A new parameter of geomagnetic storms for space weather applications.

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Contents

JGR, 2014, 2017, 2019; Geoscience Letters, 2016
EPS, 2017; Astrophysical Journal, 2019

1. Introduction and definitions

Space extends from the surface of the Earth to the imaginary edge of the universe.

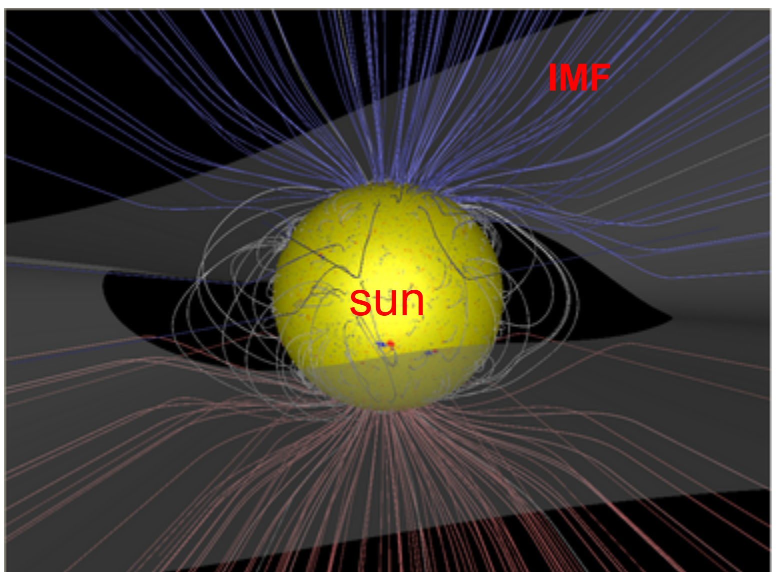
For our purpose, space is confined within the heliosphere or the region of space influenced by the Sun.

Space Climate

Space contains solar wind and magnetic field (IMF) originating from the Sun and flowing out through the interplanetary space (IPS).

Normal solar wind has speed ~400 km/s, density <5 cm^{-3}, pressure <5 nPa, temperature ~5 MK.

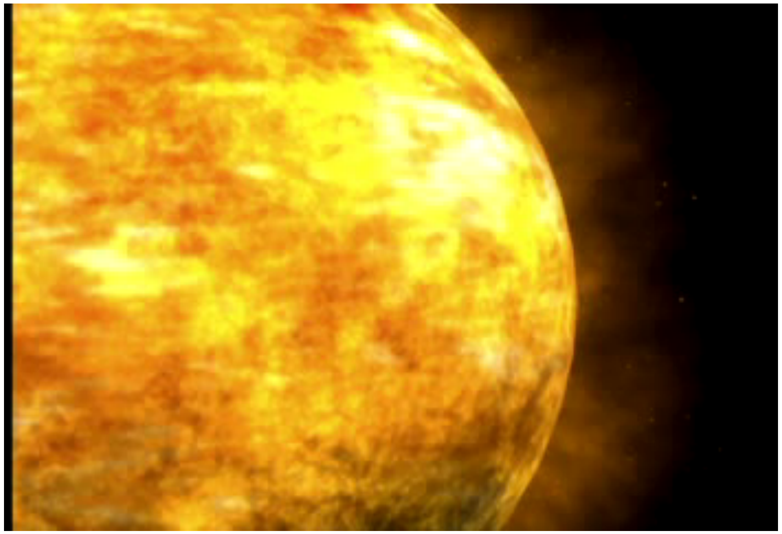
Normal IMF <5 nT.



Space Climate is the expected variation of solar wind and IMF from their past average values.

Space weather represents the temporal behavior of solar wind and IMF.

Space weather begins with an eruption in the solar corona.
(Corona is the outer layer of the Sun).



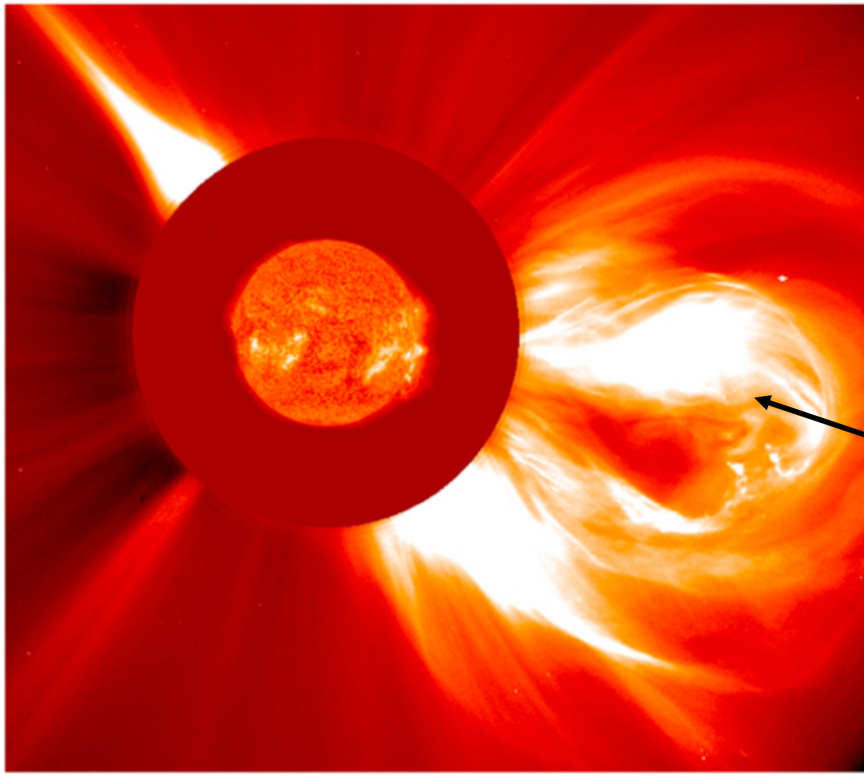
NASA video

Solar eruption

- Emits electromagnetic radiation (solar flare) reaching the earth in 8.5 minutes.
- Ejects coronal mass (CME) together with magnetic field reaching the earth in 1-3 days depending on its speed.

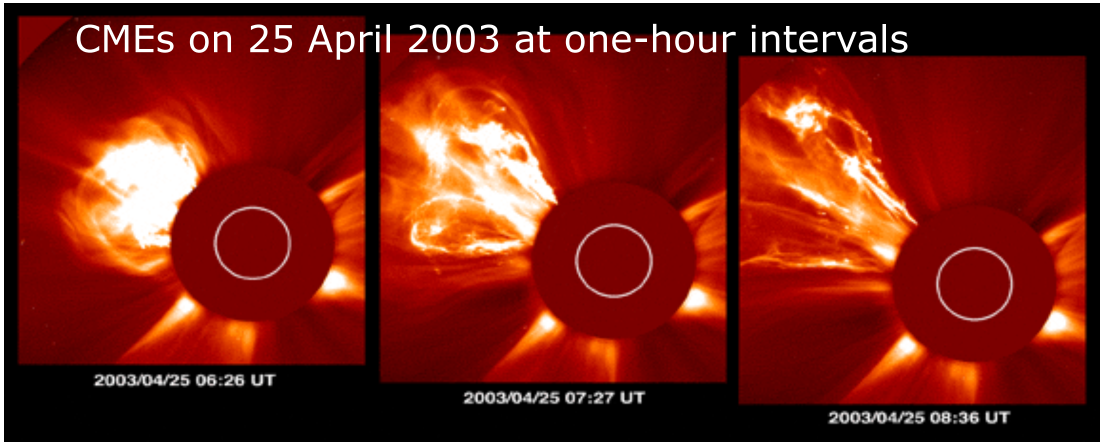
C3_Apr01.mpg

CME is coronal mass ejection



SOHO image of the sun at 304 Aº (inner) and CME (outer). 02 December 2003.

ICME and Space Weather



- CMEs flow out through the IPS (as ICME) with speed up to 1000s km/s (400 km/s), density up to 100 cm^{-3} (<5 cm^{-3}), magnetic field up to 100 nT (<5 nT), temperature ~0.5 MK (5 MK), and reach the Earth in 1-3 days.
- While flowing out, ICMEs produce rapid and sometimes severe changes in IPS and environment of the planets.
- The **changes** are collectively known as **Space Weather.**

Space Weather

- **ICMEs** produce space weather (or changes) in IPS (ICME shock, SEPs, HSS, CIRs, ctc).

- **ICMEs** produce space weather in the planet's (Earth's) environment
  - Magnetosphere gets suddenly compressed
  - Ring current intensifies
  - Geomagnetic storms and auroras occur
  - Radiation belts change
  - Plasmasphere changes
  - Ionospheric electric fields and currents change
  - High latitude thermosphere gets heated and expands (thermospheric storms)
  - Ionospheric density and temperature change (ionospheric storms)
  - etc.

The **changes** collectively are known as **Space Weather.**

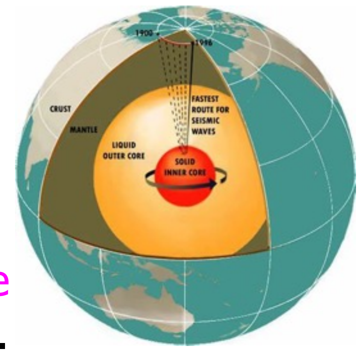
- In last 60 years, 35 super space weather events occurred. But only 5 of them were severe and 55 were normal, why?

