Dependence of the cross polar cap potential saturation on the type of solar wind streams

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Abstract.

We compare of the cross polar cap potential (CPCP) saturation during magnetic storms induced by various types of the solar wind drivers. By using the model of Siscoe-Hill [Hill et al., 1976; Siscoe et al., 2002a, b, 2004; Siscoe, 2011] we evaluate criteria of the CPCP saturation during the main phases of 257 magnetic storms ($Dst_{min} \leq -50$ nT) induced by the following types of the solar wind streams: magnetic clouds (MC), Ejecta, the compress region Sheath before MC ($Sh_{MC}$) and before Ejecta ($Sh_{E}$), corotating interaction regions (CIR) and indeterminate type (IND). Our analysis shows that occurrence rate of the CPCP saturation is higher for storms induced by ICME (13.2%) than for storms driven by CIR (3.5%) or by IND (3.5%). The CPCP saturation was obtained more often for storms initiated by MC (25%) than by Ejecta (2.9%); it was obtained for 8.6% of magnetic storms induced by sum of MC and Ejecta, and for 21.5% magnetic storms induced by Sheath before them (sum of $Sh_{MC}$ and $Sh_{E}$). These results allow us to conclude that occurrence rate of the CPCP saturation at the main phase of magnetic storms depends on the type of the solar wind stream.
1. Introduction

As well known the main cause of geomagnetic storms is solar wind electric field $E_y = V_x \times B_z$, where $V_x$ is radial component of solar wind velocity and $B_z$ is the southward component of interplanetary magnetic field (IMF). Solar wind includes various types of streams characterized by different behavior of strength and structure of IMF, density and velocity of solar wind, and these types of streams result in different forms of geomagnetic activity [Boudouridis et al., 2004; Borovsky and Denton, 2006; Huttunen et al., 2006; Pulkkinen et al., 2007; Yermolaev et al., 2007; Plotnikov and Barkova, 2007; Longden et al., 2008; Turner et al., 2009; Despirak et al., 2011; Nikolaeva et al., 2011; Guo et al., 2011; Yermolaev et al., 2012].

There are 5 geoeffective types/subtypes of the solar wind (SW): (1) Corotation Interaction Region (CIR), when high velocity stream of SW from coronal hole interacts with slow SW above the streamer belt; (2) Magnetic Clouds (MC), or well organized structures with enhanced IMF magnitude, large and smooth rotation of IMF vector over period $\sim 1$ day; low proton temperatures [Burlaga et al., 1981]; (3) Ejecta, with less organized structure than MC; (4) Sheath or compression region before the leading edge of MC ($Sh_{MC}$); and (5) Sheath before Ejecta ($Sh_E$) (for example, see [Yermolaev et al., 2009]).

The cross polar cap potential saturation is one of differences between CME- and CIR-induced geomagnetic storms [Borovsky and Denton, 2006]. It is known that potential across polar cap is increasing with growth of $E_y$. But sometimes its value does not change with increasing of $E_y$ (i.e. it reaches the saturation threshold) under favorable solar wind conditions often associated with strong magnetic storms [Reiff and Luhmann,
The cross polar cap potential saturation is confirmed experimentally (for example, [Nagatsuma, 2002; Shepherd et al., 2002; Hairston et al., 2003; Boudouridis et al., 2004; Hairston et al., 2005; Borovsky and Denton, 2006; Shepherd, 2007]).

Also this phenomena is agreed with MHD simulations [Raeder et al., 2001; Siscoe et al., 2002a; Merkine et al., 2003]. For an explanation of CPCP saturation it was proposed several models, although the physical mechanism is still debated [Siscoe et al., 2002a, b, 2004; Kivelson and Ridley, 2008; Lavraud and Borovsky, 2008; Borovsky et al., 2009; Gao et al., 2013].

