# Interplanetary conditions leading to superintense geomagnetic storms (Dst $\leq -250$ nT) during solar cycle 23

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[1] The interplanetary causes of superintense geomagnetic storms (superstorms, Dst $\leq -250$ nT) that occurred during solar cycle 23 are studied. Eleven superstorms occurred during the cycle, five close to solar maximum (2000–2001) and six in the post-maximum/declining phase (2003–2004). About 1/3 of the superstorms were caused by magnetic clouds (MCs), 1/3 by a combination of sheath and MC fields, and 1/3 by sheath fields alone. The interplanetary parameter best correlated with peak Dst was the time-integrated $E_y$ during the storm main phase (in contrast with peak $B_s$ and/or peak $E_y$ for less intense geomagnetic storms). The range of peak Dst for these storms was −263 to −422 nT. The storm main phase durations had a range of 3–33 h. We conclude from this study that: (1) only MCs and/or interplanetary sheaths had fields intense enough and with long enough durations to cause superstorms; (2) superstorms occurred only in the maximum and declining phases; (3) the total energy transferred from the solar wind to the magnetosphere is best correlated with the time-integrated solar wind Ey parameter. **Citation:** Echer, E., W. D. Gonzalez, and B. T. Tsurutani (2008), Interplanetary conditions leading to superintense geomagnetic storms (Dst $\leq$ −250 nT) during solar cycle 23, *Geophys. Res. Lett.*, *35*, L06S03, doi:10.1029/2007GL031755.

## 1. Introduction

[2] Geomagnetic storms are large disturbances in the Earth's magnetosphere, usually measured through the ring current *Dst* index [*Sugiura*, 1964; *Gonzalez et al.*, 1994], and produced by enhanced solar wind-magnetosphere energy coupling through the magnetic reconnection mechanism [*Dungey*, 1961; *Gonzalez et al.*, 1994]. Intense geomagnetic storms are defined when the peak value of this index reaches −100 nT, while extreme storms (also called great magnetic storms or superstorms), are usually defined when *Dst* reaches values of −250 nT [*Tsurutani et al.*, 1992; *Gonzalez et al.*, 2002]. These very intense events can occur in any part of the solar cycle and have dramatic consequences for space weather. The largest storm so far was the historical flare/storm event reported by Carrington in 1859, with an estimated *Dst* of −1760 nT [*Tsurutani et al.*, 2003]. In this paper, the interplanetary causes of the 11 superstorms which occurred during solar cycle 23 are studied in detail. The relationship between the storm peak *Dst* and the peak values of the interplanetary magnetic field (IMF), $B_z$ southward ($B_s$) component and dawn-dusk electric field ($E_y$) are also examined, based on the magnetic reconnection mechanism [*Dungey*, 1961; *Akasofu*, 1981] and on Burton's energy conservation equation [*Burton et al.*, 1975]. The superstorm properties will be compared with those for lower intensity storms.

## 2. Method of Analysis

[3] For this paper we have used the *Dst* index [*Sugiura*, 1964] published by the World Data Center for Geomagnetism, Kyoto (http://swdcdb.kugi.kyoto-u.ac.jp/) and the interplanetary data observed by ACE [*Stone et al.*, 1998]. We have used ACE high resolution plasma and magnetic field data (64 s) to identify the interplanetary causes of the magnetic storms. Further we have used 1-hour *Dst*, *Vsw*, *B*, $B_z$ and $E_y$ data (OMNIdatabase) to determine the magnetic storm parameters: peak $B_s$ and peak $E_y$ that precede peak *Dst*, and the integrated $E_y$ value during the storm main phase. The storm main phase was considered from the time when *Dst* starts to decrease to the peak negative *Dst*. Only periods with positive $E_y$ were taken into account to calculate the integrals. For the November 2001 and October 2003 events, we used the reprocessed plasma data presented by *Skoug et al.* [2004], *Tsurutani et al.* [2004], and *Mannucci et al.* [2005].

[4] In this paper, only interplanetary structures that contributed to a storm main phase development are noted. Thus, cases when a combination of structures leads to a more complex storm recovery phase are not considered as causes of the geomagnetic storm itself. In the "Sh + MC" category, both structures contribute to the storm main phase development, but the dominant role changed from storm to storm. We have excluded from this category the cases when a sheath field leads to a small *Dst* increase followed to a recovery to low/positive values and then the MC field drives the storm main phase.

