Geomagnetic Storms

Y. Kamide

Kyoto University

Outline

1. 磁気嵐とは？
2. 磁気嵐研究の歴史
3. エネルギーバランス基本方程式
4. 磁気嵐とサブストームの関係
5. 最近のトピックス
   - 太陽活動周期と磁気嵐
   - ダブル磁気嵐
   - 磁気嵐時のオーロラベルトのサイズ
   - 電離圏粒子の環電流への役割

磁気嵐といえば……

「地球磁場が全世界で乱れる」というイメージ

1960年代初めまで、研究者もそう思っていた

しかし、

「磁気嵐の構成要素はサブストーム」

↓

「サブストームは磁気嵐でなくても起きる」（Chapman, 1961）

↓

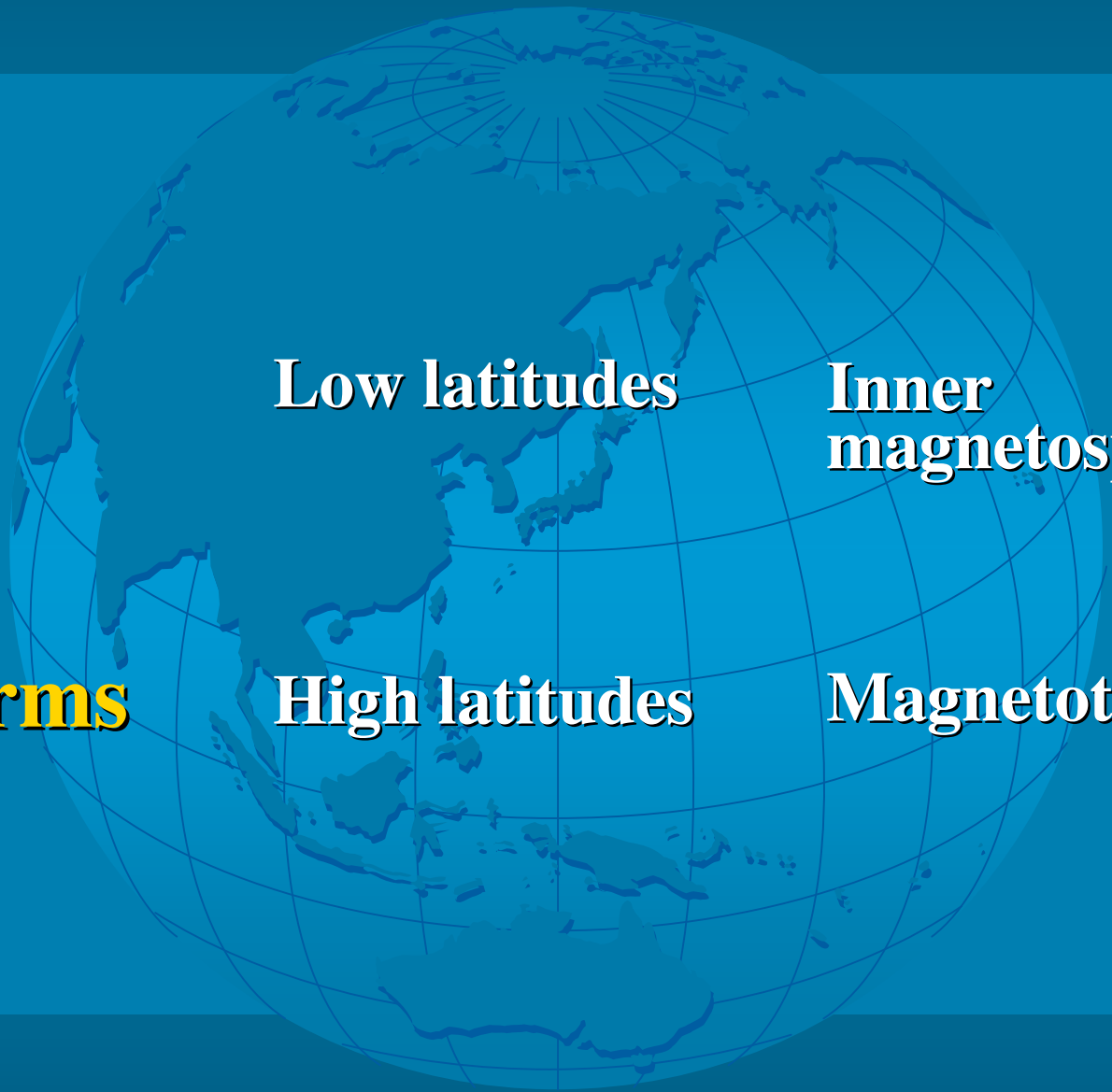
そのようなサブストームこそ多い

どうでもいい人は

Geomagnetic disturbances

↓

磁場擾乱（じょうらん）

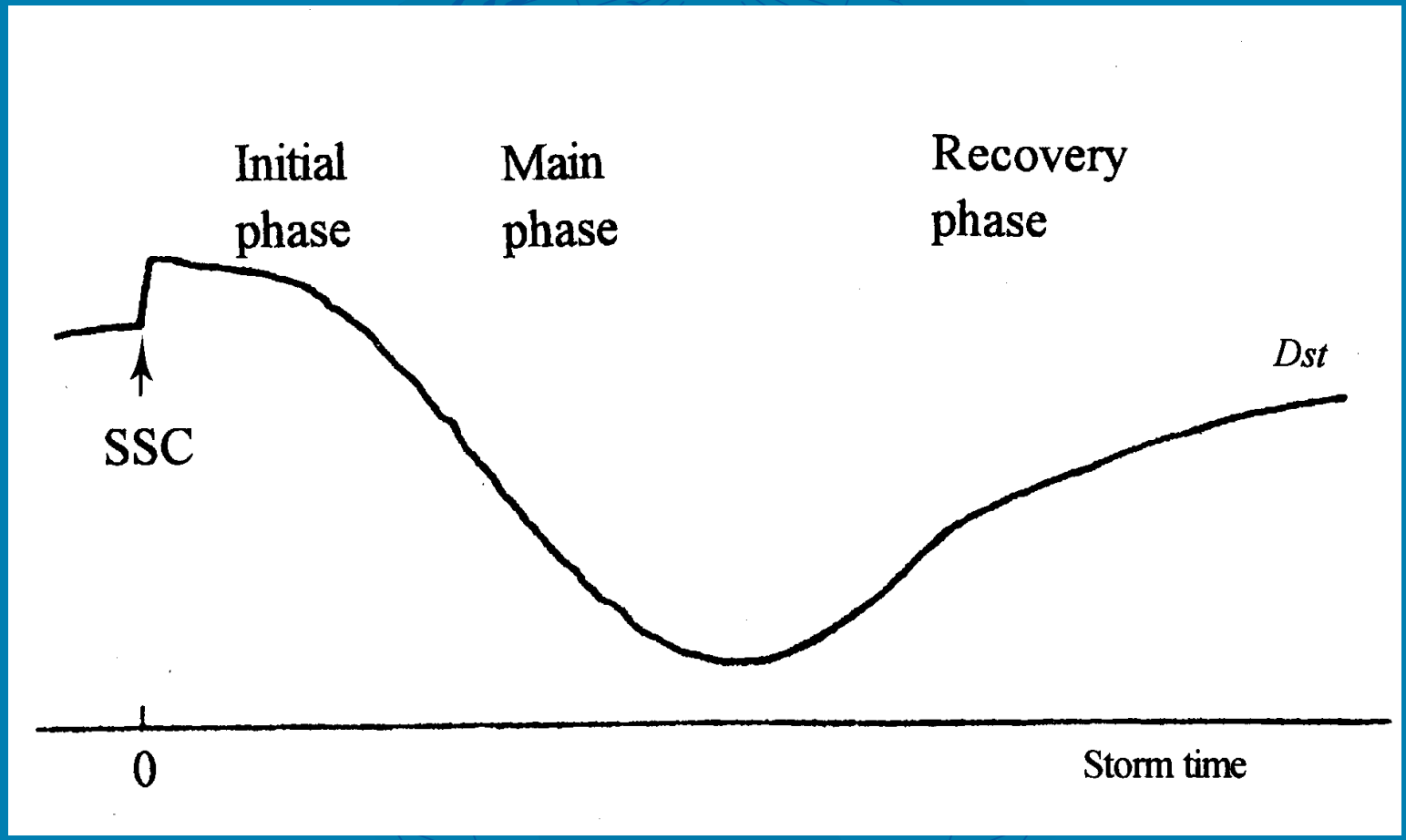


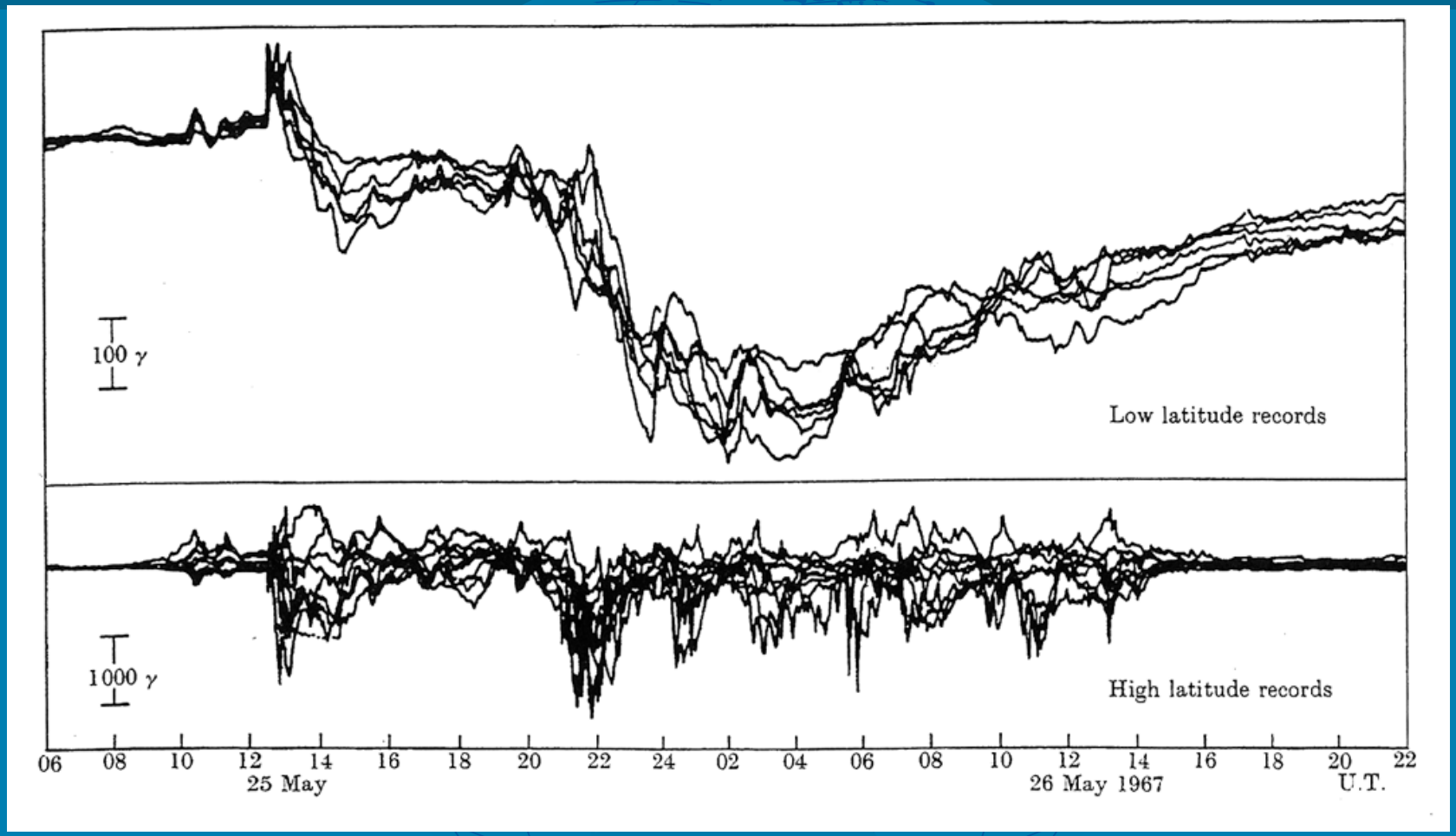
Storms	**Low latitudes**	**Inner magnetosphere**
Substorms	**High latitudes**	**Magnetotail**

