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# Search of possible correlations between the strength of geomagnetic storms and interplanetary magnetic field measurements

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# Search of possible correlations between the strength of Geomagnetic Storms and Interplanetary Magnetic Field measurements

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ABSTRACT

*In the work presented here we performed a statistical analysis of possible correlation between the strength of geomagnetic storms on Earth and the corresponding evolution of interplanetary magnetic field. To perform this task, we analysed the evolution of Dst index and the corresponding evolution of the interplanetary field strength between 1998 and 2012, during all major storms (defined as those with Dst < -50 nT) occurred in this time interval. Results show the existence of a quite strong anti-correlation (coefficient $C_{cor}$ = -0.61 ± 0.06) between the minimum values of the Dst index ($Dst_{min}$) attained during the storms, and the maximum values of the interplanetary magnetic field in 24h time intervals centred on the storms. Moderately strong correlations are also observed between $Dst_{min}$ and the average interplanetary magnetic field $B_{avg}$ ($C_{cor}$ = -0.55 ± 0.14), and between $Dst_{min}$ and the variance of the field $B_{sig}$ ($C_{cor}$ = -0.56 ± 0.11). On average, the maximum value of interplanetary magnetic field is reached 3.0 hours before the minimum value of Dst on Earth. A full list of considered geomagnetic storms is provided in the Appendix.*

*Results presented here have been obtained after a 2-months student mobility period for traineeship under ERASMUS Program.*

## 1. INTRODUCTION

The Sun is a continuous source of plasma (mostly protons, electrons, and alpha particles) expanding in the whole interplanetary space and creating the heliosphere. This plasma is ejected in a superposition between stationary processes – leading to the solar wind flow – and sporadic processes – leading to solar eruptions (flares, erupting prominences, Coronal Mass Ejections – CMEs). The interaction between plasmas expelled from the Sun and the magnetic fields surrounding the Earth creates the magnetosphere: this is the natural shield that prevent most of the energetic particles (of solar and other origins) to penetrate the inner magnetosphere and interact with the higher layers of the Earth's atmosphere creating (with a chain of nuclear reactions) the so-called "air showers" of particles, that could endanger any form of life living on the planet.

Nevertheless, in the most extreme cases, fluxes of Solar Energetic Particles (SEPs) being accelerated in solar flares and/or during CME early acceleration phases can penetrate the Earth's magnetosphere resulting in dangerous populations of high-energy particles, that could endanger astronauts, spacecraft and satellites, result in enhanced particle shower, and generate ionospheric disturbances. A few days after the flare, an interplanetary shock wave and the associated Interplanetary CME may impact the Earth's magnetosphere, generating a sequence of events that finally result in a global disturbance of the geomagnetic field, called "geomagnetic storm". All these effects (and many other effects; see Fig. 1) are being studied over the last 20 years by many scientists working on a broad discipline called "Space Weather".

Strengths of geomagnetic storms are measured with many different geomagnetic indices, and one of the most important ones is the so-called "*Dst*-index" (from "disturbance storm time"), which is mostly representative of the intensity of ring currents formed around the Earth during the storm. In quiet conditions the value of *Dst* is around zero (because *Dst* measures the deviation of the geomagnetic field from quiet conditions); then

usually the geomagnetic storm is classified as “moderate” or “intense” for *Dst* values being < -50 nT and < -100 nT, respectively.

Unfortunately forecasting of geomagnetic storms is at present not possible, but very important information are provided by spacecraft in orbit around the Sun-Earth Lagrangian point L1, located between the Sun and the Earth approximately at $1.5 \cdot 10^6$ km from the Earth. From this vantage point many spacecraft are monitoring in situ the interplanetary space conditions, and data acquired in L1 can be used to provide short-term alerts, considering that a solar plasma disturbance traveling at ~1000 km/s takes approximately 40 minutes to cover the distance between L1 and the nose of the Earth’s magnetosphere.

For all the above reasons, in this work we analysed the evolution of the interplanetary magnetic fields measured during geomagnetic storms, looking for possible correlations between different properties of the interplanetary field and the strength of the resulting storm. To search similar correlations is very important, not only to improve our understanding of physical processes responsible for the storms, but also to forecast future storms based on the interplanetary in situ data measured in L1.