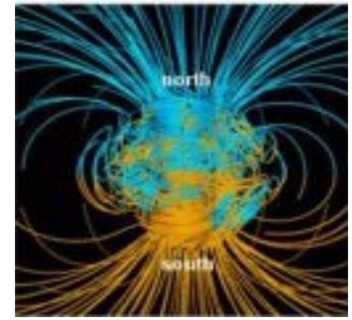
- If a space weather event like the Carrington event of 1859 occurs at present times, it can cause damages costing up to 1-2 trillion US Dollars

- **It is important to study Space Weather.**
- **Understand what determines the severity of SW.**
- **Whether it can be forecasted and predicted.**

Geomagnetic storm (Dst storm)

The geomagnetic field has three components



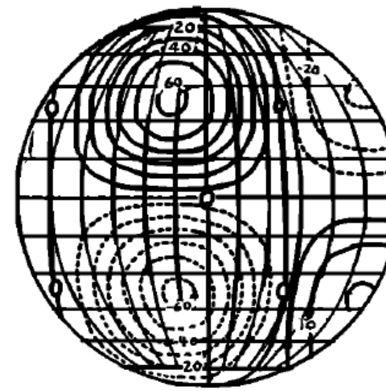


Main field

Main field (F_M)

The rotation of Earth's molten metallic outer core produces the main dynamo current (eastward). This current produces

F_M = ~32000 nT (positive)



Sq current

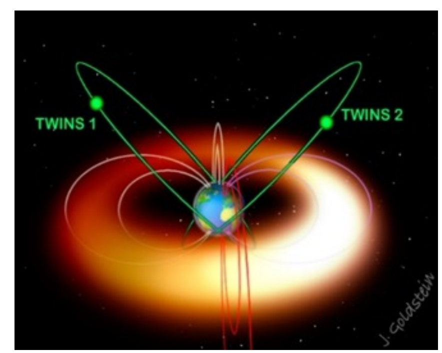
Sq field (F_I)

Ionospheric Sq current (eastward) produces

F_I = ~40 nT (positive)

Ring current (westward at L = 3-7) under quiet conditions produces

F_R = ~-20 nT (negative)



Ring current

Total quiet field F_T = F_M + F_I – F_R = made 0 -----------

(~32000 nT) + (40 nT) - (20 nT) (in Dst index)

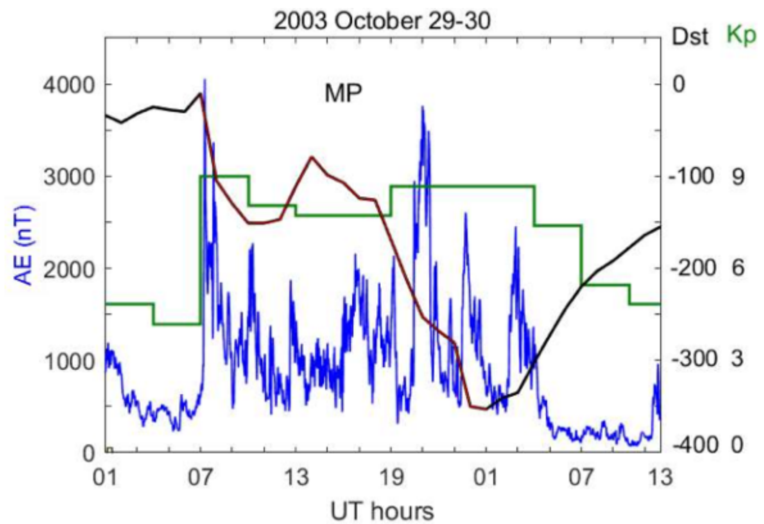
Under solar disturbed conditions, the ring current increases, which causes F_R more negative or F_T decreasing below zero.

The decrease of F_T is a geomagnetic (Dst) storm.

Geomagnetic storms and indices

The magnetospheric and ionospheric currents contribute differently to the geomagnetic storms at different latitudes.

The storms are represented by the indices such as the Dst index (low latitude), Kp index (mid latitude), and AE index (high latitude).



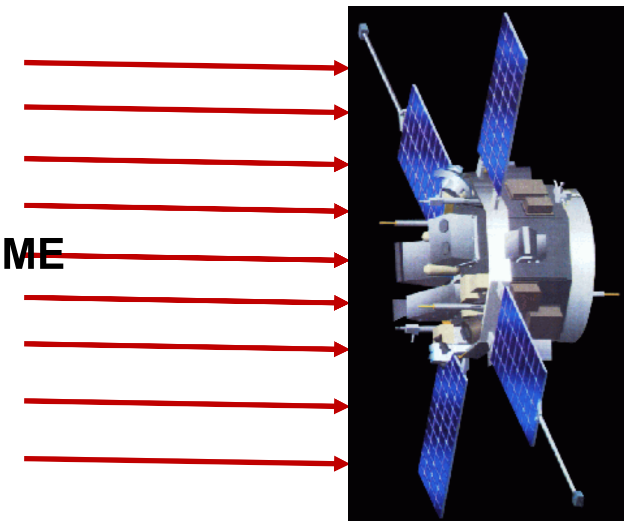
Earth's weather sometimes becomes **severe** and causes serious damages.

Like Earth’s weather, Space Weather sometimes becomes **severe.**

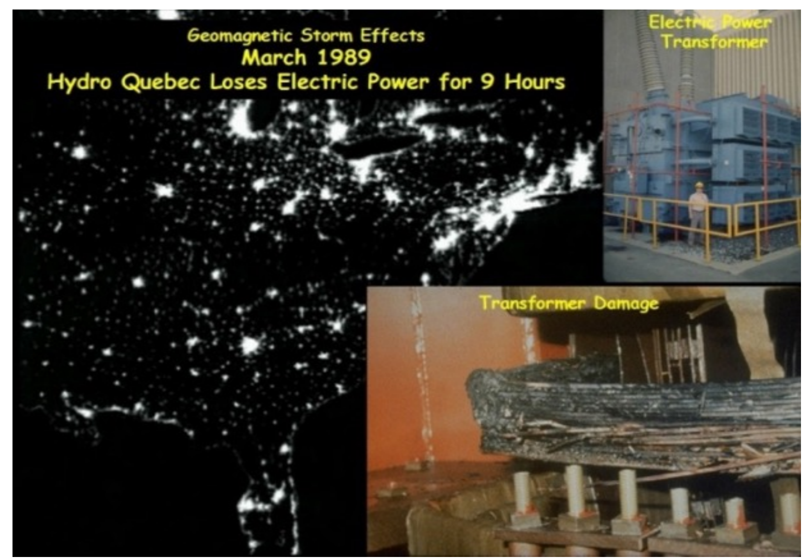
When it becomes severe, it can cause serious damages in the high-tech society.

Satellite system damage

Fast CME



Ground system damage on **13 March 1989**



Over 6 million people in Quebec lost electric power for over 9 hours.

Definition and examples of *Severe space weather*

A **Severe space weather** (SvSW) is defined as the SW that causes electric power outage and/or tele-communication failure.

Space weather events that do not cause such severe effects are normal space weather (NSW).

