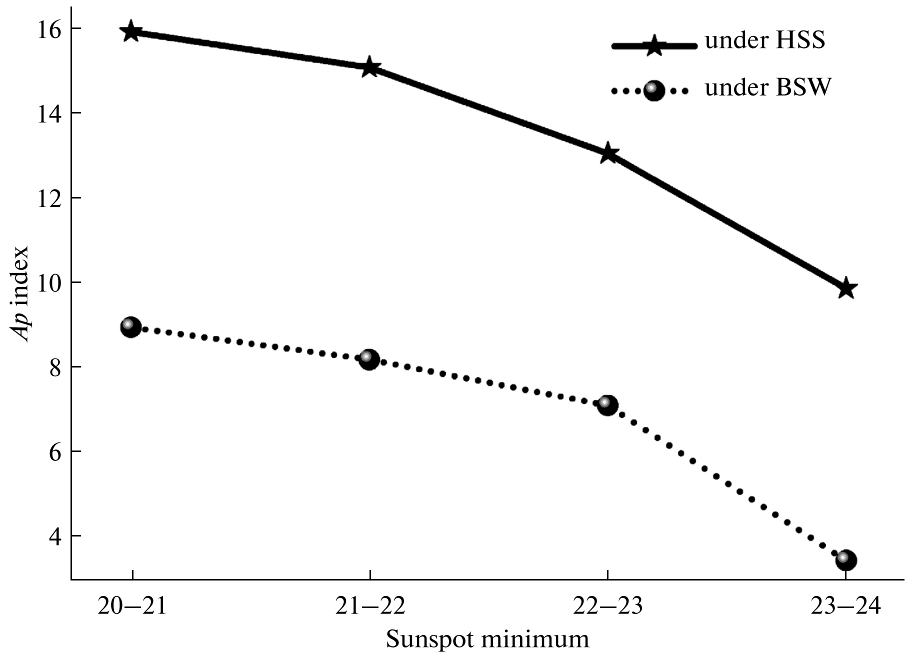

Fig. 3. Averaged *Ap* index at last four solar minima under the influence of HSS (solid line) and background solar wind (BSW) (dotted line).

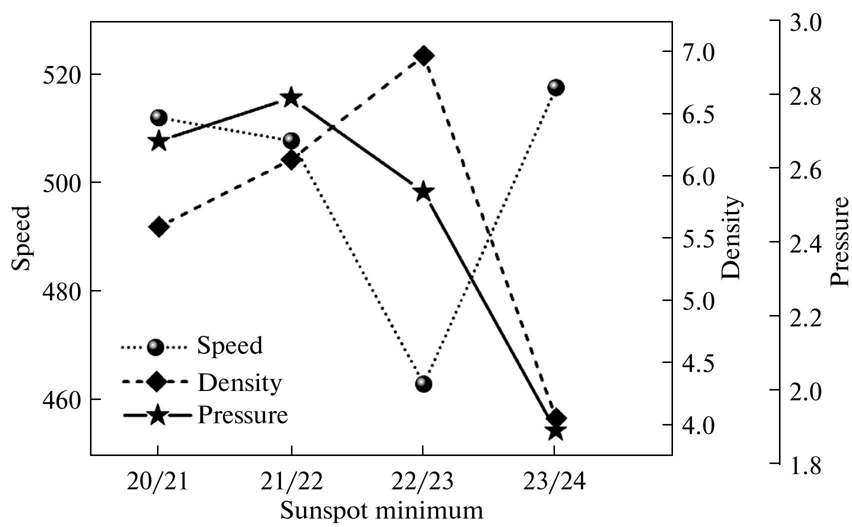

Fig. 4. Averaged HSS parameters—speed, km/s (dotted line); density, N/cm^3 (dash line); pressure, nPa (solid line) at last four solar minima.

As can be seen in Fig. 5, the average geomagnetic activity when the BSW speed does not exceed 450 km/s (slow background solar wind), drops three times from minimum (20–21) to minimum (23–24). In this period the average solar wind speed drops by 10–15%, while the magnetic field drops 1.5 times and the density almost 2 times. We can therefore conclude that the major factor which defines the geomagnetic activity when there are not CMEs and HSS, is the solar wind pressure and its influence on the Earth's magnetosphere.

With increasing average velocity of the BSW, the above relation gradually reverses, and for BSW speed above 490 km/s (fast BSW), the *Ap* index decreases with increasing speed of the BSW—Fig. 6.