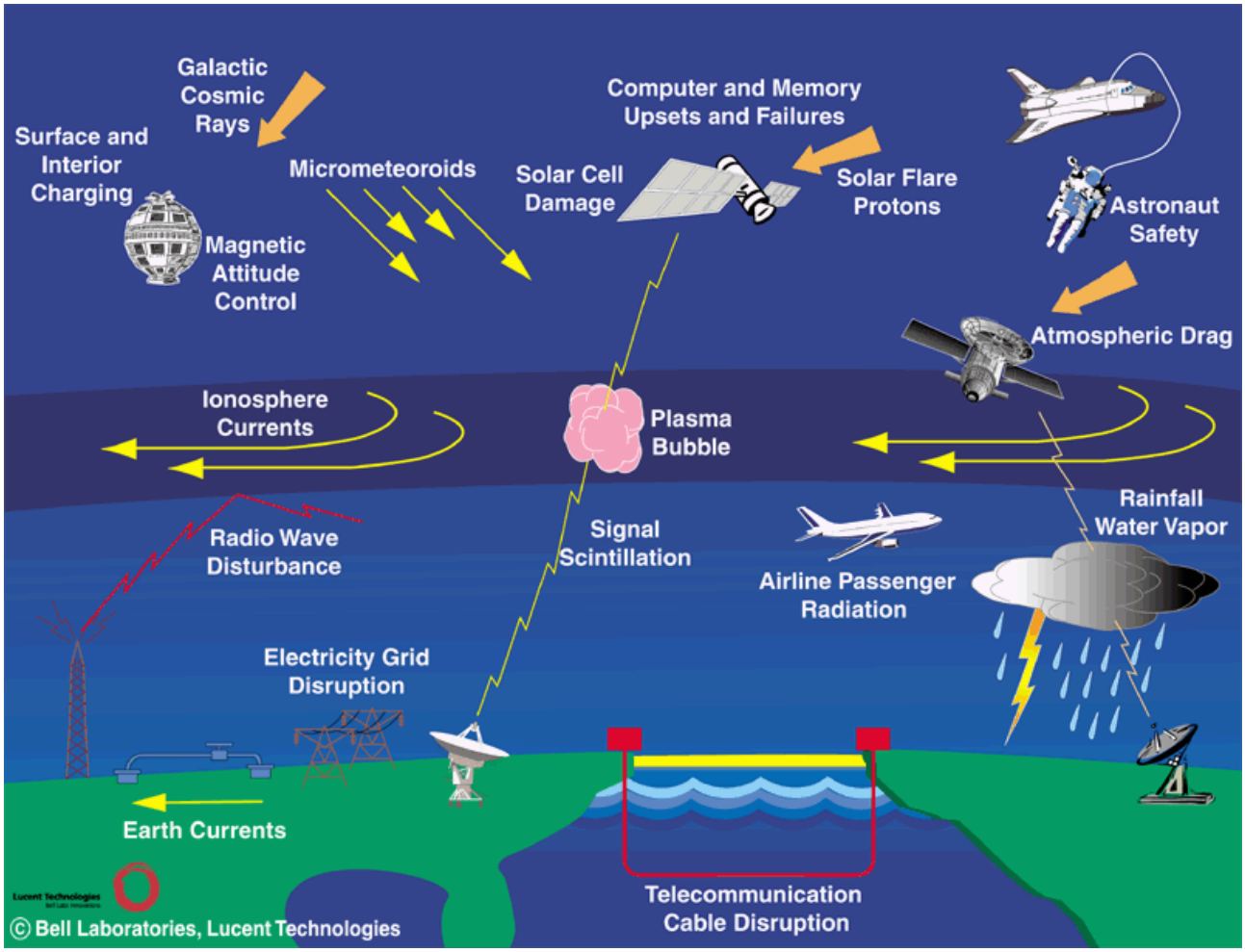


Figure 1: list of possible effects on Earth of major geomagnetic storms (Spacegrant.montana.edu/msiproject/spaceweather)

Previous authors (e.g. Kim et al., 2005; Gonzalez & Echer 2005) found for instance a quite good correlation between the maximum value of $|Dst|$ and the average value $B_z$ of the $z$-component of interplanetary magnetic field (the field vector component perpendicular to the ecliptic plane), as it is shown in Fig. 2. The usual interpretation for this correlation is that when the interplanetary field has a significant component $B_z < 0$ this enhance the probability of magnetic reconnection between the interplanetary and magnetospheric fields, thus increasing the magnetospheric convection process and allowing part of the disturbed plasma to penetrate the magnetosphere. Correlations between *Dst* index values and CME properties have been studied as well (e.g. Kim et al. 2010).

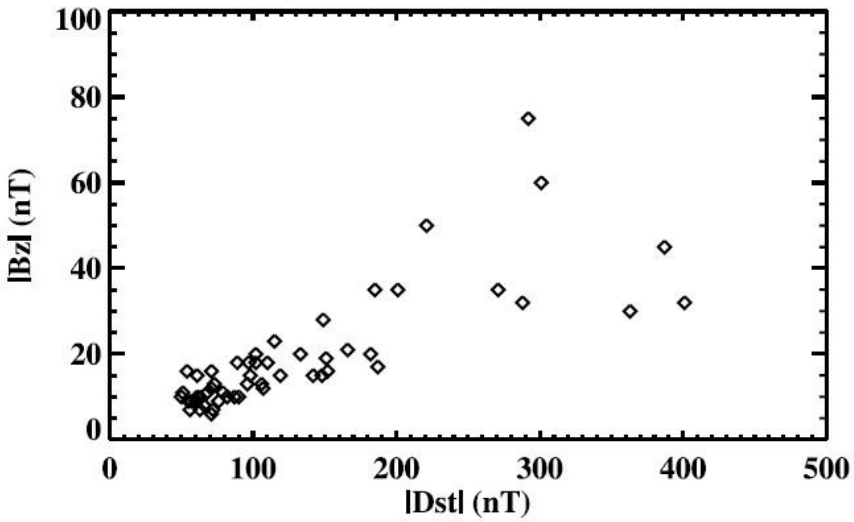


Figure 2: relationship between $B_z$ and |Dst| (from Kim et al. 2005).

Other authors (e.g. Ji et al. 2010) focused on the possible correlations between the minimum *Dst* value ($Dst_{min}$) and the so-called convection electric field, whose *y*-component (aligned with the dawn-to-dusk direction) is given by $E_y = V_x B_y$, where $V_x$ is the radial component of the interplanetary plasma outflow speed.

In this work we focused on the evolution of planetary (Earth) *Dst* index between years 1998 and 2012 (15 years of data) by making a comparison with the evolution of interplanetary magnetic field strength measured in L1 during the storms. After a description of datasets analysed, we describe the analysis methods and provide our results and conclusions.

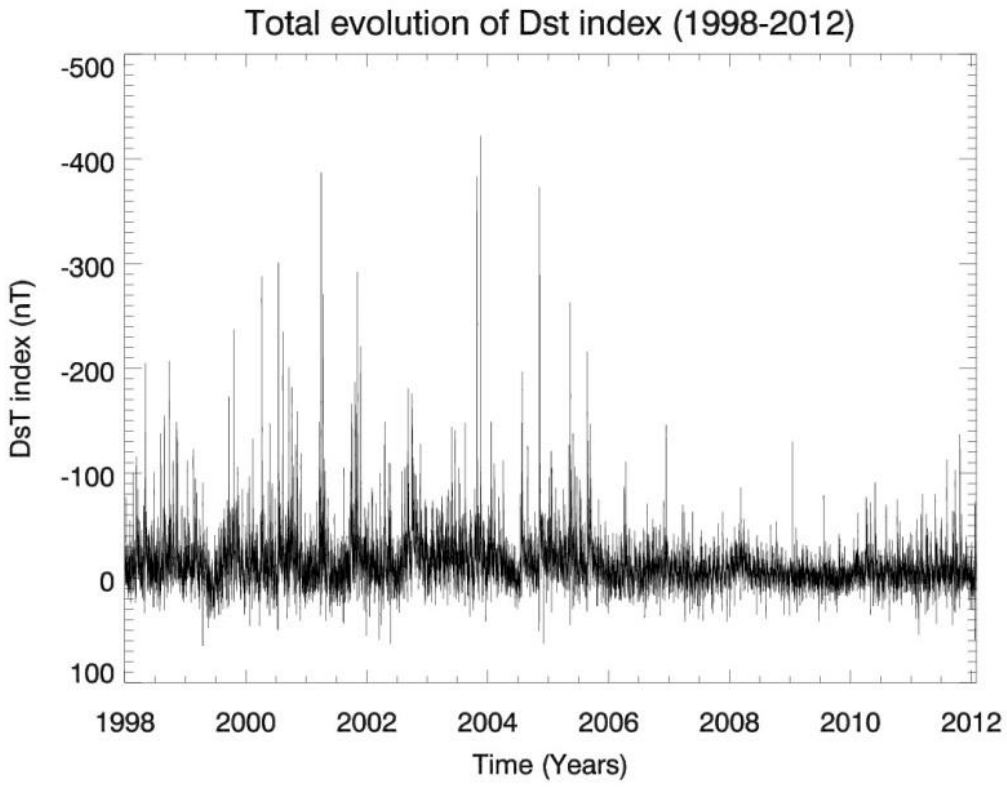


Figure 3: total evolution of *Dst* index values considered in the present analysis.