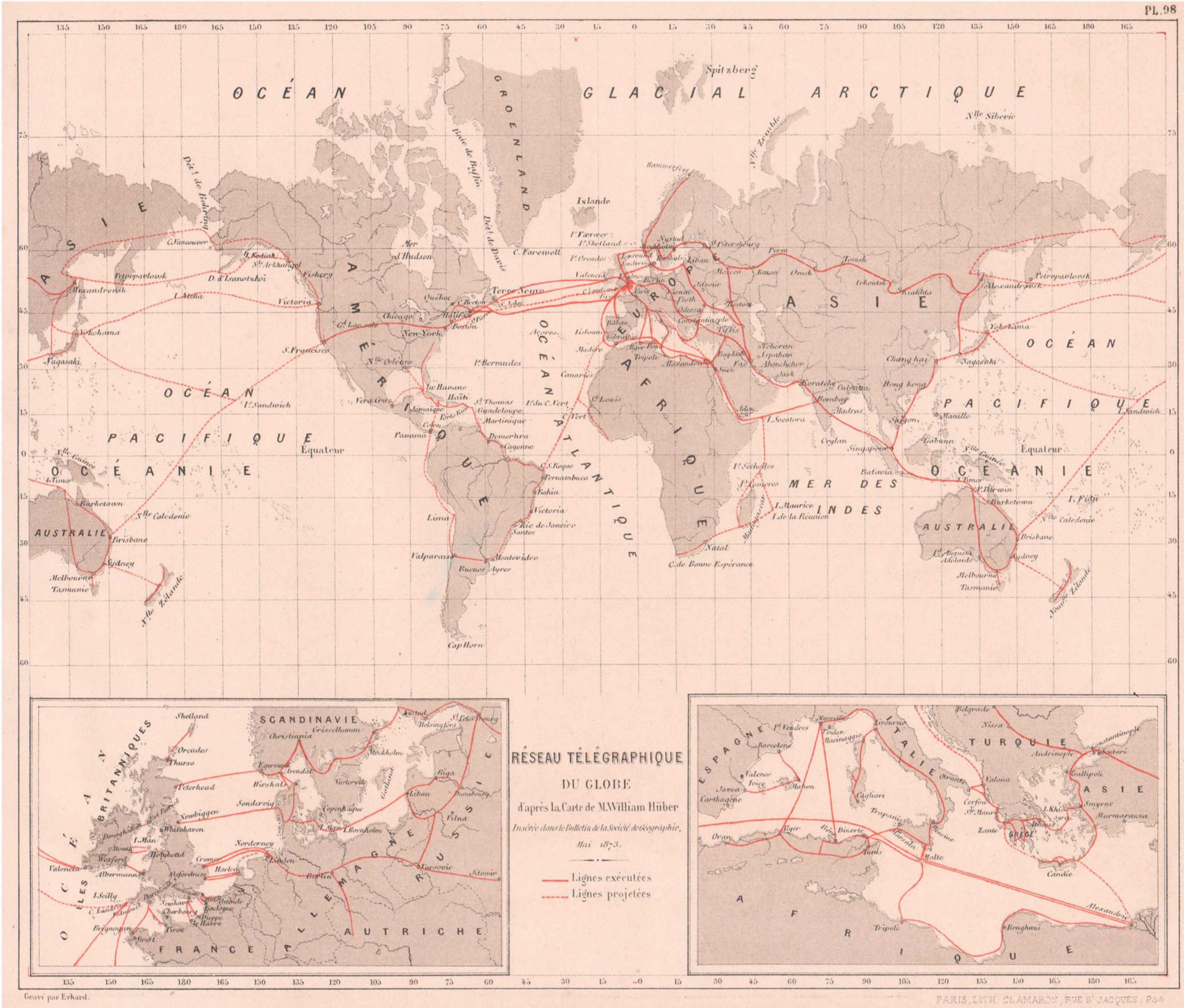
Note: SvSW can also damage satellite systems, satellite (GPS) communication and navigation, oil and gas metal pipe lines, etc. It can also affect space travelers.

Examples of SvSW and NSW

https://www.youtube.com/watch?v=KqXtwAZFfUQ

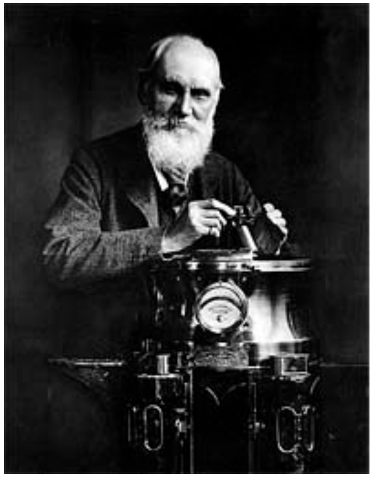
The most famous Space Weather
(Carrington event in 1859)

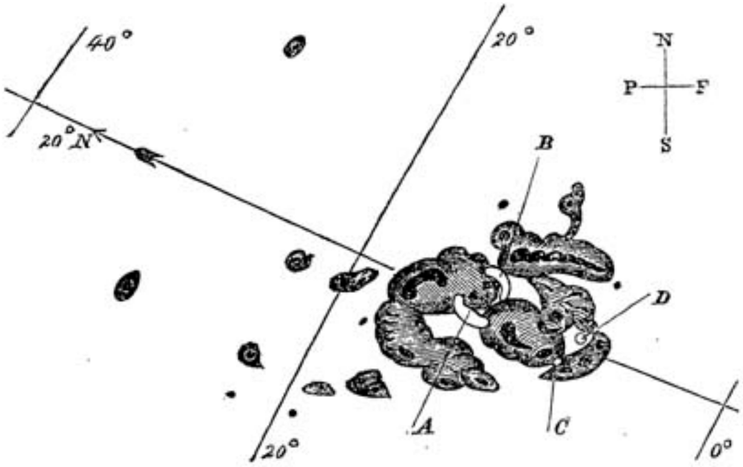
Telegraph network in 1863



Transatlantic telegraph communication began in 1858.

Carrington event of 1859 - most famous space weather event





On 1st September 1859 Carrington spotted a cluster of enormous **dark Spots** on the Sun, and two patches of **intensely bright and white light** erupted from the dark spots.

Five minutes later the fireballs vanished, and **within hours** their **impacts** were felt across the globe.

Carrington, 1859

Estimated speed of the CME > 2200 km/s

Cliver and Svalgaard, 2004

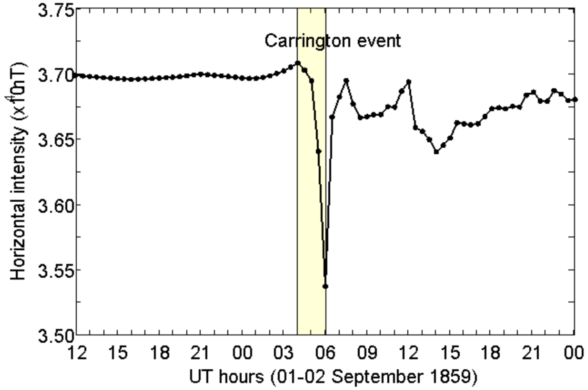
Impacts of Carrington event

- Telegraph communications failed.

- Electric power grids would have been on fire.

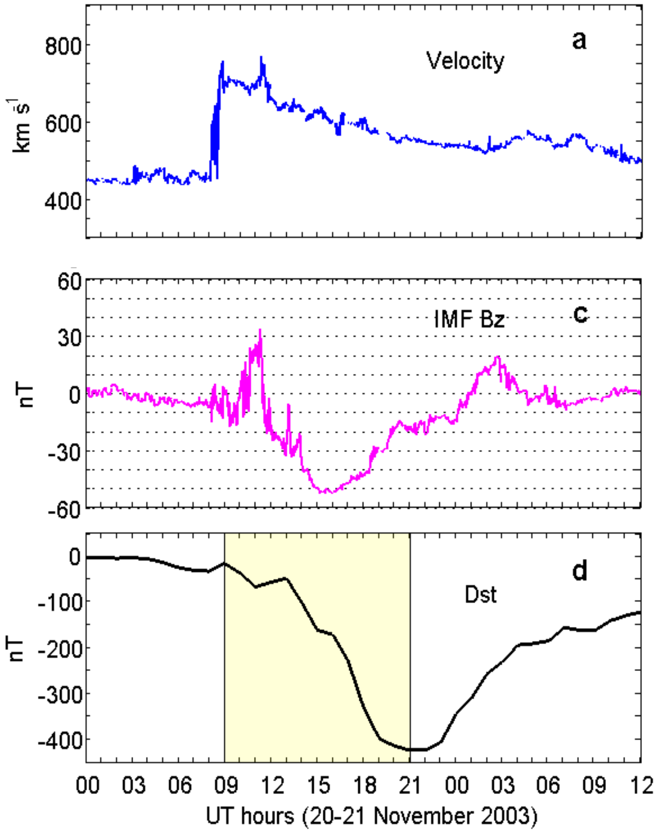
- The night sky was on fire - brilliant auroras.

- Produced an **extreme geomagnetic storm**
  MP duration ≈ 2 hrs, no fluctuations
  H $range_{MP}$ ≈ 1710 nT
  Mean H $range_{MP}$ ≈ 700 nT
  $(dH/dt)_{MPmax}$ ≈ 1390 nT/hr.



- The extreme characteristics indicate that a huge amount of energy was put into the geospace in a short duration, so that the geospace responded impulsively.

NSW on 20-21 November 2003

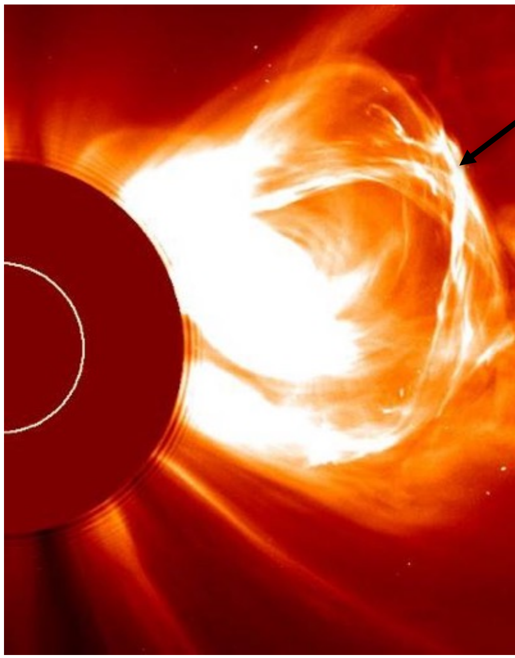


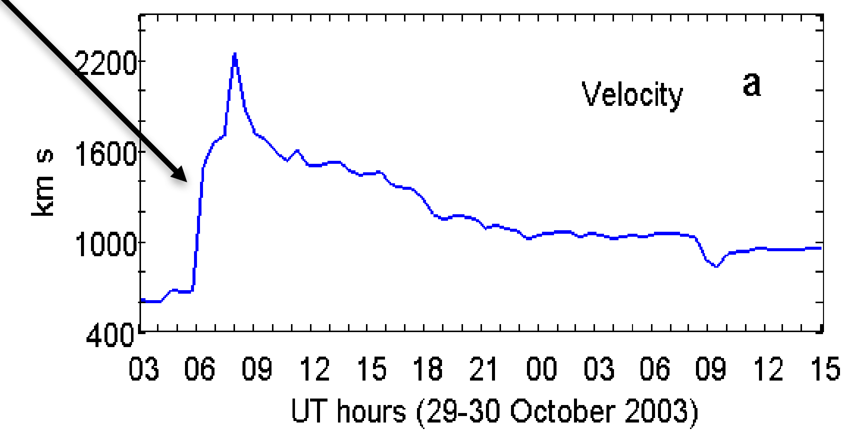
This space weather event resulted in the most intense geomagnetic storm in last two solar cycles, DstMin = -422 nT.