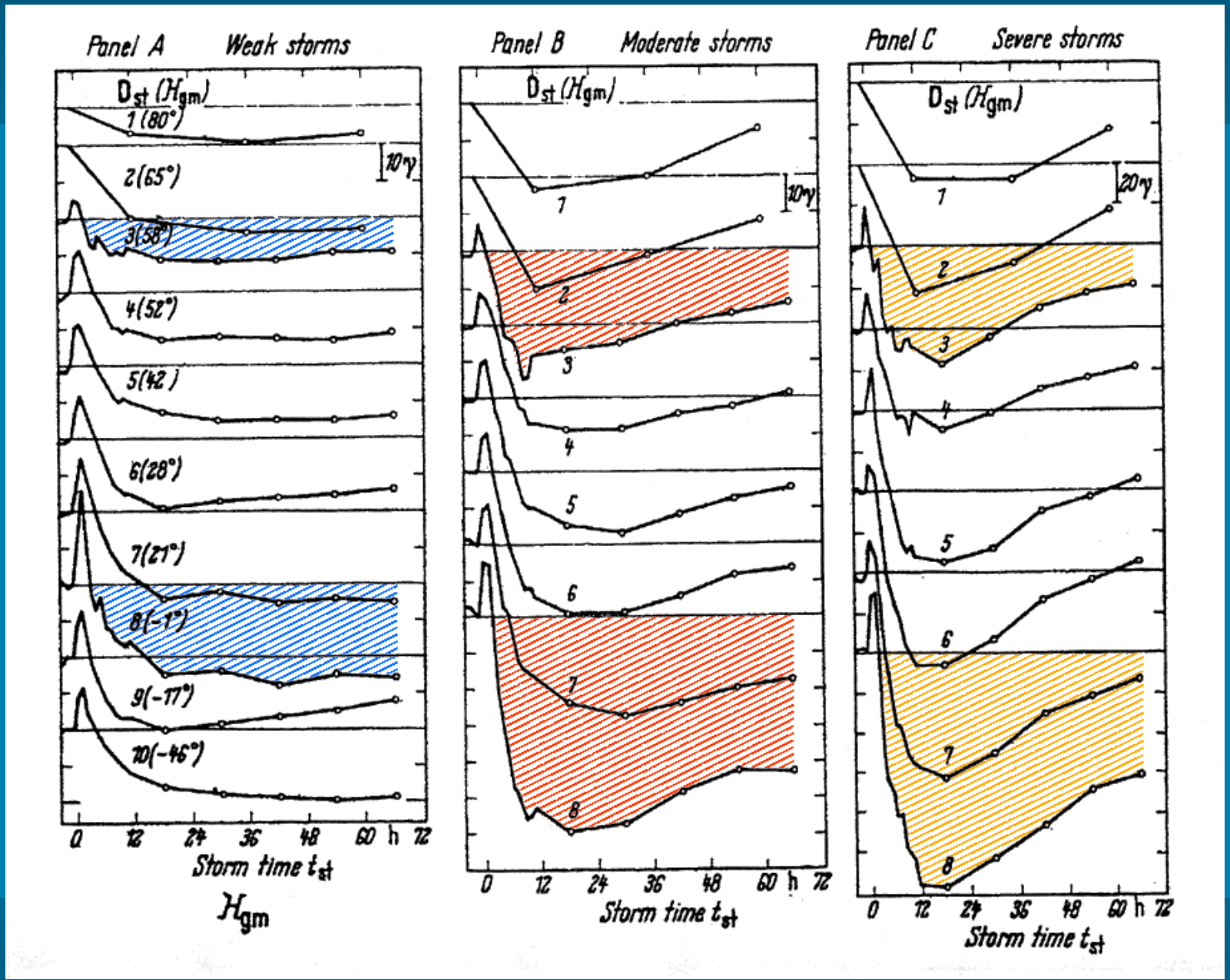
Chapman [1961]

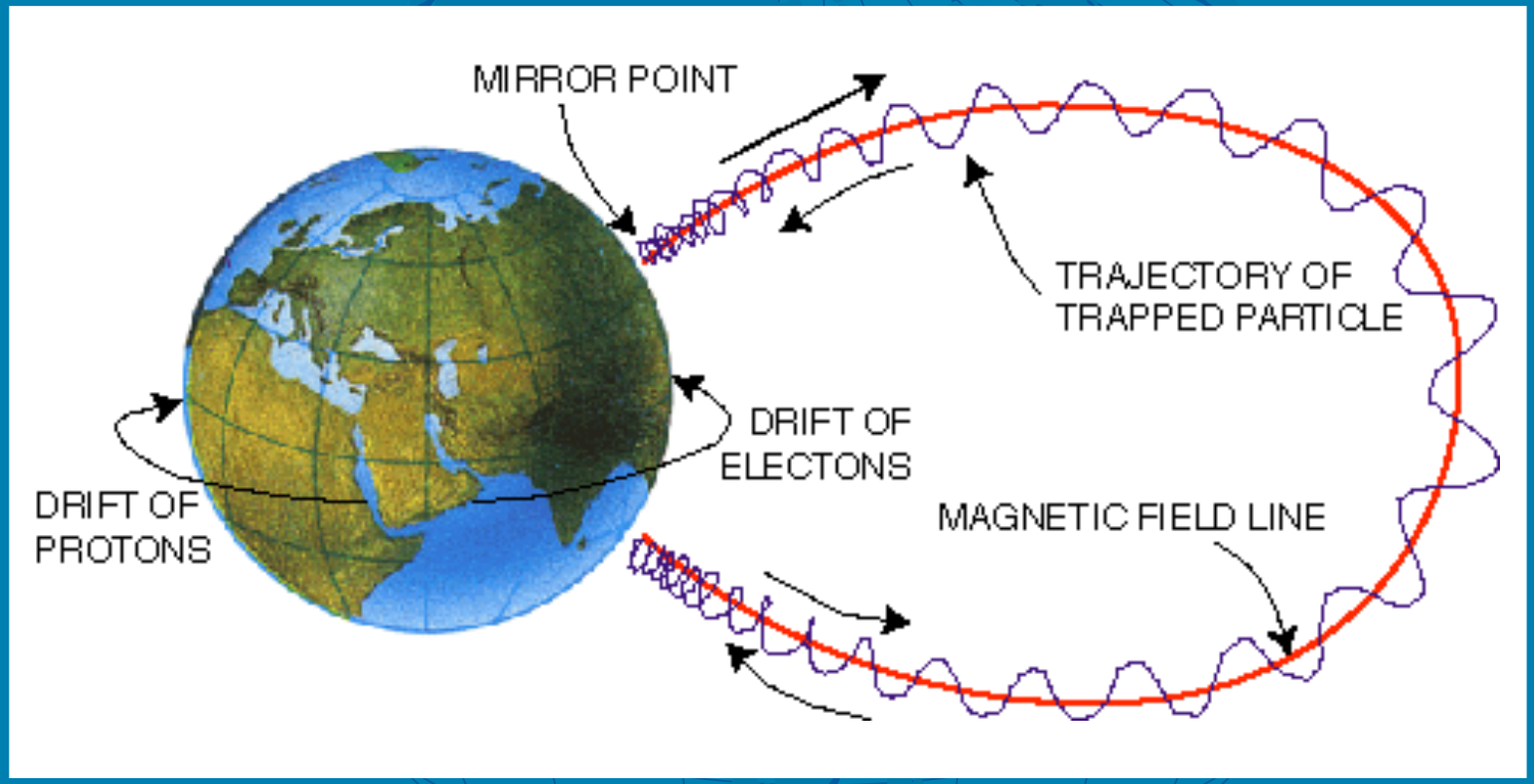
A magnetic storm consists of sporadic and intermittent usually polar disturbances, lifetime being one or two hours. These I call polar substorms.

Although substorms occur most often during magnetic storms, they appear also during quiet periods.


Initial
phase
Main
phase
Recovery
phase
Dst
SSC
0
Storm time

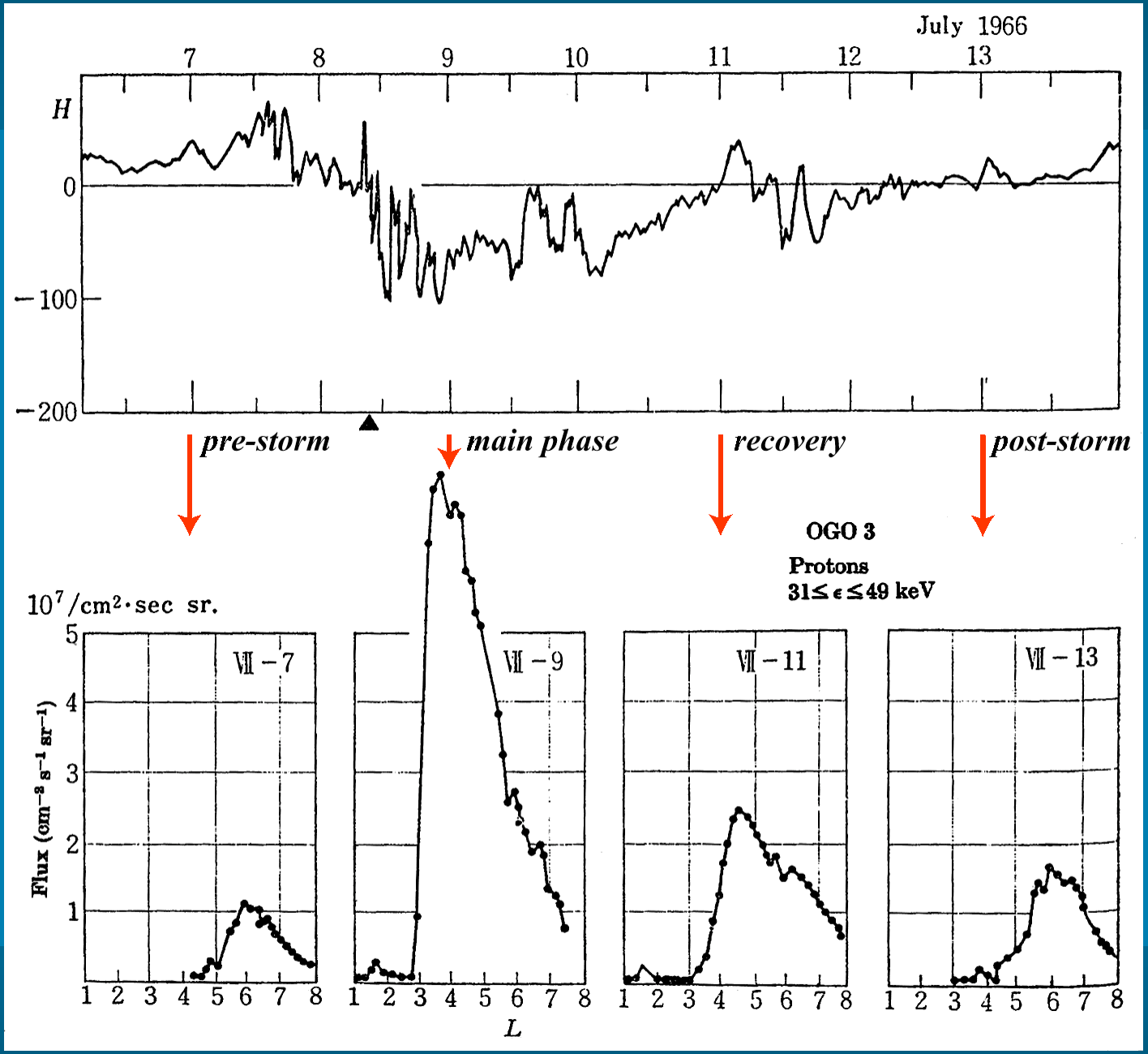

100 γ
Low latitude records
1000 γ
High latitude records
06 08 10 12 14 16 18 20 22 24 02 04 06 08 10 12 14 16 18 20 22
25 May
26 May 1967
U.T.


Panel A
Weak storms
Dst (Hgm)
1 (80°)
2(65°)
3(58°)
4(52°)
5(42°)
6(28°)
7(21°)
8(-1°)
9(-17°)
10(-46°)
10γ
0 12 24 36 48 60 h 72
Storm time tst
Hgm
Panel B
Moderate storms
Dst (Hgm)
10γ
Storm time tst
Panel C
Severe storms
Dst (Hgm)
20γ
Storm time tst


MIRROR POINT
TRAJECTORY OF
TRAPPED PARTICLE
DRIFT OF
ELECTONS
DRIFT OF
PROTONS
MAGNETIC FIELD LINE

$$j_{\perp} = \frac{\vec{B}}{B^2} \times \left[\nabla P_{\perp} + (P_{//} - P_{\perp}) \frac{(\vec{B} \cdot \nabla)}{B^2} \vec{B} \right]$$

where $\vec{B}$ is the local magnetic field vector, while $P_{\parallel}$ and $P_{\perp}$ are the pressure tensor components perpendicular and parallel to the magnetic field.