The authors [Borovsky et al., 2009] compare several models for explanation of CPCP saturation dividing them into two types: "reconnection models" and "postreconnection models". The reconnection models explain the reduction of CPCP by reduction in the reconnection rate at the dayside of the magnetosphere, i.e., by reduction of SW-magnetosphere coupling [Hill et al., 1976; Pudovkin et al., 1985; Raeder et al., 2001; Siscoe et al., 2002a; Merkin et al., 2005a, b; Raeder and Lu, 2005; Ridley, 2005; Hernandez et al., 2007]. The postreconnection models explain decreasing of CPCP by processes occurring after the solar wind plasma reconnects with magnetosphere [Winglee et al., 2002; Siscoe et al., 2002b; Ridley, 2007; Kivelson and Ridley, 2008]. From these models the authors [Borovsky et al., 2009] choose the MHD-generator model [Kivelson and Ridley, 2008] as the best one because it agree with results of global MHD modeling.

The investigations (for example, [Lavraud and Borovsky, 2008; Siscoe, 2011] show that CPCP predicted by [Siscoe et al., 2002b] is similar one predicted by [Kivelson and Ridley,
The similarities and differences between these two models were investigated in the work [Gao et al., 2013]. The authors compare mathematical formulas and predictions of both models with data measurements. The results of the analysis show that both models predict similar saturation limits mathematically and give similar model predictions for CPCP value measured during time interval 1999–2009 [Gao et al., 2013].

Authors of the works [Siscoe et al., 2002a, b, 2004; Siscoe, 2011] on the basis of the hypothesis [Hill et al., 1976], have developed a theoretical model of coupling between the solar wind and the magnetosphere and ionosphere, which predicts the CPCP saturation. It occurs, when the region I current system generates a magnetic field which is approximately equal to dipole field at the dayside magnetopause [Hill et al., 1976; Siscoe et al., 2002a, b, 2004; Siscoe, 2011]. Authors formulated the criterion of CPCP saturation which connects transpolar potential with the value of interplanetary electric field, solar wind dynamic pressure and ionospheric conductance [Siscoe et al., 2002a, b, 2004; Siscoe, 2011].

According to numerous works [Hill et al., 1976; Balan et al., 1993; Siscoe et al., 2002a, b; Ober et al., 2003; Siscoe et al., 2004; Floyd et al., 2005; Borovsky and Denton, 2006] the saturation of the polar cap potential occurs when a saturation parameter:

\[
Q = V_a \Sigma_p / 806 = V_a F^{10.7^{1/2}} / 1050 > 2
\]  

where \(V_a\) is the Alfven velocity in the solar wind, \(\Sigma_p\) is the height-integrated Pederson conductivity of the ionosphere; according the work [Robinson and Vondrak, 1984] its value can be determined as \(\Sigma_p = 0.77 F^{10.7^{1/2}}\), where \(F^{10.7}\) is solar radio flux as proxy \(\Sigma_p\) (see details in papers by [Borovsky and Denton, 2006; Lavraud and Borovsky, 2008] and references therein).
Using OMNI2 data set authors [Borovsky and Denton, 2006] obtained that the saturation of polar cap potential (i.e. $Q > 2$) was usually observed for CME-driven storms, but rarely observed for CIR-driven magnetic storms. It should be noted that in accordance with author’s definition the CME-driven magnetic storms include all storms initiated by various interplanetary manifestations of CME: sheath, ejecta, and magnetic cloud [Borovsky and Denton, 2006]. Note that authors [Borovsky and Denton, 2006] used international sunspot number $Sn^{1/2}$ (with time resolution 1 month) as proxy $\Sigma_p$.

In contrast to previous papers we separately study magnetic storms induced by various components of CME manifestations. Also as proxy $\Sigma_p$ we used the solar radio flux $F10.7$ which correlates with $Sn$ value, but gives more real values for $\Sigma_p$ [Ober et al., 2003].

The main aim of our work is an estimation of the CPCP saturation during the main phase of magnetic storms induced by different types of the solar wind streams which include CIR, and separately types of ICME such as magnetic clouds (MC), Ejecta, and Sheath before them ($Sh_{MC}$ and $Sh_E$, respectively). Separation of Sheath-storms on 2 types $Sh_{MC}$ and $Sh_E$ is partly justified by one of the results of the work [Nikolaeva et al., 2011]. Magnetic storms induced by $Sh_{MC}$ have lower value of $Dst_{min}$ and higher value of $AE$ index.