But it does not cause any damage.

So it is a normal space weather (NSW).

ICME front or ICME shock





ICME front (or shock) **velocity ΔV** is the difference between the velocities two hours after and two hours before the start of the velocity increase.

2. New parameters

Conventionally, the geomagnetic storm intensities (DstMin, Kpmax and AEmax) have been used for space weather applications on Earth.

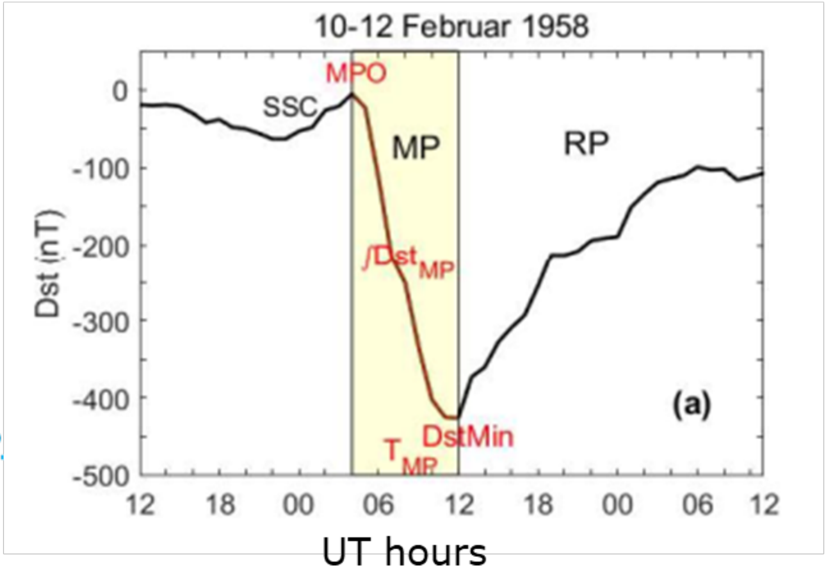
However, while studying what determines the severity of space weather, we realized that the storm intensities cannot distinguish between SvSW and NSW.

So, we introduced a new derived parameter called **impulsive Dst (or IpsDst)** and extended it to **IpsKp** and **IpsAE**

$$\mathrm{IpsDst} = \left(\int_{T_{MP}} |Dst_{MP}| dt\right) / T_{MP}$$

$$= \int Dst \text{ during MP / duration of MP}$$

IpsDst gives the mean value of Dst during MP.



- IpsDst is proportional to total energy input / duration of energy input. The higher the energy input and shorter the duration, the larger the IpsDst and more impulsive its action, So the name IpsDst.

- IpsDst contains most important characteristics of Dst storms (SSC, $\int Dst_{MP}$, DstMin, T_{MP}, and $(dDst/dt)_{MPmax}$).

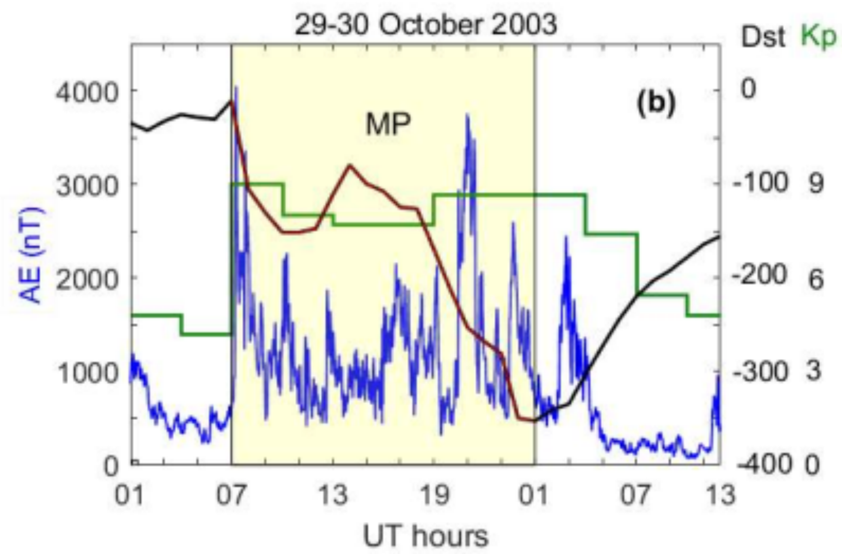
  It therefore captures many important processes (ICME shock, magnetopause compression, SSC and energy input) leading to SvSW.

- IpsDst is derived for all storms (≤-50 nT) automatically identified in Kyoto Dst since 1957.

IpsKp and IpsAE

IpsKp = $\Sigma Kp_{MP}/T_{MP}$

IpsKp gives the mean value of Kp during the MP of Dst storm when main energy input occurs.



IpsAE = $\Sigma AE_{MP}/T_{MP}$

IpsAE gives the mean value of AE during the MP of Dst storm when main energy input occurs.

3. Applications of new parameters

(i) Distinguishing between SvSW and NSW

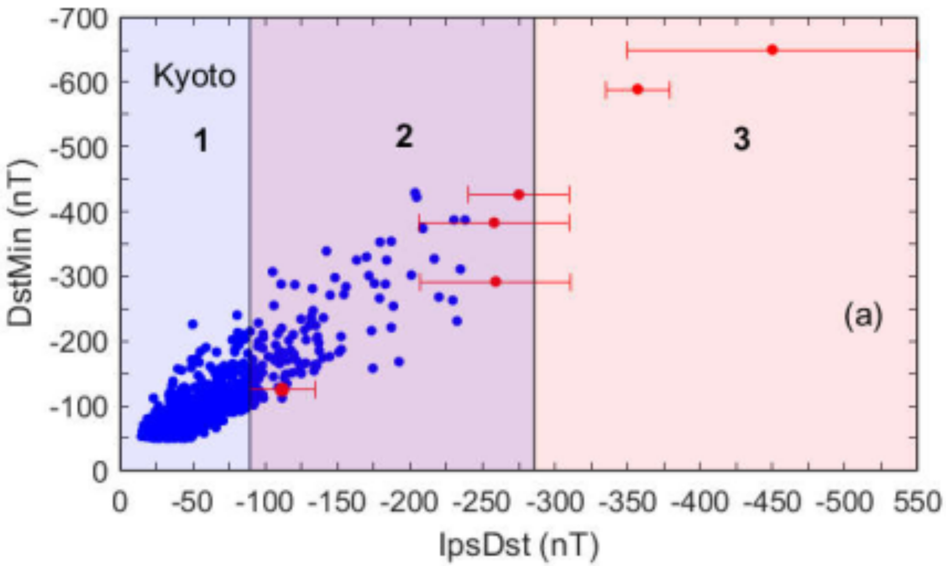
SvSW (since 1957)