July 1966
7
8
9
10
11
12
13
H
0
−100
−200
pre-storm
main phase
recovery
post-storm
OGO 3
Protons
31≤ϵ≤49 keV
10⁷/cm²·sec sr.
Flux (cm⁻² s⁻¹ sr⁻¹)
Ⅶ−7
Ⅶ−9
Ⅶ−11
Ⅶ−13
1 2 3 4 5 6 7 8
L

The beginning of solar-terrestrial physics:

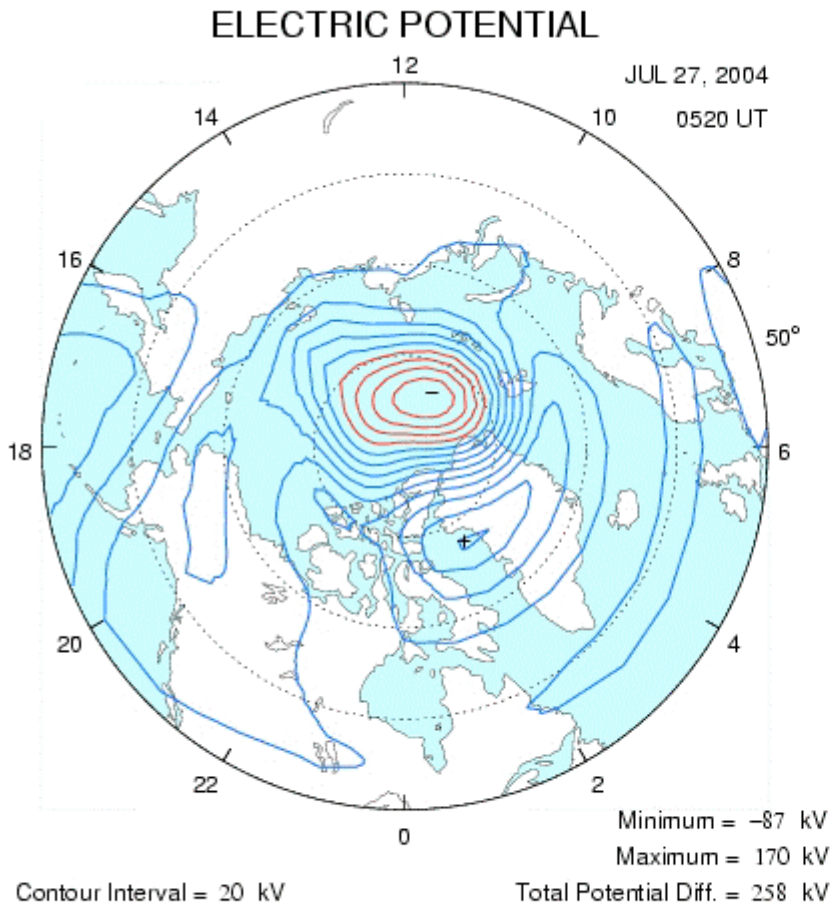
(1) The discovery of geomagnetic storms (later term) by Graham in 1724
(2) The discovery by Oersted in 1820 that electric currents produce magnetic forces
(3) The law of Ampère's force in 1821
(4) Electromagnetic induction by Faraday in 1831

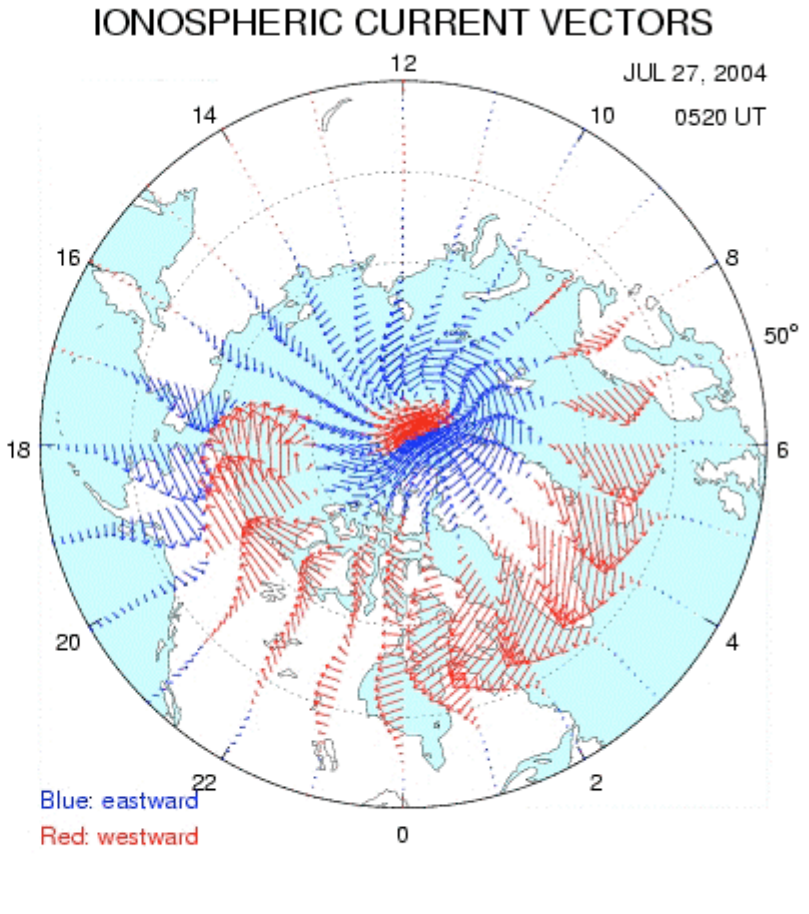
which were to lead subsequently to Maxwell's equations of electromagnetism.

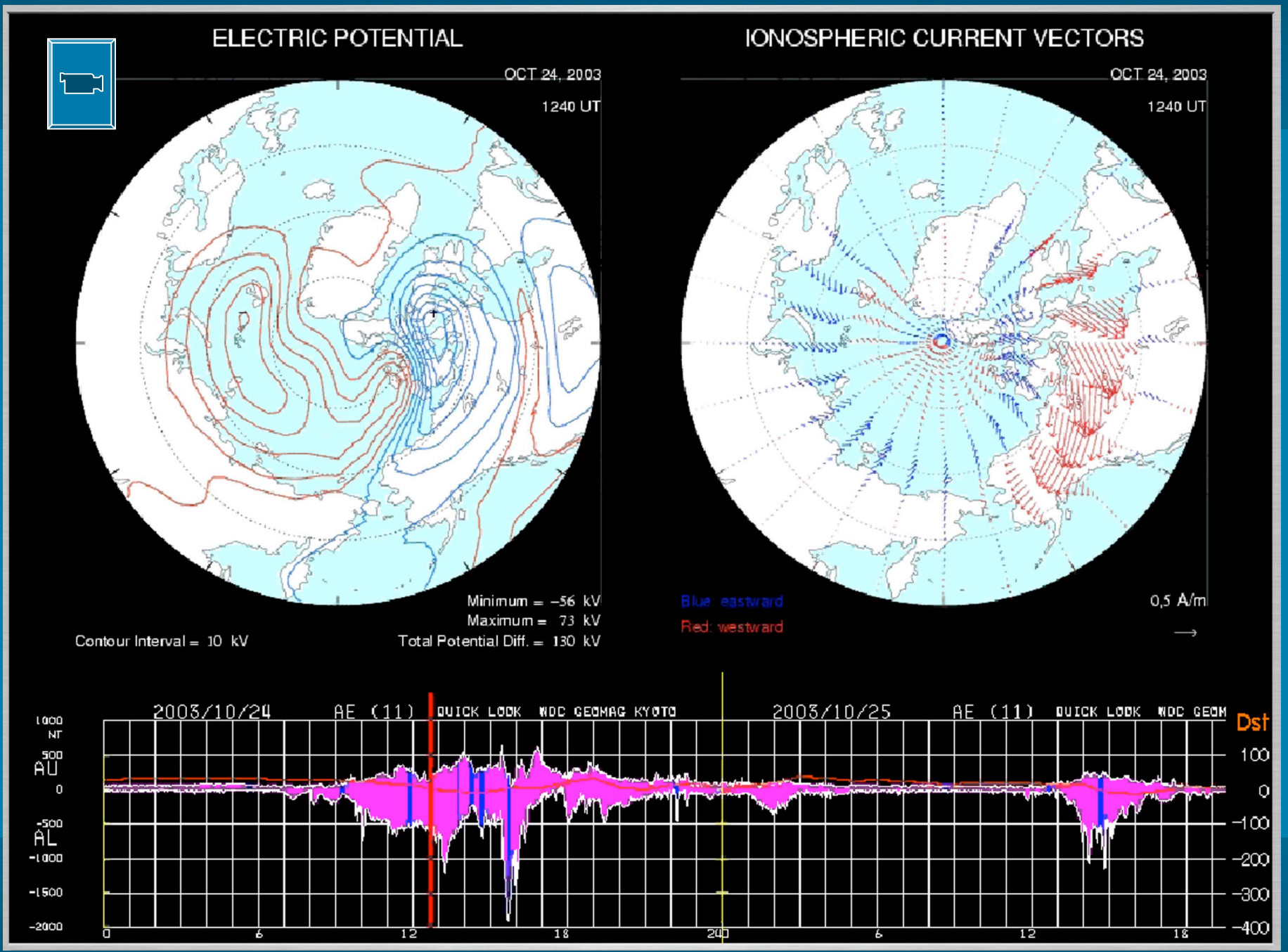
Who, and when, introduced the "geomagnetic storm" into the scientific community?

Alexander von Humboldt (1769-1859) used "magnetisches Ungewitter" (magnetic thunderstorms) to describe the variability of geomagnetic needles, which were associated with the occurrence of "light meteor," (auroras). He thought that magnetic disturbances and auroras are two manifestations of the same phenomenon.

It was found that the storm-time disturbance generally reduces the daily mean value of the horizontal intensity. During the First Polar Year (1882-1883), scientists defined "geomagnetic storms" as intense, irregular variabilities of geomagnetic field which occur as a consequence of solar disturbances.


ELECTRIC POTENTIAL
JUL 27, 2004
0520 UT
12
14
10
16
8
50°
18
6
20
4
22
2
0
Minimum = −87 kV
Maximum = 170 kV
Contour Interval = 20 kV
Total Potential Diff. = 258 kV


IONOSPHERIC CURRENT VECTORS
JUL 27, 2004
0520 UT
12
14
10
16
8
50°
18
6
20
4
22
2
0
Blue: eastward
Red: westward


ELECTRIC POTENTIAL
OCT 24, 2003
1240 UT
Minimum = -56 kV
Maximum = 73 kV
Total Potential Diff. = 130 kV
Contour Interval = 10 kV
IONOSPHERIC CURRENT VECTORS
OCT 24, 2003
1240 UT
Blue: eastward
Red: westward
0,5 A/m
2003/10/24 AE (11) QUICK LOOK WDC GEOMAG KYOTO
2003/10/25 AE (11) QUICK LOOK WDC GEOM
1000 NT
500
AU
0
-500
AL
-1000
-1500
-2000
Dst
100
0
-100
-200
-300
-400
0
6
12
18
20
6
12
18

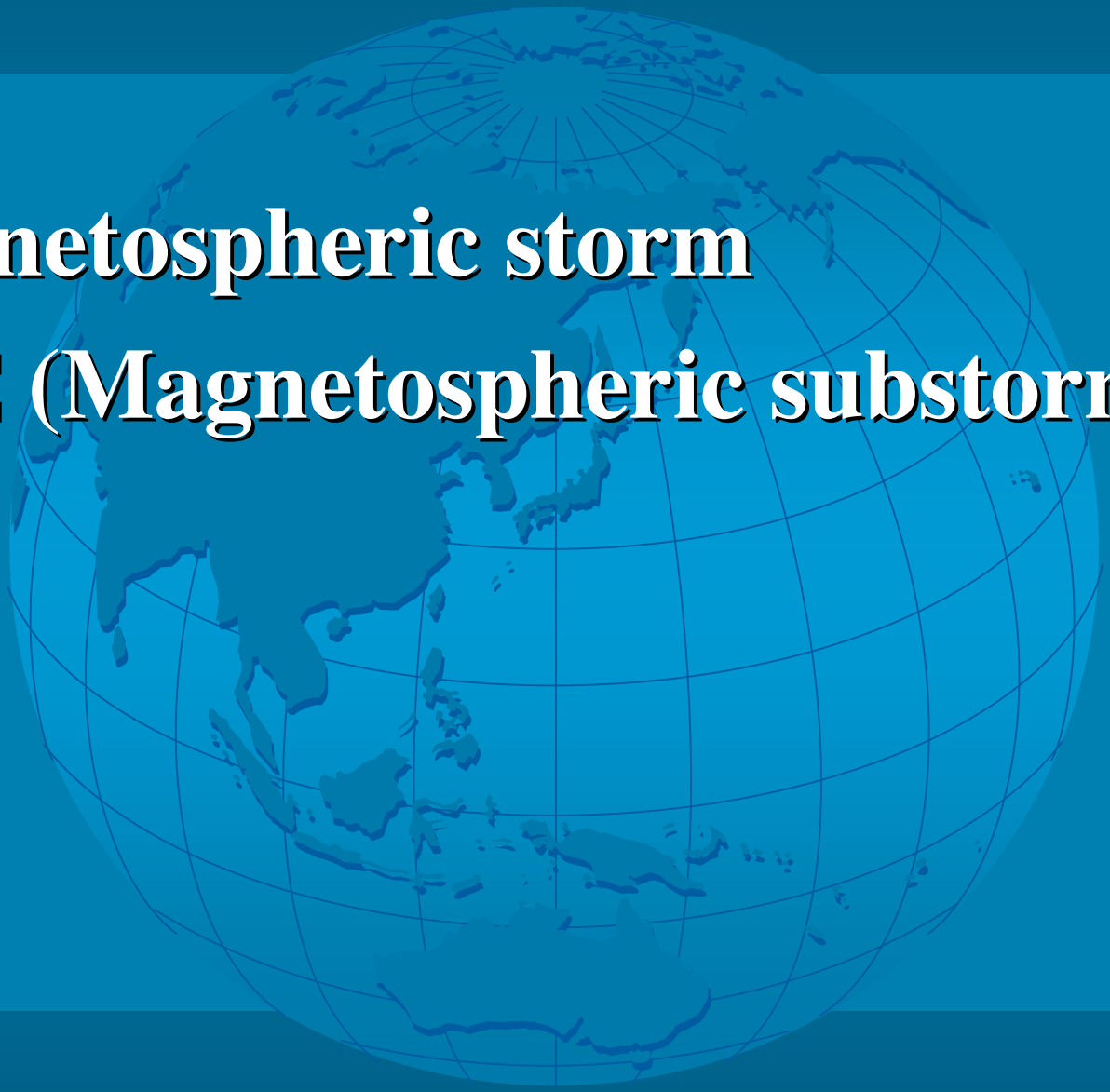
Energy Balance Equation:

$$\mathrm{d}E/\mathrm{d}t = Q - L$$

$$= Q - E/\tau$$

$$\frac{\Delta B}{B_0} = -\frac{2}{3}\frac{E}{E_m}$$

where B_0 is the average surface geomagnetic field intensity at the magnetic equator (~0.3 gauss), E is the total energy of the ring current particles and $E_m = B_0^2 R_E^3 / 3 = 10^{18}$ J, is the energy of the Earth's dipole field at the Earth's surface.