## 2. SELECTED DATA AND ANALYSIS

### *2.1 Evolution of the planetary Dst index*

The evolution of the *Dst* index has been downloaded from the NOAA catalog available on-line via anonymous FTP (ftp://ftp.ngdc.noaa.gov/STP/GEOMAGNETIC_DATA/INDICES/DST/). For this analysis we downloaded the values of Dst reported for years between 1998-2008, and the quick-look preliminary files available for years 2009-2012. The *Dst* values (units of nT) are provided with cadence by one hour.

After data download, we first created a single data file containing all the values for the *Dst* index in the above period. In the input files the time is provided for each year in units of "day-of-year" (DoY), hence the first step to create a single file was to convert all the different time values for each year to the same starting day. This has been done with the IDL routine ANYTIM (distributed within *SolarSoftware*), by converting all the provided time values from units of DoYs to units of seconds starting from January 1$^{st}$ 1979, and then by subtracting to all the values the number of seconds corresponding to January 1$^{st}$ 1998. The resulting total evolution of *Dst* index starting from 1998 to 2012 is shown in Figure 3.

As a second step we identified all major geomagnetic storms; in particular for this work we considered as a "major storm" when during the storm $Dst < -50$ nT. With this definition we selected a total of $N_{storm} = 592$ storms that occurred between 1998 and 2012. For each storm we extracted the minimum *Dst* value reached during the storm ($Dst_{min}$), and the corresponding time ($t_{min}$). The list of events was provided as an output file in TXT format; full list of the considered events is provided in the APPENDIX 1 at the end of this paper, together with the corresponding values of $Dst_{min}$.

### *2.2 Evolution of the interplanetary L1 magnetic field*

The evolution of the interplanetary magnetic field $B_{L1}$ as measured in the Sun-Earth Lagrangian-point L1 by the MAG instrument on-board ACE spacecraft has been downloaded via anonymous FTP from the on-line catalog (ftp://mussel.srl.caltech.edu/pub/ace/level2/mag/). The MAG catalog provides the acquired data in HDF format, with time cadence by 16 seconds, one file per year; each file is about 270 MB.

After the data download, it is necessary to read all the files and to extract only the information required for this analysis, hence the values for the total interplanetary magnetic field $B_{L1}$; in this first analysis we didn't consider different components of the magnetic field ($B_x$, $B_y$, $B_z$), but simply the total field strength. To read all the data we employed the IDL routine HDF_READ: this routine requires (with a graphical user interface – GUI) to select for each file the quantities to be exported in the IDL input arrays. Hence, in order to run the routine iteratively over all different files, it was necessary first to define a template defining the data to be extracted from the HDF files. This was done by using the HDF_BROWSER routine. Once the template file was created, this was used as an input for the HDF_READ routine to import all the HDF files, extract the selected information, and save only the extracted evolution of $B_{L1}$ and the corresponding times (converted again as done before for the *Dst* evolution) in output SAV files.

### *2.3 Comparison between planetary Dst values and interplanetary magnetic field evolutions*

Once the geomagnetic storms with Dst < -50 nT have been identified, for each time $t_{min}$ we extracted the corresponding time evolution $B_{storm}(t)$ of $B_{L1}$ over a 24h time interval centred on time $t_{min}$. Moreover, for reference comparison we also extracted for each storm the time evolution $B_{pre}(t)$ of $B_{L1}$ over a 24h time interval but centred on time $t_{min}$ – 24h, to have also the pre-storm evolution of $B_{L1}$ in a 24h time interval before time $t_{min}$. A few examples of $B_{L1}$ evolutions over 24h during the first 9 selected geomagnetic storms are shown in Figure 4 and Figure 5 for years 2003 and 2006, respectively. The corresponding evolutions of interplanetary field $B_{L1}$ observed one day before each storm are shown in Figure 6 and Figure 7 for years 2003 and 2006, respectively.

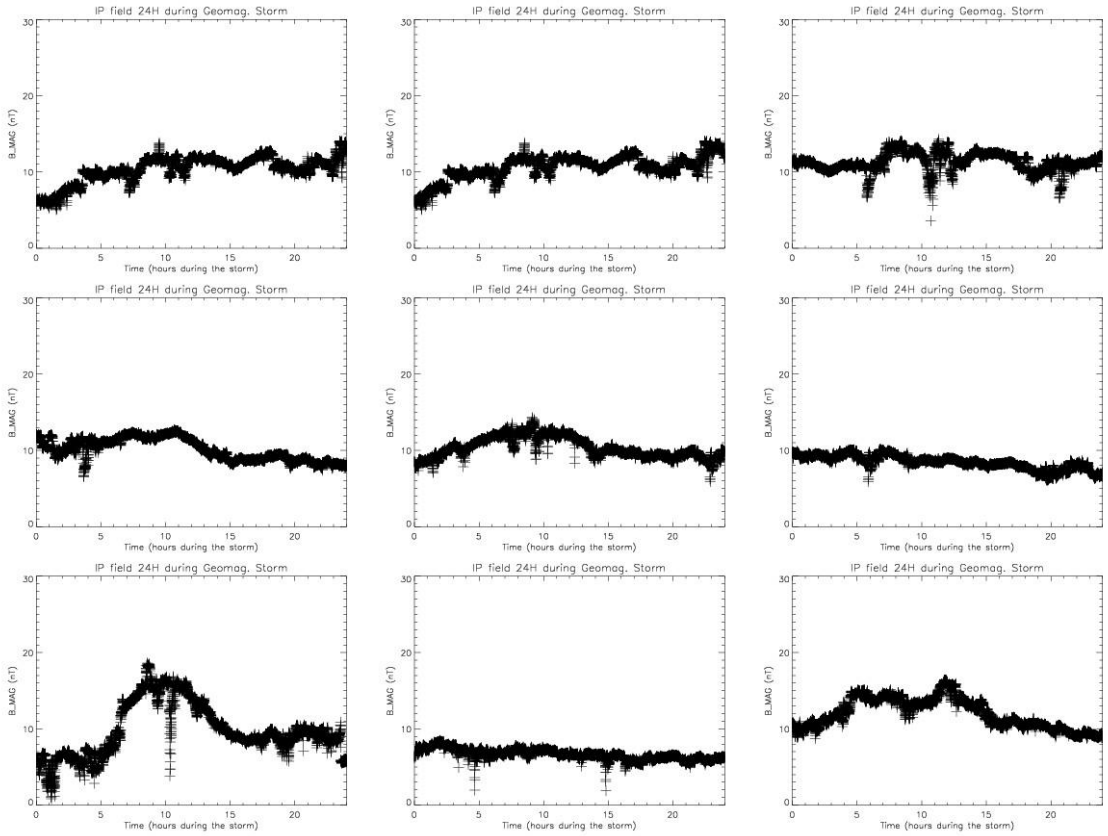


**Figure 4: 24h evolution of the interplanetary magnetic field $B_{L1}$ during the first 8 selected geomagnetic storms (Dst < -50 nT) that occurred in 2003.**

