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STUDY OF AURORAL ACTIVITY THE MAIN PHASE OF MAGNETIC STORMS DURING CIR AND ICME EVENTS

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Abstract
The relationship of substorm indices with interplanetary medium parameters and magnetic storm characteristics during the main phase of magnetic storms caused by CIR and ICME events is investigated. Over the period 1990–2017, 107 magnetic storms driven by (81) CIR and (65) ICME events have been selected. Liner correlations between substorm indices and Dst variations, as well as with parameters of the interplanetary medium during the main phase of magnetic storms induced by CIR and ICME events, is analyzed.

1. Introduction
It is known that during periods of a prolonged southward Bz component of the interplanetary magnetic field (IMF) in the Earth's magnetosphere together with substorm disturbances there occur magnetic storms. The amplification of magnetospheric-ionospheric currents during magnetic storms leads to an increase the geomagnetic activity indices. The low latitude Dst index [*Burton et al.*, 1975] is used to estimate the magnetic storm intensity. The high latitude AE index characterizes the intensity of the auroral current and is an indicator of substorm activity [*Davis and Sugiura*, 1966]. Auroral activity is also assessed by the planetary (mid-latitude) Kp index [*Khorosheva*, 2007]. To take into account the spatial features of the influence of the equatorial drift of the auroral electrojet on AE and Kp during magnetic storms, we examine the SuperMAG SME index [*Newell and Gjerloev*, 2011]. The SME index is calculated using data from more than 100 geomagnetic stations, covering the range of geomagnetic latitudes from 40° to 80°. The SME index, unlike AE (Kp), allows for a more accurate assessment of the auroral electrojet intensity.

Correlation analysis of dependence between interplanetary medium parameters and geomagnetic indices activity during periods of magnetic storms showed that the southward Bz component of the IMF, whose efficiency is connected with the influence of SW electric field (Esw=V×Bz), is the main reason for the generation of geomagnetic disturbances [*Burton et al.*, 1975; *Gonzalez et al.*, 1994; *Kane*, 2010]. However, the results of recent statistical and morphological studies suggest that the development of magnetic storms and substorms differs depending on the type of the solar wind (SW) [*Gonzalez et al.*,1999; *Plotnikov and Barkova*, 2007; *Yermolaev et al.*, 2010]. The following SW types are distinguished: interplanetary coronal mass ejections (ICME) including magnetic clouds (MC) and pistons (ejecta), regions of interaction between fast and slow streams (CIR), and compression regions before ICME (Sheath). Each SW type has a specific set of SW and IMF parameters. The analysis of dependence between the geomagnetic indices and SW electric field revealed that the value of AE index during the main phase of magnetic storm does not depend on Esw or the dependency is weak ($r < 0.5$) for almost all types of SW, except MC and Sh_{MC} [*Nikolaeva et al.*, 2011]. In the event of MC a nonlinear dependence of the AE index on Esw is observed. The relation of Kp index and Esw is characterized by a linear empirical dependence for CIR events and nonmonotonic dependence for MC events [*Plotnikov and Barkova*, 2007]. In papers by *Plotnikov and Barkova* (2007), *Nikolaeva et al.* (2011), the extreme values of Dst, AE and Kp indices were compared with the minimum values of IMF Bz component and convective electric field Esw, or compared the minimum value of Dst (Dst_{min}), values of AE and Kp at the moment of approach of Dst_{min} with the values of Bz (Esw) for this moment of time. These approaches compare only individual (extreme) points during the development of process and consider the dynamics of magnetic storm generation process rather weakly. In present paper we will consider average values of auroral indices during the main phase of magnetic storm and carried out the comparative analysis with average values of interplanetary medium parameters. The average values of interplanetary medium parameters and geomagnetic activity indices allow us to estimate the development of the magnetic storm main phase as a whole. A joint analysis of auroral indices allow one to understand a picture of development of the substorm disturbances during periods of a magnetic storm more precisely.

The purpose of this work is to investigate the relationship between the substorm activity and Dst index variation during the main phase of a magnetic storm, and also their dependence on the Esw (Bz) for various types of the SW.