11 February 1958
04 August 1972 **?**
13 March 1989
06 November 2001
30 October 2003

01-02 September 1859

Over 800 NSW

IpsDst Vs. DstMin



SvSW

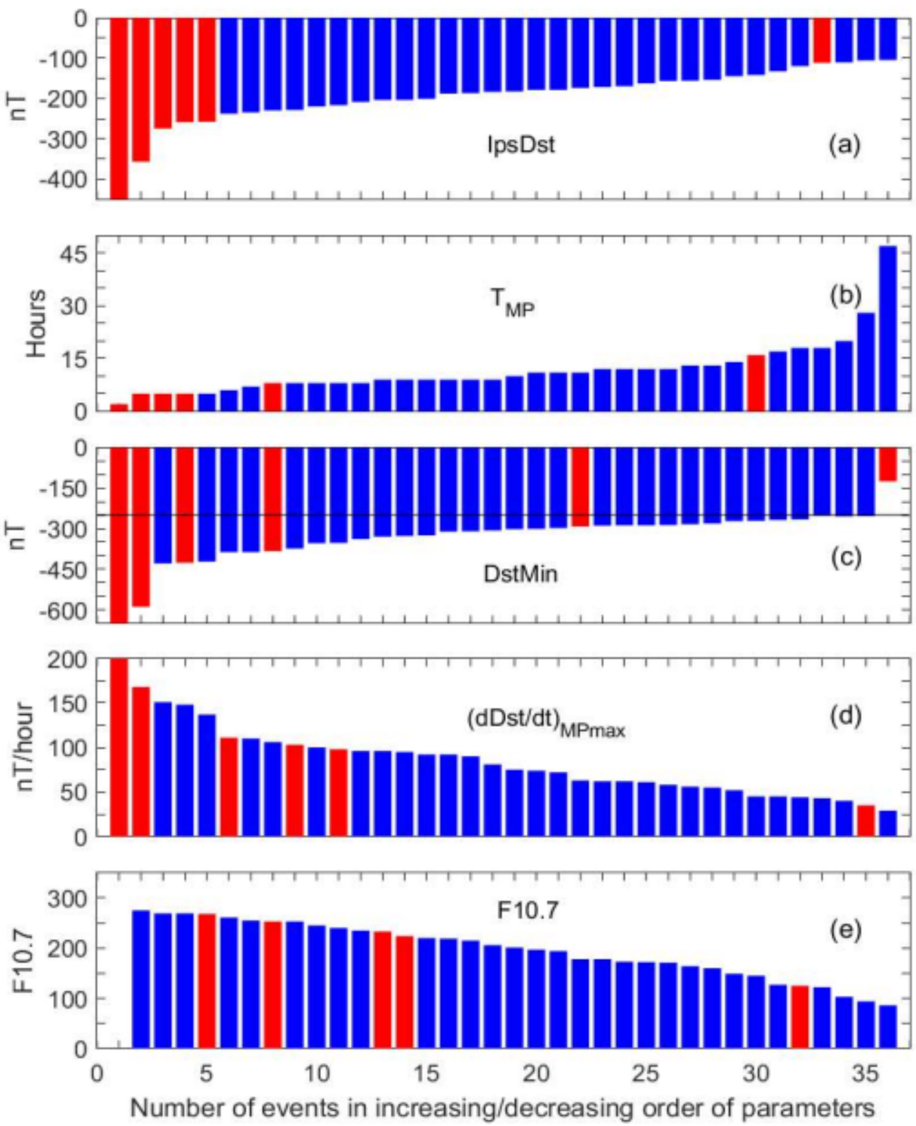
11 February 1958
04 August 1972 ?
13 March 1989
06 November 2001
30 October 2003

01-02 September 1859

Over 800 NSW

IpsDst distinguishes 5 out of the 6 SvSW events from over 800 NSW events.

IpsDst Vs all other Dst parameters

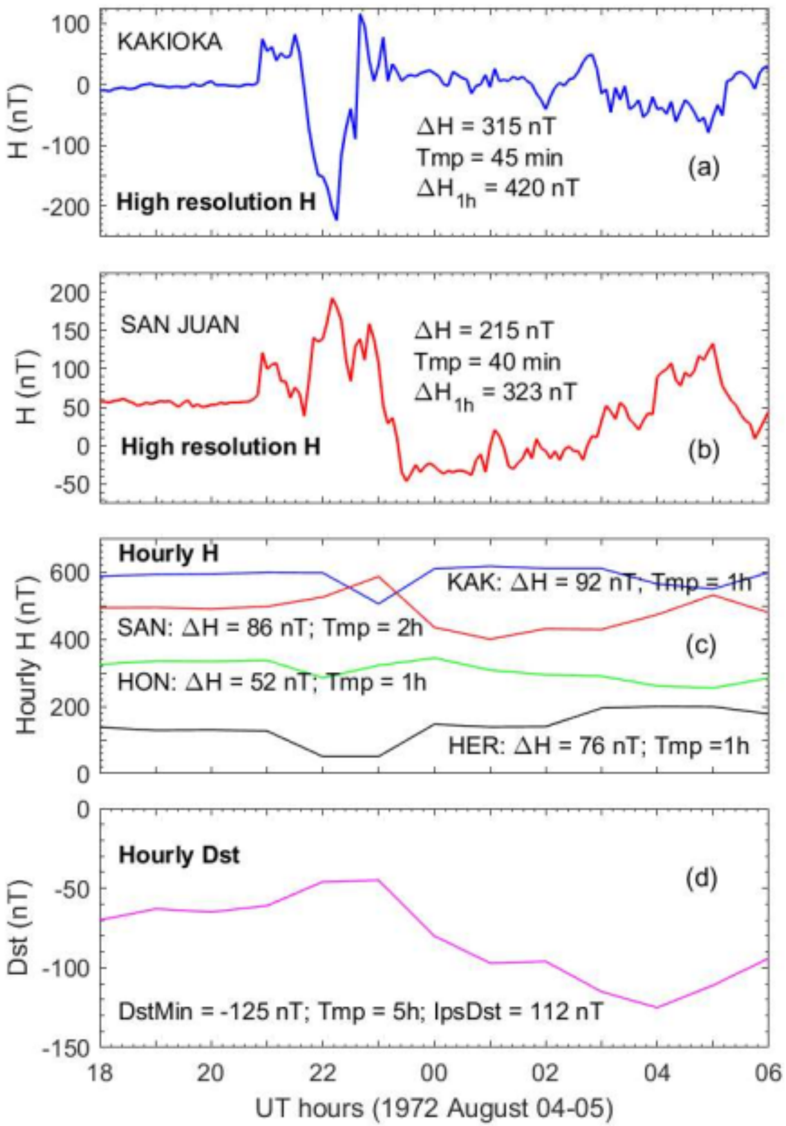


Parameters of all super storms and one intense storm (04 August 1972)

- Red corresponds to SvSW and blue to NSW.
- IpsDst distinguishes 5 out of the 6 SvSW events.

IpsDst does not seem distinguishing the lone SvSW event on 04 August 1972. (DstMin = -125 nT). It is discussed next.

04 August 1972



Re-analyzed characteristics of the storm on 04 August 1972

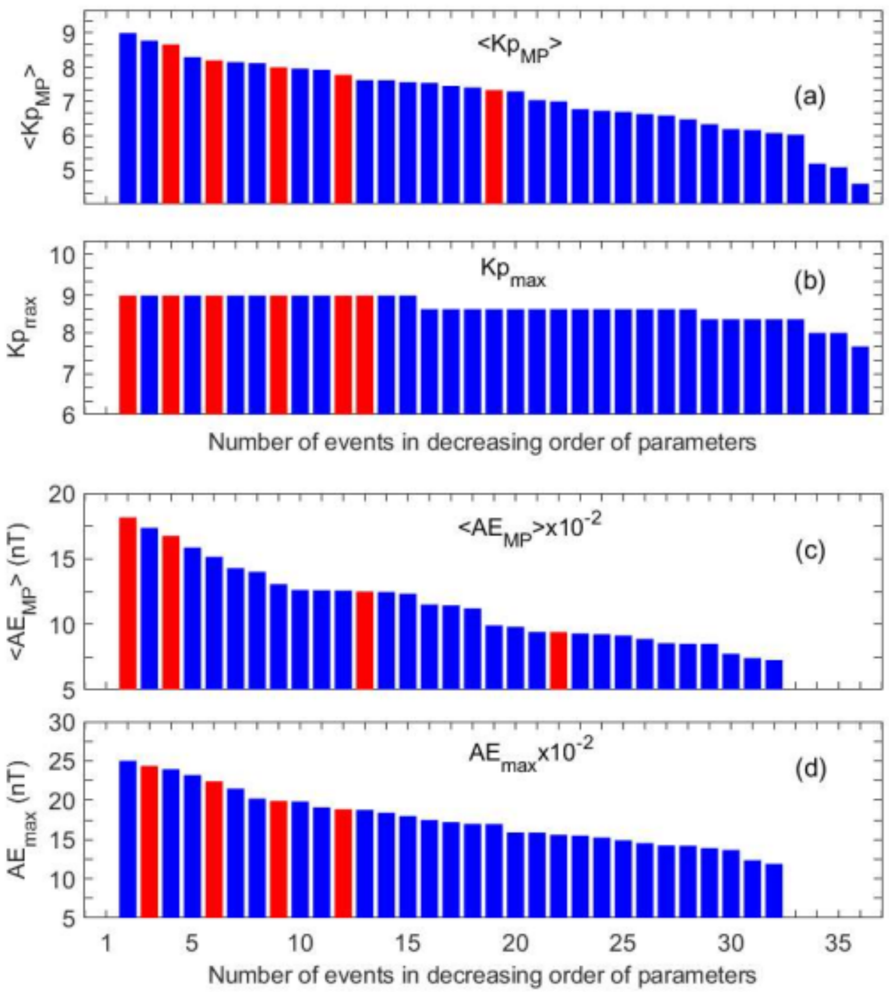
ΔH at Kakioka = 315 nT in 45 min.
(ΔH_{1H} = 420 nT)

ΔH at San Juan = 215 nT in 40 min.
(ΔH_{1H} = 325 nT)

The large H-ranges of short durations are not represented in the Dst of 1 hour resolution.

In short, **high resolution IpsDst** will be a powerful parameter.

