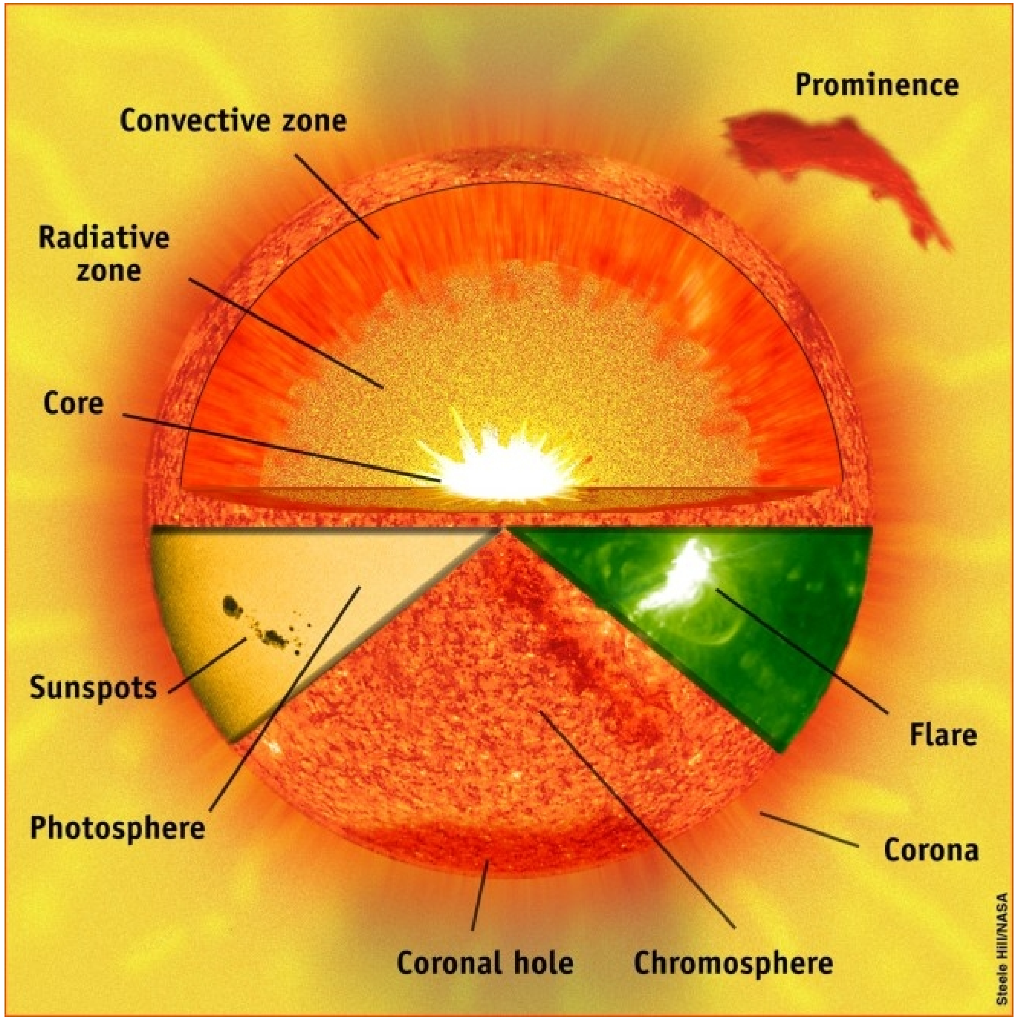
Space Weather ~ Affects of solar activities onto Earth

"Cause-Effect" Time Intervals range from **immediate** (precisely, 8 minutes) to **several days**.

Two difficulties arise for forecasting (modelling):

- Highly precise **solar storm** model (**Magnetic reconnection** simulation by means of **Magnetohydrodynamics** (**MHD**))
- Very complicated **geomagnetic storm** model

From the beginning... (What are **solar activities**?)



Static solar activities

The quasi-periodic 11-year solar cycle (and thus the appearance of sun spots) can be explained by **solar dynamo theory** (and the convective zone is the region where the process is in progress).

Transient and violent solar activities

The explosive phenomena such as solar flares, prominences and CMEs take place over the sun spots but in the corona**.**

►These are the actual situation of solar storms.

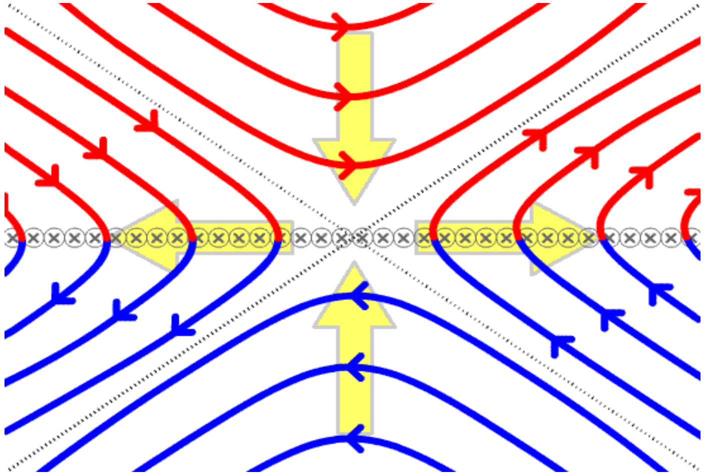
Solar Wind to Solar Storm

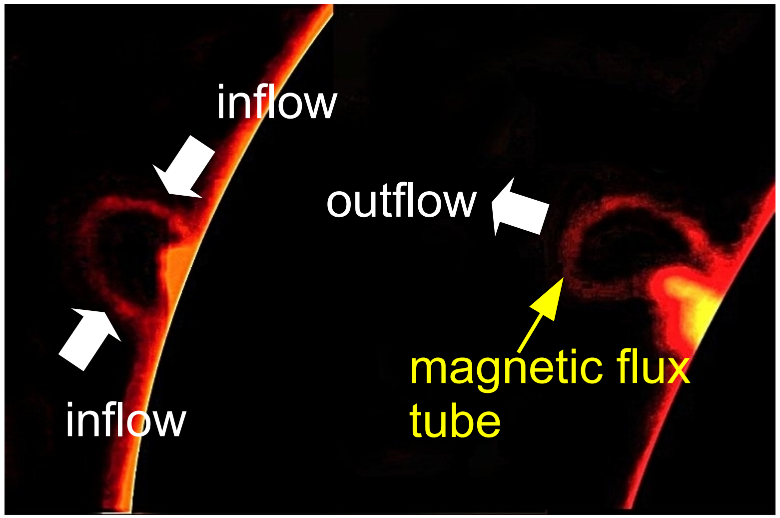
Heliospheric current sheet

Solar wind is composed of the **solar magnetic fields** (***B***, conventionally it is called the **interplanetary magnetic fields**, B_{IMF}) and **plasma** wound around the magnetic fields (e.g. the solar magnetic fields as a **guiding centre** for plasmas).

