Extreme Events and Super Storms

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What are we talking about?

- On the Sun
  - Flares, CMEs
- In Interplanetary Space
  - Shocks, Magnetic Clouds, MIRs → GMIRs
- At the Earth
  - GLEs, Forbush decreases, Geomagnetic Storms (Aurorae)

Outline

- Solar Events / GLEs / Extreme events
- Geomagnetic Storms / Superstorms
- Modeling of geomagnetic effects of cosmic rays during magnetic storms
- The Carrington event (superstorm event)
- Summary and Conclusions

Solar Events I

- see presentations by:

  - Gopalswamy
  - Bieber
  - Nymmik

Solar Events II

- Occurrence frequency:

  - from 1/day (at low energies)

    to

  - 1/year for GLEs
- Occurrence through the solar cycle:
  - Gnevyshev Gap
- Amplitude shows log-normal distribution

  → extreme events (definition?)

Extreme Solar Events (GLEs) I

Examples of super events:

- February 23, 1956,
- September/October 1989,
- January 20, 2005

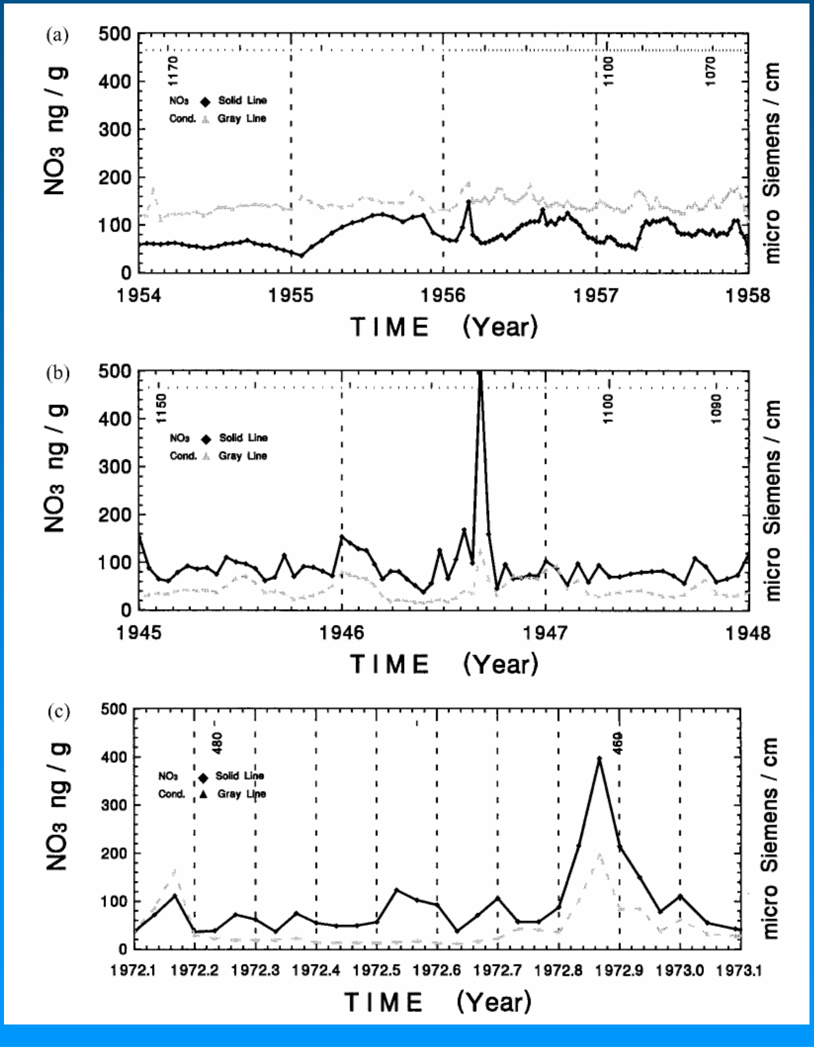
Major criteria for classification are e.g.

- the peak flux
- the event integrated >10 MeV (>30 MeV) total proton fluence near Earth

- Maximum particle energy
- …

Extreme Solar Events (GLEs) II

From a 125.6 m ice core drilled at Summit, Greenland (72N, 38W, altitude 3210 m) and two shorter cores drilled at Windless Bight (78S, 167E) on the Ross Ice Shelf, in Antarctica



McCracken et al., JGR **106**(A10), 21’585–21’598, 2001

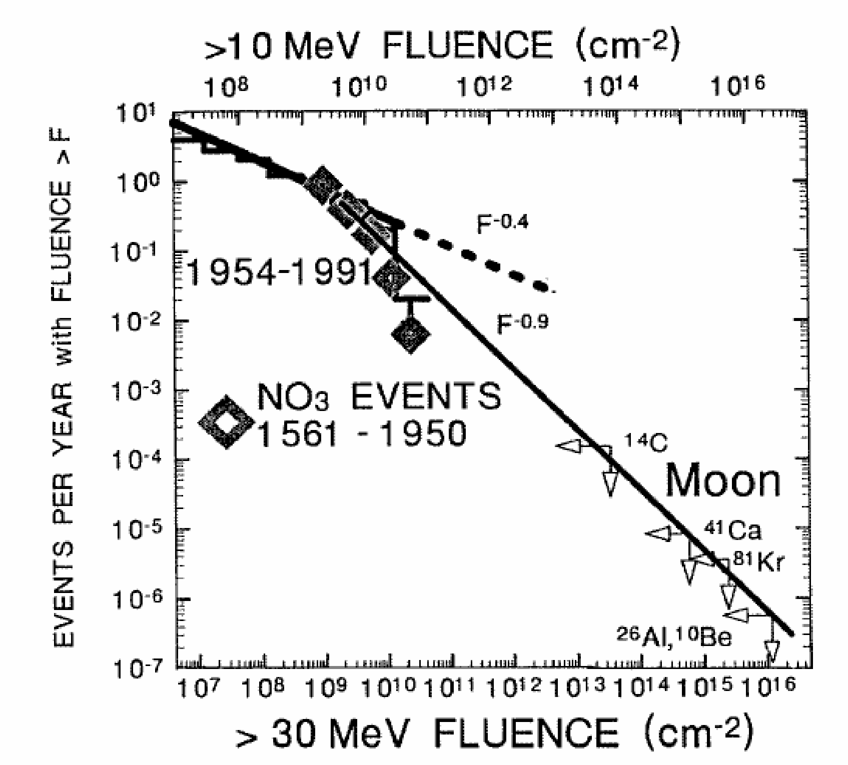
Extreme Solar Events (GLEs) III

70

Impulsive Nitrate Events
(30 MeV Proton Fluence >2 x 10^9 cm^{-2})
in the Interval 1561–1950

McCracken et al., JGR **106**(A10), 21’585–21’598, 2001

Extreme Solar Events (GLEs) IV



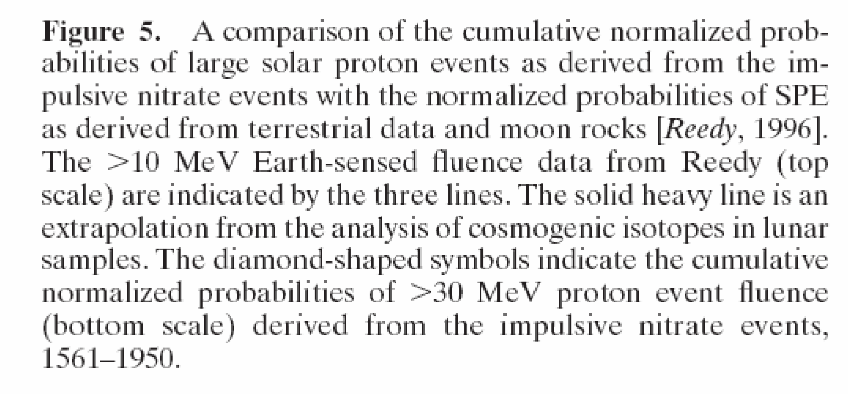


Figure 5. A comparison of the cumulative normalized probabilities of large solar proton events as derived from the impulsive nitrate events with the normalized probabilities of SPE as derived from terrestrial data and moon rocks [*Reedy*, 1996]. The >10 MeV Earth-sensed fluence data from Reedy (top scale) are indicated by the three lines. The solid heavy line is an extrapolation from the analysis of cosmogenic isotopes in lunar samples. The diamond-shaped symbols indicate the cumulative normalized probabilities of >30 MeV proton event fluence (bottom scale) derived from the impulsive nitrate events, 1561–1950.