In given work we analyze different types of magnetic storms (including their subtypes) in order to estimate what types/subtypes of SW more often lead to non-linear type of interaction with magnetosphere-ionosphere system (which manifests itself in CPCP saturation). In addition we used solar radio flux at 10.7 cm (with time resolution 1 day) as proxy $\Sigma_p$. 
2. Data

For our analysis we use OMNI data of interplanetary parameters and the "The Catalog of Large-scale Solar Wind Phenomena during 1976–2000" (site ftp://ftp.iki.rssi.ru/pub/omni/) [King and Papitashvili, 2005; Yermolaev et al., 2009]. The method of identification of different types of SW on the basis of plasma and magnetic field data is described in detail in the work [Yermolaev et al., 2009]. The technique of determination of connection between magnetic storms and their interplanetary drivers is the following. If the minimum of $Dst$ index lies in an interval of a type of solar wind streams or is observed within 1–2 hours after it we believe that the given storm has been generated by the given type of streams [Yermolaev et al., 2010].

To calculate the saturation parameter $Q$ for different drivers we select 257 magnetic storms with $Dst \leq -50$ nT and with full set of solar wind parameters needed for calculation of parameter according relation (1). The solar wind data for calculation of Alfven velocity $V_a$ and solar radio flux $F10.7^{1/2}$, which used as proxy $\Sigma_p$, were received from OMNI data base [King and Papitashvili, 2005].

The following types of the solar wind streams are sources of the magnetic storms: corotating interaction regions, CIR – 56 magnetic storms; magnetic clouds, MC – 24 magnetic storms; the compression regions ahead MC, $Sh_{MC}$ – 5 events; Ejecta – 69 events; the compression regions ahead Ejecta, $Sh_E$ – 46 events, and indeterminate type IND (the sources which are impossible to determine because of data gap) – 57 events. To compare results of this paper with previous results [Borovsky and Denton, 2006] we calculate similar parameters for sum of subtypes of ICME, magnetic clouds MC and Ejecta (MC+Ejecta).
3. Results

Figure 1 shows the distribution of 257 magnetic storms with $Dst \leq -50$ nT in dependence on type of the solar wind driver. We see that only 22% of storms driven by CIR, but 56% of all storms are driven by sum $MC + Ejecta + Sheath$ (including 36% storms driven by sum $(MC + Ejecta)$ and 20% storms driven by Sheath $(Sh_{MC} + Sh_{E})$ ahead $(MC + Ejecta)$).

The results of evaluation of saturation parameter $Q$ and corresponding solar wind parameters: Alfvén velocity $V_a$ and the solar radio flux $F_{10,7}^{1/2}$, which are included in the formula (1) for $Q$, are presented in Figure 2. In the Figure 2 the occurrence distribution of the polar cap saturation parameter $Q$ is binned according type of solar wind drivers (top panel). In the middle and bottom panels in Figure 2 the Alfvén velocity $V_a$ and solar radio flux $F_{10,7}^{1/2}$ are binned, respectively.

The following designations are used for different types of magnetic storms (in Figure 2 a, c, e): thick blue line for CIR, thin blue line for IND, solid brown line for MC, dotted brown line for $Sh_{MC}$, solid red line for Ejecta, dotted red line for $Sh_{E}$, solid purple line for sum of $MC + Ejecta$, and dotted purple line for sum $Sh_{MC} + Sh_{E}$, or Sheath. The right panels (b, d, f) in Figure 2 present the same data as in the left panels, but all magnetic storms are selected only into 3 main types of drivers as it was made in work by [Borovsky and Denton, 2006]: (1) CIR (thick grey line), (2) MC (thin black line), (i.e., CIR and MC repeat that on the left in Figure 1), and (3) ICME, which includes all of the interplanetary manifestations of CME: magnetic clouds (MC) and Ejecta, also the compression region
Sheath (i.e. sum of $MC + Ejecta + Sheath$). This type is close to CME-driven storms in paper [Borovsky and Denton, 2006] and below we compare them. The right panels (b, d, f) in Figure 2 permit to compare our results with other works.