Figures 5 and 6 show that the fast BSW causes more significant geomagnetic disturbances than the slow BSW, which can be expected. The surprising fact is that the average geomagnetic activity is higher when the Earth is under fast BSW influences than when it is in periods of HSS influences. In the period when there are fast BSW, the magnetic field does not change its

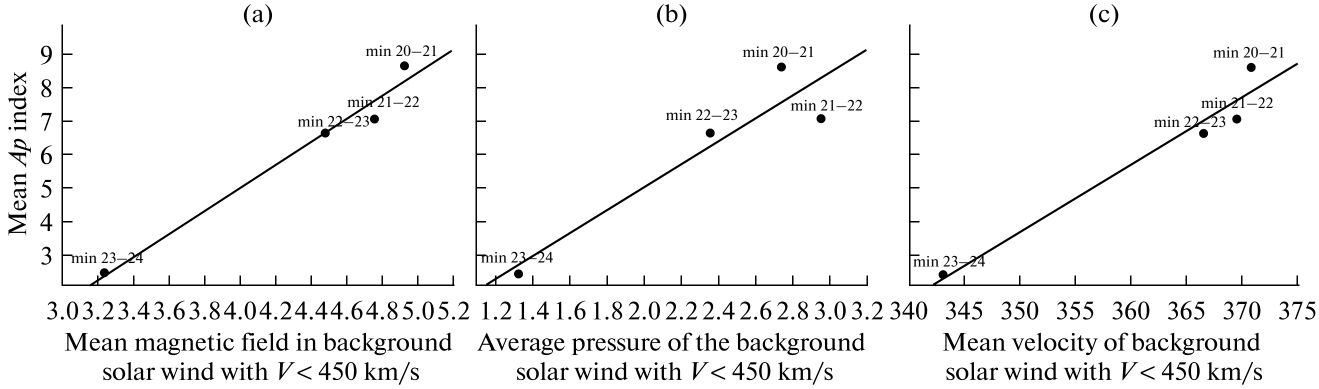

Fig. 5. Geomagnetic *Ap* index as a function of the speed, magnetic field and pressure in periods with background solar wind with $V < 450$ km/s in the last four solar minima.

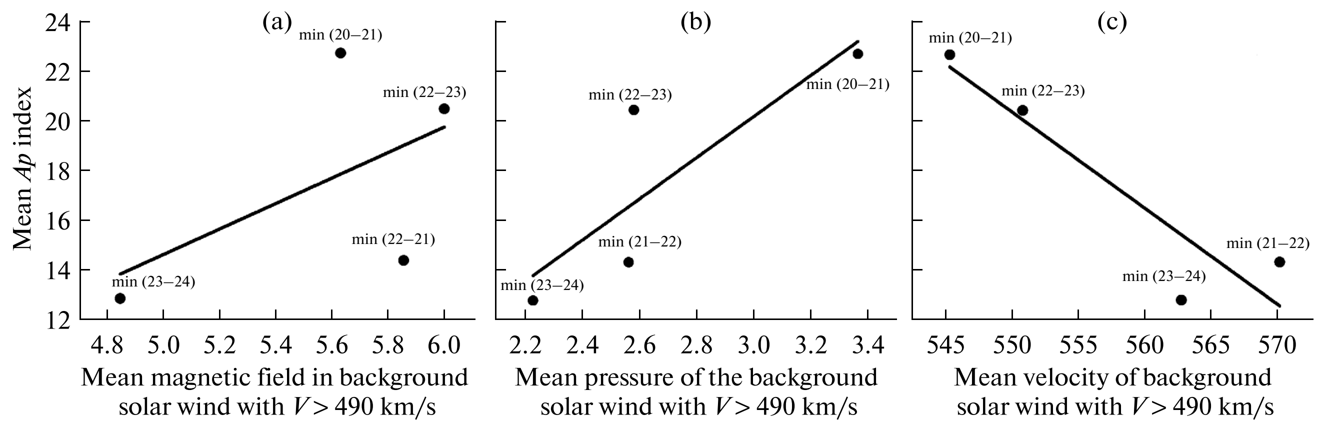

Fig. 6. Geomagnetic *Ap* index as a function of the speed, magnetic field and pressure in periods with background solar wind with $V > 490$ km/s in the last four solar minima.

average values except for the last solar minimum, when there is a serious drop. On the other hand the average pressure decreases with increasing speed, probably due to the fact that the solar wind density decreases faster than the speed increases, which may be the explanation of the decrease in the *Ap* index with increasing speed of the solar wind with $V > 490$ km/s.