2. Data and Results

For the period 1990–2017, we are selected 146 magnetic storms with $Dst_{min} \leq -50$ nT, induced by CIR (81) and ICME (65) events. Other SW types that induce a magnetic storm were not considered in this paper. A magnetic storm is considered to be related to SW of a given type if the main phase and the minimum Dst coincide in time with SW of this type. The method of classifying SW types is described in detail in [*Yermolaev et al.*, 2009, 2010]. On the website (ftp.iki.rssi.ru/pub/omni/catalog) is a catalog of SW types.

For each event we calculate average values of AE ($\sum AE/\Delta T$), Kp ($\sum Kp/\Delta T$), SME ($\sum SME/\Delta T$)indices and the rate of magnetic storm development ($|\Delta Dst|/\Delta T$). The $\sum AE$, $\sum Kp$ and $\sum SME$ are summary values of geomagnetic indices during the main phase of magnetic storm. The duration of main phase (ΔT) have been determined as the temporal interval from the moment of sharp decrease of the Dst index (Dst_0) up to the minimum value of Dst (Dst_{min}). The value of $|\Delta Dst|$ has been calculated using the following formula: $|\Delta Dst| = |Dst_{min} - Dst_0|$. Hourly indices were taken on the websites (https://supermag.jhuapl.edu, http://wdc.kugi.kyotou.ac.jp/dstae/index.html). To account for the SW and IMF parameters, hourly average data (http://www.omniweb.com) is used to determine average values of the dawn-to-dusk electric field and southward Bz during the main phase of magnetic storm. Coordinate system of the SW and IMF parameters is GSM. To reveal the relationship between the geomagnetic indices and interplanetary medium parameters, we have used a linear approximation as the simplest way to establish the relationship between the values. Pearson's correlation coeffcients and their probabilities were calculated to establish statistical significance [*Bendat and Piersol*, 1971].

Fig. 1 presents the dependences of AE_{aver} and Kp_{aver} indices on the average value of SW electric feld (Esw_{aver}) for the magnetic storms induced by the CIR and ICME events. Because of the absence of data on the SW electric feld in some events, Fig. 1 presents a smaller number of events. Fig. 1 shows that geomagnetic indices (AE, Kp) linearly depend on Esw_{aver} for the magnetic storms induced by the CIR and ICME events. For the ICME events the highest correlation coefficient between Kp_{aver} and Esw_{aver} is observed (r=0.77, P=0.99).

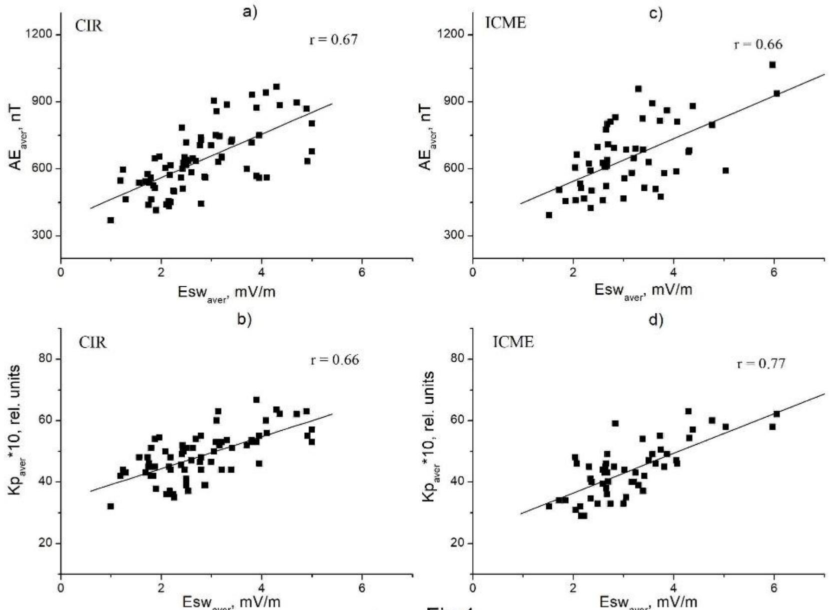

Fig.1

Figure 1. Dependence of AE_{aver}, Kp_{aver} indices on the average value of electric field of the solar wind for the storms induced by the CIR (a, b) and ICME (c, d) events: squares — separate magnetic storms; straight lines — linear approximation; r — correlation coefficient.