In Table 1 there are presented average and median values of Alfven velocity $V_a$, parameter of saturation $Q$, and $F10.7^{1/2}$ (as proxy $\Sigma_p$) for different types of SW drivers. We can see that MC- and $Sh_{MC}$- storms have the highest values of $Q$, $V_a$, $F10.7^{1/2}$; while CIR-, and IND-storms have the lowest ones with factors 2, 1.7, 1.3, respectively.

Median values of $Q$ depend on type of magnetic storms and change (in 2.8-1.8 times) from maximal values 2.4 and 1.53 (for $Sh_{MC}$- and MC- storms, respectively), to minimal values of 0.91 and 0.85 (for IND- and CIR- storms, respectively). The median value $Q$ is higher for $Sh_{MC}$- storms than for MC-storms (factor 1.6). In our sample of storms the factor between median values $Q$ for MC- and CIR- storms is equal 1.8 (against 2.9, in [Borovsky and Denton, 2006]). The median value of $Q$ for CME-driven storms given by [Borovsky and Denton, 2006] is lower with factor 1.4 in comparison with $Q$ for ICME-driven storms (see Table 1 and Figure 2b). Such discrepancy may be explained by different events statistics in samples and by using $Sn^{1/2}$ as proxy $\Sigma_p$.

The median values $V_a$ are changing between maximum values 145 and 112 km/s for ShE- and MC-storms, respectively, and minimal values 70 and 78 km/s for IND-storms and CIR- and Ejecta- storms, respectively. For storms induced by (MC+Ejecta) and by compression region Sheath ($= Sh_{MC} + Sh_E$) the median values $V_a$ are very close (98.6 and 96 km/s, respectively). For storms induced by MC and $Sh_{MC}$ the factor between median values $V_a$ is 1.3. The work [Borovsky and Denton, 2006] contains the following
median values of $V_a$: 78 km/s for CIR-storms and 131 km/s for MC- storms and 95 km/s for CME- driven storms. These values are close to our results.

The highest median values of solar radio flux $F_{10.7}^{1/2} = 16$ are associated with $Sh_{MC}$-storms, the lowest values $F_{10.7}^{1/2} = 12.5$ and 12.8 have storms induced by CIR and IND (factor 1.3). The magnetic storms induced by MC+Ejecta and by Sheath have equal median values $F_{10.7}^{1/2} = 13.5$. But $Sh_{MC}$-storms have the median values $F_{10.7}^{1/2} = 16$ larger than for MC-storms $F_{10.7}^{1/2} = 13.45$ (with factor 1.2). In work [Borovsky and Denton, 2006] there are presented following median values of $S_n^{1/2}$ (used as proxy $\Sigma_p$): for CIR-storms $S_n^{1/2} = 4.8$ (relative to our median value $F_{10.7}^{1/2} = 12.5$), for MC- storms $S_n^{1/2} = 8.7$ (our median value $F_{10.7}^{1/2} = 13.4$), for CME-storms $S_n^{1/2} = 9.9$ (our median value $F_{10.7}^{1/2} = 13.55$). So the range of conductivity changing is equal 1.3 in our work (when solar radio flux $F_{10.7}^{1/2}$ as proxy $\Sigma_p$), in respect to factor 2 in work [Borovsky and Denton, 2006], in which sunspot number $S_n^{1/2}$ was used as proxy conductivity.

In Table 2 there are presented the number of magnetic storms driven by various types of SW for 3 levels of saturation parameter $Q$. It is seen that high value of saturation parameter $Q > 2$ was observed in 3.8 times more often for storms driven by ICME than by CIR and IND; also parameter $Q > 2$ is occurred in 8.6 times more often for MC- storms than for Ejecta- storms, and in 2.5 times more often for Sheath-storms than for (MC+Ejecta)- driven storms.

Some decreasing of saturation parameter $Q > 1.8$ (10% decreasing of saturation parameter) leads to an increase number of storms driven by ICME (factor 1.2), mainly due to (MC+Ejecta)-driven storms than Sheath-driven storms (factor 1.37); also it leads to increasing number of Ejecta- and CIR-storms (with factors 2 and 2.6, respectively). The
criterion \( Q > 1 \) is performed for 2/3 of all ICME- storms versus 1/3 of CIR- and IND-storms, and for almost all \( Sh_{MC} \)- and MC- storms (80%).