Magnetospheric storm

$= \Sigma$ (Magnetospheric substorm)$_i$

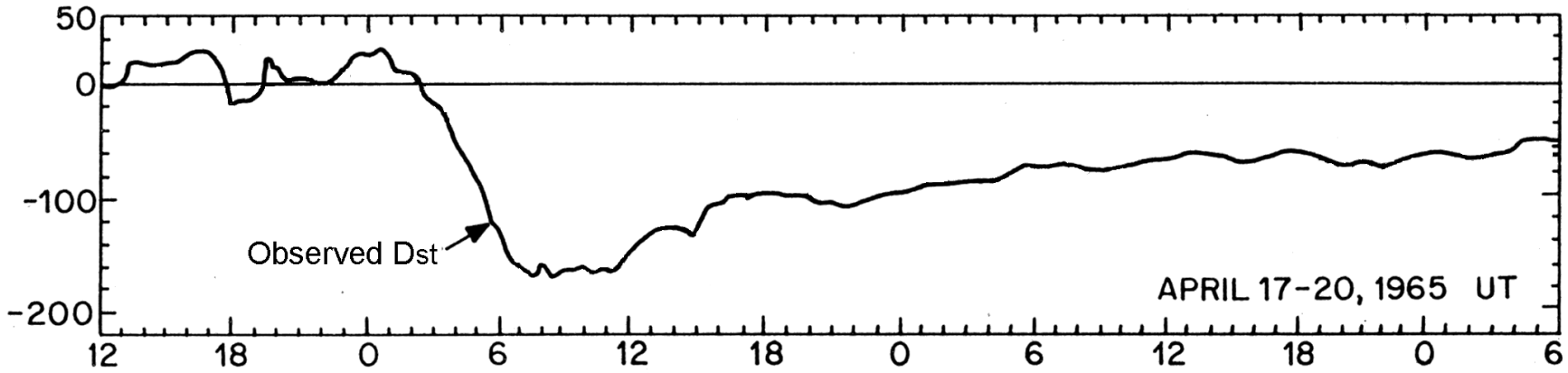


Figure 8. Comparison of the *Dst* index and the energy of the ring current computed on the basis of the assumption that the injection rate into the ring current is related to *AE* so that it is maximum at the beginning of the main phase and decays exponentially thereafter. [After *Kamide and Fukushima,* 1971].

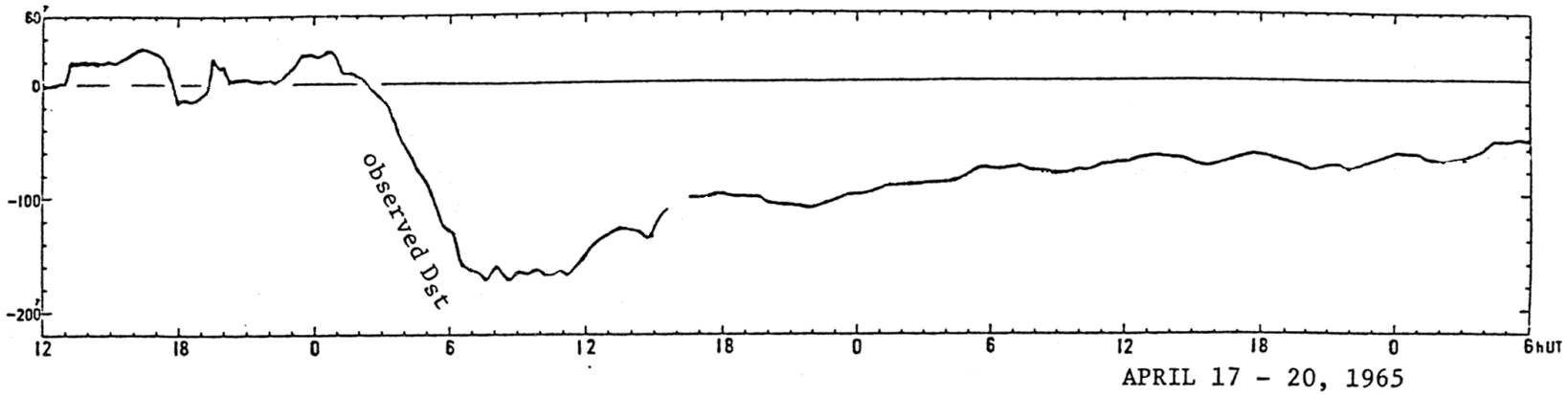


Fig. 2. Comparison of the *Dst* index and the energy of the ring current computed on the basis of the assumption that the injection rate into the ring current is related to *AL* in such a way that it is maximum at the beginning of the main phase and decays exponentially thereafter.

Magnetospheric storm

$= \Sigma$ (Magnetospheric substorm) $_i$

Magnetospheric storm

$= \Sigma \alpha_i$ (Magnetospheric substorm) $_i$

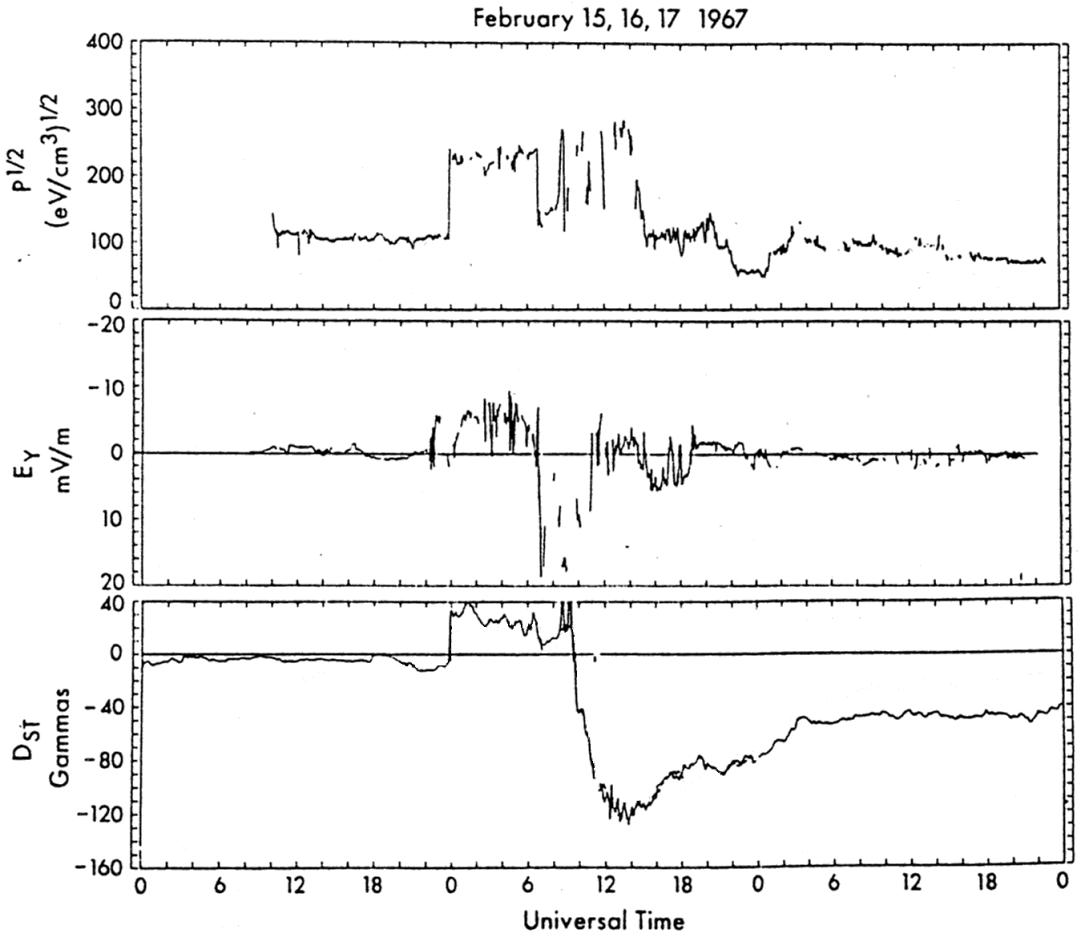
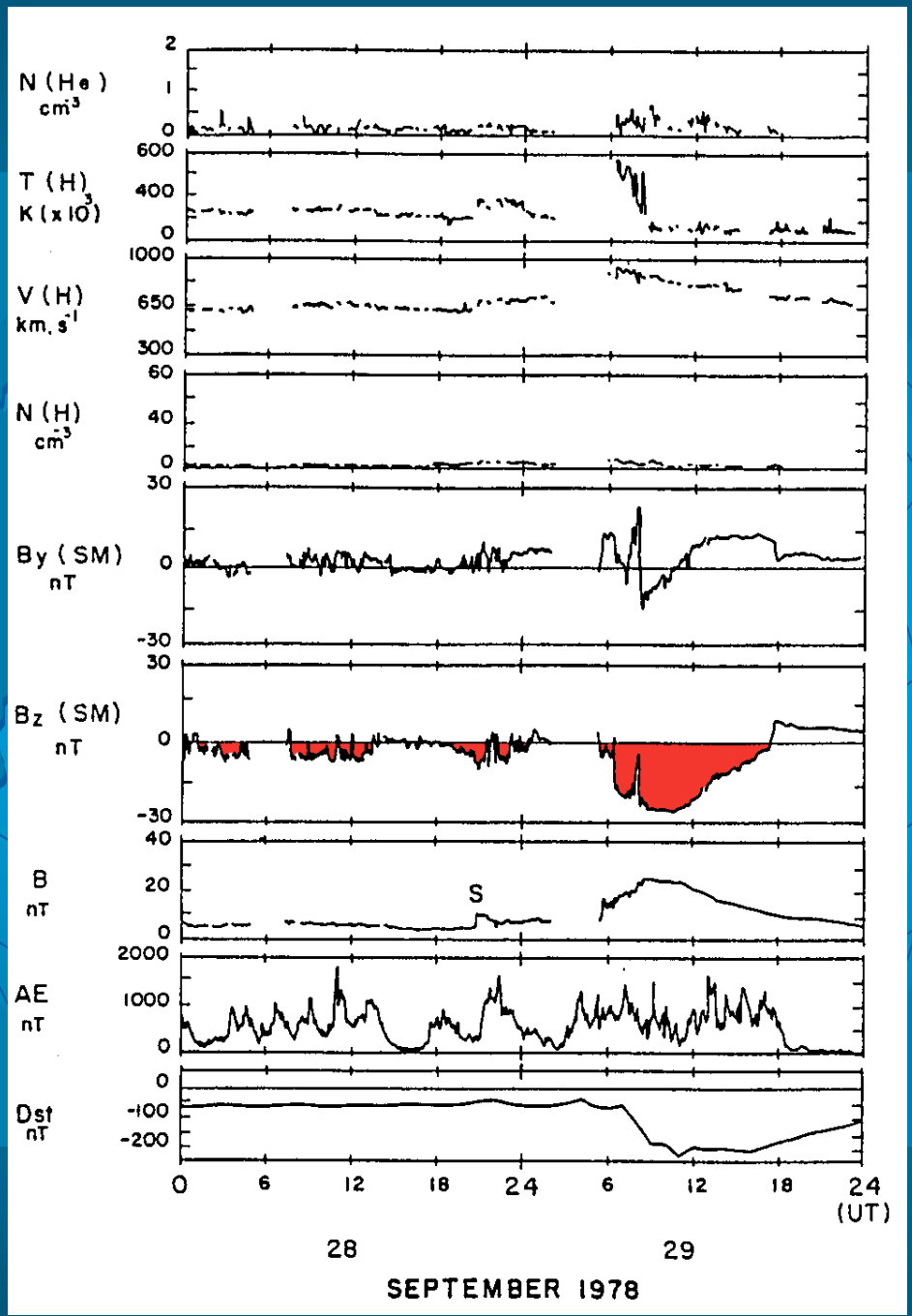
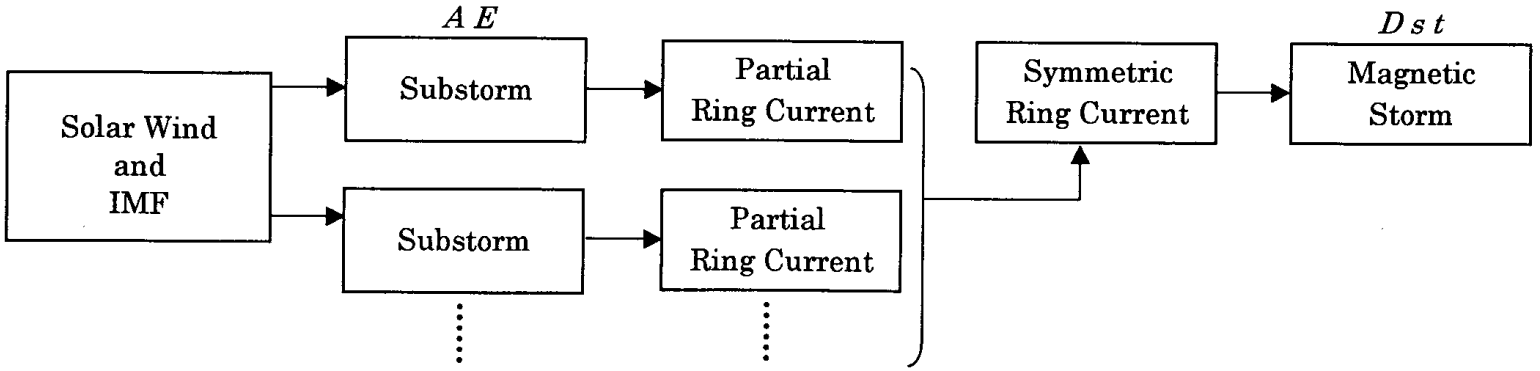