McCracken et al., JGR **106**(A10), 21’585–21’598, 2001

Powerful Magnetic Storms

Powerful geomagnetic storms during the solar cycles 19 – 21:
November 13, 1960
August 5, 1972
February 8, 1986

On March 13, 1989, a major storm caused one third of Canada and part of upstate New York to lose electrical power.

The largest storm of solar cycle 23 occurred on November 20, 2003, with a Dst index of −472 nT.

Major criteria for classification are e.g.

- Amplitude of magnetic indices, e.g. Dst, Kp, …
- …

In many cases, magnetic storms are associated with solar partcle events and/or Forbush decreases (Fd)

Causes of Magnetic Storms I

- **~90% of the large geomagnetic storms (Dst < -100 nT) are associated with CMEs**

- **Tsurutani *et al. (1992)* have examined the interplanetary and solar causes of five largest geomagnetic storms during the period 1971–1986 and found that the extreme value of the southward IMF *B*z, rather than the solar wind speeds, are the primary causes of great magnetic storms**

(Tsurutani, B. T., Gonzalez, W. D., Tang, F. and Lee, *Geophys. Res. Lett*., 1992, 19, 73.)

Causes of Magnetic Storms II

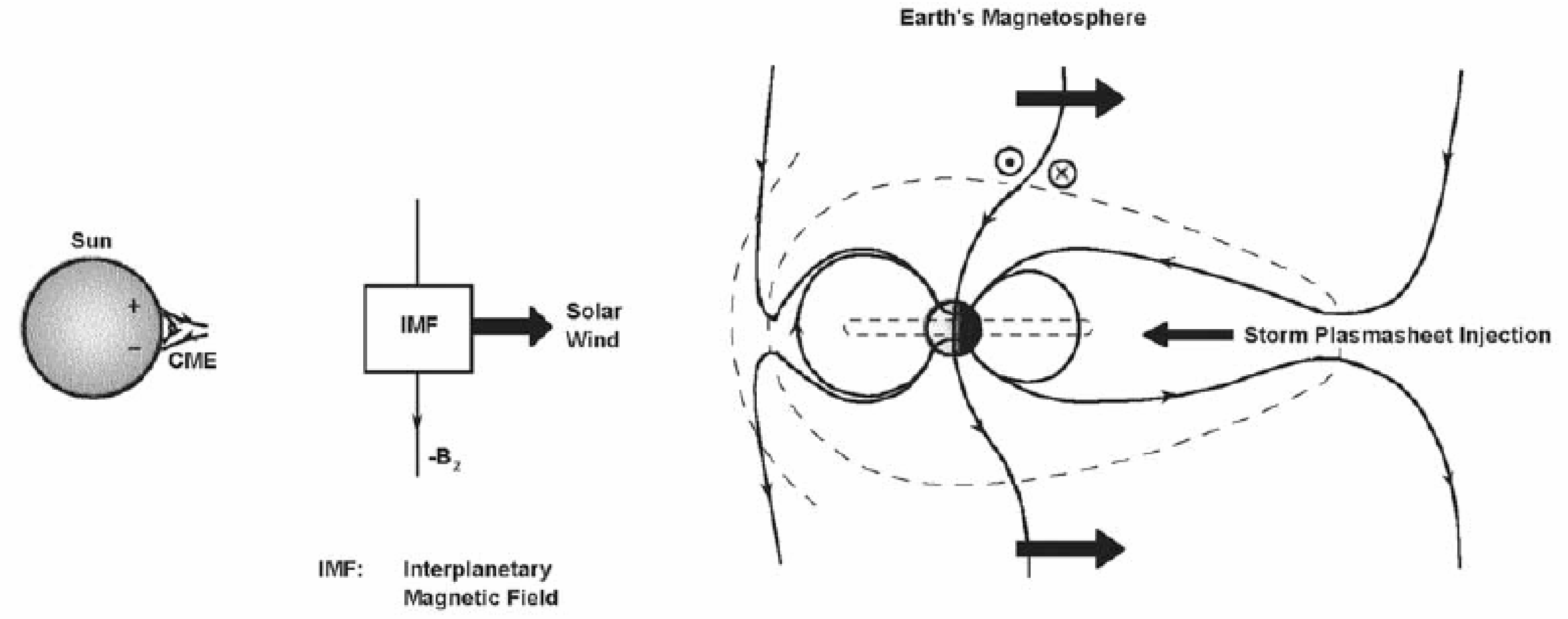


Figure 1. A schematic showing the magnetic reconnection process.

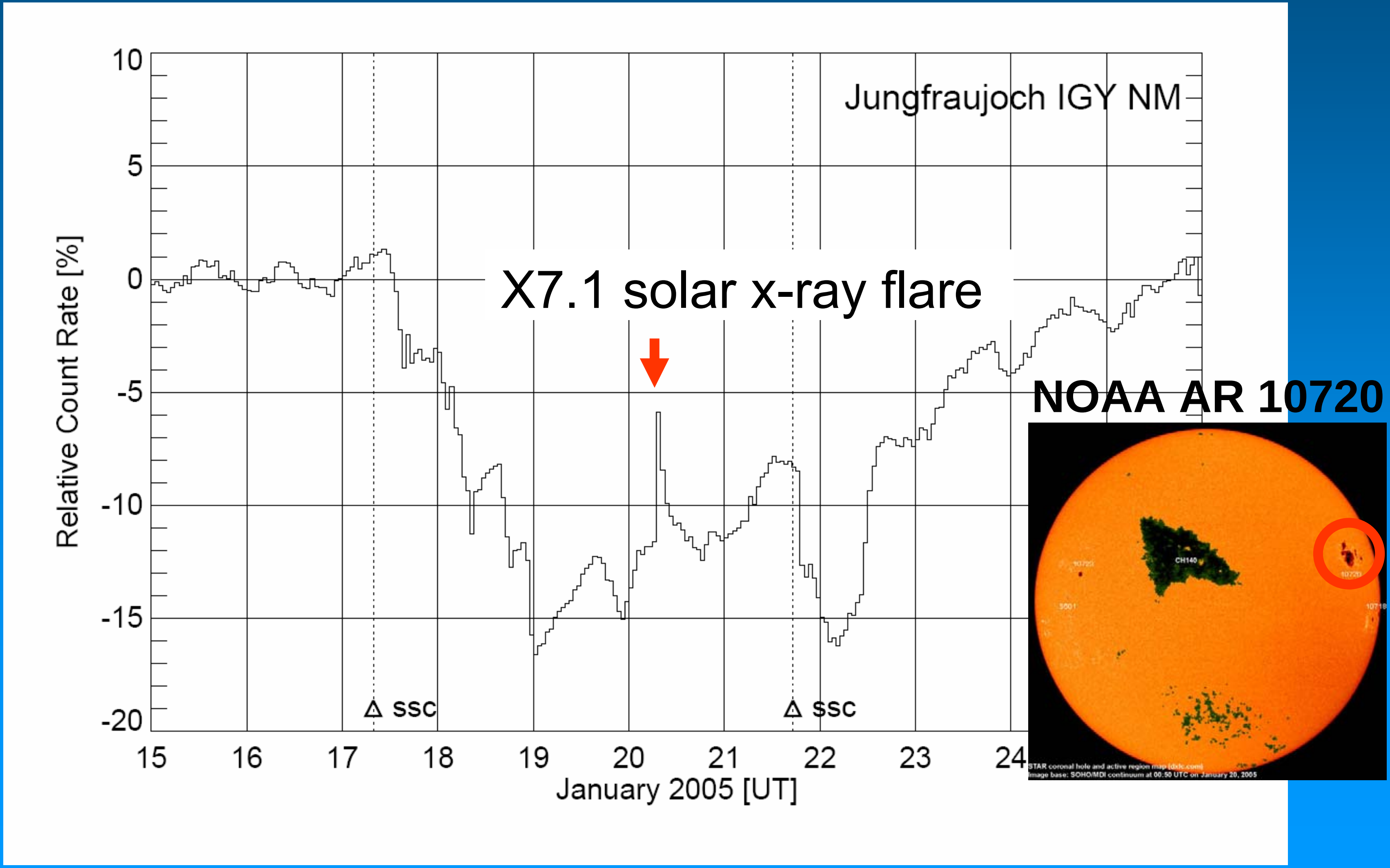
A schematic showing the magnetic reconnection process.