Solar storm is, on the other hand, the **release of magnetic energy** associated with **the collapse of the magnetic topology** (**magnetic reconnection**).

Magnetic reconnection – The mechanism for creating **solar flare**, prominence and **CME**





1) Field lines (and associated plasma) flow **inward** from **above** and **below** the separator,

2) Field lines **reconnect**, and spring **outward horizontally**.

Problem – This process is not well understood: once started, it proceeds many orders of magnitude faster than predicted by standard models (resistive MHD).

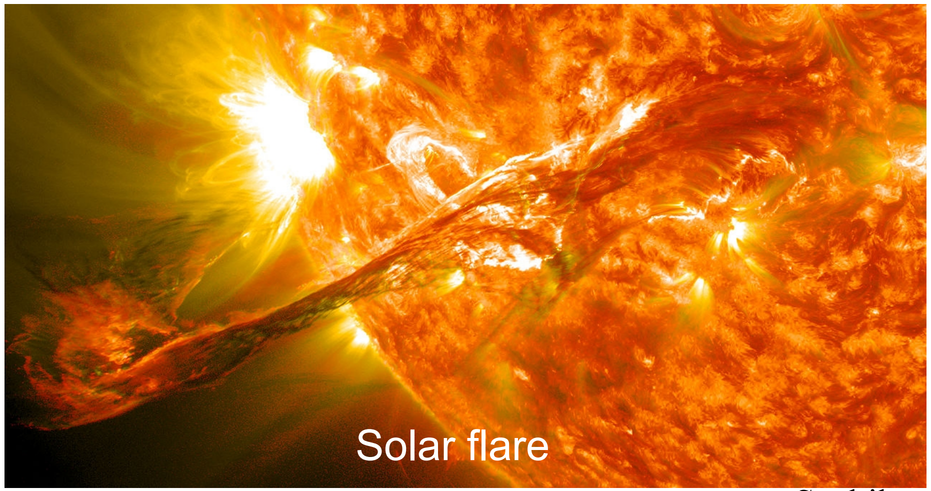
What are **solar storms** / **geomagnetic storms**?

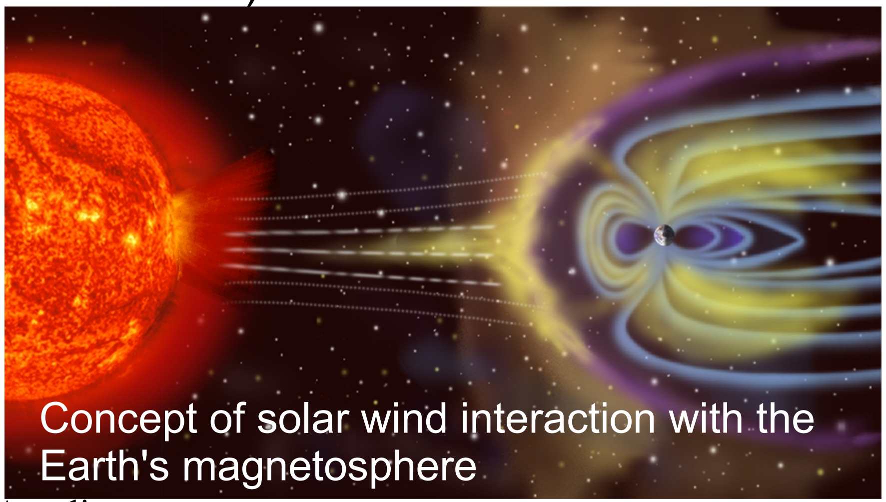
The followings are referred as **solar storms**:

- **Solar flare** … large explosion in the solar atmosphere, mostly EM waves
- **Coronal mass ejection (CME)** … massive burst of solar wind (frozen-in magnetic fields associated with plasma), sometimes associated with solar flares
- **Solar particle event (SPE)** … direct impact of particles that are emitted by the Sun and subsequently accelerated by solar flares up to (or more than) 10 MeV.

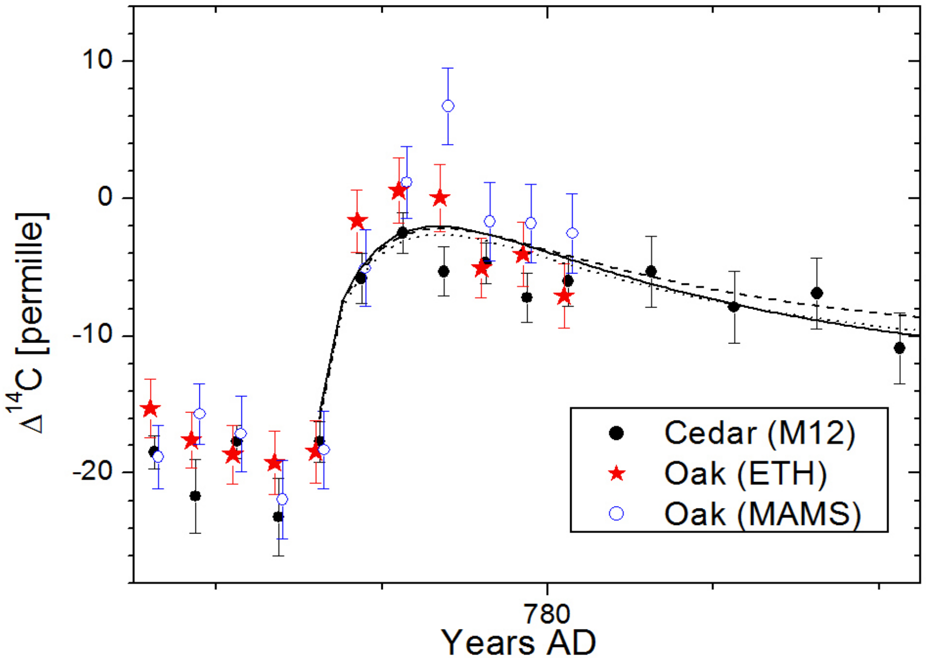
- **Geomagnetic storms** … the interaction of the solar outbursts with Earth's magnetic fields (precisely, **concomitant** of solar storm)

Time difference


Solar flare


Concept of solar wind interaction with the Earth's magnetosphere

How **frequent** are **solar storms**?