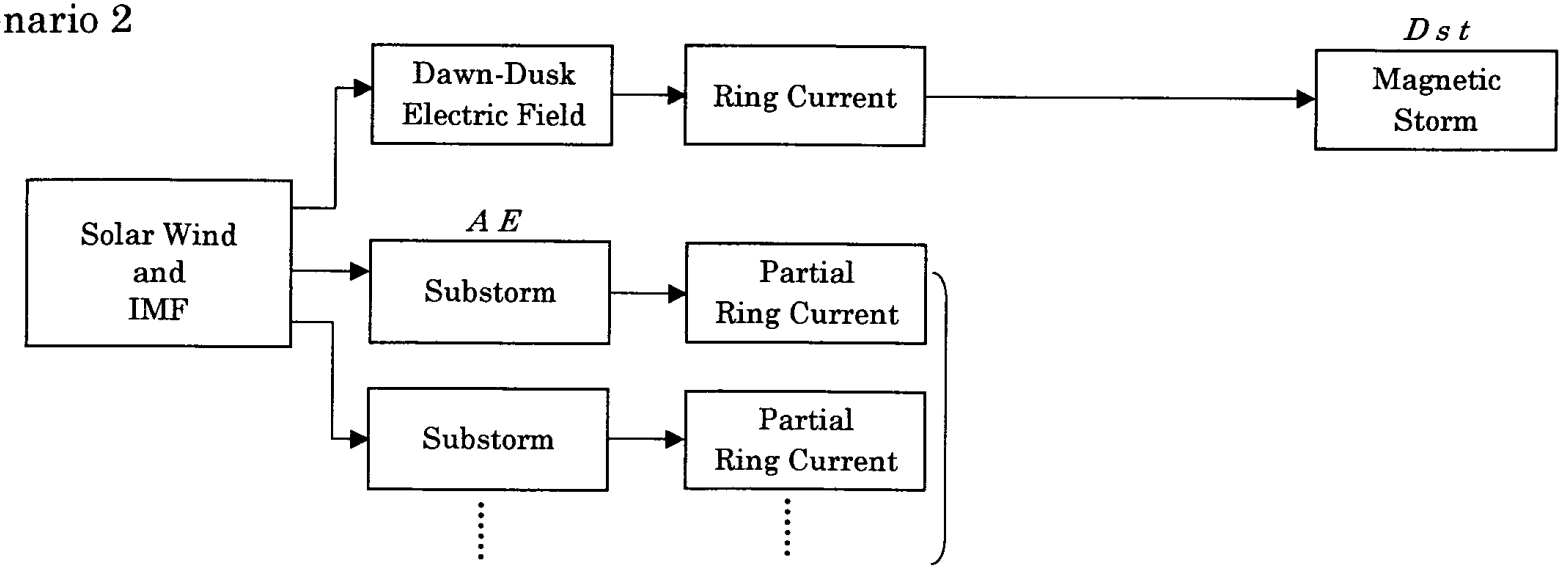
Fig. 3. The square root of the solar wind dynamic pressure, the dawn-dusk interplanetary electric field, and the predicted (dashed line) and observed (solid line) *Dst*. After BURTON *et al.* (1975).


N (He)
cm-3
2
1
0
T (H)
K (x 10)
600
400
0
V (H)
km. s-1
1000
650
300
N (H)
cm-3
60
40
0
By (SM)
nT
30
0
-30
Bz (SM)
nT
30
0
-30
B
nT
40
20
0
S
AE
nT
2000
1000
0
Dst
nT
0
-100
-200
0
6
12
18
24
6
12
18
24
(UT)
28
29
SEPTEMBER 1978

Scenario 1



Scenario 2

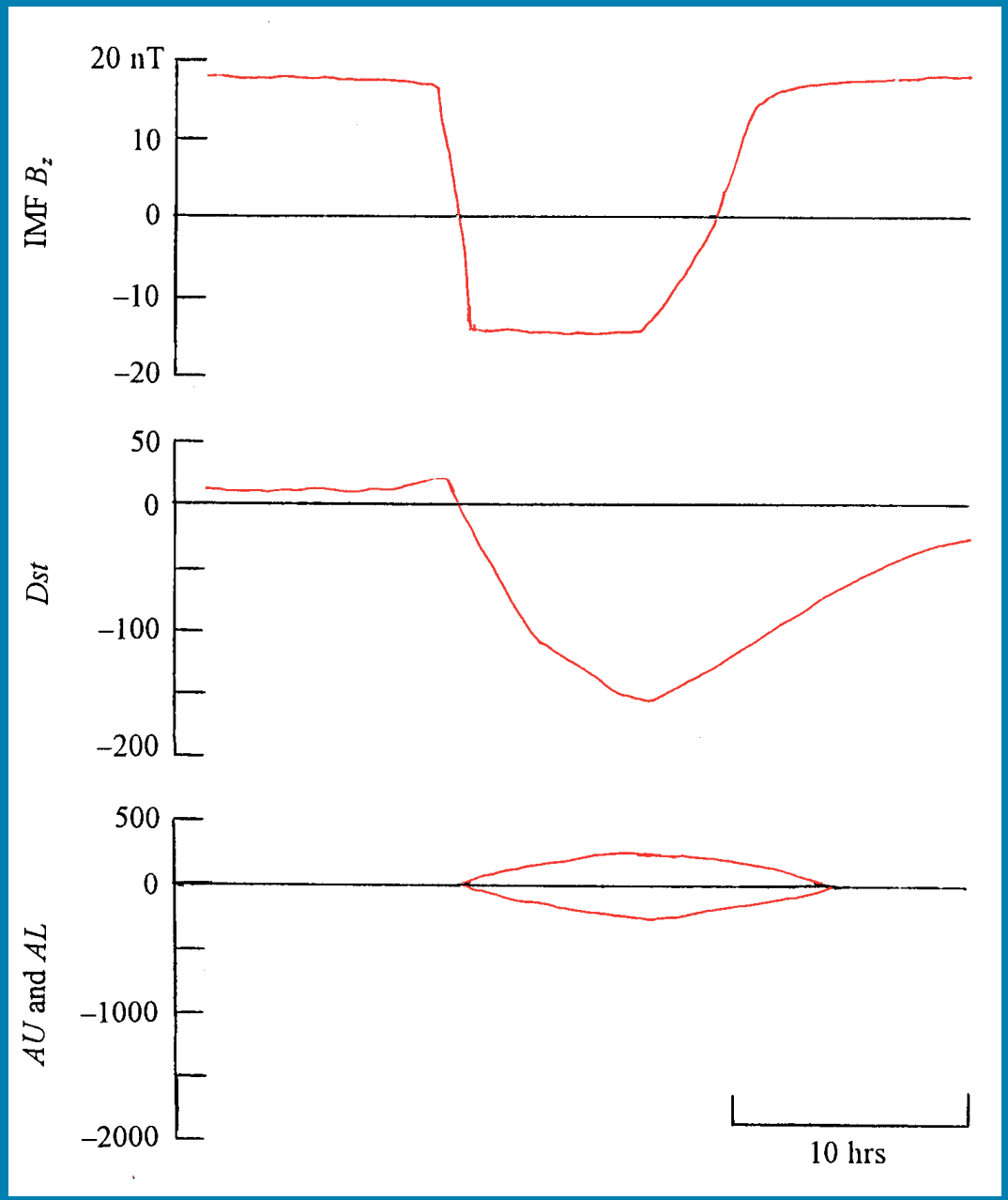


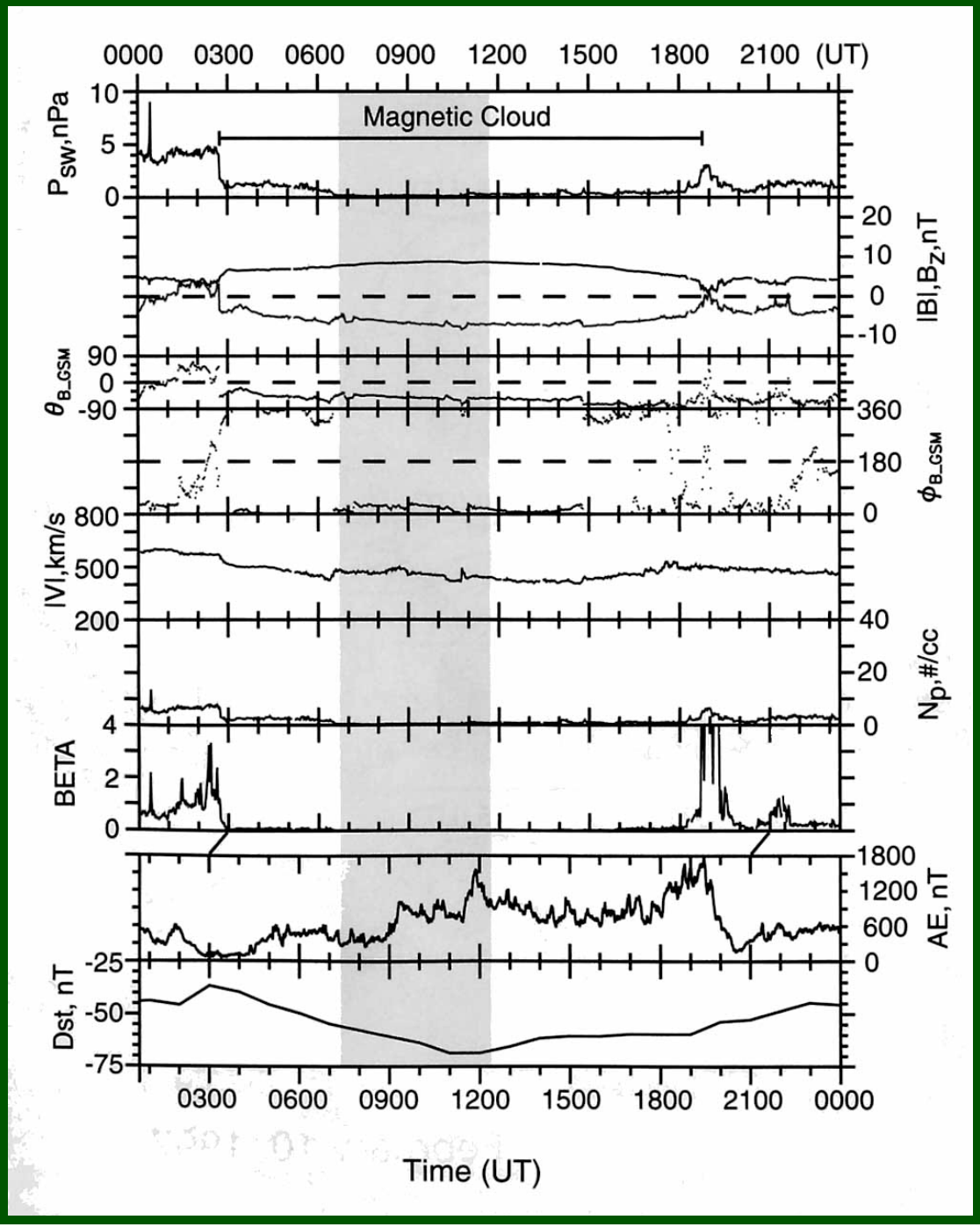
Magnetospheric storm

$= \Sigma$ (Magnetospheric substorm) $_i$

Magnetospheric storm

$= \Sigma \alpha_i$ (Magnetospheric substorm) $_i$


20 nT
10
0
−10
−20
IMF B_z
50
0
−100
−200
Dst
500
0
−1000
−2000
AU and *AL*
10 hrs