Tsurutani et al., JGR **108**(A7), 1268, 2003

Solar Events and Magnetic Storms I

- **GLE precedes magnetic storm (Fd)**
- **GLE occurs during a large magnetic storm or/and Fd that was triggered by preceding solar activity**
- **Magnetic storm or/and Fd occurs without GLE**

January 2005 Observations



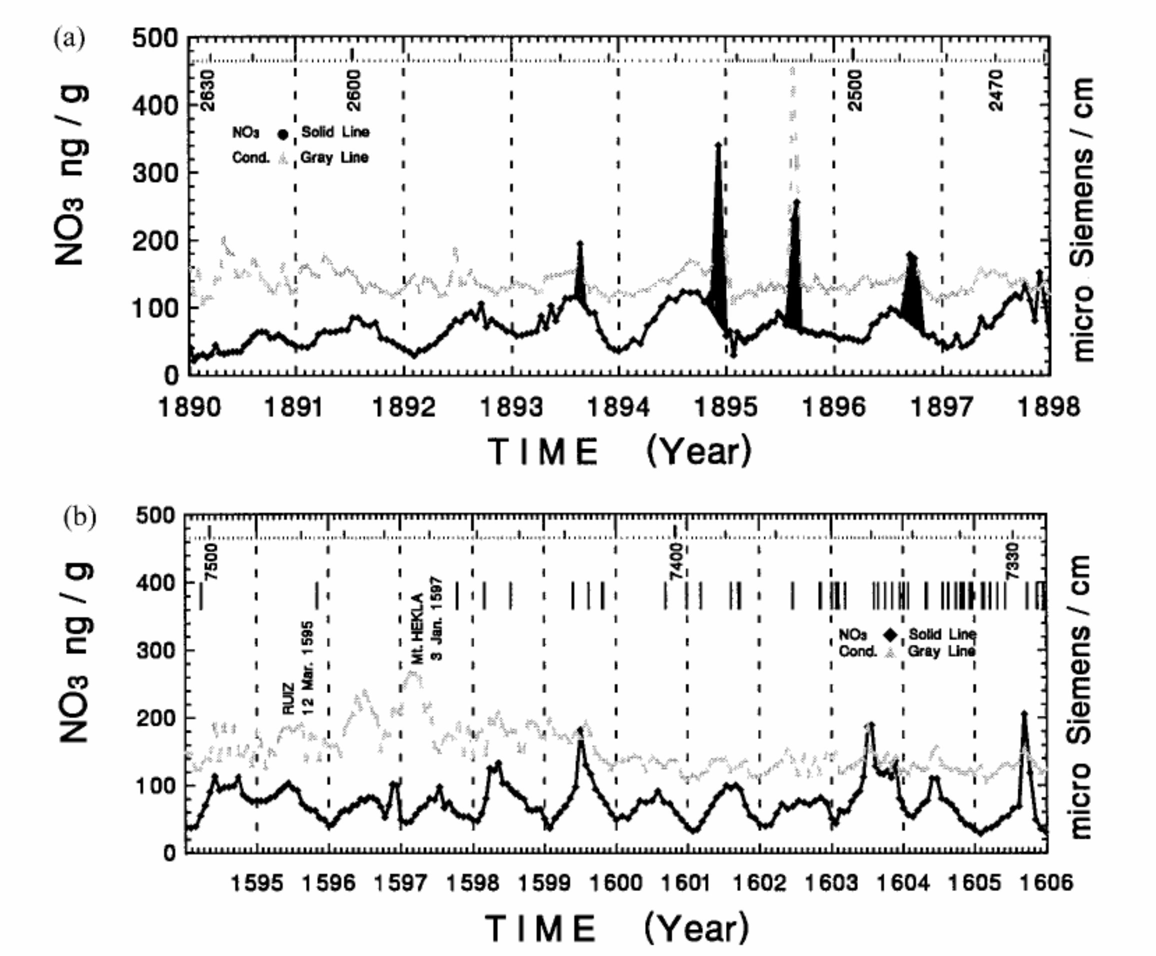
Solar Events and Magnetic Storms II

1890 – 1897: exceptional period

five large impulsive events

only one other episode of comparable frequency (circa 1600–1610)

The years 1892 (nine great magnetic storms) and 1894 (eight great magnetic storms) contain the highest number of magnetic storms for any year in the Greenwich list of the 112 great magnetic storms that occurred between 1874 and 1952 [see Royal Greenwich Observatory, 1955].



McCracken et al.,JGR,**106**(A10), 21’585–21’598, 2001

Solar Events and Magnetic Storms III

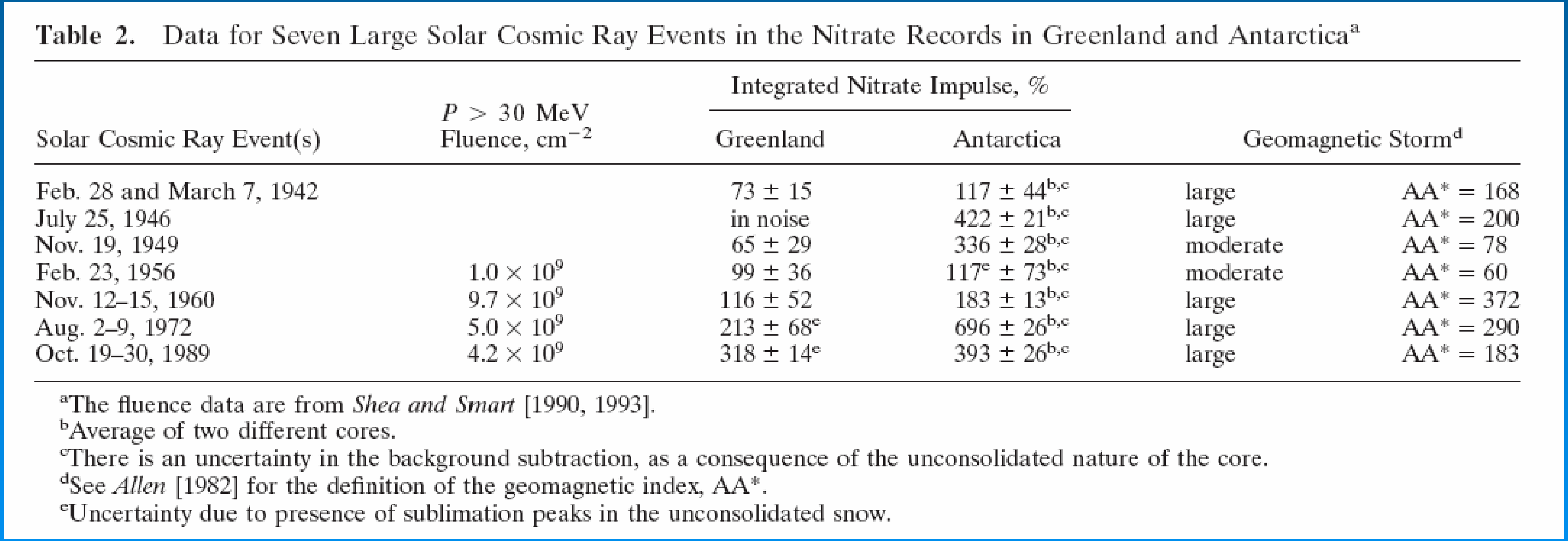


Table 2. Data for Seven Large Solar Cosmic Ray Events in the Nitrate Records in Greenland and Antarctica[a]

		Integrated Nitrate Impulse, %			
Solar Cosmic Ray Event(s)	$P > 30$ MeV Fluence, cm^{-2}	Greenland	Antarctica	Geomagnetic Storm[d]	
Feb. 28 and March 7, 1942		73 ± 15	117 ± 44[b,c]	large	AA* = 168
July 25, 1946		in noise	422 ± 21[b,c]	large	AA* = 200
Nov. 19, 1949		65 ± 29	336 ± 28[b,c]	moderate	AA* = 78
Feb. 23, 1956	1.0×10^9	99 ± 36	117[e] ± 73[b,c]	moderate	AA* = 60
Nov. 12–15, 1960	9.7×10^9	116 ± 52	183 ± 13[b,c]	large	AA* = 372
Aug. 2–9, 1972	5.0×10^9	213 ± 68[e]	696 ± 26[b,c]	large	AA* = 290
Oct. 19–30, 1989	4.2×10^9	318 ± 14[e]	393 ± 26[b,c]	large	AA* = 183

[a] The fluence data are from *Shea and Smart* [1990, 1993].

[b] Average of two different cores.