The curve with sharp increase and slow decrease (of **carbon-14** contents in several species of trees) means that **instant production of ^{14}C in the atmosphere and the event duration is short**.

There is no record on **supernova** and thus gamma-ray burst seems unlikely to cause this event.

Most likely cause so far is **solar flare**/**solar energetic particles** and associated **solar proton events** in the atmosphere.

References:
Miyake, F.; Nagaya, K.; Masuda, K.; Nakamura, T. (2012). "A signature of cosmic-ray increase in AD 774–775 from tree rings in Japan". Nature 486 (7402): 240–242.
Usoskin, I. G. et al. (2013). "The AD775 cosmic event revisited: The Sun is to blame". Astronomy & Astrophysics 552 (1): L3. ArXiv:1302.6897.

Such 774 AD event may occur **once per tens of millennia**, while weaker events (for instant, a factor 1.5 less of the 774 AD event) may occur **once per a millennium or even a century**.

List of **solar storms** within the (almost) latest century

- Solar storm of 1859 ("**Carrington event**") (*solar maximum*)
- Aurora of November 17, 1882 (*solar maximum*)
- May 1921 geomagnetic storm (*descending phase*)
- March 1989 geomagnetic storm (*solar maximum*)
- August 1989 (*solar maximum*)
- Bastille Day event of July 14, 2000 (*solar maximum*)
- Halloween solar storms, 2003 (*descending phase*)

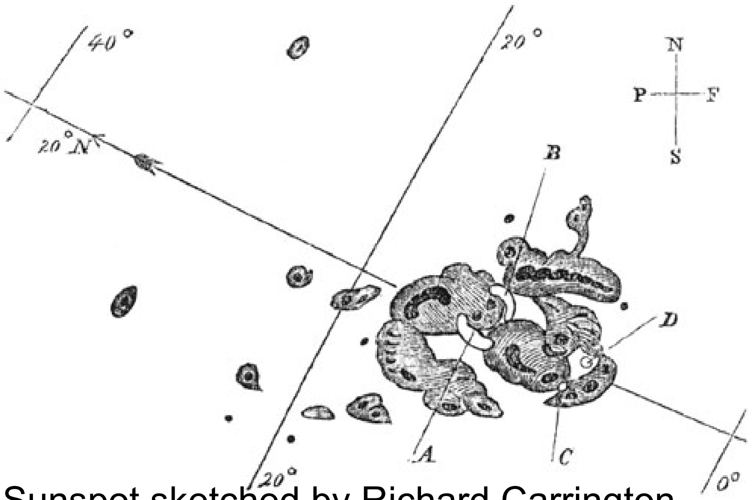
Since the Carrington event we have not encounter ***extreme solar storm*** *(once per a century) yet.*

The followings are the events not affecting Earth

- 4 November 2003 (*descending phase*)
- 23 July 2012 ("**Solar storm of 2012**") (*ascending phase*)

Since Solar Cycle 23 the solar activities seem irregular, and thus space weather forecasting seems much difficult.

Carrington Event



Sunspot sketched by Richard Carrington, 1895.

- A huge **CME** hit the Earth's magnetosphere and one of the largest **geomagnetic storms** on record (as recorded by ground-based magnetometers) was induced.

- **Aurora** of the unprecedented was visible as far from the poles as Sub-Saharan Africa, Tampico in Mexico, Cuba and Hawaii.

- **Telegraph systems** all over Europe and North America failed.

- According to a study in 2013, economic damage due to the similar event to the US alone has been estimated at $0.6–2.6 trillion.

Reference: Lloyds' and AER, "Solar Storm Risk to the North American Electric Grid", 2013.

- **The solar storm of 2012 was of similar magnitude, but it passed Earth's orbit without striking the Earth**.

Reference: http://science.nasa.gov/science-news/science-at-nasa/2014/23jul_superstorm/

Intermediate Summary
- What are requirements for space weather forecasting?

- **Accurate models for both solar and geomagnetic storms** … *As current situation, we should correspond with continuous monitoring of the Sun and empirical/statistical models using the data from the monitoring.*
- **Wherever possible, the calculation of plausible frequency of solar storms** … *Studies from astrophysics (evolution of stars in the Main Sequence) and palaeoclimatology (e.g. tracing ^{14}C contents)*

- **To clarify that's do alarm "for what"** … Let's have a look at the **individual impact and damage** due to solar storms and geomagnetic storms in the following sections.

Effects/influences of **solar flare**, **CME** and **SPE** (1)