4. Discussion

Obtained results not only confirm the conclusions of the work [Borovsky and Denton, 2006] that the storms driven by ICME(MC+ Ejecta+ Sheath) the most often satisfy criterion of CPCP saturation, but also we obtained indications that the most often the CPCP saturation is associated with magnetic storms driven by Sheath \((Sh_{MC} + Sh_{E})\) than by (+Ejecta) (21.5% in comparison with 8.6%, respectively). The occurrence rate of CPCP saturation for Sheath-driven storms is comparable with occurrence rate of saturation for MC-driven storms (21.5% in comparison with 25%, respectively). Thus during the main phase of magnetic storms the values of saturation parameter \( Q \), Alfven velocity \( V_a \), and proxy Pederson conductivity \( \Sigma_p \sim F10^{7^{1/2}} \) change in dependence on type of SW stream with the largest difference between them for CIR-driven storms and subtypes \( Sh_{MC} \)- and MC- driven storms.

In contrast to paper by Borovsky and Denton [2006] we found saturation separately for different parts of ICME: MC and Ejecta, Sheath before MC and Ejecta.

The obtained results are not a surprise and may be explained by changing of SW parameters inside different types of SW streams which induced the magnetic storms. Also the occurrence rate of magnetic storms, induced by ICME, is higher near the maximum phase of solar activity when solar radio emission is stronger and ionospheric conductivity is higher. While the occurrence rate for CIR- driven magnetic storms is higher near the minimum phase of solar activity when solar radio emission is lower.
The $Q$ values are dependent not only on variation of $V_a$ but also on $\Sigma_p$ variation. But on average contribution of $V_a$ is greater than contribution of $\Sigma_p$ (see Table 2). On average the contribution of $V_a$ in value of saturation parameter $Q$ exceeds the contribution of the solar radio emission almost an order of magnitude (factor 7-9).

Figure 3 shows the saturation parameter $Q$ versus $V_a$ and $Q$ versus $F10.7^{1/2}$ for 4 types of SW streams CIR, MC, MC+Ejecta, Sheath($= Sh_{MC} + Sh_E$).

For all 4 types of SW the dependence of saturation parameter $Q$ on Alfvenic velocity $V_a$ is linear with high coefficients of correlation (changes between $r=0.92$ for CIR-storms and $r=0.97$ for MC-storms). Coefficient of determination equals $r^2 = 0.94$ for MC-driven storms and $r^2=0.84$ for CIR-storms, that is about 94% and 84% variations of $Q$ and $V_a$ are common for magnetic storms driven by MC and CIR, respectively. While linear dependence of the saturation parameter $Q$ on the solar radio flux $F10.7^{1/2}$ (proxy $\Sigma_p$) is weaker (coefficients of correlation change between $r=0.61$ for CIR-storms and $r=0.15$ for MC-storms). Thus only 2% and 5% of the variations in $Q$ and in $F10.7^{1/2}$ are common for MC- and MC+Ejecta- storms, respectively; and 20% and 37% of variations of both parameters are common for Sheath - and CIR- storms, respectively. The strong linear dependence of $Q$ on $V_a$ with high values of correlation coefficients during magnetic storms driven by all types of SW may be explained by more large contribution of $V_a$ in value of parameter $Q$ in comparison with ionospheric conductivity.

As it is seen in Figure 3 a necessary condition for fulfilment of saturation criteria $Q > 2$ is not only high Alfvenic velocity of SW ($V_a > 125 - 150$ km/s), that is high dayside reconnection rate, but also large ionospheric conductivity $\Sigma_p$ (range changing of solar
radio flux $F^{10.7^{1/2}} \sim 10-17$ corresponds to variation of conductivity $\Sigma_p \sim 7.7-13.1 \text{ S}$). Contribution of each of these terms in the $Q$ value depends on the type of SW stream.

We can assume that 80% of saturation can be explained by the processes external magnetosphere-ionosphere system [Ridley, 2005]. The high Alfven velocity $V_a$ means more efficient reconnection between interplanetary magnetic field at the dayside of magnetosphere. On the other hand $V_a$ connected with Mach number $Ma(\sim V/V_a)$. The dependence of $Q$ versus $Ma$ (not presented here) show that criteria of saturation ($Q > 2$) corresponds to the low values of Mach number ($< 4.5$) for all types of magnetic storms.