[c] There is an uncertainty in the background subtraction, as a consequence of the unconsolidated nature of the core.

[d] See *Allen* [1982] for the definition of the geomagnetic index, AA*.

[e] Uncertainty due to presence of sublimation peaks in the unconsolidated snow.

McCracken et al.,JGR,**106**(A10), 21’585–21’598, 2001

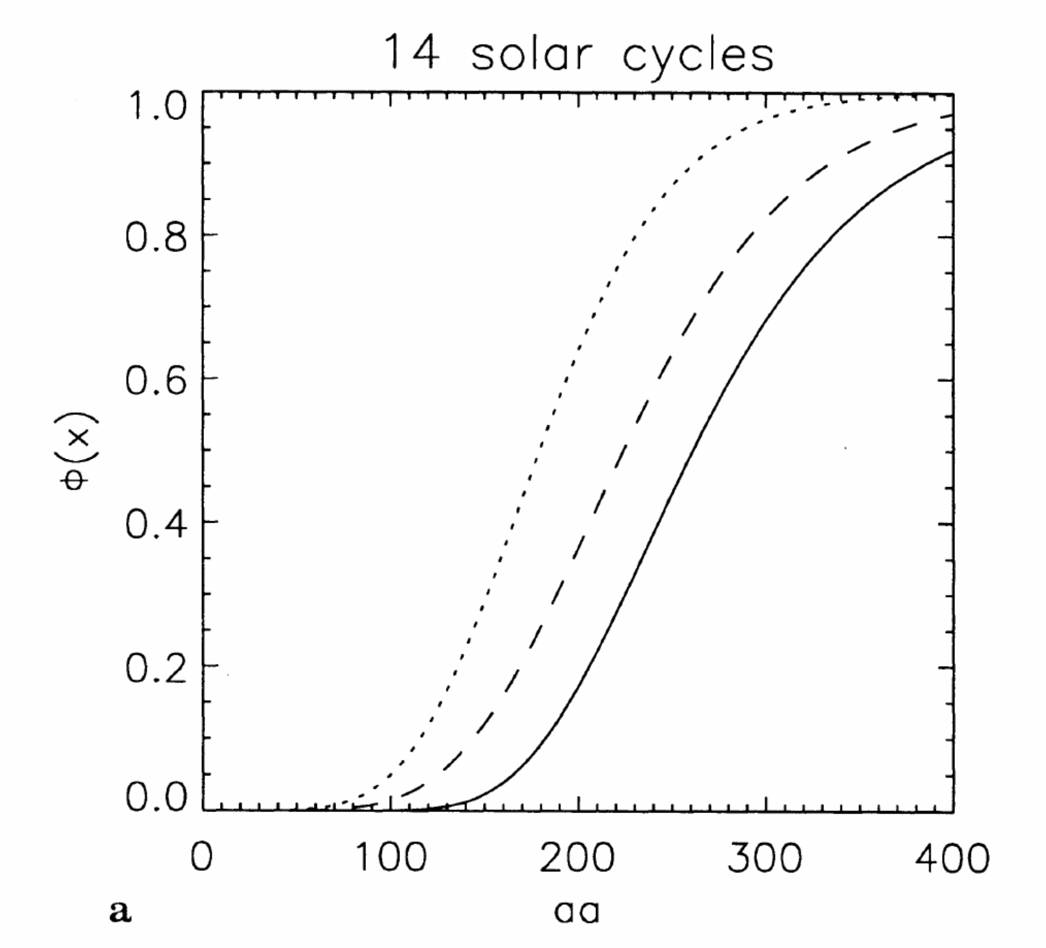
Super Storms

Super storms: "Super storms" are defined to be the largest 2% of geomagnetic storms from 1932 through 1995, selected using ground-based magnetic indices.

J.T. Bell, M.S. Gussenhoven, and E.G. Mullen (JGR, 102, 14189-14198, 1997) found that super storms are most likely to occur on the downslope from maximum and near the equinoxes.

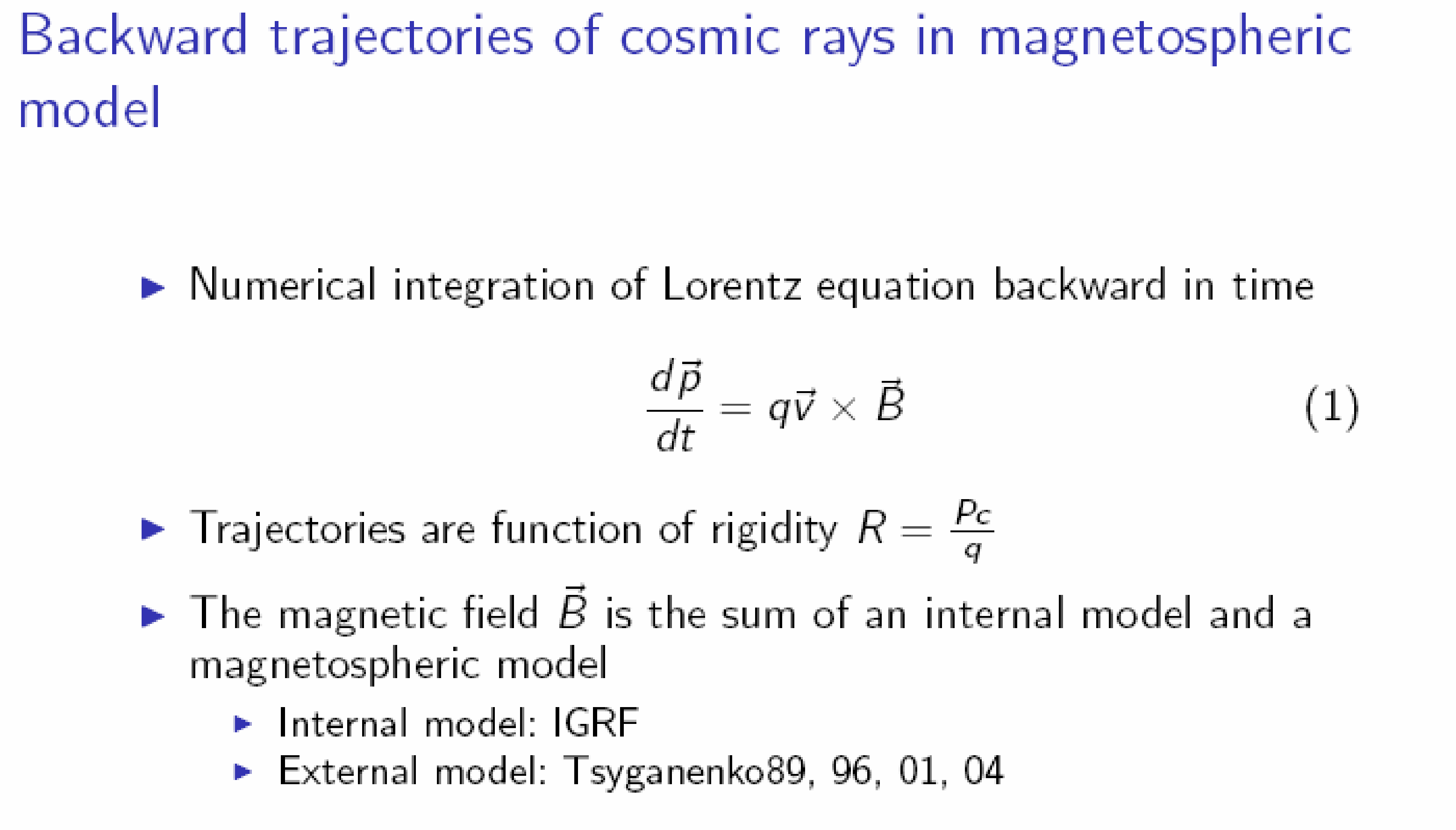
Superstorms at 2004 AGU Fall Meeting
Eos Trans. AGU, 85(47), Fall Meet. Suppl.,

Plot of the probability that a given observation of a first, second and third largest geomagnetic storm in a solar cycle is less than aa (for solar cycles 9-22) The continuous, dashed and dotted curves refer to the first, second, and third largest geomagnetic storms, respectively