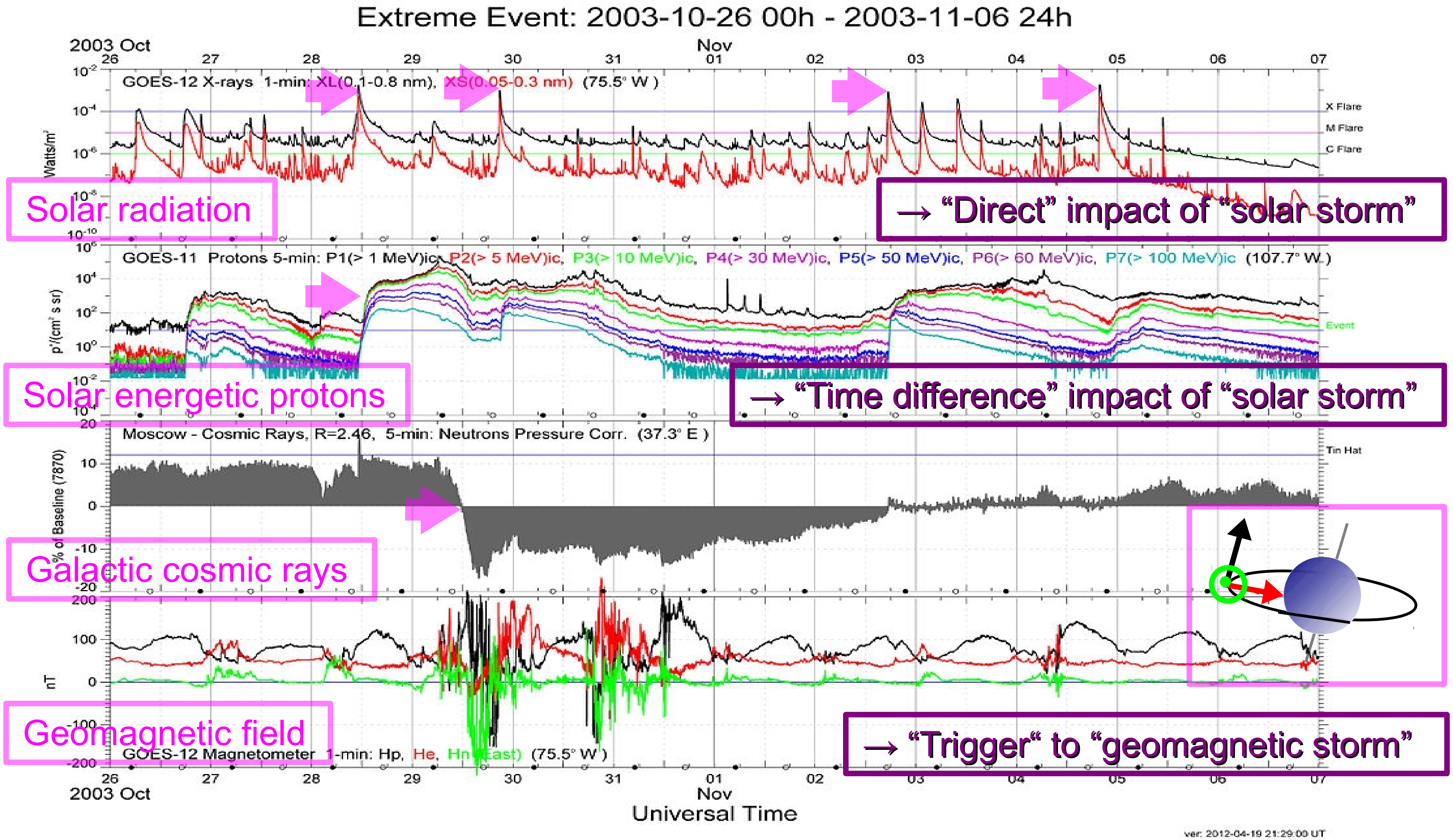
Spacecraft anomalies	Spacecraft orbit changes	Radiation hazard on human bodies
Disruption of GPS and other spacecraft signals	Disruption of long-distance radio signals	

- Spacecraft anomalies (from LEO and upwards)

… **Radiation damage** and **spacecraft charging** are common as spacecraft anomalies. **Radiation damage** takes place when solar energetic particles pass through the spacecraft and into electronic components. **Spacecraft charging** is the accumulation of electrostatic charge, and if enough charge is built up, a discharge occurs.

… The 46 of the 70 spacecraft failures have occurred and been reported in October, 2003 (**Halloween solar storms**).

Halloween solar storms, 2003



GOES 12 was one of the series of geostationary (~5.6 R_E) orbiting satellites.

Effects/influences of **solar flare**, **CME** and **SPE** (2)

Spacecraft anomalies	**Spacecraft orbit changes**	**Radiation hazard on human bodies**
Disruption of GPS and other spacecraft signals	Disruption of long-distance radio signals	

- Spacecraft orbit changes (LEO)

… In particular, LEO (low Earth's orbit) satellites are affected seriously by **air drag**. When both **exosphere** and **thermosphere** get extra heat (via collision with solar radiation such as solar EUV), both the layers expand and rise, and thus the LEO satellites will be affected by **air drag**.

- Radiation hazard on human bodies (ISS/LEO)

… By both ionising radiation (solar energetic particles) and electromagnetic radiation

Effects/influences of **solar flare**, **CME** and **SPE** (3)

Spacecraft anomalies	Spacecraft orbit changes	Radiation hazard on human bodies
Disruption of GPS and other spacecraft signals	Disruption of long-distance radio signals	

- Disruption of GPS and other spacecraft signals (Ionosphere)

… Solar (E)UV is the cause of photo-ionisation of the high-altitude atmosphere, and the photo-ionised layer is called **Ionosphere**. The ionosphere bends **radio waves**. When the medium through which the radio waves travel is disturbed, the radio information is distorted and can become unrecognisable. The VHF band can be distorted totally and UHF band can propagate but the receiver cannot keep to lock when the ionosphere is distorted.

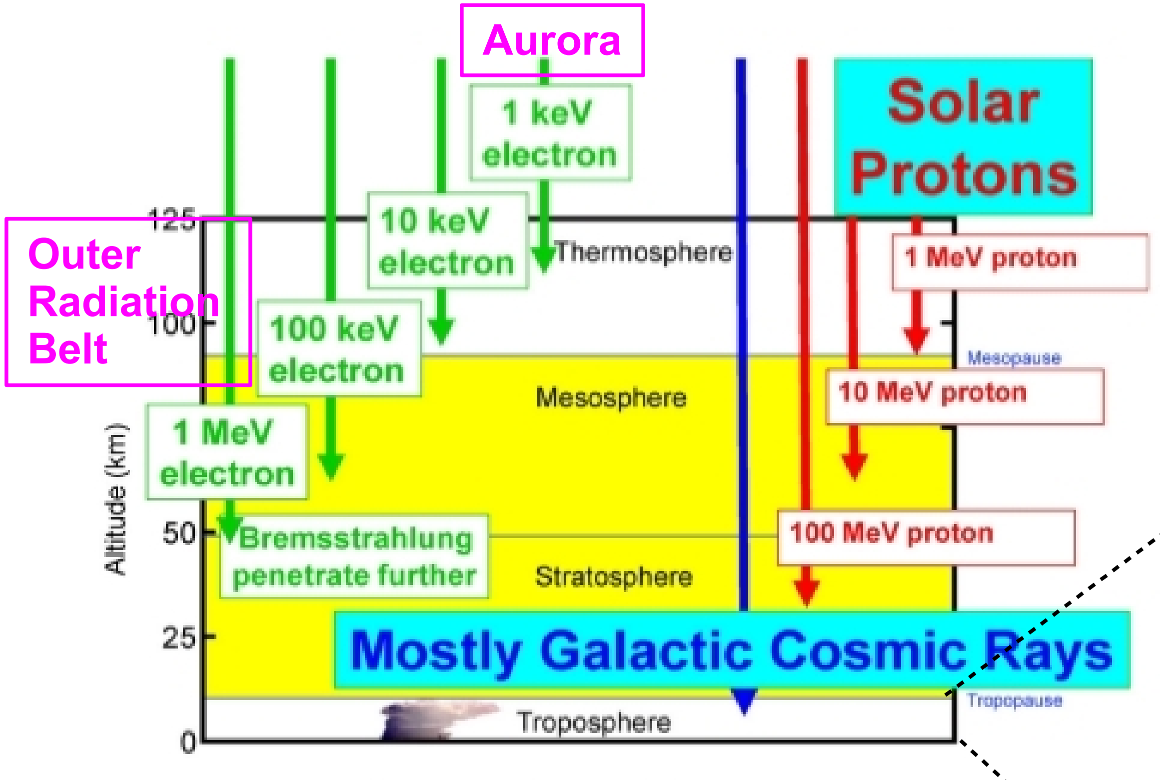
Effects/influences of **solar flare**, **CME** and **SPE** (4)