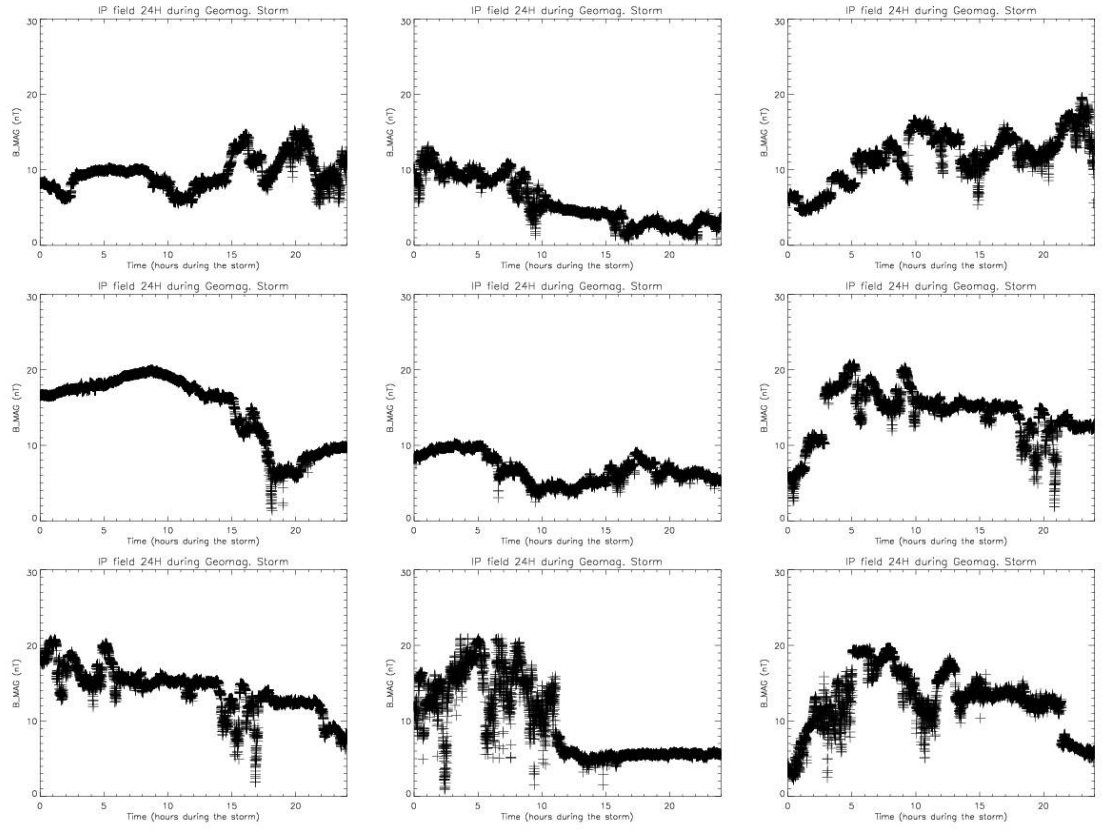


**Figure 5: same as Figure 4 plotted for year 2006.**

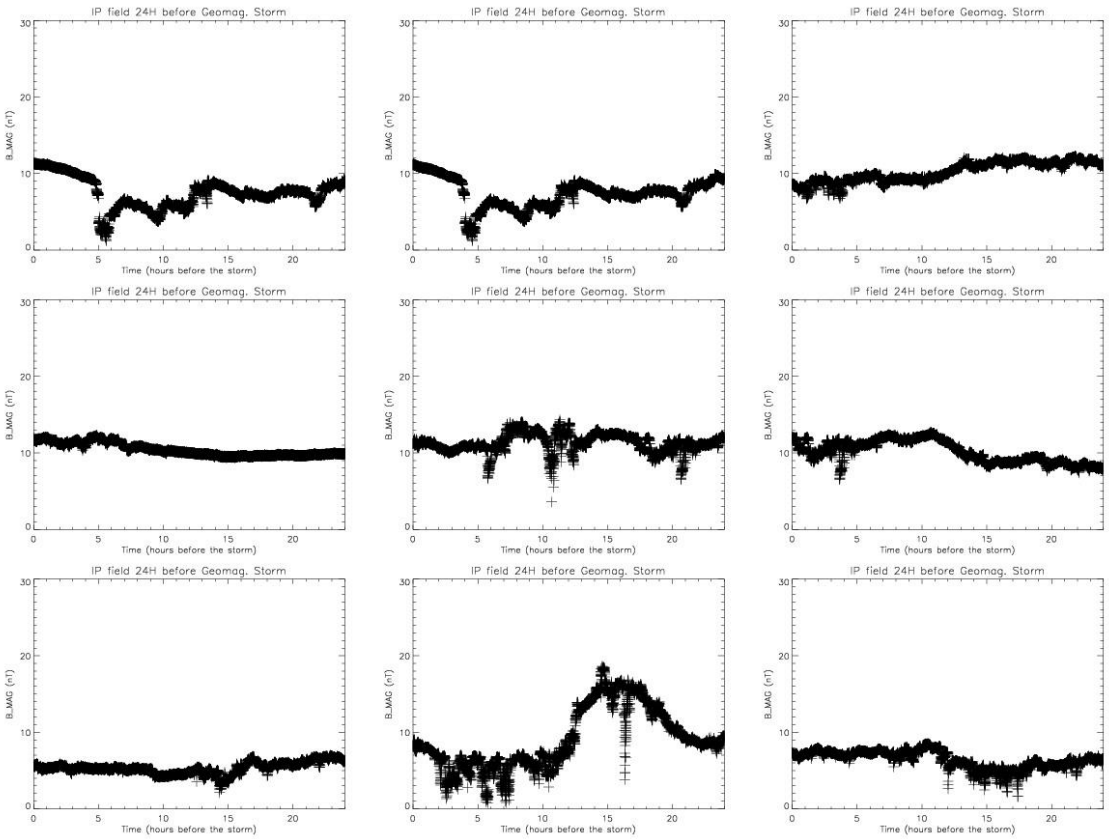


**Figure 6: 24h evolution of the interplanetary magnetic field $B_{L1}$ 1 day (24h) before the first 8 selected geomagnetic storms (Dst < -50 nT) that occurred in 2003 and shown in Figure 4.**