Willis et al., Ann. Geophysicae **15**, 719-728, 1997

Modeling of geomagnetic effects of cosmic rays during magnetic storms

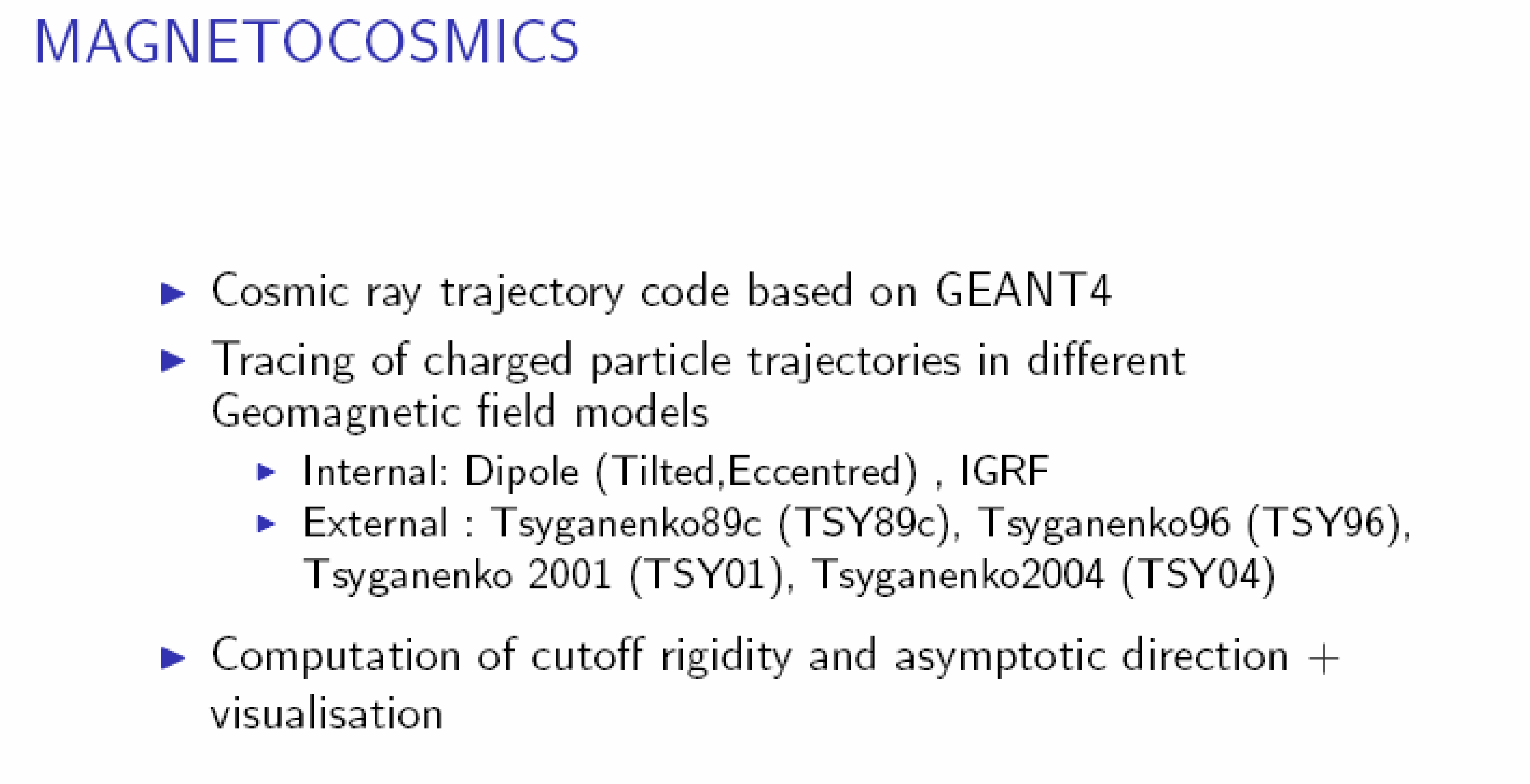


Backward trajectories of cosmic rays in magnetospheric model

- Numerical integration of Lorentz equation backward in time

$$\frac{d\vec{p}}{dt} = q\vec{v} \times \vec{B} \qquad (1)$$

- Trajectories are function of rigidity $R = \frac{pc}{q}$
- The magnetic field $\vec{B}$ is the sum of an internal model and a magnetospheric model
    - Internal model: IGRF
    - External model: Tsyganenko89, 96, 01, 04

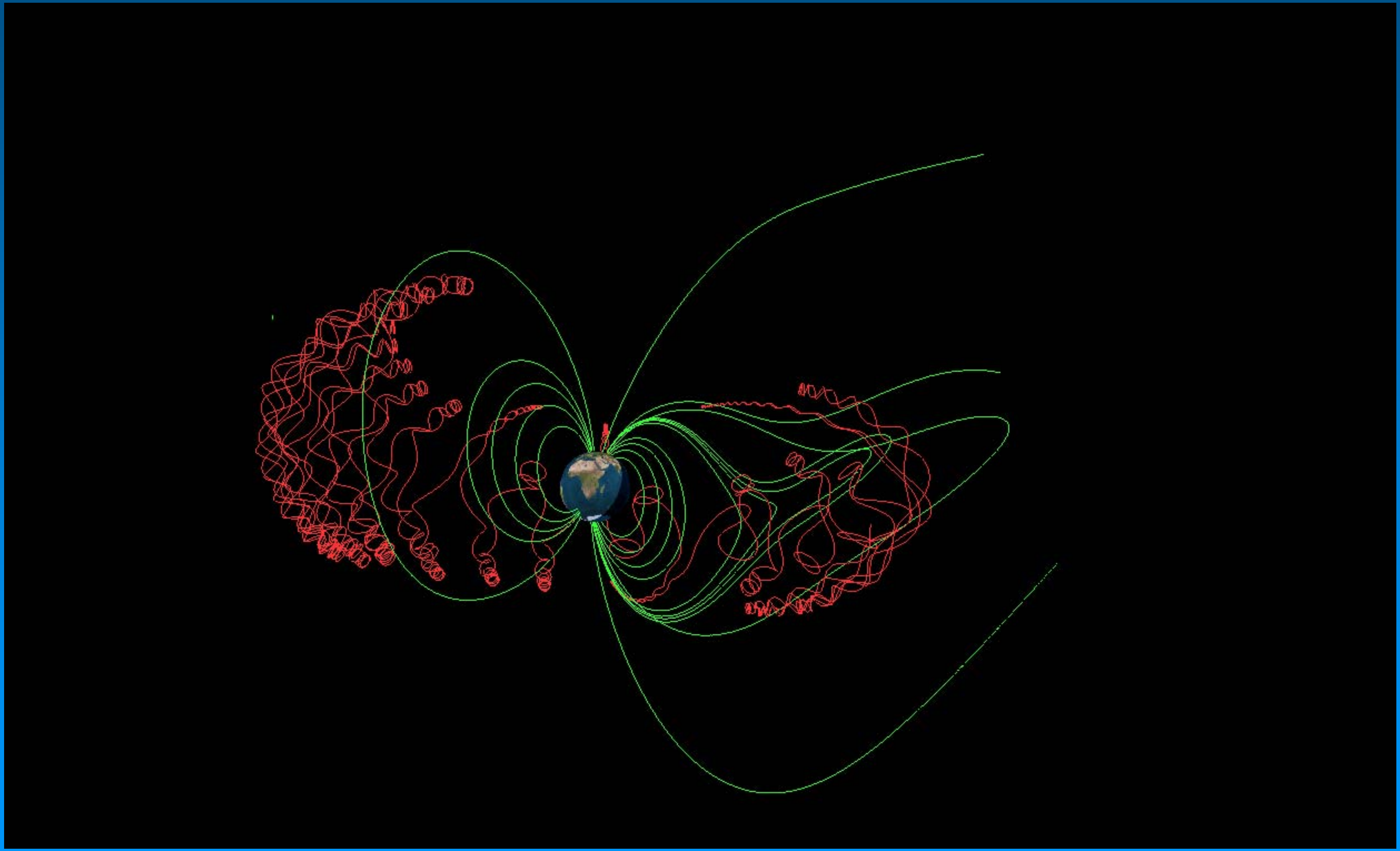


MAGNETOCOSMICS

- Cosmic ray trajectory code based on GEANT4
- Tracing of charged particle trajectories in different Geomagnetic field models
  - Internal: Dipole (Tilted,Eccentred) , IGRF
  - External : Tsyganenko89c (TSY89c), Tsyganenko96 (TSY96), Tsyganenko 2001 (TSY01), Tsyganenko2004 (TSY04)
- Computation of cutoff rigidity and asymptotic direction + visualisation

Desorgher, L., MAGNETOCOSMICS: Geant4 application for simulating the propagation of cosmic rays through the Earth's magnetosphere, http://reat.space.qinetiq.com/septimess/magcos/, 2004