Spacecraft anomalies	Spacecraft orbit changes	Radiation hazard on human bodies
Disruption of GPS and other spacecraft signals	**Disruption of long-distance radio signals**	

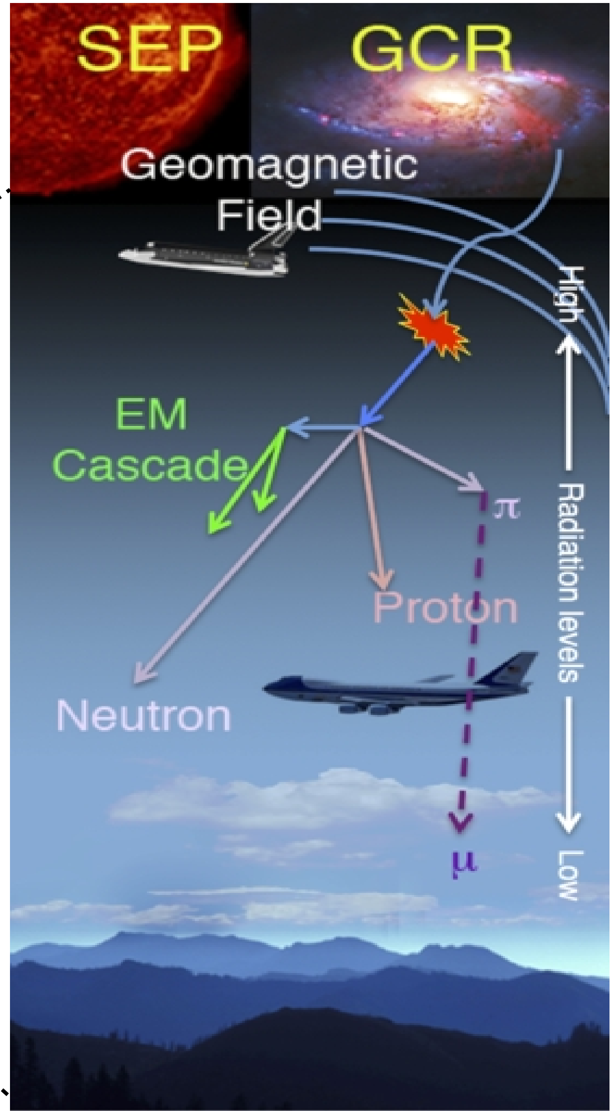
- Disruption of long-distance radio signals (Ionosphere)

… HF communications used by ships and aircraft will be affected by the ionospheric disturbance.

Solar Energetic Particles (SEPs) (1)