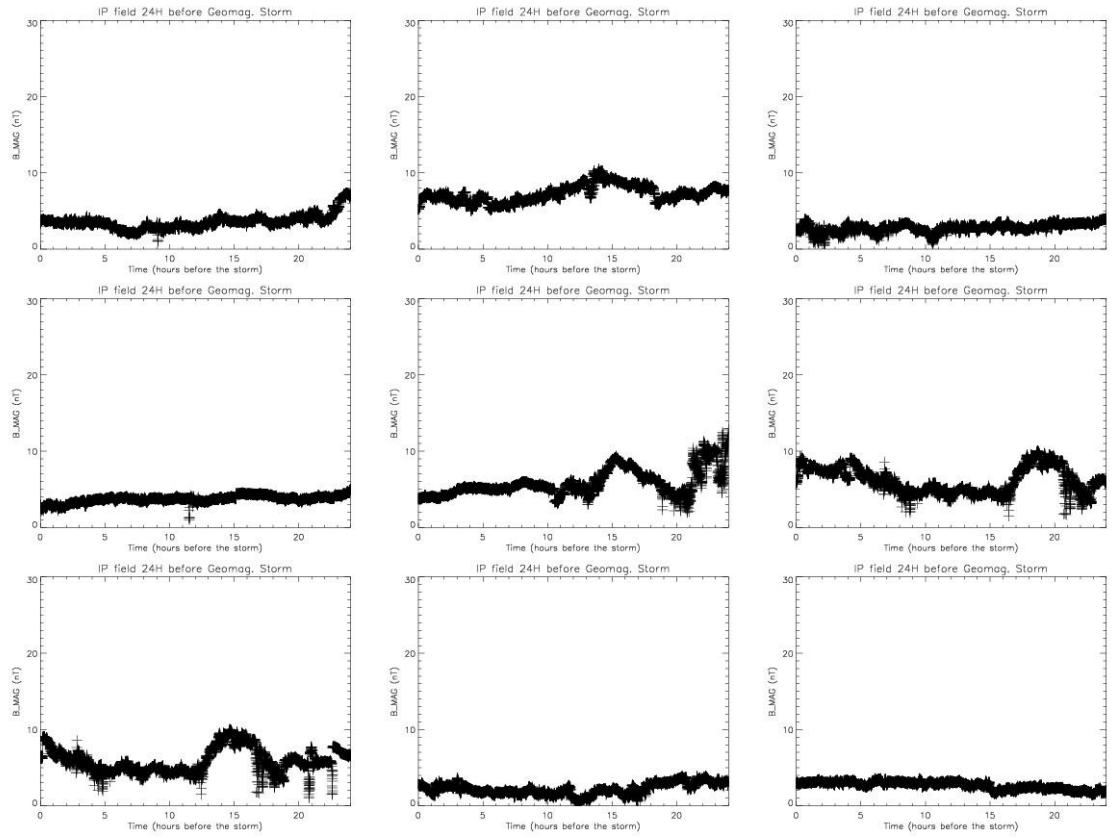


**Figure 7: same as Figure 6 plotted for year 2006.**

The aim of this work was to identify possible correlations between $Dst_{min}$ and the evolution of $B_{L1}$. Hence, for each selected 24h time interval we extracted the following quantities characterizing the interplanetary magnetic field before and during the storms:

- Average interplanetary magnetic field $B_{avg}$;
- Maximum interplanetary magnetic field $B_{max}$;
- Variance of interplanetary magnetic field $B_{sig}$.
- Skewness of interplanetary magnetic field $B_{ske}$;

Each one of the above quantities has been determined for each geomagnetic storm and before each geomagnetic storm. The resulting values of $B_{avg}$, $B_{max}$, $B_{sig}$, and $B_{ske}$ have been then correlated with the corresponding values of $Dst_{min}$ for all the selected geomagnetic storms. This has been done year by year with the CORRELATE routine in IDL, thus providing us with a yearly sequence of correlation coefficients $C_{cor}$ between each one of the above parameters and $Dst_{min}$ values. For comparison, the same correlation coefficients have been computed also with the magnetic field evolution in the 24h interval one day before the storm.

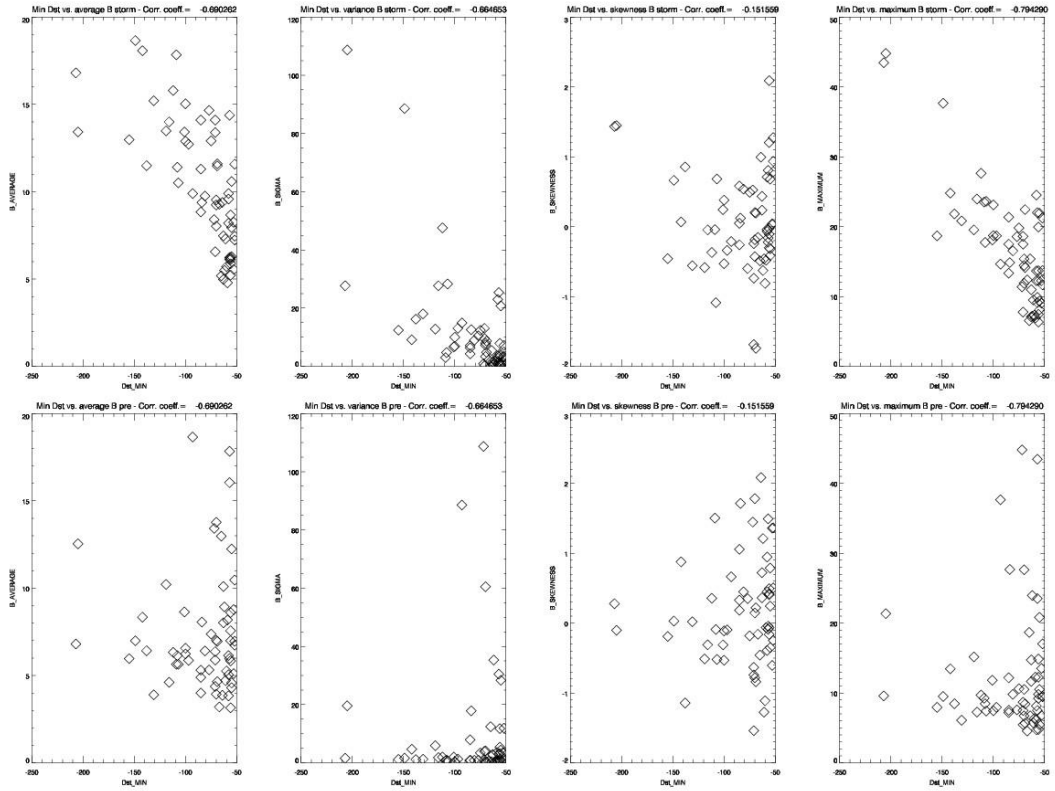


**Figure 8: example of correlation plots for year 1997. The plots show the distribution of $B_{avg}$ (first column left), $B_{sig}$ (second column), $B_{ske}$ (third column) and $B_{max}$ (fourth column) as a function of corresponding $Dst_{min}$ for all identified geomagnetic storms. Top row shows the distributions computed with magnetic field during the storm, bottom row show the distributions computed with magnetic field one day before the storm.**

## 3. RESULTS AND DISCUSSION

An example of resulting scatter plot distributions for $B_{avg}$, $B_{max}$, $B_{sig}$, and $B_{ske}$ values as a function of corresponding $Dst_{min}$ values are shown in Figure 8 for year 1997. This Figure shows that during the storms (top row) some correlation is present between $Dst_{min}$ and $B_{avg}$ (left column), $B_{max}$ (right column), and $B_{sig}$ (middle left column), while no apparent correlation seems to exist between $Dst_{min}$

and $B_{ske}$ (middle right column). Moreover, this Figure also demonstrates that (as expected) no correlation exist between $Dst_{min}$ and all above parameters when we consider the interplanetary magnetic field evolution in a time interval one day before the storm (bottom row).