Magnetocosmics

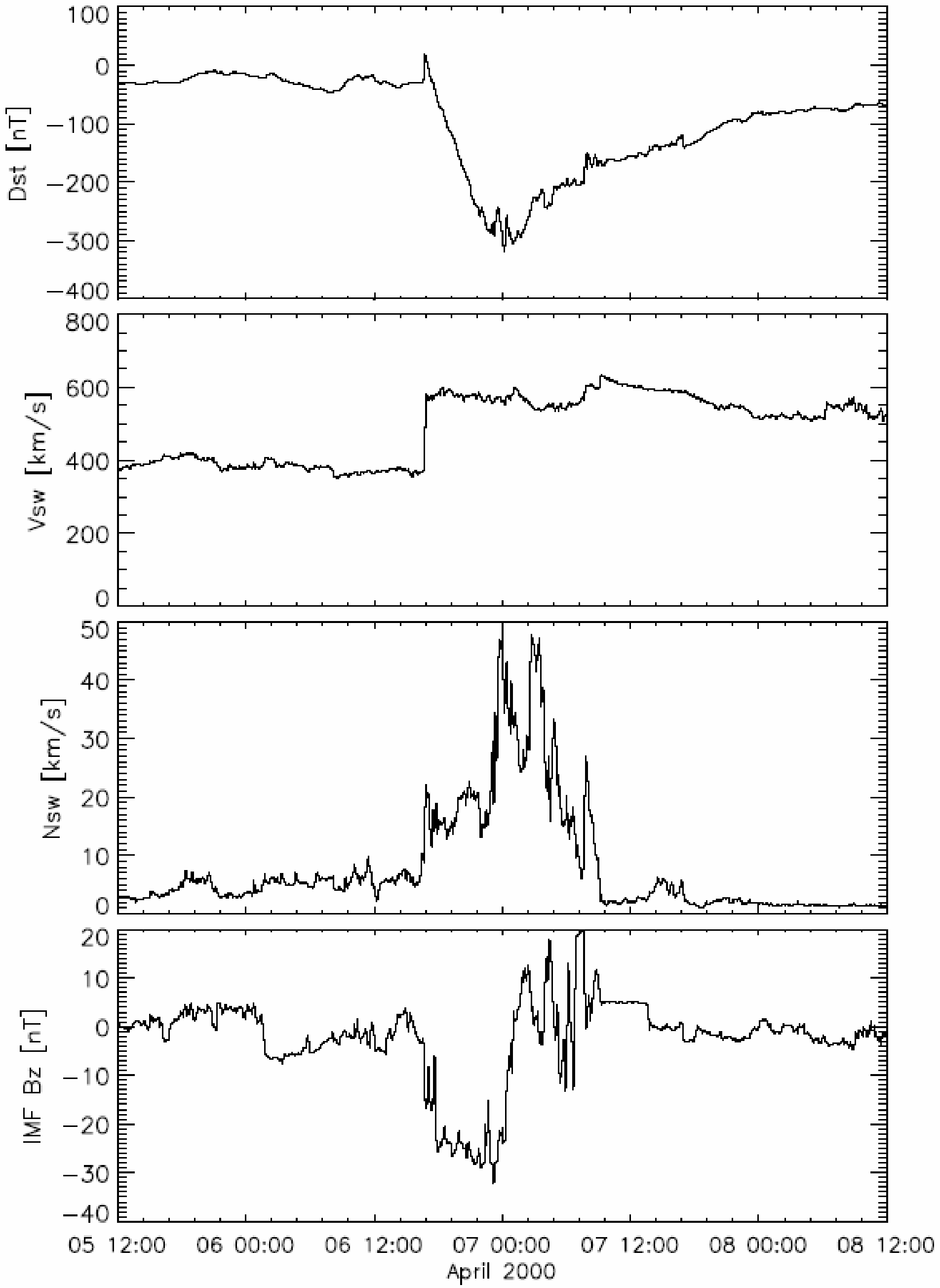


Cosmic Ray Trajectories - p – 1 GeV

Application of

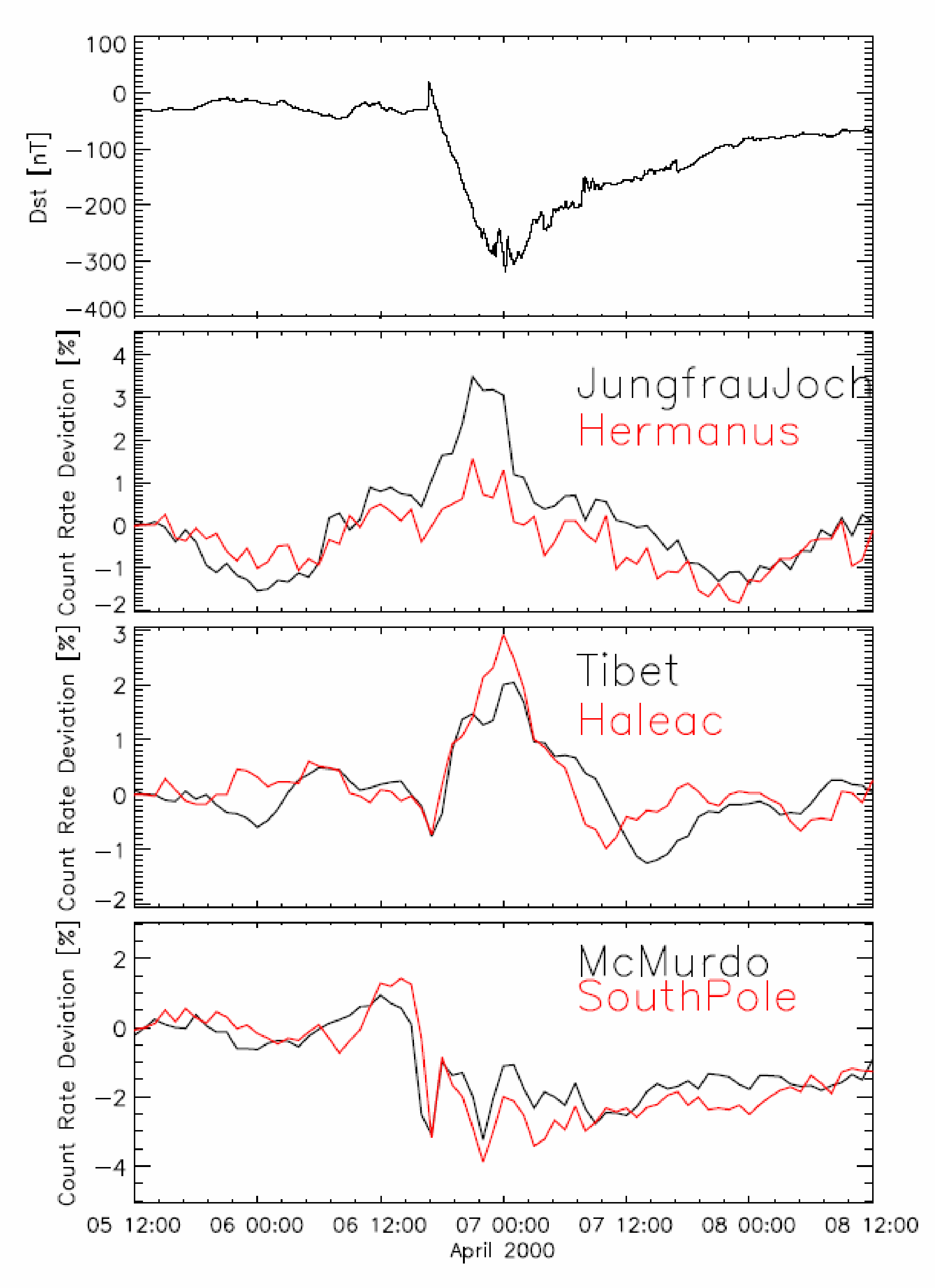
MAGNETOCOSMICS

to
April 6, 2000