0000 0300 0600 0900 1200 1500 1800 2100 (UT)
Magnetic Cloud
P_{SW},nPa
10
5
0
|B|,B_Z,nT
20
10
0
-10
θ_{B_GSM}
90
0
-90
360
180
0
ϕ_{B_GSM}
|V|,km/s
800
500
200
40
20
0
N_p,#/cc
BETA
4
2
0
1800
1200
600
0
AE, nT
-25
-50
-75
Dst, nT
0300 0600 0900 1200 1500 1800 2100 0000
Time (UT)

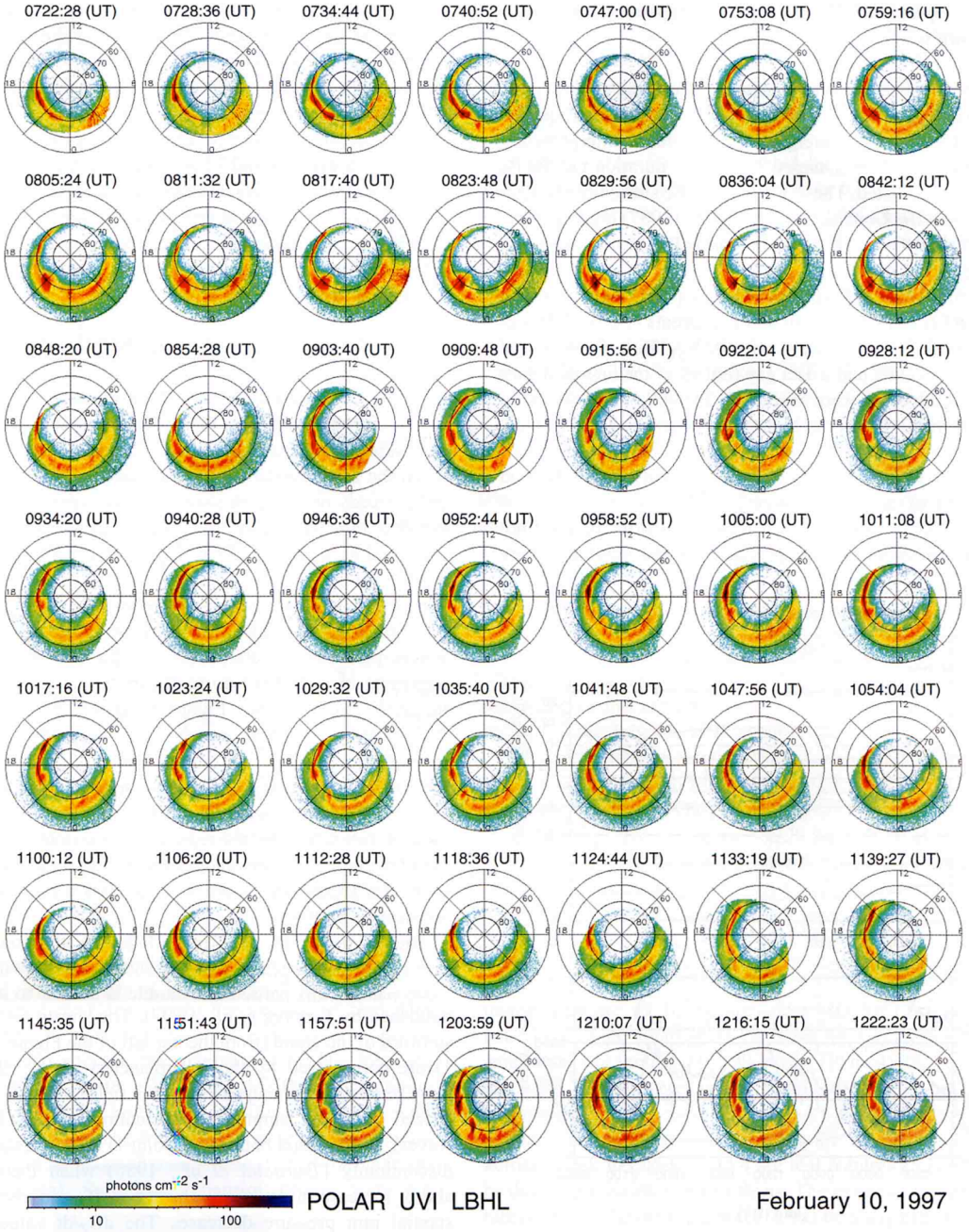
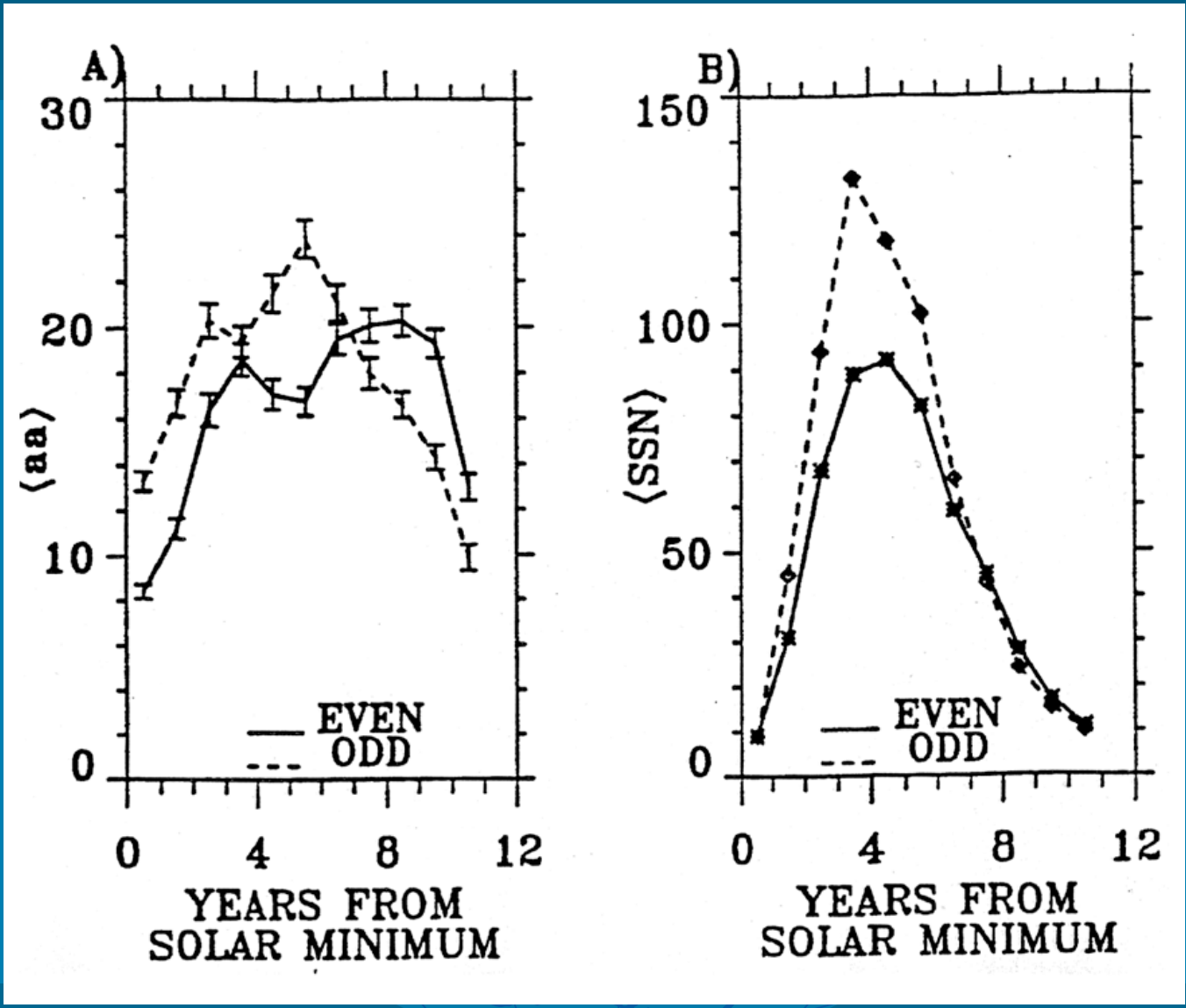
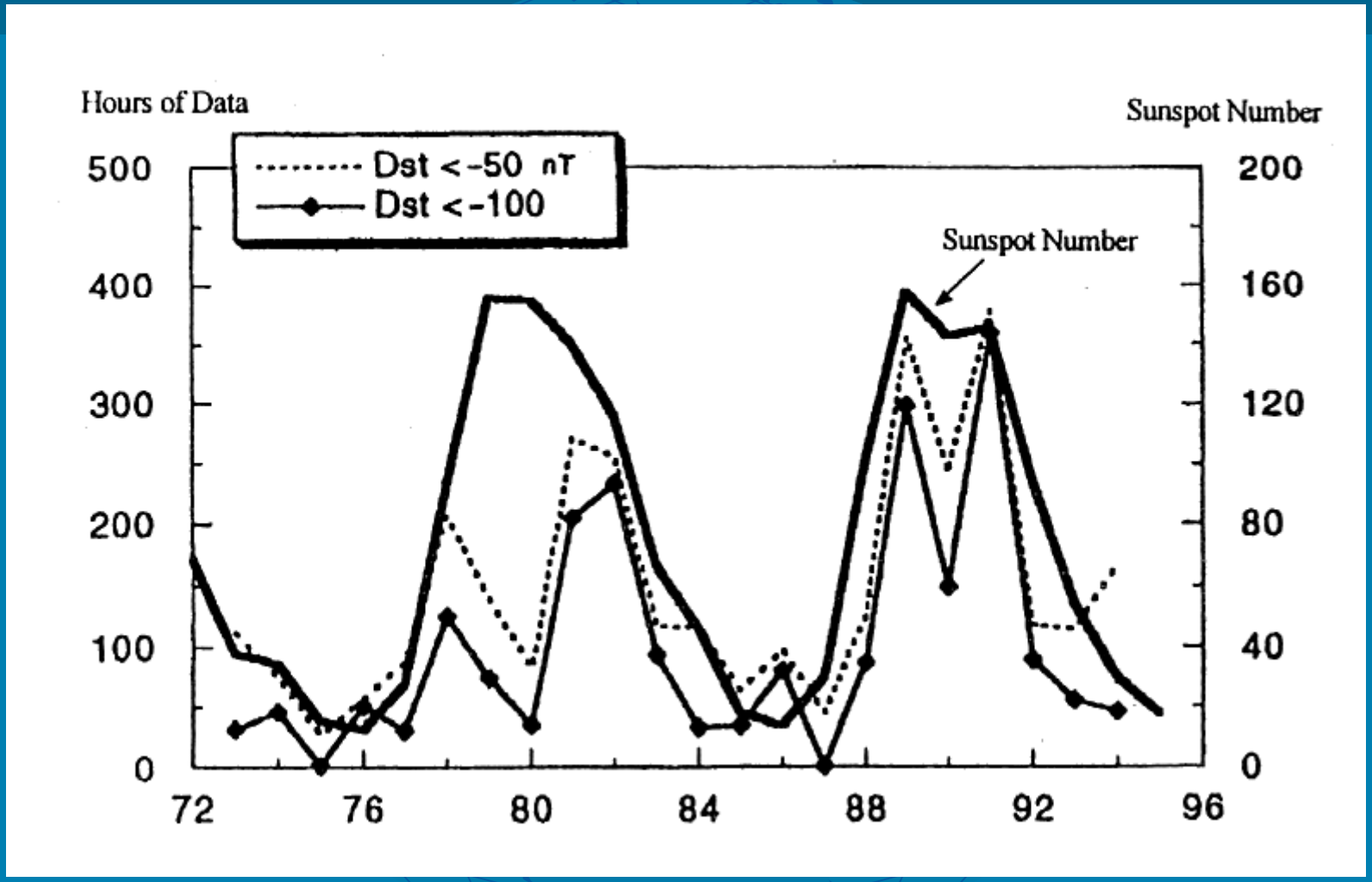
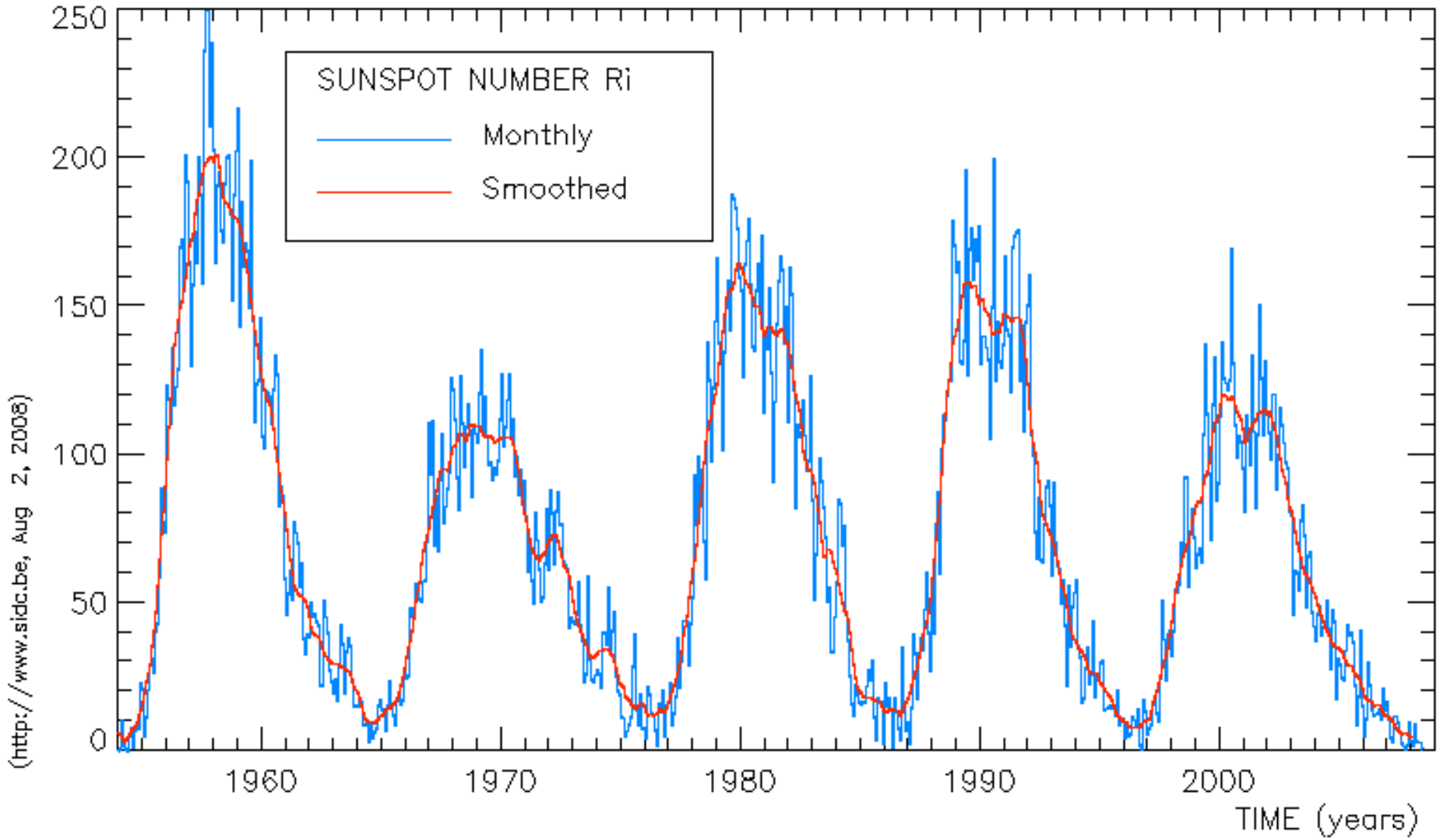
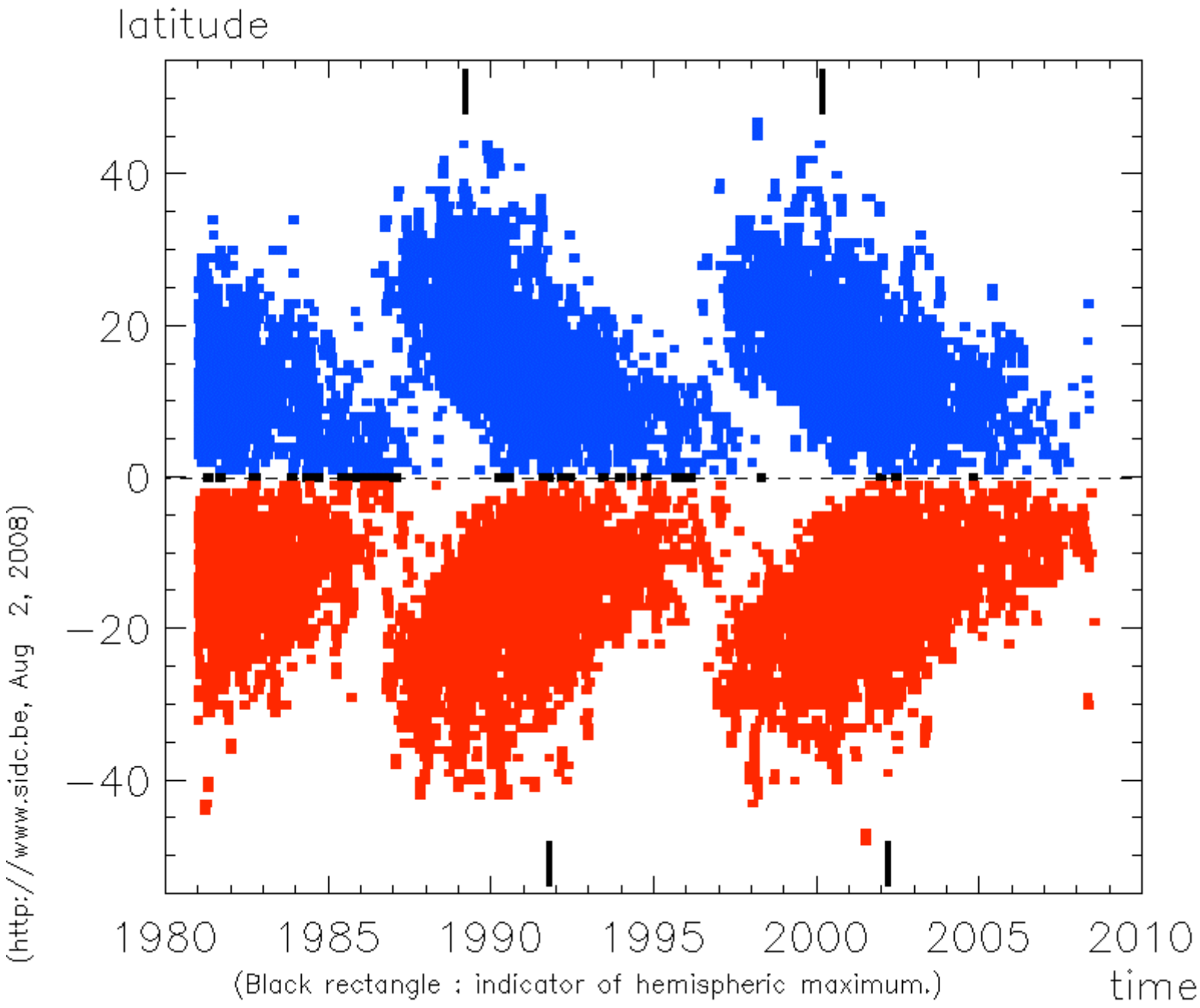