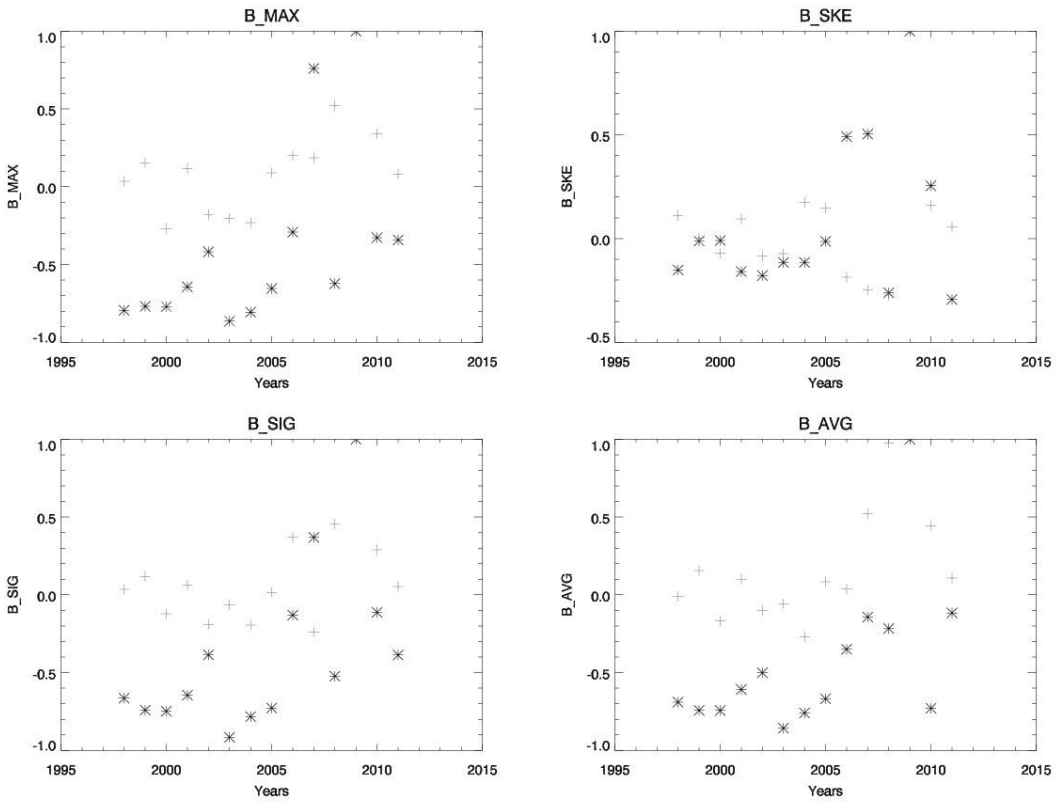


**Figure 9: evolution of yearly averaged correlation between $Dst_{min}$ and the maximum interplanetary magnetic field $B_{max}$ (top left), its variance $B_{sig}$ (bottom left), skewness $B_{ske}$ (top right), and average value $B_{avg}$ (bottom right). In each plot we show the values of correlation computed for 24h intervals during the storms (asterisk symbols) and one day before the storms (plus symbols).**

By considering all years with available both *Dst* and *B* measurements, and by performing yearly averages of correlation coefficients $C_{cor}$ measured for different storms, we obtained yearly values plotted in Figure 9 as a function of time. According to this Figure, $B_{avg}$, $B_{max}$, and $B_{sig}$ are in general all anti-correlated with $Dst_{min}$, while no clear correlation is present between $B_{ske}$ and $Dst_{min}$. Also, considering that the minima of solar activity cycle occurred during years 1996 and 2008, no clear trend is present as a function of time during the solar cycle.

In the end, by averaging all the yearly correlation coefficients $C_{cor}$ as a function of time, we obtained the values listed in Table 1. Values in this Table led us to conclude that the largest correlation is observed between $Dst_{min}$ and $B_{max}$, while the smaller correlation is observed between $Dst_{min}$ and $B_{ske}$. Values of correlation coefficients obtained with the magnetic field measurements acquired one day before the storm have been used as an estimate of uncertainty in the correlation coefficients measured on average during the storms.

| Average correlation between | During the storm | One day before the storm |
|---|---|---|
| $Dst_{min}$ and $B_{avg}$ | $C_{cor}$ = -0.55 ± 0.14 | $C_{cor}$ = +0.14 |
| $Dst_{min}$ and $B_{max}$ | $C_{cor}$ = -0.61 ± 0.06 | $C_{cor}$ = +0.06 |
| $Dst_{min}$ and $B_{sig}$ | $C_{cor}$ = -0.56 ± 0.11 | $C_{cor}$ = +0.11 |
| $Dst_{min}$ and $B_{ske}$ | $C_{cor}$ = -0.13 ± 0.02 | $C_{cor}$ = -0.02 |

**Table 1: summary of average correlation coefficients between $Dst_{min}$ and different parameters of interplanetary magnetic field.**

## 4. SUMMARY AND CONCLUSIONS

In this work we showed that a significant correlation ($C_{cor}$ = -0.61 ± 0.06) exists between the minimum values of the *Dst* index measured during major geomagnetic storms (*Dst* < -50 nT) and the maximum values of the interplanetary magnetic field measured in 24 hours long time intervals during the storms. Nevertheless, despite this quite good correlation, the quantity $B_{max}$ cannot be easily used as a proxy to forecast the possible strength of the incoming geomagnetic storm.