magnetic storm



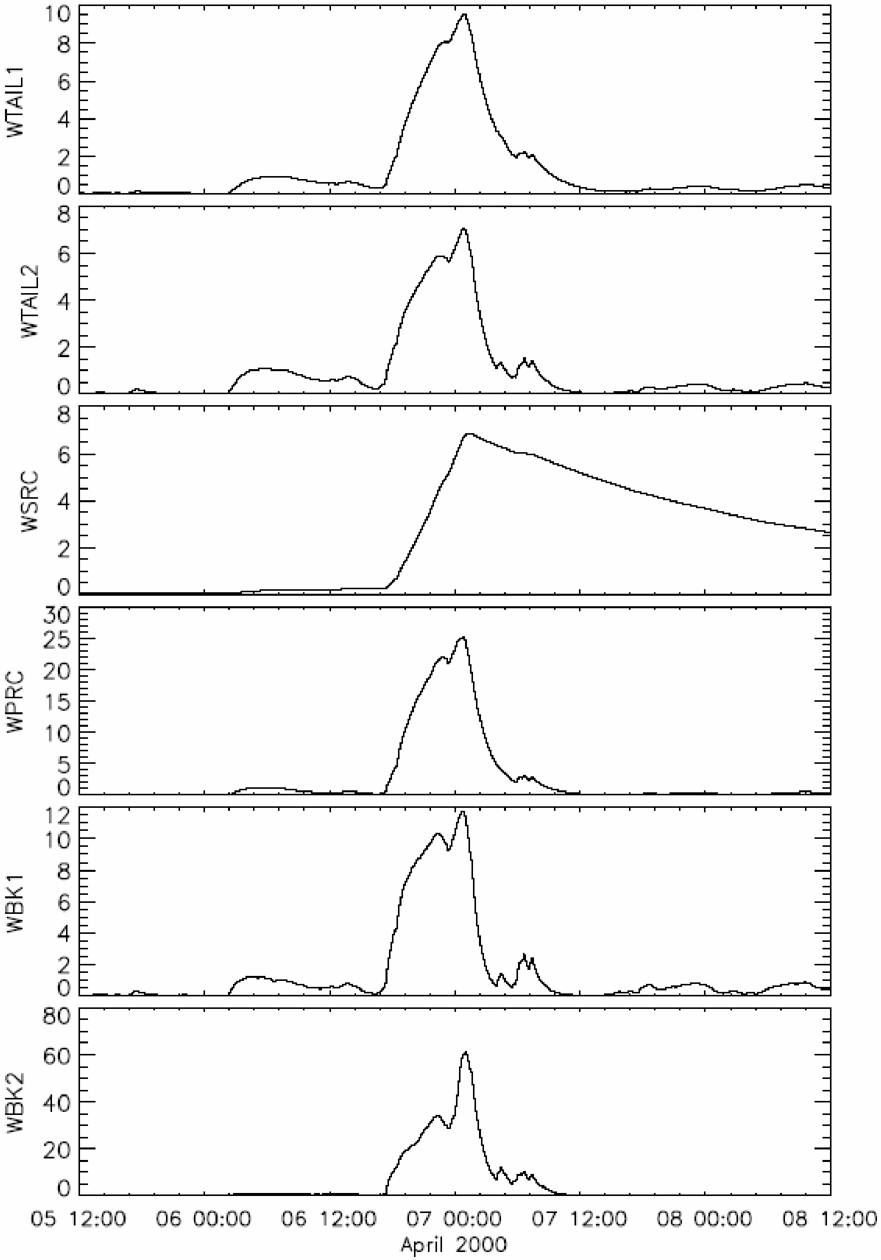
April 6, 2000

NM data



April 6, 2000

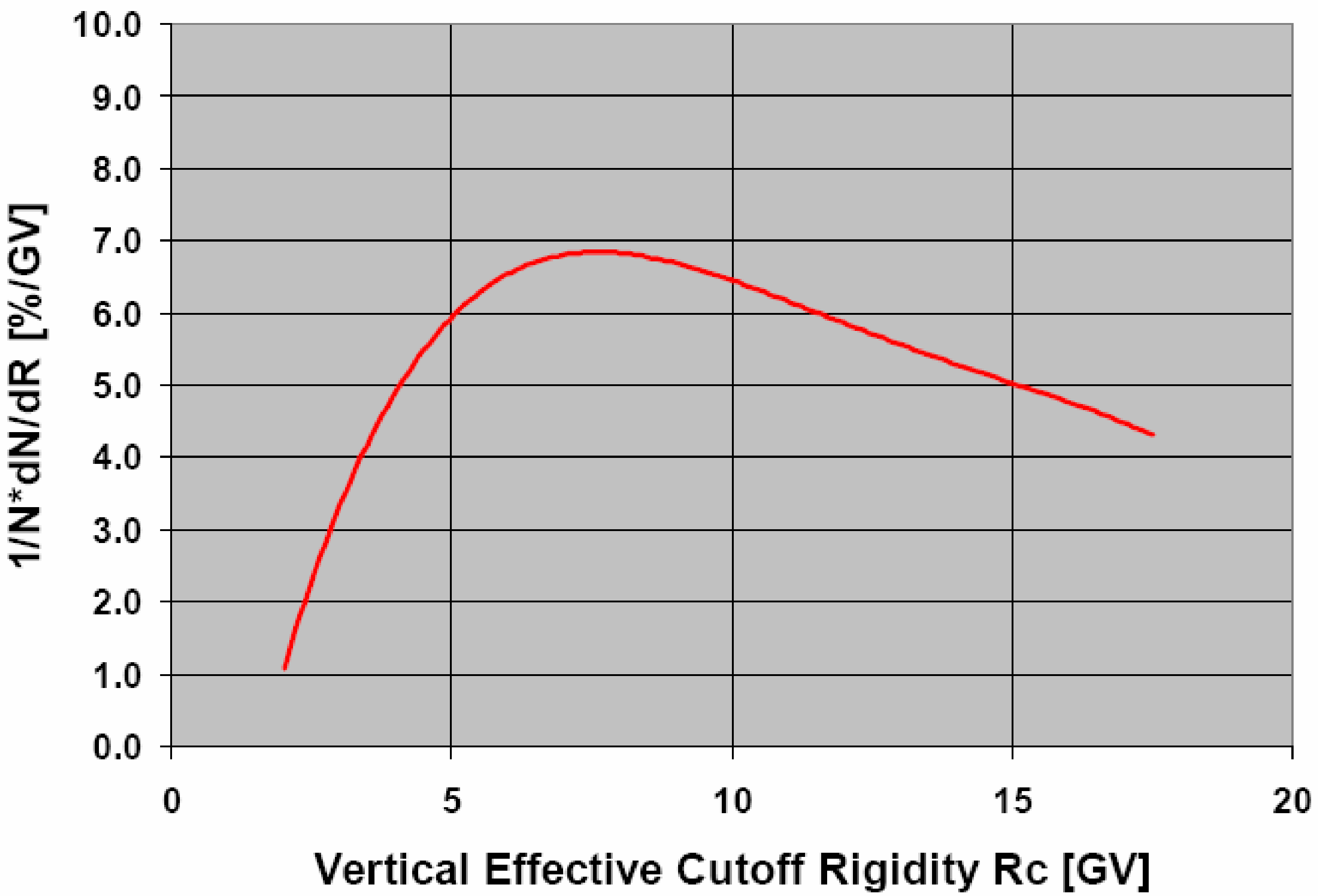
parameters of TSY04 magnetic field model