[5] Eleven superstorms (*Dst* $\leq -250$ nT) during solar cycle 23 have been identified and studied. Table 1 presents these storms and their geomagnetic and interplanetary parameters. For the identification of the interplanetary causes, the nomenclature and definitions and references cited above are followed. See also a companion paper by *Gonzalez et al.* [2007].

## 3. Results

[6] Table 1 presents the geomagnetic and interplanetary parameters for the 11 super-intense magnetic storms of solar cycle 23. In Table 1 we present the time, date and value of the peak *Dst*, the storm main phase duration, the peak

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**Table 1.** Geomagnetic and Interplanetary Parameters of Superstorms of Solar Cycle 23

| Time UT, Kyoto; Date, mm/dd/yy | $Dst_p$, nT | tm, h | $Bs_p$, nT | $B_p$, nT | $Vsw_p$, km/s | $Ey_p$, mV.m$^{-1}$ | $\int$Eydt, mV.m$^{-1}$.h | IP Structure |
|---|---|---|---|---|---|---|---|---|
| 01:00 04/07/2000 | −287 | 6 | 27 | 31 | 589 | 16 | 76 | SH |
| 01:00 07/16/2000 | −301 | 10 | 49 | 52 | 1040 | 51 | - | MC |
| 09:00 03/31/2001 | −387 | 5 | 45 | 47 | 716 | 31 | 99 | SH + MC |
| 00:00 04/12/2001 | −271 | 8 | 20 | 34 | 732 | 15 | 92 | SH + MC |
| 07:00 11/06/2001 | −292 | 12 | 64 | 66 | 750 | 45 | 130 | SH |
| 01:00 10/30/2003 | −353 | 33 | 26 | 47 | 1300 | 27 | 154 | SH + MC |
| 23:00 10/30/2003 | −383 | 18 | 27 | 38 | 1200 | 27 | 91 | SH |
| 21:00 11/20/2003 | −422 | 17 | 51 | 56 | 703 | 31 | 197 | MC |
| 07:00 11/08/2004 | −373 | 11 | 45 | 48 | 730 | 29 | 200 | MC |
| 10:00 11/10/2004 | −289 | 23 | 25 | 41 | 809 | 18 | 120 | SH + MC |
| 09:00 05/15/2005 | −263 | 3 | 38 | 54 | 895 | 34 | 65 | MC |

values of IMF $B_s$, IMF magnitude $B$, solar wind speed $Vsw$, the interplanetary y-component electric field $E_y$, and the integrated $E_y$ during the storm main phase. Storm peak $Dst$ values vary from −263 to −422 nT. Five storms have peak $Dst > -300$ nT, and only the November 20, 2003 has peak $Dst < -400$ nT. It is noted that the largest storms in this cycle were weaker than the bigger storms observed in other cycles (for solar cycle 22, the March 14, 1989 superstorm was $Dst = -589$ nT). The storm main phase duration varied from 3 h for the 15 May 2005 storm to 33 h for the October 29–30 2003 storm. Figure 1 shows the 1-h $Dst$ indices for these 11 storms. The "double" storms of October 29–30 and 30 2003 and November 8–9 and 9–10 2004 are marked in the same plot as "1" and "2".

[7] From Figure 1 the reader can note that some storms have a simple, single step main phases, such as those during April 07 2000, July 16 2000, March 31 2001, April 11 2001, the second storm on October 30 2003, November 20 2003 and May 15 2005. The storms that occurred on October 29–30 2003 and November 8–9 and 9–10 2004 have a 2–3 step main phases. The dual superstorms of October 29–30 and 30, 2003 were caused by two ICME events [*Mannucci et al.*, 2005] which were in turn associated with two major solar flares [*Tsurutani et al.*, 2006]. From Mannucci et al., the first storm was caused by a combination of sheath + magnetic cloud fields and the second event shock compression of slow speed cloud material (see also discussion by *Skoug et al.* [2004] and *Farrugia et al.* [2006]).