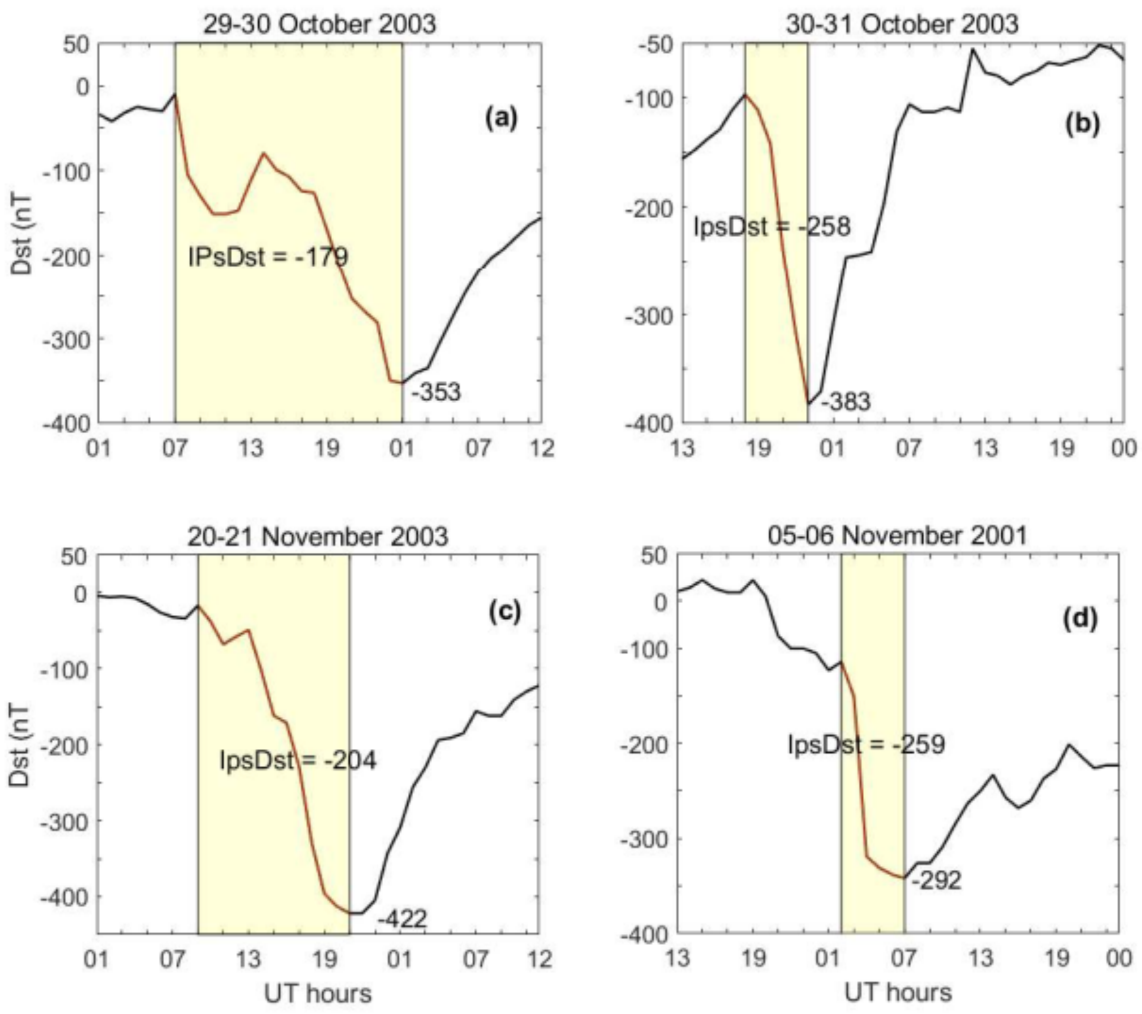
Capability of IpsKp and IpsAE



With IpsKp and IpsAE, the SvSW and NSW events are mixed up.

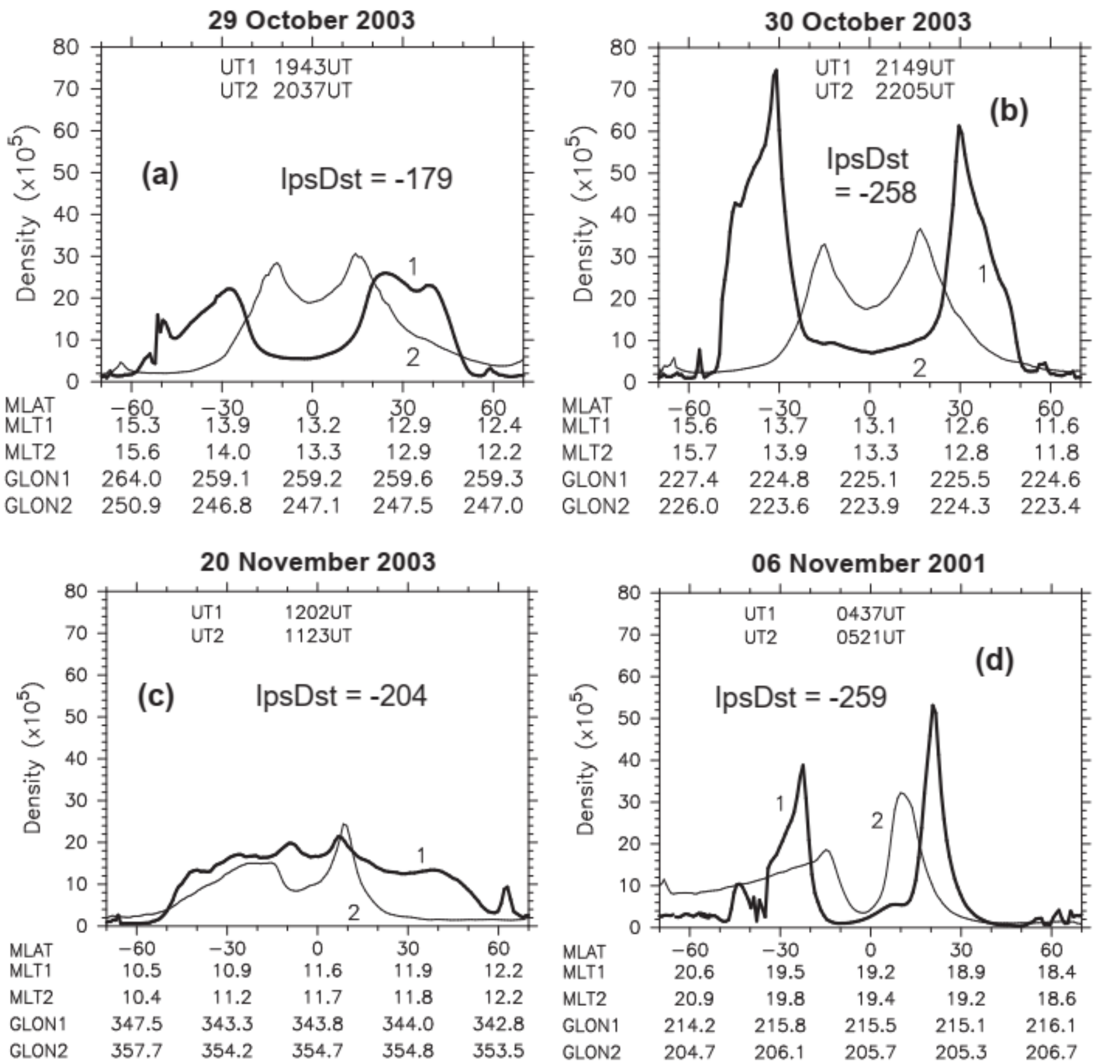
In other wards, IpsKp and IpsAE are not able to distinguish between SvSW and NSW.

IpsDst and ionospheric storms



Examples of four super storms: (a) and (c) of low IpsDst and
(b) and (d) of large IpsDst.

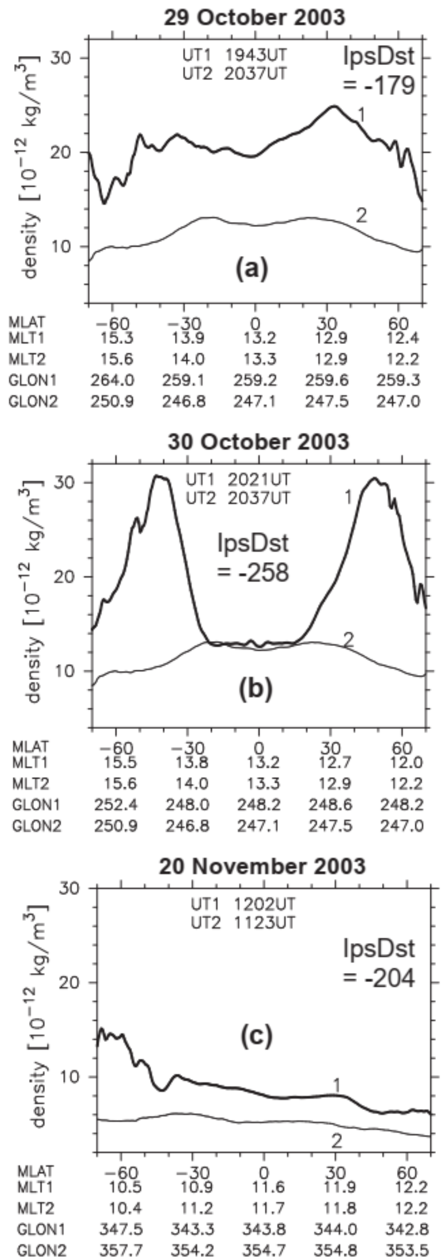
IpsDst and ionospheric storms



CHAMP Ne data

- Large IpsDst is associated with strong ionospheric storms.