Fig. 2 illustrates the correlation between SME_{aver} and Esw_{aver} ($|Bz_{aver}|$) for CIR- and ICME-induced magnetic storms. Fig. 2 indicates that for SW of both types SME_{aver} increases linearly with Esw_{aver} and $|Bz_{aver}|$. There are high and close correlation coefficients between SME_{aver} and Esw_{aver} for CIR (r=0.77) and ICME (r=0.81) events, whereas the correlation coefficients between SME_{aver} and $|Bz_{aver}|$ for CIR (r=0.62) and ICME (r=0.73) are lower and markedly different (Fig. 2, b, d).

Fig.3 (a, c) shows the correlation between SME_{aver} and the rate of magnetic storm development ($|\Delta Dst|/\Delta T$) during CIR and ICME events. The relationship between SME_{aver} and $|Dst_{min}|$ is displayed in Fig. 3 (b, d). Fig. 3, a, c shows that in magnetic storm main phases during CIR and ICME events SME_{aver} increases with $|\Delta Dst|/\Delta T$. We have obtained close correlation coefficients between SMEaver and $|\Delta Dst|/\Delta T$ for CIR (r=0.5) and ICME (r=0.54) events. For CIR (r=0.67) and ICME (r=0.6) events, high correlation coefficients are also observed between SME_{aver} and $|Dst_{min}|$ (Fig. 3 (b, d)). The slope of straight lines relative to the X-axis differ slightly for CIR and ICME events.

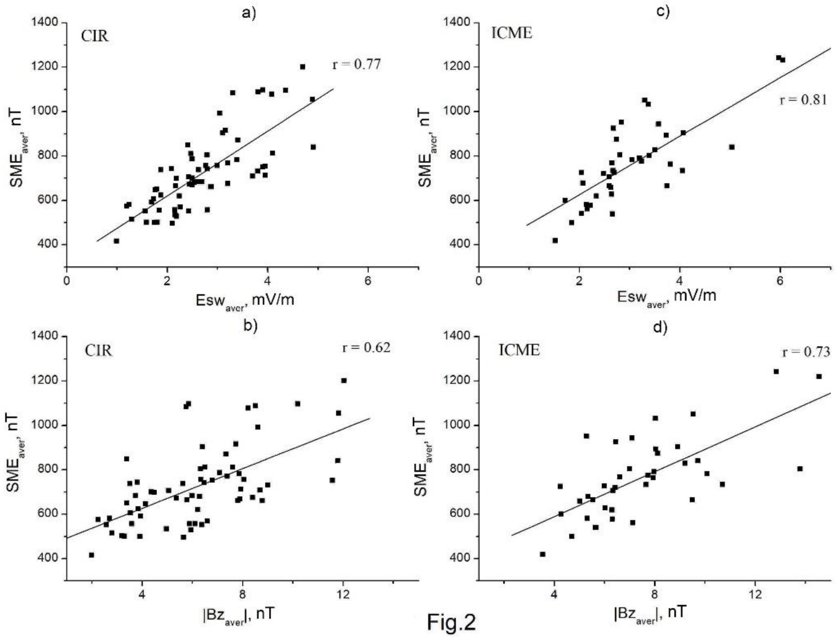

Figure 2. SME_{aver} versus the mean values of the SW electric field and the southward IMF Bz modulus during main phases of CIR- and ICME-induced magnetic storms.