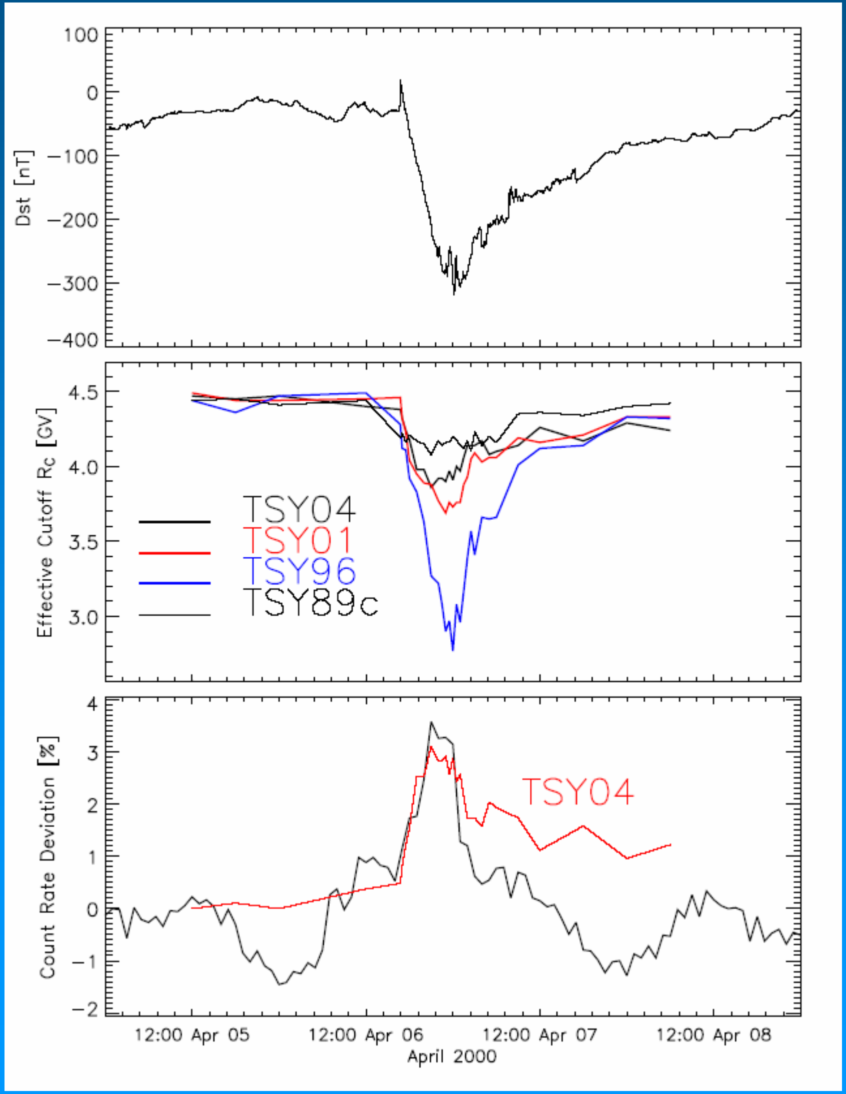
Calculation of

Change in Cutoff Rigidity
and then of
Change in NM Count Rate

Effect of Cutoff Changes on Neutron Monitor Count Rates

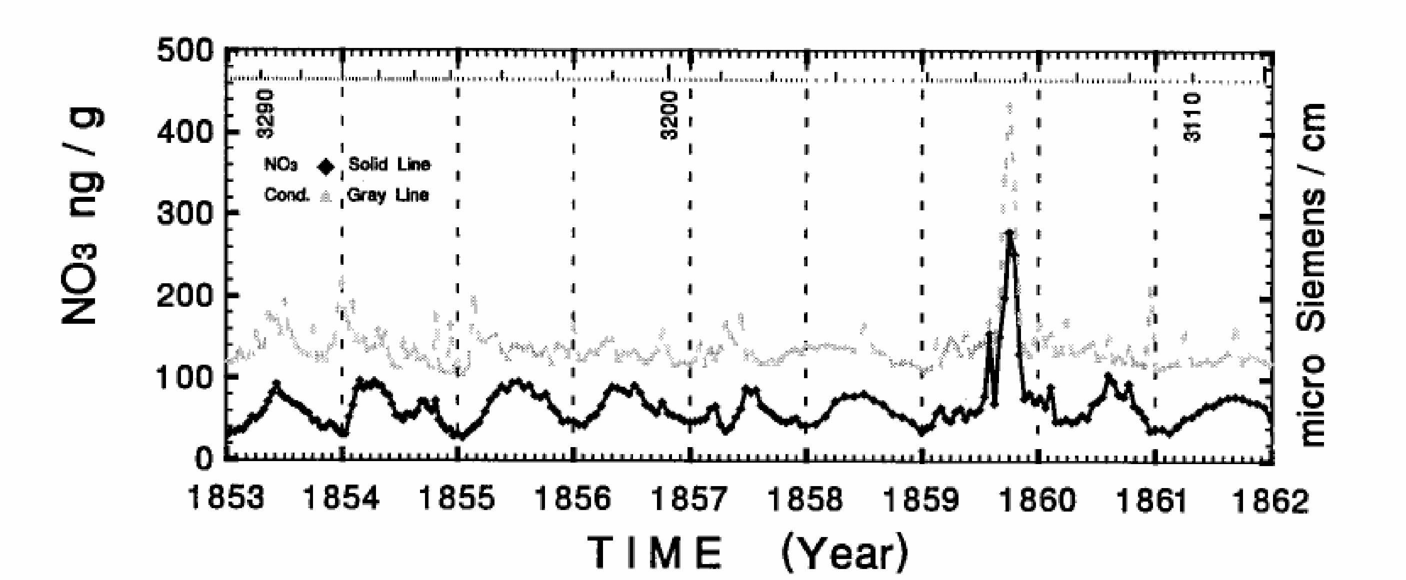


Example of April 6, 2000 Results



The Carrington Event I

Carrington [1860] and *Hodgson* [1860] independently observed a white light flare on September 1, 1859, which was accompanied by a large geomagnetic crochet.



omnidirectional fluence (>30 MeV): 18.8 x 10^9 cm^{-2}

McCracken et al.,JGR,**106**(A10), 21’585–21’598, 2001

The Carrington Event II

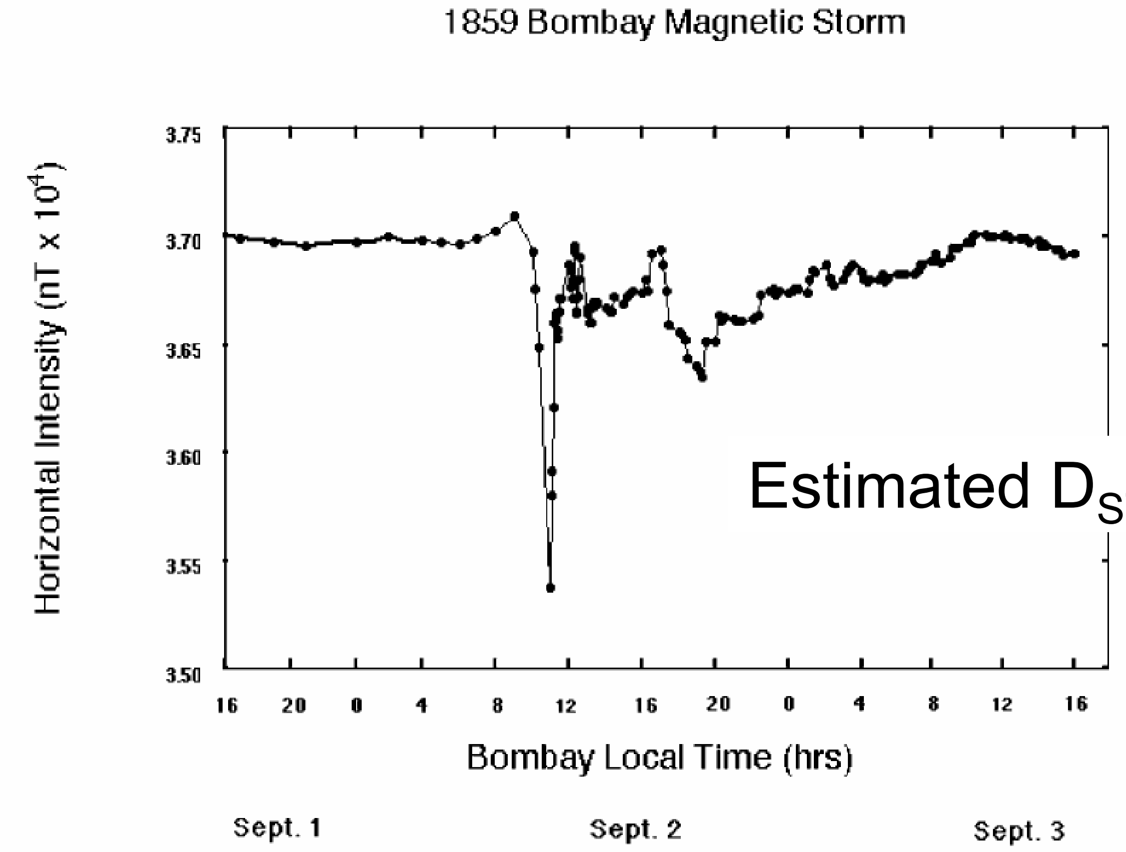


Figure 3. The Colaba (Bombay) magnetogram for the 1–2 September 1859 magnetic storm.

Estimated D_{ST} ~1760 nT.

Tsurutani et al., JGR **108**(A7), 1268, 2003

Summary and Conclusions

- Identification of extreme events in polar ice has significantly improved our knowledge about occurrence frequency and fluence
- Progress in study of superstorms (e.g. identification of causes, forecasting), but more work needed
- Modeling of superstorm effects on cosmic rays still far from being complete