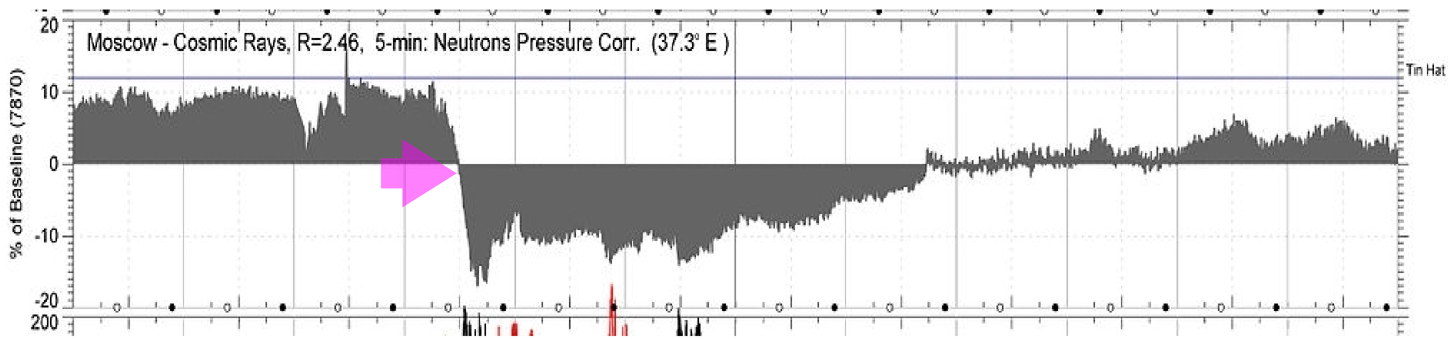
Atmospheric Structure



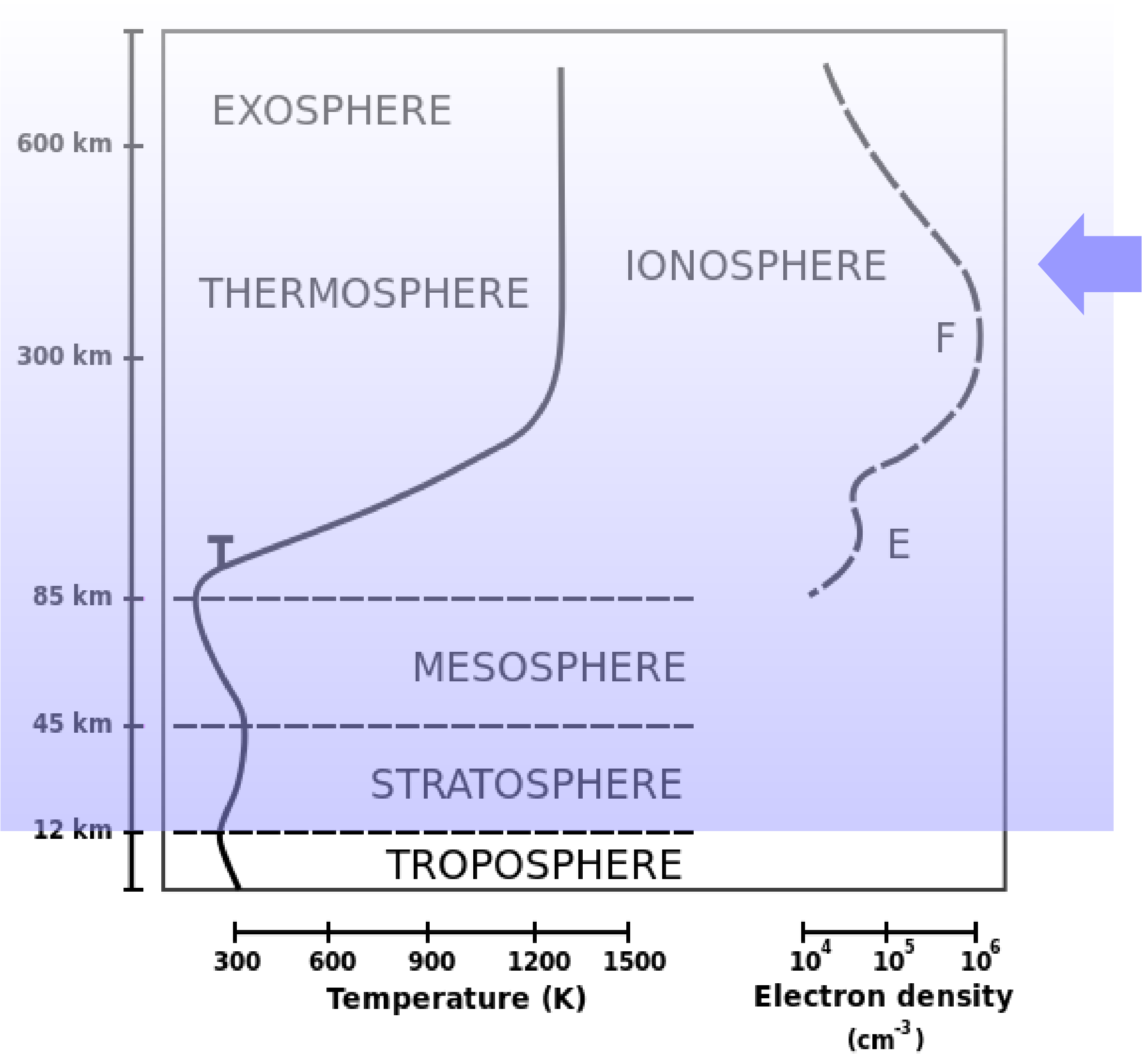
Solar Energetic Particles (usually protons and neutrons) are less energetic compared to Galactic Cosmic Rays (GCR) and **do not penetrate the troposphere, but interact with the upper atmospheres**.

Solar Energetic Particles (SEPs) (2)

SEPs are always accompanied by **interplanetary magnetic field** (i.e. **solar magnetic field**).
When solar storm-associated interplanetary magnetic fields press the Earth's magnetic fields (**geomagnetic fields**), the geomagnetic fields are strengthened.
The strengthening of geomagnetic fields suppresses the penetration of GCRs into the atmosphere, and **this decrease of GCRs in the atmosphere** is called **Forbush Decrease**.



For what **space physicists** are responsible?