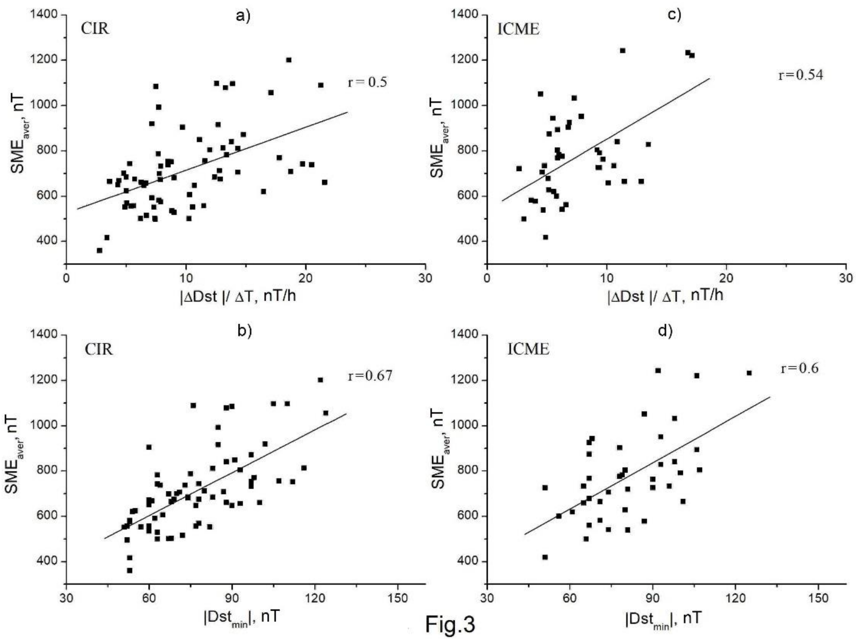

Figure 3. SMEaver versus the magnetic storm development rate and the Dst_{min} modulus during main phases of CIR- and ICME-induced magnetic storms.

3. Discussion and conclusion

The relationship of the geomagnetic indices both with the magnetic storm characteristics ($|\Delta Dst|/\Delta T$ and $|Dst_{min}|$) and SW electric field during the main phase of magnetic storms induced by the CIR and ICME events for the 1979 to 2000 period was studied. A joint analysis of geomagnetic indices (AE, Kp) allowed us to assume that the obtained correlation coefficients of the substorm indices (AE, Kp) during the main phase of magnetic storms induced by the CIR and ICME events were associated with the location of auroral currents relative to the stations by which the AE and Kp indices were constructed. We associated the shift of auroral currents with the value of southward Bz IMF during CIR and ICME events. In the CIR events, unlike the ICME ones, small values of southward Bz IMF were observed. Perhaps, a signifcant increase of the southward IMF Bz in the ICME events leads to a shift of auroral current to lower latitudes, as a result we observe a higher correlation coefficient between Kp_{aver}&Esw_{aver} (Kp_{aver}&$|Bz_{aver}|$) than in CIR events. We see a similar pattern between auroral indices (AE, Kp) and the rate of storm development ($|\Delta Dst/\Delta t$)

[*Boroyev et al.*, 2020]. It is known that the variation of the Dst index (d|Dst|/dt) during the main phase of magnetic storm is caused by the SW electric field [*Kane*, 2010; *Yermolaev et al.*, 2010; *Nikolaeva et al.*, 2014]. If we accept variations of Dst index as |ΔDst|/ΔT then in the work by *Yermolaev et al.* (2016) the rate of storm development is defined by the average value of SW electric field (Esw_{aver}), which is a modification of *Burton et al.* (1975) formula. Thus, a comparative analysis of variations of substorm indices (AE, Kp) allows us to estimate the possible location of auroral currents during periods of the main phase of magnetic storms during the CIR and ICME events. The latitude of auroral electrojets during CIR and ICME events does not affect the SME index, as opposed to the AE and Kp indices. As seen in Figure 2, b, d, there are high and close correlation coefficients between SME and during CIR (r=0.77) and ICME (r=0.81) events. The SW type has no effect on the relationship between SME_{aver} and Esw_{aver}. We see a similar pattern between SME and |ΔDst|/ΔT.

The results of the analysis lead to the following conclusions:

1. The analysis of average values of AE and Kp indices during the main phase of magnetic storm depending on the SW electric field has shown that geomagnetic indices (AE, Kp) linearly depend on Esw_{aver} for the magnetic storms induced by the CIR and ICME events. For the ICME events the highest correlation coefficient between Kp_{aver} and Esw_{aver} is observed (r=0.77).

2. It is shown that there is a strong correlation between the SME index and interplanetary medium parameters at the main phase of magnetic storms during CIR and ICME events. Unlike the AE and Kp, the close values of correlation coefficients between SME and SW electric field (southward IMF Bz) were obtained for CIR and ICME events. The relationship with the SW type (CIR/ICME) between the SME and the interplanetary medium parameters has not been found.

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