It should be noted that we used in our calculations the solar radio flux $F^{10.7^{1/2}}$ as proxy integrated Pederson conductivity $\Sigma_p$. The real system of field aligned currents also includes currents zone 2, but usually it not presented in MHD models (e.g., [Raeder et al., 1998]). Further investigations are required.

5. Conclusions

By using the model of Siscoe-Hill [Hill et al., 1976; Siscoe et al., 2002a, b, 2004; Siscoe, 2011] we evaluate criteria of the CPCP saturation (parameter saturation $Q = V_a F^{10.7^{1/2}/1050} > 2$) during the main phases of 257 magnetic storms ($Dst_{\min} \leq -50 \text{ nT}$) induced by the following types of the solar wind streams: corotating interaction regions, CIR – 56 magnetic storms; magnetic clouds, MC – 24 magnetic storms; the compression regions ahead MC, $Sh_{MC}$ – 5 events; Ejecta – 69 events; the compression regions ahead Ejecta, $Sh_E$ – 46 events, and indeterminate type IND (the sources which are impossible to determine because of data gap) – 57 events. Also we calculate similar parameters for sum of subtypes of ICME, magnetic clouds MC and Ejecta (MC+Ejecta).
We obtained and analyzed the occurrence distribution of saturation parameter \( Q \) values, of the Alfven velocity \( V_a \) and of solar radio flux \( F_{10.7}^{1/2} \) (as proxy height-integrated Pederson conductivity \( \Sigma_p \)) according type of solar wind drivers.

The median values of \( Q \) depend on type of magnetic storms and change in \( \sim 2.8-1.8 \) times between maximal values for \( Sh_{MC} \)- and MC- storms and minimal values for CIR-storms. The median value \( Q \) is higher in \( \sim 1.6 \) times for \( Sh_{MC} \)- storms than for MC-storms.

The median values of \( V_a \) are changing in \( 1.4-1.8 \) times between maximum values for ShE- and MC-storms and minimal values for CIR- and Ejecta- storms, respectively. For storms induced by MC and \( Sh_{MC} \) the factor between median values \( V_a \) is \( \sim 1.3 \).

The median values of solar radio flux \( F_{10.7}^{1/2} \) change in \( 1.3 \) times between maximum values for \( Sh_{MC} \)- storms and minimal values \( F_{10.7}^{1/2} \) for CIR-storms. The median values \( F_{10.7}^{1/2} \) are larger in \( \sim 1.2 \) times for \( Sh_{MC} \)- storms than for MC-storms.

Thus we obtained that during the main phase of magnetic storms the values of saturation parameter \( Q \), Alfven velocity \( V_a \), and proxy Pederson conductivity \( \Sigma_p \) change in dependence on type of SW stream with the largest difference between them for CIR-driven storms and subtypes \( Sh_{MC} \)- and MC- driven storms.

The saturation parameters \( Q \) values are dependent on variations of both parameters as Alfvenic velocity \( V_a \) as ionospheric conductivity \( \Sigma_p \). But on average the contribution of \( V_a \) in value of saturation parameter \( Q \) exceeds in \( \sim 7-9 \) times the contribution of \( \Sigma_p \) variation of the solar radio emission \( F_{10.7}^{1/2}(\sim \Sigma_p) \).
Our analysis allows us to make following main conclusions.

1) On the main phase of magnetic storms the CPCP saturation depends on type of the solar wind stream induced the magnetic storm.

2) The saturation criterion \((Q > 2)\) of the CPCP is performing mainly for strong magnetic storms initiated by ICME(MC+Ejecta+Sheath) \((13.2\% \text{ storms})\), and in \(\sim 3.5\) times rarely for CIR- and IND- storms \((3.5\%)\).

3) Most often saturation criterion \((Q > 2)\) of cross polar cap potential is satisfied for storms driven by MC \((25\%)\) than by Ejecta \((2.9\%)\);

4) The saturation \((Q > 2)\) of cross polar cap potential in 2.5 times more often is satisfied for Sheath- storms \((21.5\%)\) than for storms driven by sum of MC+Ejecta \((8.6\%)\);

5) Decreasing of saturation level on 10\% \((Q > 1.8)\) increases the number of ICME-storms with the CPCP saturation to 20\% (by 40\% due to storms driven by sum of MC+Ejecta and by 9\% due to storms driven by Sheath).