An interesting question is whether the fast and slow BSW have the same source or whether they are manifestations of different solar phenomena. To answer this question we compare the parameters of these two types of BSW with the parameters of HSS. As can be seen in Fig. 7, the parameters of fast BSW are very similar to those of HSS. The average temperature of both HSS and faster BSW in all minima is higher than 1×10^5 K and the density does not exceed 9 cm^{-3}. In contrast to this, the temperature of the slow BSW is always lower than 1×10^5 K and the density reaches 12 cm^{-3}. It can be seen that two distinct types of solar wind are identified—the first one is slow BSW and the second one encompasses fast BSW and HSS.

The background solar wind faster than 490 km/s and HSS have similar influence on the geomagnetic activity, and the same characteristics. Probably they have similar origin—low latitude coronal holes and overexpanding polar coronal holes, while the slower BSW comes from the heliospheric current sheet. Most probably, the fast BSW is not recognized as HSS because some of the postulated HSS characteristics are not present, like the sudden rise of the solar wind speed.

5. SUMMARY AND CONCLUSION

In the present work we have established: 1. Neither the portion of time in which the Earth is subjected to the influences of HSS nor the number of HSS have any significant effects on the average geomagnetic activity during sunspot minima. The significantly increased time under HSS influence between 21 and 24 solar cycles have not led to higher geomagnetic activity, but exactly the opposite. It turns out that the HSS factor important for geomagnetic activity in sunspot minima is not the number or duration of HSS, but

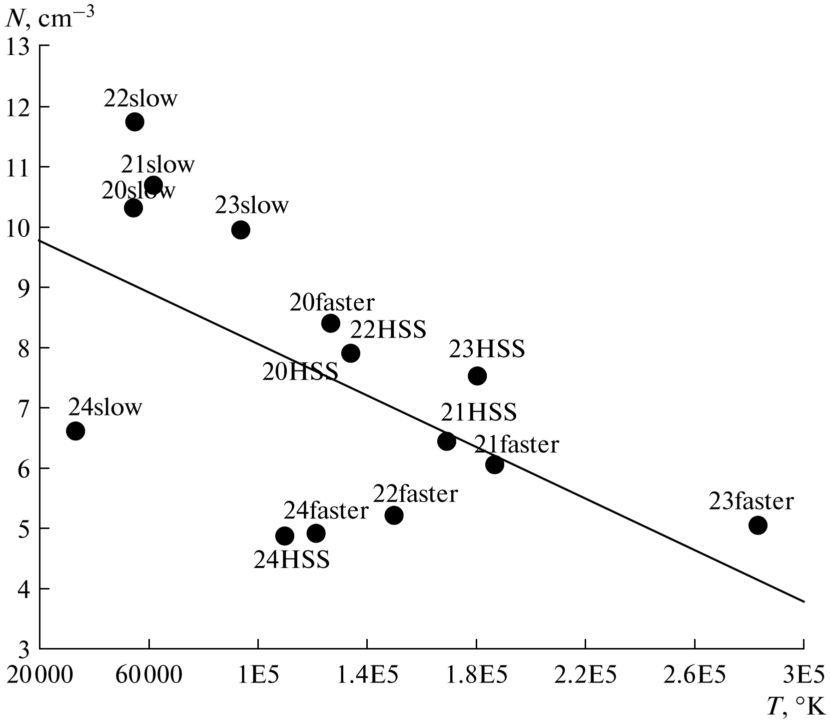

Fig. 7. Averaged temperature and density for HSS, slow and fast solar wind in the different solar cycles.

instead the internal properties of HSS, and mostly the pressure. The consistent decreasing of the pressure during the last four solar minima leads to lower averaged geomagnetic activity.

2. Another important factor causing variations in geomagnetic disturbances is the background solar wind (BSW). It was shown that BSW should be divided into two components:

—Slow BSW: this wind does not exceed 450 km/s. Its source is the heliospheric current sheet. The geomagnetic disturbances, caused by slow BSW are comparatively weak with averaged *Ap* index in interval 3–10.

—Fast BSW: this wind has speeds over 490 km/s. It is more geoeffective than the slow BSW and its averaged *Ap* index is in the interval 12–22. Fast BSW has the same properties as HSS and probably they have the same origin—coronal holes.

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