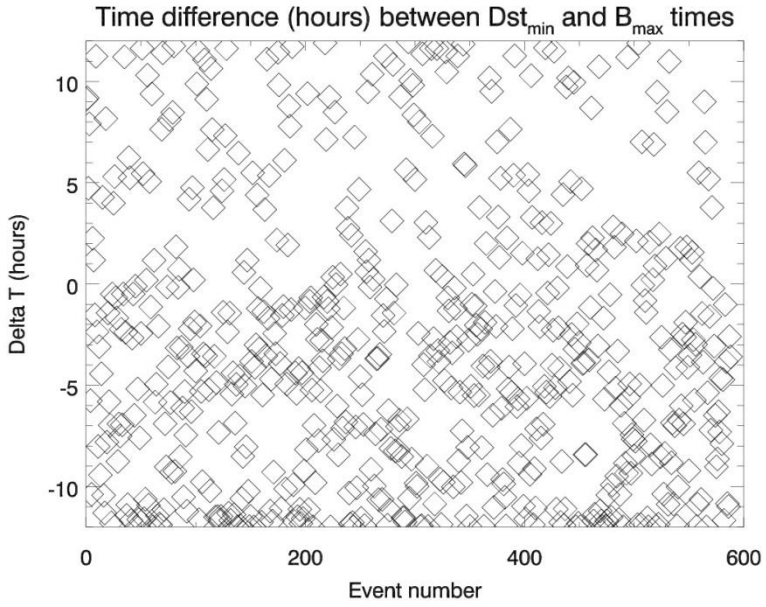


**Figure 10: scatter plot of time differences (hours) between $Dst_{min}$ and $B_{max}$ times.**

The reason for this conclusion is given in Figure 10, showing the scatter plot of time differences $\Delta t$ between $Dst_{min}$ and $B_{max}$ times. This plot shows that the time difference distribution is quite uniform, and basically all possible cases are observed, with positive and negative values of $\Delta t$. In particular, by averaging over the almost 600 considered events we obtain and average $\Delta t$ equal to $\langle \Delta t \rangle$ = (-3.0 ± 6.8) hours, hence the maximum value of interplanetary magnetic field is reached on average 3.0 hours before the minimum value of *Dst* on Earth. This result is in quite good agreement for instance with Gonzalez & Echer (2005), but with a very large (1–σ) distribution by ±6.8 hours, making any forecasting based on interplanetary $B_{max}$ values not possible.

In a future development of this work we plan to consider not only values of total field |*B*|, but also single components of *B*, as well as the convection electric field which is given by $E_y = V_x B_y$.


## ACKNOWLEDGEMENTS

Results presented here have been obtained after a 2-months student mobility period for traineeship under ERASMUS Program, in a collaboration between University of Iasi (Romania), University of Turin (Italy), and the INAF-Turin Astrophysical Observatory. D.A. acknowledges support by “Erasmus” Grant.


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Kim, R.-S., Cho, K.-S., Moon, Y.-J., et al. 2005, JGR, 110, A11104

Kim, R.-S., K.-S. Cho, Y.-J. Moon, et al. 2010, JGR, 115, A12108

APPENDIX 1: list of selected major geomagnetic storms ($Dst_{min}$ < -50) and $Dst_{min}$ values.

| Day (UT) | Hour (UT) | $Dst_{min}$ (nT) |
|---|---|---|
| 98/01/07 | 02:00:00.014 | -77 |
| 98/01/30 | 11:00:00.055 | -55 |
| 98/02/17 | 19:00:00.110 | -100 |
| 98/02/18 | 00:00:00.000 | -100 |
| 98/03/10 | 15:59:59.780 | -116 |
| 98/03/11 | 00:00:00.000 | -107 |
| 98/03/12 | 00:00:00.000 | -62 |
| 98/03/15 | 03:59:59.780 | -71 |
| 98/03/21 | 14:00:00.220 | -85 |
| 98/03/25 | 15:00:00.000 | -56 |
| 98/03/29 | 18:59:59.780 | -56 |
| 98/04/24 | 05:00:00.220 | -69 |
| 98/04/26 | 15:00:00.000 | -63 |
| 98/05/02 | 11:00:00.220 | -85 |
| 98/05/03 | 03:00:00.000 | -70 |
| 98/05/04 | 00:00:00.000 | -205 |
| 98/05/05 | 00:00:00.000 | -119 |
| 98/05/06 | 00:00:00.000 | -72 |
| 98/05/07 | 08:00:00.220 | -52 |
| 98/05/08 | 18:59:59.780 | -56 |
| 98/05/09 | 18:00:00.000 | -63 |
| 98/06/14 | 09:00:00.000 | -67 |
| 98/06/26 | 01:59:59.561 | -101 |
| 98/07/16 | 15:00:00.000 | -58 |
| 98/08/06 | 07:59:59.561 | -138 |
| 98/08/07 | 00:00:00.000 | -108 |
| 98/08/20 | 16:59:59.561 | -71 |
| 98/08/26 | 22:59:59.561 | -97 |
| 98/08/27 | 00:00:00.000 | -155 |
| 98/08/28 | 00:00:00.000 | -84 |
| 98/08/29 | 00:00:00.000 | -65 |
| 98/08/30 | 01:59:59.561 | -56 |
| 98/08/31 | 10:00:00.439 | -60 |
| 98/09/01 | 16:00:00.439 | -55 |
| 98/09/18 | 12:59:59.121 | -52 |
| 98/09/24 | 06:00:00.000 | -85 |
| 98/09/25 | 02:00:00.879 | -207 |
| 98/09/26 | 00:00:00.000 | -75 |
| 98/09/27 | 00:00:00.000 | -57 |
| 98/09/30 | 23:00:00.879 | -53 |
| 98/10/01 | 00:00:00.000 | -58 |
| 98/10/02 | 18:59:59.121 | -56 |
| 98/10/03 | 02:00:00.879 | -59 |
| 98/10/07 | 18:00:00.000 | -70 |
| 98/10/08 | 00:00:00.000 | -64 |

| | | |
|---|---|---|
| 98/10/19 | 03:59:59.121 | -112 |
| 98/10/20 | 00:00:00.000 | -71 |
| 98/10/21 | 00:00:00.000 | -70 |
| 98/10/22 | 17:00:00.879 | -53 |
| 98/10/24 | 00:00:00.000 | -52 |
| 98/11/06 | 06:59:59.121 | -61 |
| 98/11/07 | 12:59:59.121 | -81 |
| 98/11/08 | 00:00:00.000 | -149 |
| 98/11/09 | 05:00:00.879 | -142 |
| 98/11/10 | 00:00:00.000 | -93 |
| 98/11/13 | 06:00:00.000 | -131 |
| 98/11/14 | 00:00:00.000 | -109 |
| 98/11/15 | 00:00:00.000 | -55 |
| 98/11/16 | 00:00:00.000 | -57 |
| 98/12/11 | 06:59:59.121 | -69 |
| 98/12/25 | 09:59:59.121 | -57 |
| 98/12/29 | 09:59:59.121 | -58 |
| 99/01/13 | 17:00:00.879 | -112 |
| 99/01/14 | 00:00:00.000 | -101 |
| 99/01/15 | 03:59:59.121 | -56 |
| 99/01/23 | 21:59:59.121 | -55 |
| 99/02/18 | 05:00:00.879 | -123 |
| 99/02/19 | 00:00:00.000 | -106 |
| 99/02/20 | 00:00:00.000 | -58 |
| 99/02/28 | 21:00:00.000 | -94 |
| 99/03/01 | 00:00:00.000 | -95 |
| 99/03/02 | 00:00:00.000 | -80 |
| 99/03/04 | 23:00:00.879 | -54 |
| 99/03/07 | 06:00:00.000 | -57 |
| 99/03/10 | 03:00:00.000 | -81 |
| 99/03/29 | 14:00:00.879 | -56 |
| 99/04/17 | 00:59:59.121 | -91 |
| 99/07/31 | 01:00:01.758 | -53 |
| 99/08/20 | 12:00:00.000 | -56 |
| 99/08/22 | 22:59:58.242 | -66 |
| 99/08/23 | 00:00:00.000 | -66 |
| 99/08/24 | 01:59:58.242 | -55 |
| 99/09/12 | 19:00:01.758 | -61 |
| 99/09/13 | 00:00:00.000 | -74 |
| 99/09/14 | 03:00:00.000 | -65 |
| 99/09/15 | 09:00:00.000 | -55 |
| 99/09/16 | 04:59:58.242 | -67 |
| 99/09/22 | 21:00:00.000 | -173 |
| 99/09/23 | 00:00:00.000 | -155 |
| 99/09/27 | 15:00:00.000 | -64 |
| 99/09/30 | 01:59:58.242 | -62 |
| 99/10/10 | 13:59:58.242 | -67 |
| 99/10/11 | 07:00:01.758 | -52 |