[8] The interplanetary peak $B_s$ values varied from 20.5 nT to 64.0 nT. Five storms had peak $B_s < 30$ nT, four had peak between 30–50 nT and two had peak $Bs > 50$ nT. The peak $E_y$ varied from 15 to 51 mV/m. We notice that these values for all 11 superstorm events are well above the empirical $E_y$ criteria of $B_s$ fields >10 nT ($E_y > 5$ mV.m$^{-1}$) during 3 hours identified by *Gonzalez and Tsurutani* [1987] for major (Dst < −100 nT) storms. The integrated $E_y$ values were computed for the eleven storms and it varied from 65–200 mV/m-h.

[9] Figure 2 shows the interplanetary and $Dst$ data for the largest geomagnetic storm of solar cycle 23, the event during November 20 2003 [*Gopalswamy et al.*, 2005; *Huttunen et al.*, 2005; *Gonzalez et al.*, 2007]. This storm was caused by $B_s$ magnetic fields in a Y- type magnetic cloud, e.g., a magnetic cloud that has a preferential rotation in the $B_y$ component, with the $B_z$ component remaining southward, in this case. An interplanetary shock, marked by dotted lines, was observed at the ACE location at ~0730 on November 20 2003. The IMF $B$ magnitude jumped from ~8 to ~20 nT, the density and velocity from ~6 to ~20 cm$^{-3}$ and from ~440 to ~610 km/s, respectively. The

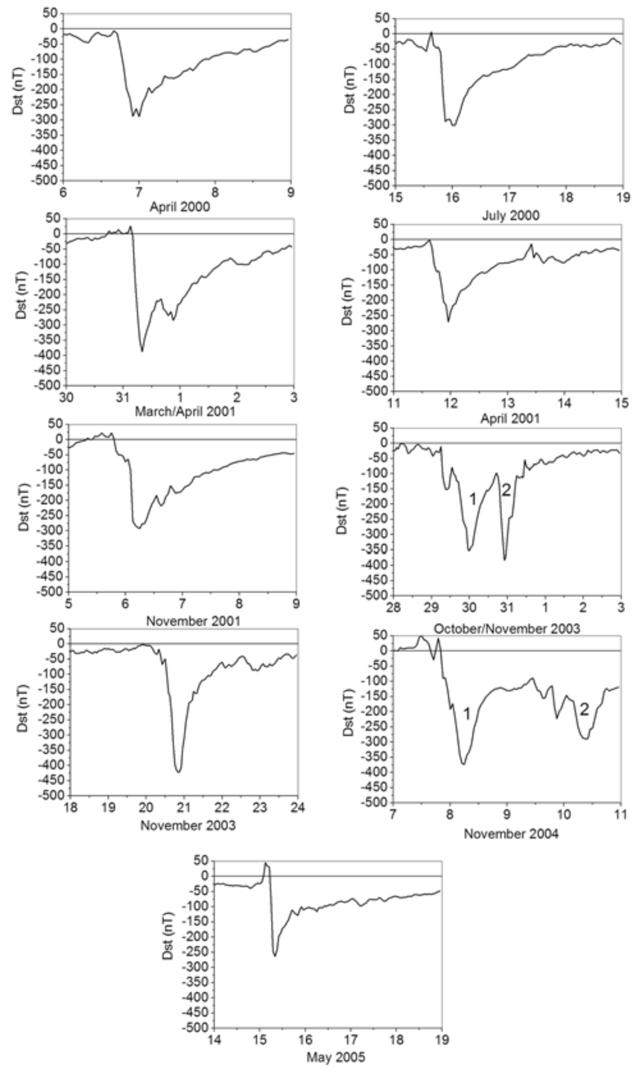


**Figure 1.** Dst index profile for the 11 superstorms that occurred during the solar cycle 23. The "double" superstorms of October 2003 and November 2004 are marked with 1 and 2.