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Figure 1. The distribution of magnetic storms with $Dst \leq -50$ nT in dependence on type of the solar wind driver (in %).

Table 1. Average and median values of $Va$, $Q$, $F10.7^{1/2}$ for magnetic storms induced by different types of SW.

| Type of SW                  | Number of storms | $Va$ Average | $Va$ Median | $F10.7^{1/2}$ Average | $F10.7^{1/2}$ Median | $Q$ Average | $Q$ Median |
|-----------------------------|------------------|--------------|-------------|------------------------|----------------------|-------------|------------|
| MC                          | 24               | 134.9        | 112         | 12.98                  | 13.45                | 1.65        | 1.53       |
| CIR                         | 56               | 84.2         | 78          | 12                     | 12.5                 | 0.98        | 0.85       |
| Ejecta                      | 69               | 85.8         | 78          | 13.18                  | 13.56                | 1.08        | 0.96       |
| $Sh_E$                      | 46               | 99.7         | 95          | 13.1                   | 13.5                 | 1.2         | 1.2        |
| $Sh_{MC}$                   | 5                | 140.7        | 145         | 15.6                   | 16                   | 2.12        | 2.4        |
| Sheath ($Sh_{MC} + Sh_E$)   | 51               | 104.7        | 96          | 13.3                   | 13.5                 | 1.33        | 1.2        |
| MC+Ejecta                   | 93               | 98.5         | 98.5        | 13.1                   | 13.5                 | 1.2         | 1.2        |
| IND                         | 57               | 76.4         | 70          | 12.8                   | 13.5                 | 0.94        | 0.91       |
| ICME (MC+Ejecta+Sheath)     | 144              | 100.3        | 93.5        | 13.2                   | 13.55                | 1.26        | 1.2        |

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Figure 2. Distributions of $Q$, $V_a$, $F_{10.7}^{1/2}$ for different types/subtypes of SW drivers. Panels (b, d, f) give the same distributions only for 3 types of SW drivers: CIR, MC, and ICME (=MC + Ejecta + Sheath).

Table 2. The number of magnetic storms driven by various types of SW for 3 levels of saturation parameter $Q$.

| Type of SW          | Number of storms | $N$ with $Q > 2$ (%) | $N$ with $Q > 1.8$ (%) | $N$ with $Q > 1$ (%) |
|---------------------|-------------------|----------------------|------------------------|----------------------|
| MC                  | 24                | 6 (25%)              | 7 (29%)                | 20 (83%)             |
| CIR                 | 56                | 2 (3.5%)             | 5 (9%)                 | 21 (37.5%)           |
| Ejecta              | 69                | 2 (2.9%)             | 4 (5.8%)               | 32 (46.4%)           |
| $S_{HE}$            | 46                | 7 (15%)              | 8 (17.4%)              | 27 (58.7%)           |
| $Sh_{MC}$           | 5                 | 4 (80%)              | 4 (80%)                | 4 (80%)              |
| Sheath ($Sh_{MC} + Sh_{E}$) | 51            | 11 (21.5%)           | 12 (23.5%)             | 31 (61%)             |
| MC+Ejecta           | 93                | 8 (8.6%)             | 11 (11.8%)             | 52 (56%)             |
| IND                 | 57                | 2 (3.5%)             | 2 (3.5%)               | 19 (33%)             |
| ICME (MC+Ejecta+Sheath) | 144          | 19 (13.2%)           | 23 (16%)               | 83 (57.6%)           |
Figure 3. A saturation parameter $Q$ versus $V_a$ (c, d, i, j) and $Q$ versus $F_{10.7}^{1/2}$ (a, b, e, f) for 4 types of magnetic storms induced by SW streams: MC (a, c), CIR (b, d), sum of (MC+Ejecta) (e, i), and Sheath ($Sh_{MC} + Sh_E$) before (MC+Ejecta) (f, j).