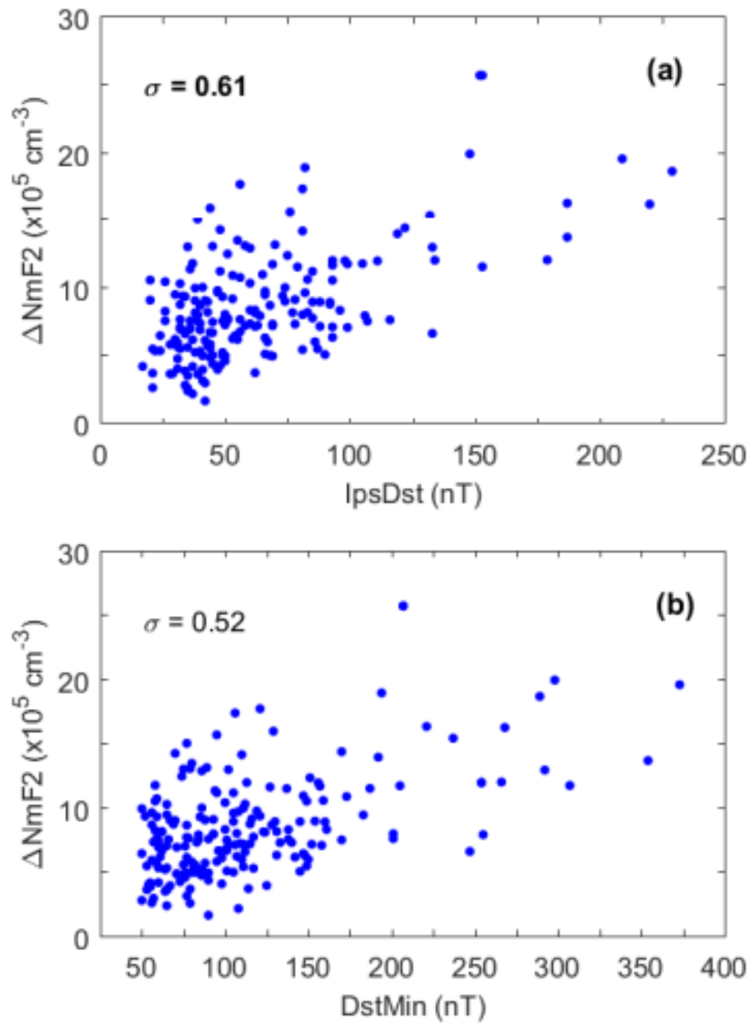
IpsDst and thermospheric storms



- Large IpsDst is associated with strong thermospheric storms.

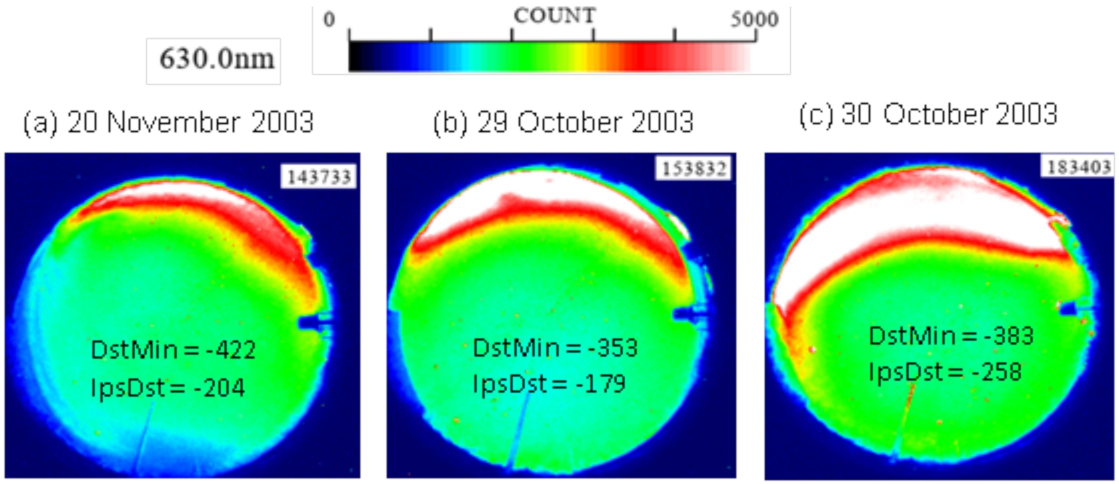
CHAMP **ρ** data

ΔNmF2 at Kokubunji during 191 storms in 1985-2005



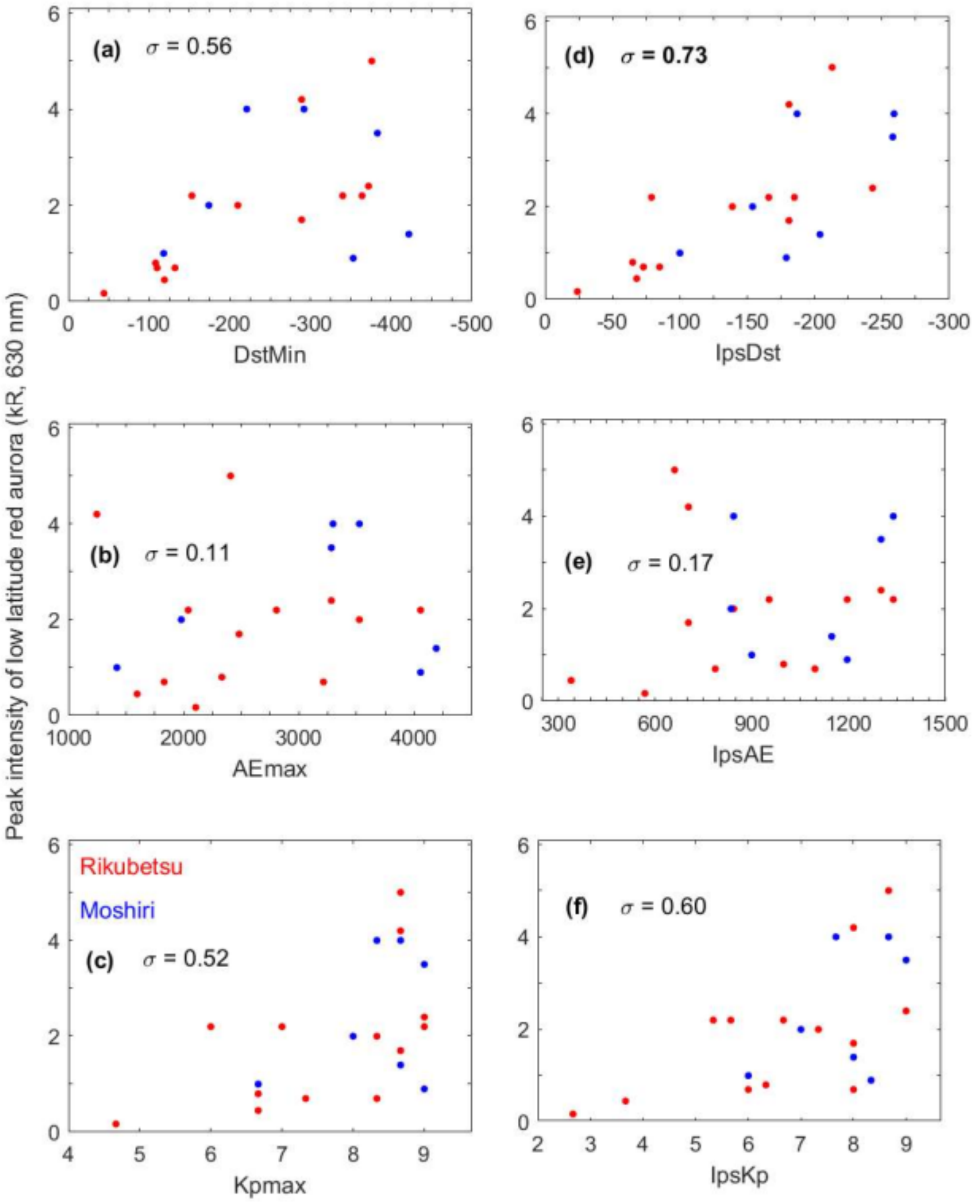
ΔNmF2 is better correlated with IpsDst than DstMin.