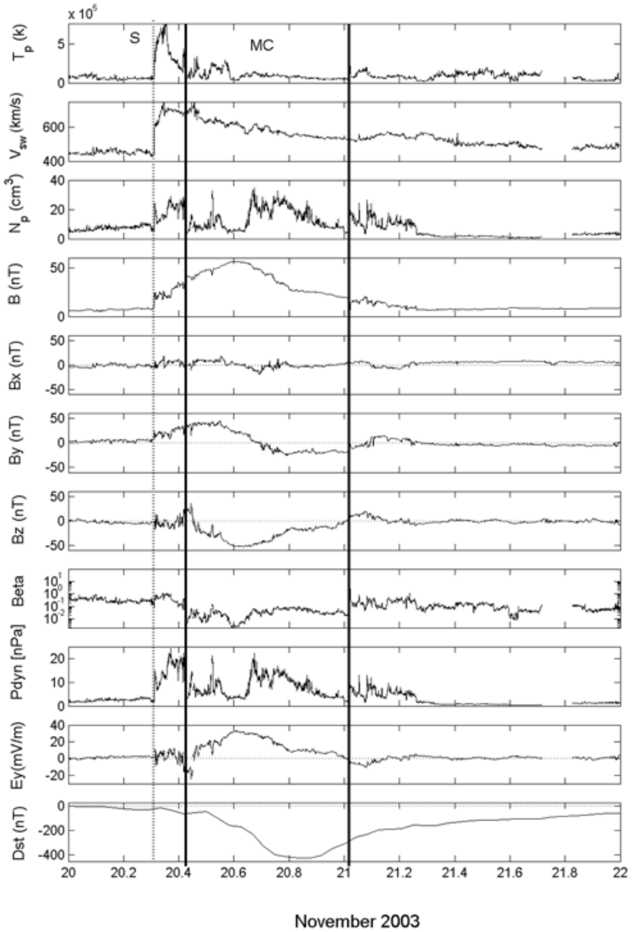


**Figure 2.** ACE solar wind and Dst index for the largest geomagnetic storm of the solar cycle 23 $Dst_p = -422$ nT, 20 November 2003. Panels are solar wind proton temperature (Tp), solar wind speed (Vsw), proton density (Np), magnetic field magnitude (B), and components (Bx, By, Bz) in GSM, plasma beta parameter (beta), dynamic pressure (Pdyn), dawn-dusk electric field component (Ey), and Dst index.

IMF $B_z$ after the shock was highly fluctuating, predominantly northward, with a short duration $B_s$ fields that did not lead to the storm development. Later, a MC with a $B_y$ rotation is observed, from ~1100 of November 20 to ~0000 November 21. The magnetic field inside the MC was very intense, with peak $B$ magnitude of 56 nT and peak $B_s$ of 51 nT. The solar source of this MC was a fast and wide halo CME studied by *Gopalswamy et al.* [2005].

[10] Figure 3 shows the correlation between peak *Dst* and peak *Vsw*, $B$, $B_s$, $E_y$ and integrated $E_y$ along the main phase. The correlation with peak $B_s$ and $E_y$ is low (r = 0.23) and is much lower with *Vsw and B* (r = 0.13–0.14). The highest correlation is found with integrated $E_y$ (r = 0.623). The *Dst*-$B_s$ and *Dst*-$E_y$ peak scatter plot shows a large dispersion, with two separated cluster of points for storms with $Dst < -300$ and $Dst > -300$ nT. However, the statistics are too low to assess if this separation is indeed real, e.g., there is some change in dynamics of solar wind-magnetosphere energy coupling at $Dst \sim -300$ nT. This of course may be just an artifact of the low sampling.

## 4. Discussion

[11] We have found that around 1/3 (4 of 11) of the superstorms are caused by MC fields, 1/3 (4 of 11) by a combination of sheath + MC fields and 1/3 (3 of 11) by sheath fields. Thus, all superstorms occurring in cycle 23 were caused by sheath and/or MC fields. There were no cases of a superstorm caused by a corotating interaction region (CIR) or heliospheric current sheet (HCS) fields.

[12] *Tsurutani et al.* [1992] have studied the five greatest storms in the period 1971–1986 and they found that 2 (40%) were caused by MCs and 3 (60%) by shock compression/field draping effects. Thus the proportion of superstorms caused only by MC and by SH/MC is the same in both studies, despite the low statistical numbers in this previous study. Further, these two studies in different solar cycles enable us to conclude that only MC and sheath fields seems to be important causes for the development of superstorms.