| | | |
|---|---|---|
| 99/10/12 | 04:59:58.242 | -60 |
| 99/10/13 | 00:00:00.000 | -61 |
| 99/10/15 | 01:00:01.758 | -67 |
| 99/10/17 | 12:00:00.000 | -77 |
| 99/10/22 | 01:00:01.758 | -237 |
| 99/10/23 | 00:00:00.000 | -76 |
| 99/10/24 | 00:00:00.000 | -71 |
| 99/10/25 | 00:00:00.000 | -54 |
| 99/10/27 | 07:59:58.242 | -61 |
| 99/10/28 | 00:00:00.000 | -66 |
| 99/10/29 | 00:00:00.000 | -59 |
| 99/11/07 | 12:00:00.000 | -67 |
| 99/11/08 | 00:00:00.000 | -73 |
| 99/11/09 | 04:00:01.758 | -57 |
| 99/11/11 | 06:00:00.000 | -55 |
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| 05/07/09 | 15:00:00.000 | -60 |
| 05/07/10 | 12:00:00.000 | -94 |
| 05/07/11 | 00:00:00.000 | -74 |
| 05/07/12 | 01:00:07.031 | -85 |
| 05/07/13 | 10:00:07.031 | -63 |
| 05/07/18 | 03:00:00.000 | -76 |
| 05/08/10 | 10:00:07.031 | -180 |
| 05/08/24 | 10:00:07.031 | -216 |
| 05/08/25 | 00:00:00.000 | -109 |
| 05/08/26 | 01:59:52.969 | -73 |
| 05/08/31 | 13:59:52.969 | -131 |
| 05/09/01 | 00:00:00.000 | -87 |
| 05/09/03 | 01:59:52.969 | -68 |
| 05/09/04 | 04:00:07.031 | -76 |
| 05/09/10 | 18:00:00.000 | -70 |
| 05/09/11 | 00:00:00.000 | -147 |
| 05/09/12 | 00:00:00.000 | -90 |

| | | |
|---|---|---|
| 05/09/13 | 00:00:00.000 | -95 |
| 05/09/14 | 00:00:00.000 | -78 |
| 05/09/15 | 13:00:07.031 | -86 |
| 05/09/16 | 00:00:00.000 | -66 |
| 05/09/18 | 10:59:52.969 | -52 |
| 05/10/31 | 15:00:00.000 | -75 |
| 05/11/01 | 00:00:00.000 | -53 |
| 05/11/13 | 15:00:00.000 | -54 |
| 05/12/11 | 10:00:07.031 | -54 |
| 06/04/05 | 06:00:00.000 | -87 |
| 06/04/06 | 04:59:52.969 | -76 |
| 06/04/09 | 06:00:00.000 | -80 |
| 06/04/14 | 04:59:52.969 | -111 |
| 06/04/15 | 01:59:52.969 | -60 |
| 06/08/19 | 19:59:52.969 | -71 |
| 06/08/20 | 00:00:00.000 | -69 |
| 06/09/24 | 07:00:07.031 | -56 |
| 06/11/10 | 01:00:07.031 | -56 |
| 06/11/30 | 07:00:07.031 | -110 |
| 06/12/15 | 00:00:00.000 | -146 |
| 06/12/16 | 00:00:00.000 | -56 |
| 07/03/24 | 06:00:00.000 | -70 |
| 07/04/01 | 07:00:07.031 | -63 |
| 07/05/23 | 12:00:00.000 | -63 |
| 07/10/25 | 21:00:00.000 | -57 |
| 07/11/20 | 13:59:52.969 | -63 |
| 08/02/28 | 22:00:07.031 | -57 |
| 08/03/09 | 04:00:07.031 | -86 |
| 08/03/27 | 21:00:00.000 | -56 |
| 08/09/04 | 04:00:07.031 | -54 |
| 08/10/11 | 10:59:52.969 | -130 |
| 09/01/14 | 00:00:00.000 | -130 |
| 09/07/22 | 03:59:45.938 | -79 |
| 10/02/15 | 21:00:00.000 | -62 |
| 10/02/16 | 00:00:00.000 | -56 |
| 10/04/05 | 15:00:00.000 | -63 |
| 10/04/06 | 00:00:00.000 | -77 |
| 10/04/07 | 00:00:00.000 | -60 |
| 10/04/12 | 00:00:00.000 | -66 |
| 10/05/02 | 12:59:45.938 | -72 |
| 10/05/03 | 00:00:00.000 | -60 |
| 10/05/29 | 06:00:00.000 | -91 |
| 10/05/30 | 20:00:14.063 | -59 |
| 10/08/03 | 21:59:45.938 | -69 |
| 10/08/04 | 00:00:00.000 | -70 |
| 10/08/05 | 00:00:00.000 | -66 |
| 10/10/11 | 15:00:00.000 | -75 |
| 10/10/26 | 11:00:14.063 | -56 |

| | | |
|---|---|---|
| 11/02/04 | 21:00:00.000 | -61 |
| 11/03/01 | 14:00:14.063 | -61 |
| 11/03/10 | 21:00:00.000 | -56 |
| 11/03/11 | 00:59:45.938 | -80 |
| 11/03/12 | 00:00:00.000 | -59 |
| 11/04/06 | 17:00:14.063 | -73 |
| 11/05/28 | 09:59:45.938 | -80 |
| 11/05/29 | 06:00:00.000 | -54 |
| 11/07/04 | 23:00:14.063 | -57 |
| 11/07/05 | 00:00:00.000 | -92 |
| 11/08/06 | 00:00:00.000 | -113 |
| 11/08/07 | 03:00:00.000 | -60 |
| 11/09/09 | 17:00:14.063 | -60 |
| 11/09/10 | 00:00:00.000 | -64 |
| 11/09/17 | 15:00:00.000 | -73 |
| 11/09/26 | 17:00:14.063 | -103 |
| 11/09/27 | 00:00:00.000 | -90 |
| 11/09/28 | 06:00:00.000 | -66 |
| 11/10/24 | 23:00:14.063 | -110 |

**Table 2: list of selected major geomagnetic storms ($Dst_{min}$ < -50 nT) between 1998-2012, and corresponding minimum values of the *Dst* index (nT) reached during the storm.**