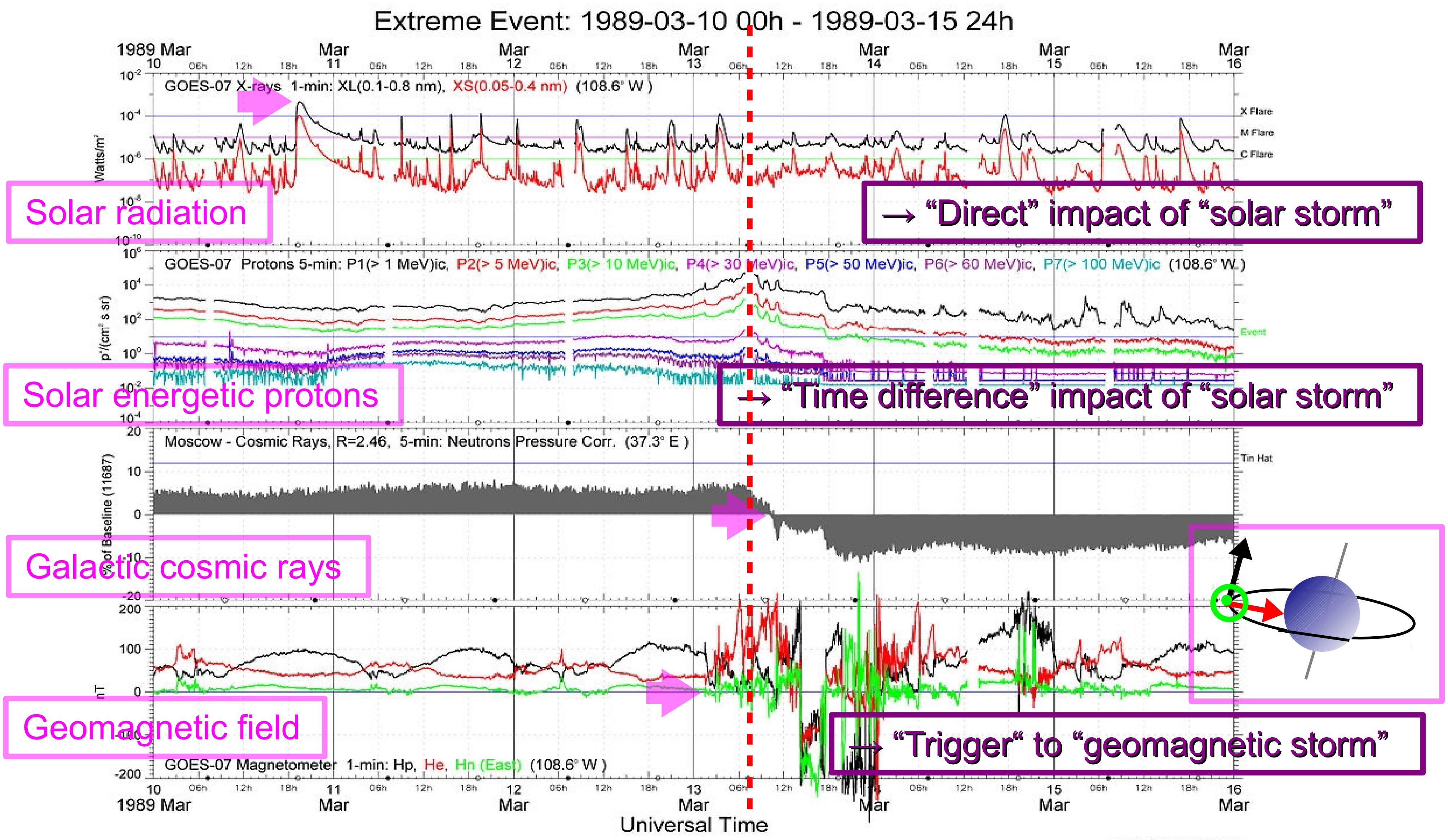


We take care of these regions and upwards (i.e. interplanetary space) and space plasmas.

Moreover, **geophysics in terms of electromagnetism**, too.
This is so-called **geomagnetic storms**.

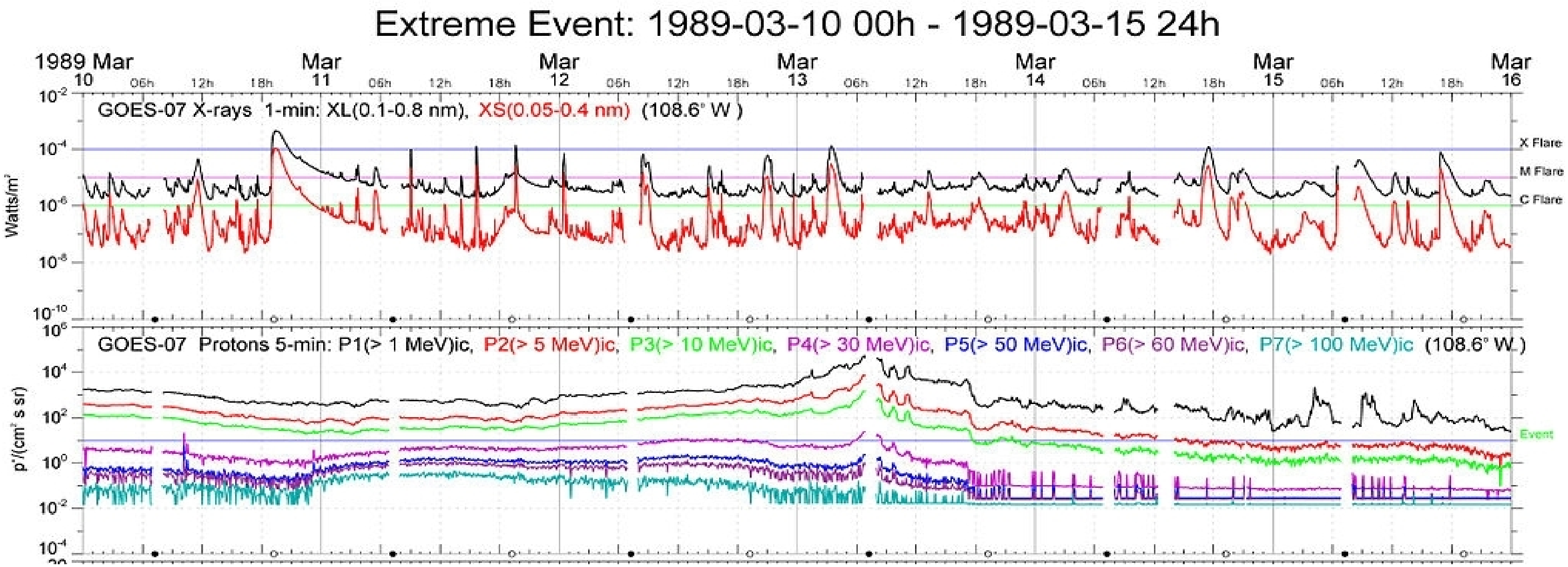
Geomagnetic storms and its Impact on the highly Electrified Modern Lives on the ground (March, 1989)

Overview of the Quebec Case (1)



GOES 07 was one of the series of geostationary (~5.6 R_E) orbiting satellites.

Overview of the Quebec Case (2)