[13] All superstorms have a much lower peak *Dst* and longer main phase duration than the extreme storm of 1–2 September 1859 with an estimated *Dst* o f −1760 nT [*Tsurutani et al.*, 2003]. Thus, we still do not have interplanetary observations associated with the more extreme events in the solar-terrestrial environment. Nevertheless, the results here obtained can give us reasonable ideas about the

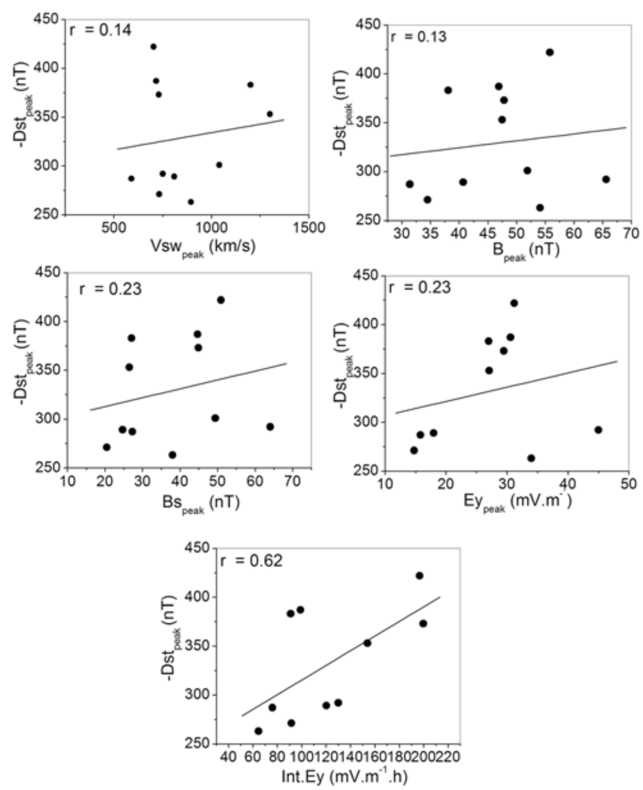


**Figure 3.** Correlations between peak Dst, and peak Vsw, B, Bs and Ey, and integrated Ey during the storm main phase.

interplanetary origins and conditions that lead to more typical superstorms.

[14] Considering intense storms ($Dst < -100$ nT) *Gonzalez et al.* [2007] have observed that four classes of IP structures, MCs (24%), sheath fields (24%), sh + MC fields (14%) and corotating interaction regions/streams CIRs (13%) are responsible for most of the storms. However, as shown here for superstorm intensity levels ($Dst < -250$ nT), only MC and sheath fields are important. *Echer and Gonzalez* [2004] have observed that the combination of two or more IP structures (called a compound structure) is more geoeffective (a larger number of them are followed by higher values of *Dst*) than simple structures, for geomagnetic storms with Dst < −100 nT. For superstorms, the combination of two structures (sh + MC and complex) is responsible for ~1/3 of the superstorms, against ~2/3 caused by only sheath or MC fields. Thus for superstorms it appears that there is a higher probability of single structures causing the events.

[15] *Gonzalez and Echer* [2005] have studied storms with $Dst < -85$ nT during the period 1997–2002. They have observed a better correlation of peak *Dst* with peak $B_s$ and $E_y$ than with integrated $E_y$ values. This is in contrast with the results obtained in this study, which implies that, for the superstorm category, the integrated energy rather than the instantaneous power transmitted to the magnetosphere is more important in energizing the ring current. For storms with $-85$ nT > $Dst$ > $-150$ nT, they obtained an average integral xx $E_y$ during the main phase of 34.3 mV.m$^{-1}$.h. The values obtained for superintense magnetic storms, are at least double this value. The average main phase duration for that set of storms was ~10 h, which is similar to that observed for the superstorms class (~11 h). The integrated $E_y$ values for superstorms are also larger than the average values for different classes of IP structures for a variation (not the peak) of 100 nT in *Dst* ($\Delta$Dst = 100 nT), determined by *Vieira et al.* [2004]. For instance, those authors have found an integral of 12x mV.m$^{-1}$.h and 14x–69x mV.m$^{-1}$.h for sheath and MC caused storms, respectively. The superstorms caused by MC and sheath fields, showed in Table 1, present values of ~76 and 64–199 mV/m-h, respectively.

[16] *De Lucas et al.* [2007] have studied the integrated energy during intense and superstorms for the period 1981–2004. They found larger integrated values of $E_y$ for superintense storms, but without a clear separation for the two storm classes, e.g., the electric field distribution was continuous. For intense storms, they have observed a range of integrated $E_y$ values of 23–125 mV.m$^{-1}$.h with on average of 59 mV.m$^{-1}$.h, while for the superstorms studied in this paper the range is 65–200 mV.m$^{-1}$.h and the average is 122 mV.m$^{-1}$.h, namely about twice the integrated *Ey* for intense storms.