Examples of three low latitude auroras



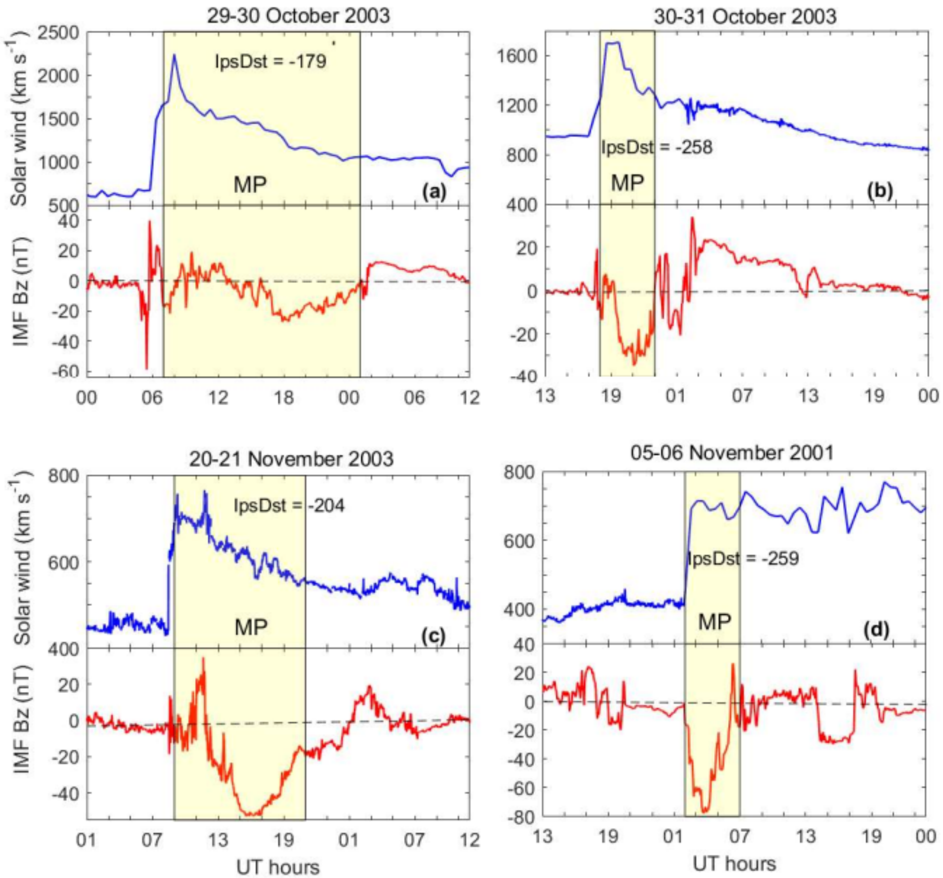
The aurora was more intense and lasted the whole night (30 October 2003) of large IpsDst

Auroral intensity Vs. storm parameters



Auroral intensity correlates best with IpsDst and better with all new parameters compared to conventional parameters.

Physical mechanism



It involves the coincidence of high ⟨V_{MP}⟩ containing a high ICME front velocity △V and large ⟨Bz_{MP}⟩ southward covering △V.

Their combined impulsive action can cause impulsive entry of a large amount of high-energy charged particles into the magnetosphere and ring current through continuous and rapid magnetic reconnection.

This leads to large IpsDst, strong ionosphere-thermosphere storms, intense aurora, and SvSW through impulsive solar wind-magnetosphere-ionosphere-ground system coupling.

Summary

- ICMEs cause changes in IPS and planet's environment.
  The changes are collectively called space weather.

- SvSW damages electric power grids, tele-communication, etc.

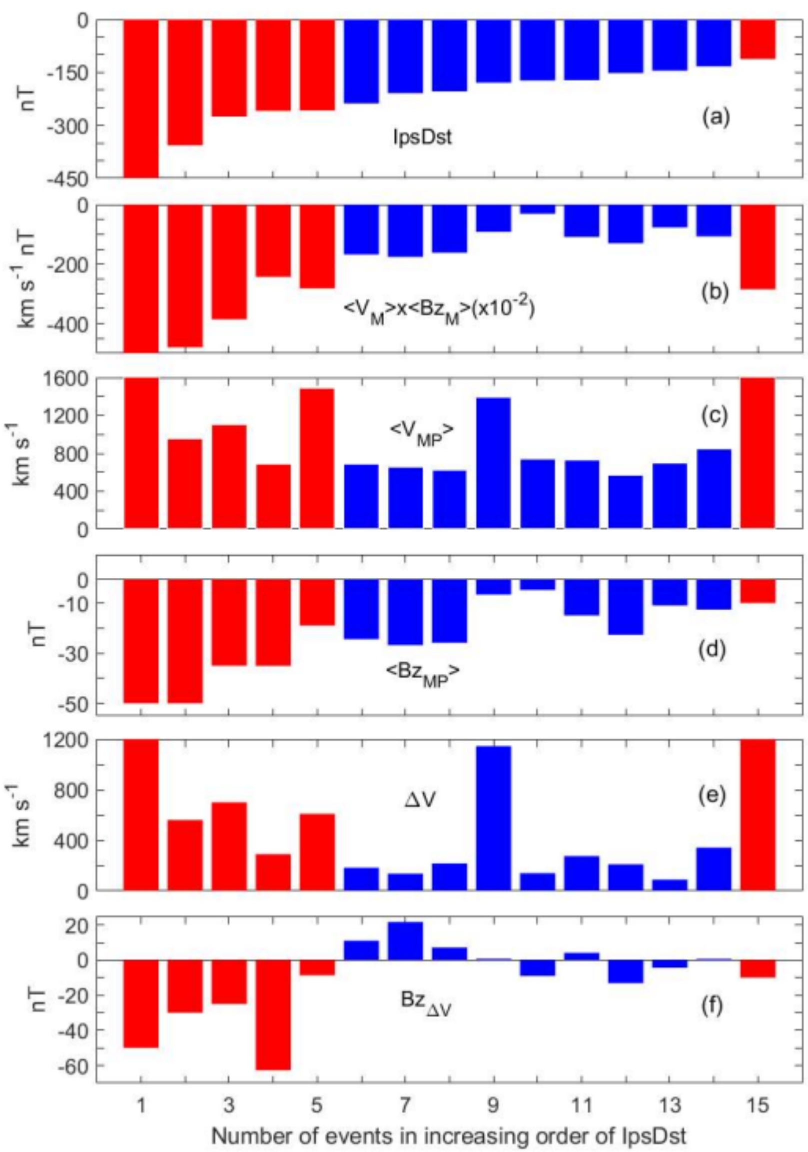
- IpsDst = $(\int_{TMP} |Dst_{MP}|dt)/T_{MP}$ is a simple but powerful parameter for space weather applications.

  - It can identify SvSW from NSW.
  - It is better for investigating ionosphere-thermosphere storms and low latitude aurora.

- IpsDst is powerful because it
  - Represents the impulsive strength of geomagnetic storms
  - Includes most important characteristics of geomagnetic storms (SSC, $\int Dst_{MP}$, DstMin, T_{MP}, and $(dDst/dt)_{MPmax}$),
  - Captures many important processes leading to SvSW (ICME shock, SSC and energy input)

- Fast ICMEs with large IMF Bz southward at its front (or shock) seems leading to large IpsDst and severe space weather through impulsive ICME-magnetosphere-ionosphere-ground system coupling.

Thank you



IpsDst of the super Dst storms since 1998, Carrington storm (number 1), and 1972 August storm (number 15) and corresponding solar wind and IMF parameters.

The coincidence of high $\langle V_{MP} \rangle$ containing a high $\triangle V$ and large $\langle Bz_{MP} \rangle$ southward covering $\triangle V$ causes large IpsDst.

The coincidence also causes large ionosphere-thermosphere storms, low latitude aurora, and SvSW through impulsive solar wind-magnetosphere-ionosphere-ground system coupling.

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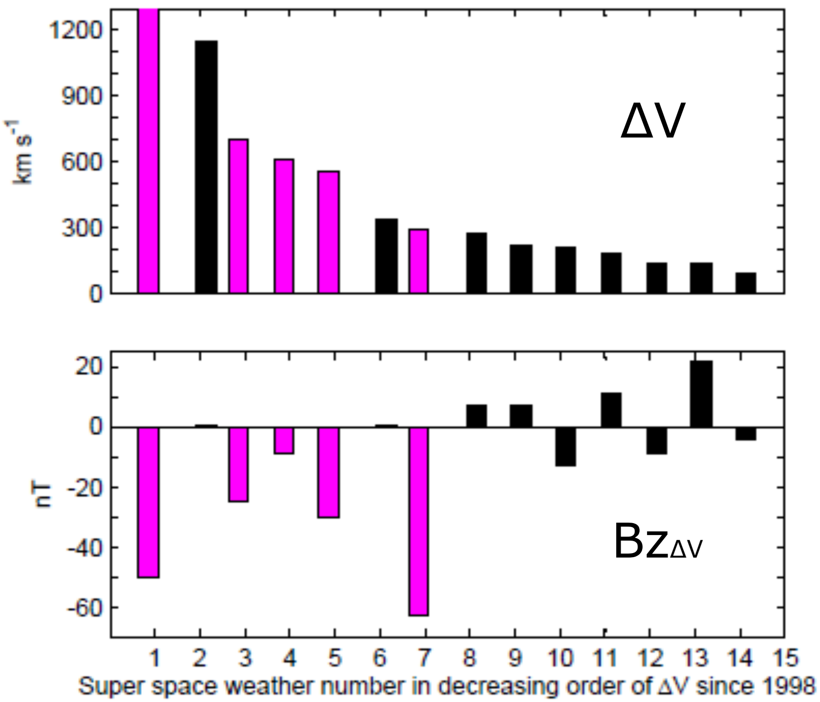
Summary-2



ΔV and Bz at ΔV corresponding to all super storms in 1998-2016.

- It is the coincidence of high **ΔV** and large **Bz** negative that determines **SvSW**.

- Low ΔV or Bz positive at ΔV causes only NSW.