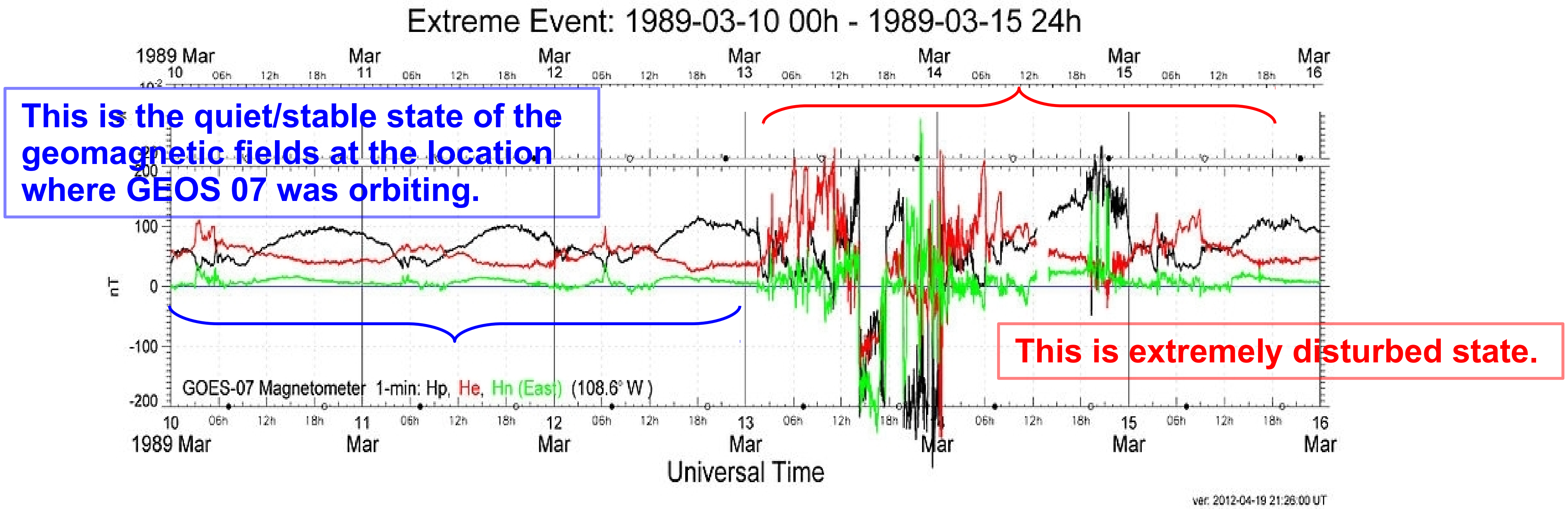


Direct and Time-difference Impacts of Solar Storm

...NASA's TDRS-1 communication satellite recorded over 250 anomalies as high-energy particles invaded the satellite's sensitive electronics. Even the Space Shuttle Discovery was having its own mysterious problems: A sensor on one of the tanks supplying hydrogen to a fuel cell was showing unusually high pressure readings on March 13.

Cited from http://www.nasa.gov/topics/earth/features/sun_darkness.html

Overview of the Quebec Case (3)



Triggering the geomagnetic storm and the associated "Quebec blackout"

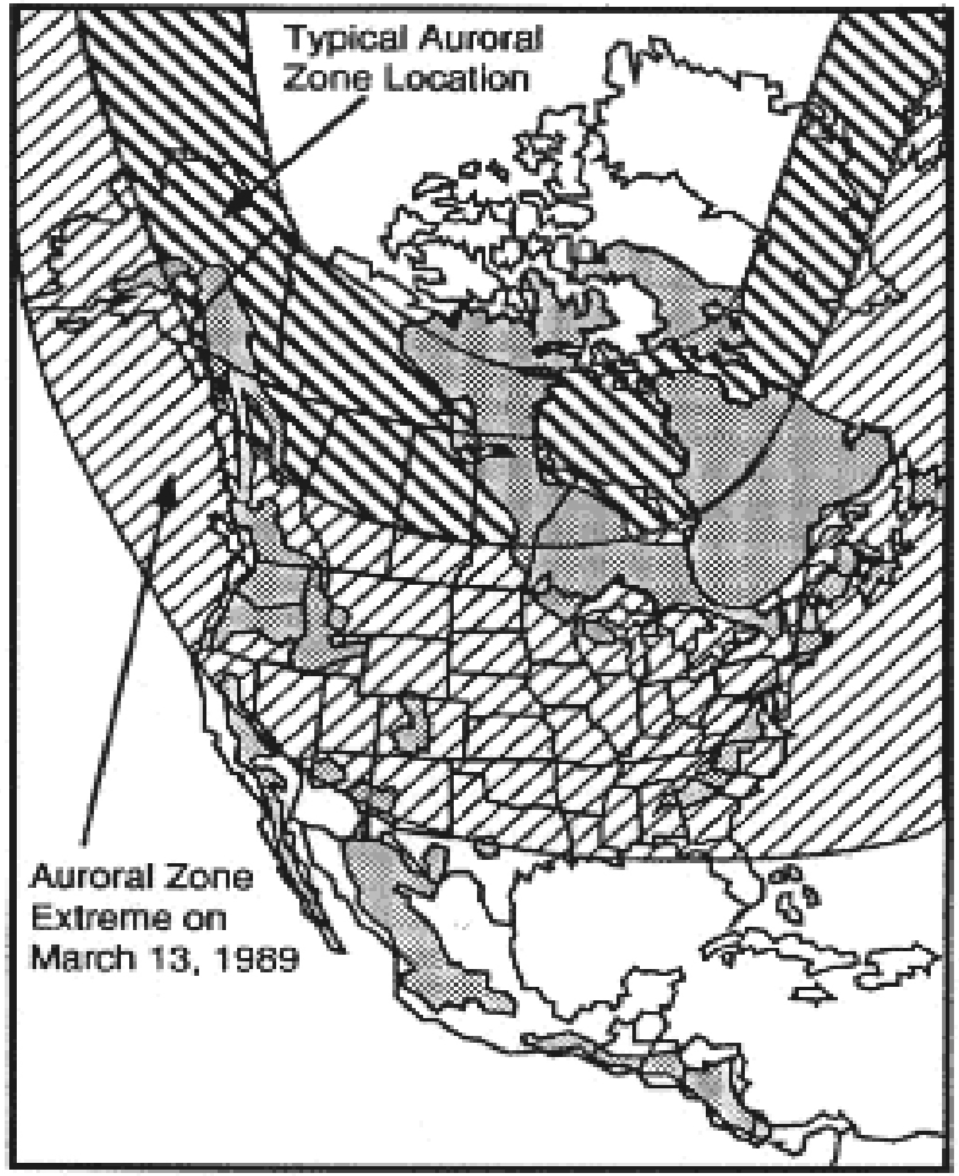
On the ground, the minimum **Dst** (index for disturbance grade of the geomagnetic fields in the equatorial region) was **-589 nT**.

The Dst is usually around -50 nT (very rarely -100 nT) during geomagnetic storm.

Dst = -589 nT corresponds to less than -1500 nT in the polar region such Quebec.

Overview of the Quebec Case (4)

Overview of the Quebec Case (5)



Explanation for the transformer damage

*Power systems in areas of **igneous rock (gray)** are the most vulnerable to the effects of intense geomagnetic activity because the high resistance of the igneous rock encourages **geomagnetically induced currents** (**GICs**) to flow in the power transmission lines situated above the rock.*

*Shown in cross-hatching are the **auroral zone** and the extremes that the aurora can reach during severe disturbances such as March 13, 1989.*

Credits: American Geophysical Union