[17] We note that for Dst < −100 nT major storms, GT(1987) found a common interplanetary condition of Bs > 10 nT (Ey > 5 mV/m) for T > 3 hrs. For the superstorms (Dst < −250 nT) studied here, the interplanetary conditions were Bs > 15 nT (Ey > 7.5 mV/m) with T > 2 hrs. For slightly more intense storms (Dst < −280 nT), the interplanetary conditions were Bs > 20 nT (Ey > 10 mV/m) for T > 3 hrs.

[18] One explanation for the integrated Bs and Dst correlation could be obtained from the Burton's model. In the energy balance equation, $\frac{dDst}{dt} = Q - \frac{Dst}{\tau}$, where $Q$ and $\tau$ are the energy input and the ring current decay time constant. For a simple case the energy function is represented by $E_y$, $Q \sim VB_S \sim E_y$. For the peak *Dst*, $dDst/dt = 0$ and $Dst_p \sim \tau E_y$. Thus it is observed for intense storms a linear relation between peak *Dst* and $E_y$. On the other hand, for superstorms, if one assumes that the term $Q$ in Burton's equation is much higher than the second term, e. g., the energy injection is much higher than the energy dissipation during the main phase, then $Dst = \int Qdt$, and $Dst_p \sim \int Eydt$. This might explain the better relation of peak *Dst* with the integral of the electric field during superstorms.

[19] It is interesting to try to assess the ring current dynamics during superstorms. In a work in preparation, the ring current asymmetry for 15 superstorms ($Dst \leq -250$ nT), for the period 1981–2004, was investigated using middle latitude geomagnetic observatories [*Echer and Gonzalez*, 2007]. It was found that most superstorms presented peak *dH* (disturbance in the −H component of the geomagnetic field) at 18–19 h LT, in the dusk sector. Further, the degree of asymmetry in the ring-current during intense and superintense geomagnetic storms was compared. This comparison is made by using the peak values of 1-min ASY-H and SYM-H indices. By comparison, a set of 15 intense ($-250 < \text{Dst} \leq -100$ nT) magnetic storms, studied by *De Lucas et al.* [2007] is used. The average (median) of the ASY/SYM ratio is 1.21 ± 0.37 (1.15) for intense storms and 1.41 ± 0.45 (1.29) for superstorms, which indicates a higher degree of asymmetry for superstorms.

[20] As it has been shown, all superstorms during solar cycle 23 have been caused by fast ICMEs (all had upstream shocks with sheaths). The superstorms can be caused by either the southward magnetic fields within the MC driving the shock/sheath, the southward fields within the sheath itself, or by both regions [see *Tsurutani et al.*, 1988]. The possibility that sheath fields will cause a superstorm depends on the strength (compression ratio) of the shock, the upstream magnetic field strength, and perhaps most importantly, the direction of the upstream fields (shock compression mechanism) and draping effects. For southward upstream magnetic fields, shock compression will intensify these fields by approximately the Mach number (up to a value of 4.0). During the post-maximum/declining phase of the solar cycle, where there are large active regions (during 2003 to 2005), there are multiple flarings and thus multiple ICMEs. Multiple shock compression of sheath plasma can lead to extreme field intensities [*Tsurutani et al.*, 2008]. However it was pointed out in the latter paper that for one event (November 08 2004), the upstream field was northward directed, so a superstorm did not result from the shock fields, but it was caused by the MC fields as discussed in this paper.

[21] In terms of space weather forecasting, we note that superstorms do not occur only near solar maximum, but equally in the declining phase. From other solar cycles, we have information that superstorms can occur even at solar minimum [*Tsurutani et al.*, 1992]. But from this study we have observed that only sheaths and MCs are geoeffective for superstorm occurrence and that the integrated electric field is the most important parameter. Thus for space

weather prediction of extreme events, constant monitoring of the solar corona and interplanetary space will be necessary. Other important advances would be a theoretical/empirical connection between the total energy stored in coronal fields before the solar eruption and the total energy carried by the solar wind to the Earth's orbit.

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