Plate 4. Polar UVI data for the shaded region of Figure 2. There are no identifiable substorm expansion phases during this ~6 hr interval.


A)
30
20
10
0
⟨aa⟩
EVEN
ODD
0
4
8
12
YEARS FROM
SOLAR MINIMUM
B)
150
100
50
0
⟨SSN⟩
EVEN
ODD
0
4
8
12
YEARS FROM
SOLAR MINIMUM


Hours of Data
Sunspot Number
Dst < -50 nT
Dst < -100
Sunspot Number
500
400
300
200
100
0
200
160
120
80
40
0
72
76
80
84
88
92
96


SUNSPOT NUMBER Ri
Monthly
Smoothed
250
200
150
100
50
0
1960
1970
1980
1990
2000
TIME (years)
(http://www.sidc.be, Aug 2, 2008)


latitude
40
20
0
−20
−40
1980
1985
1990
1995
2000
2005
2010
time
(Black rectangle : indicator of hemispheric maximum.)
(http://www.sidc.be, Aug 2, 2008)

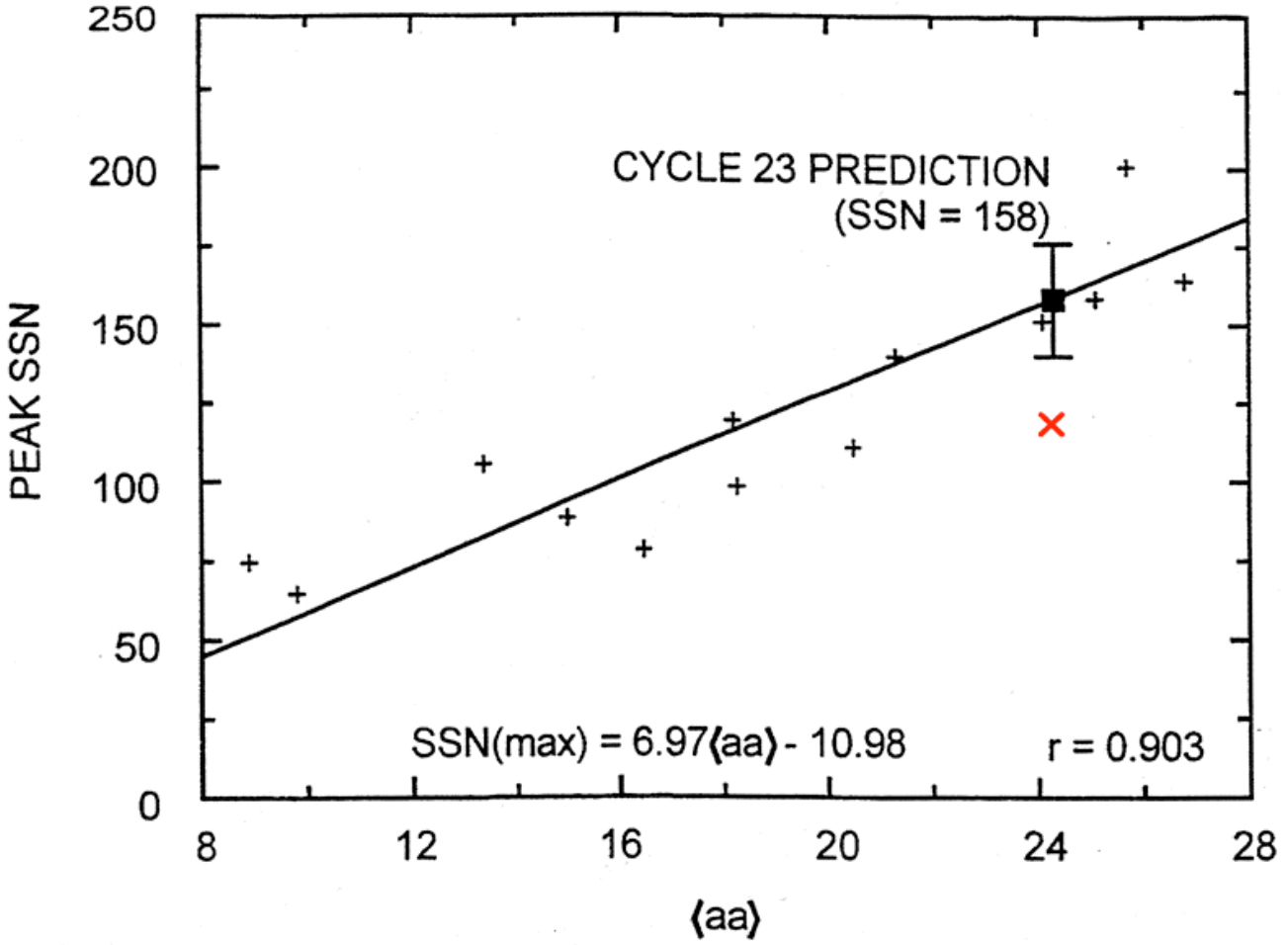
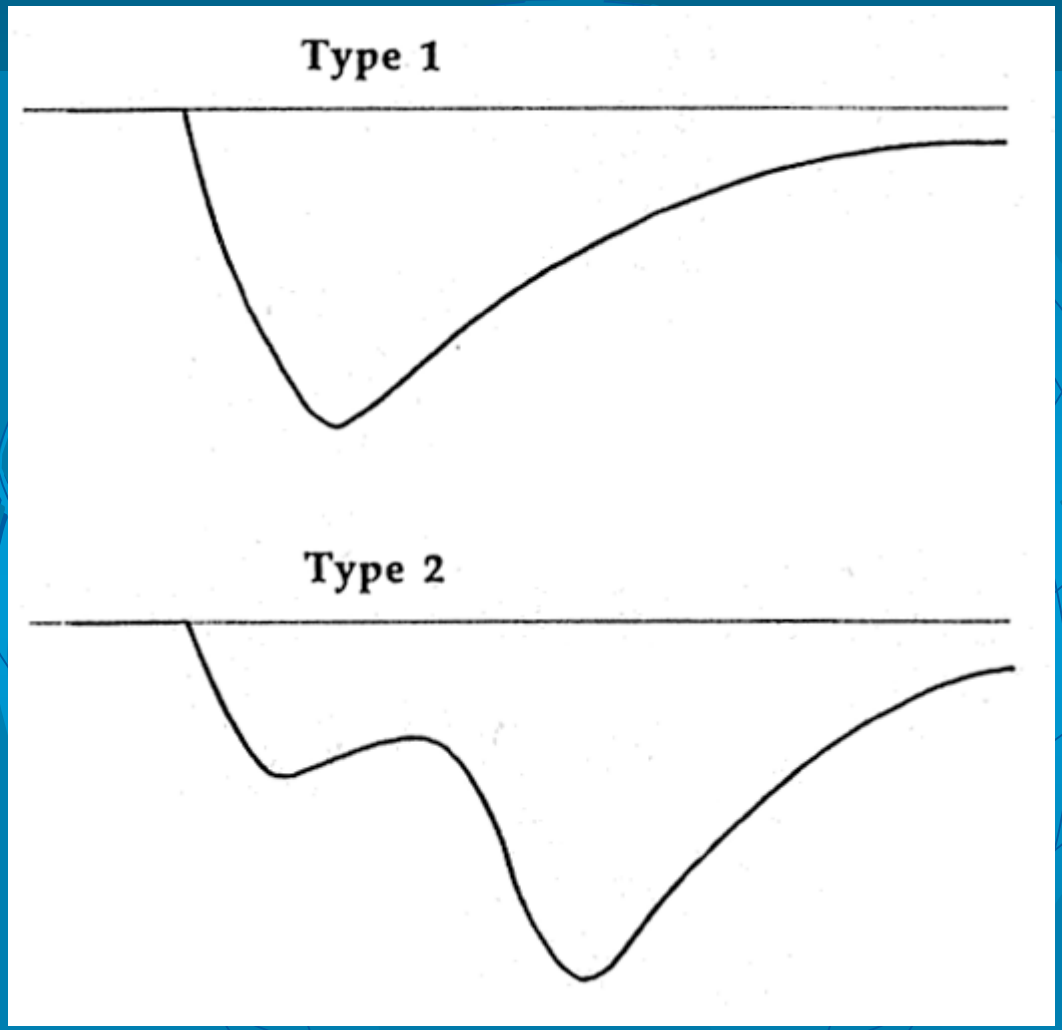
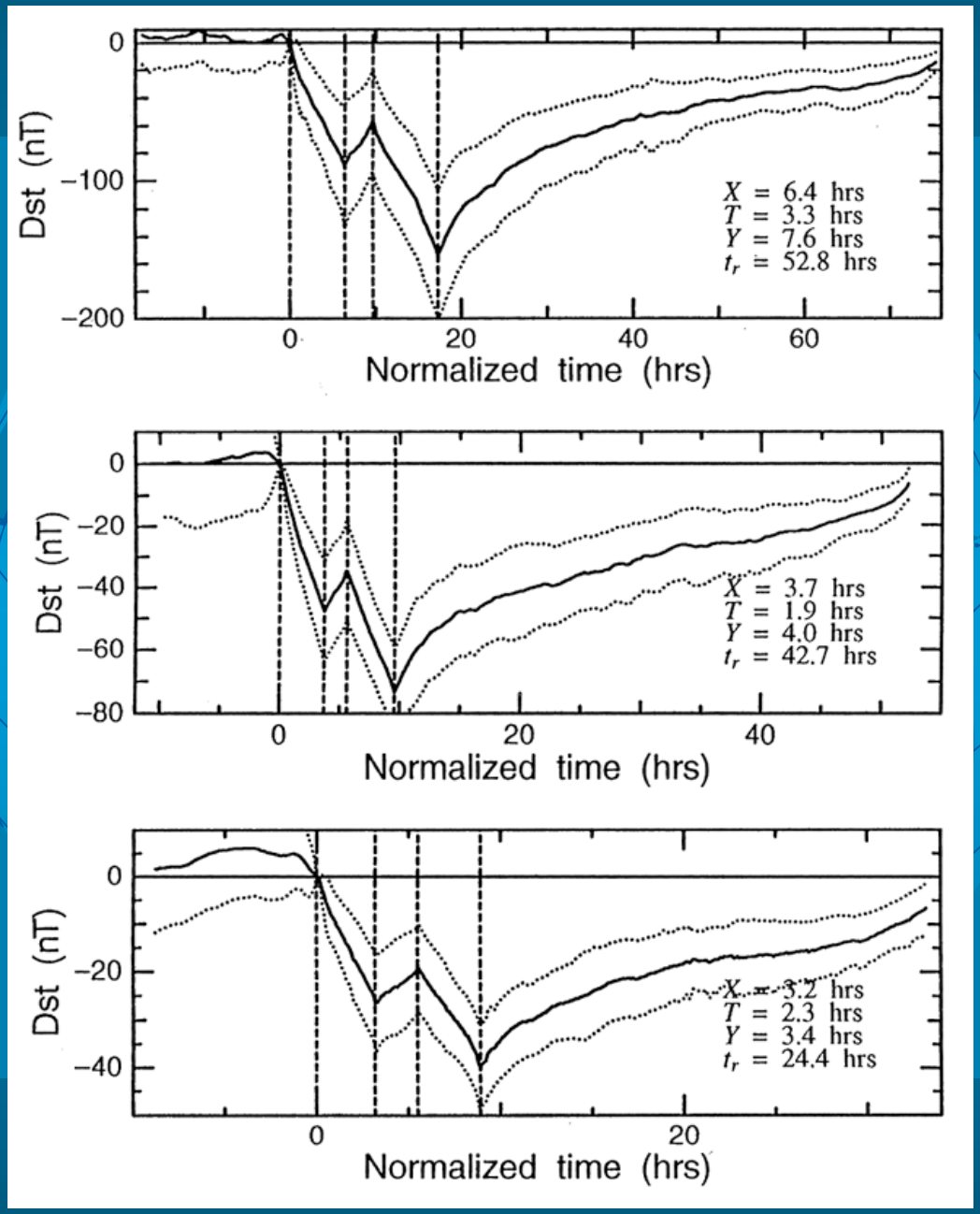
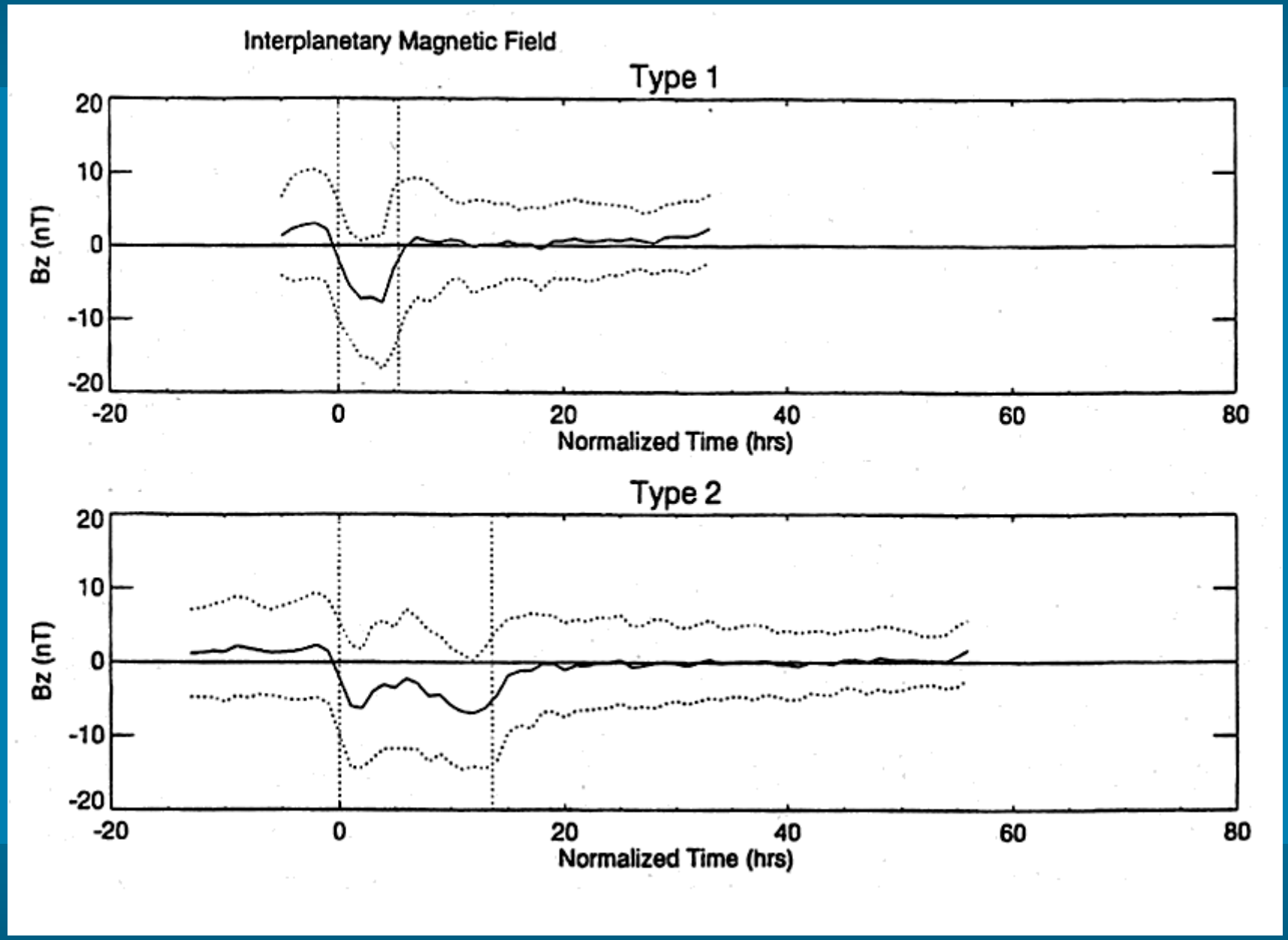


Figure 2. Regression line for peak SSN of a cycle vs *aa* averaged over the last 30% (measured backward from the smoothed sunspot minimum) of the previous cycle. The filled square indicates the prediction (158 ± 18) for cycle 23.

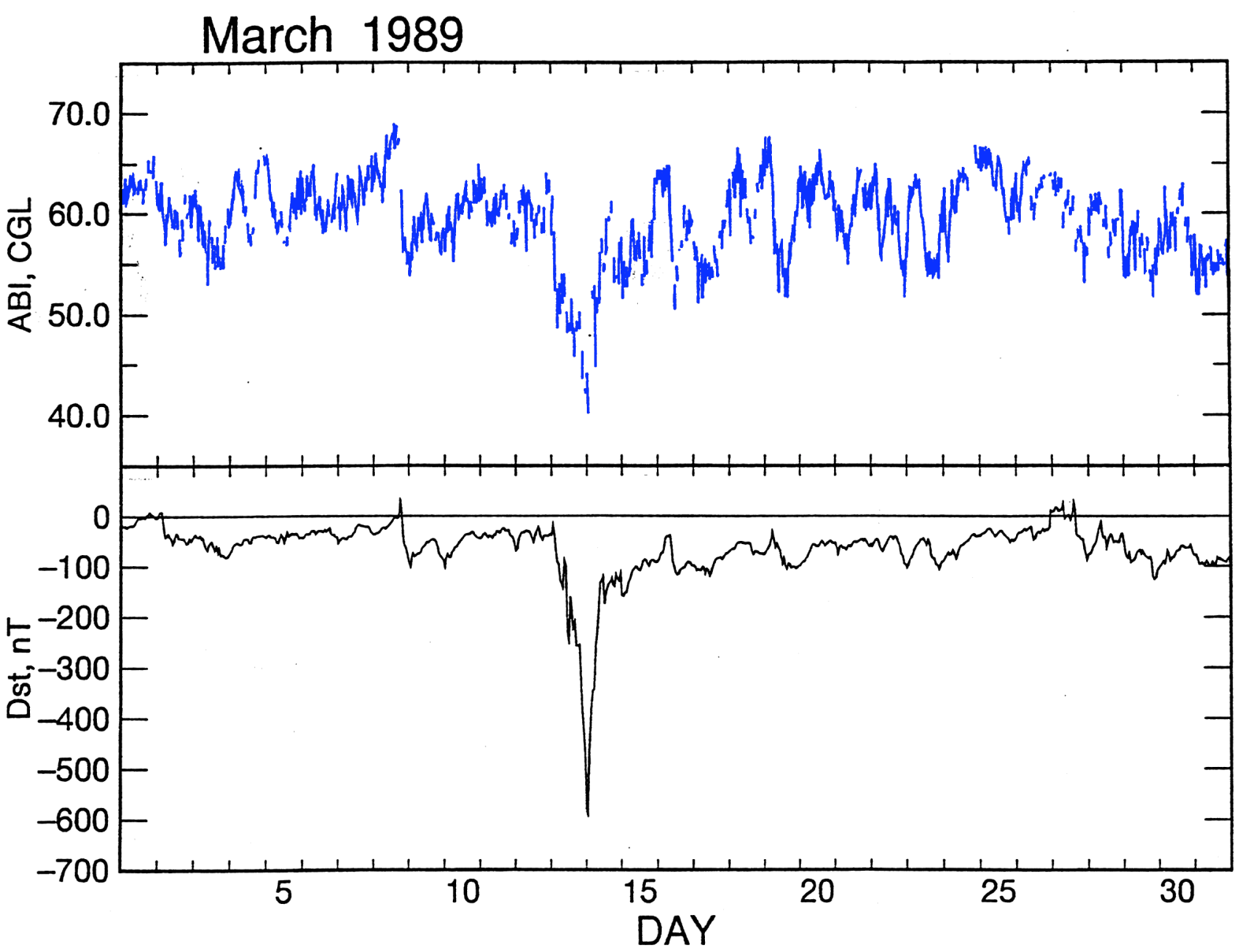

Type 1
Type 2

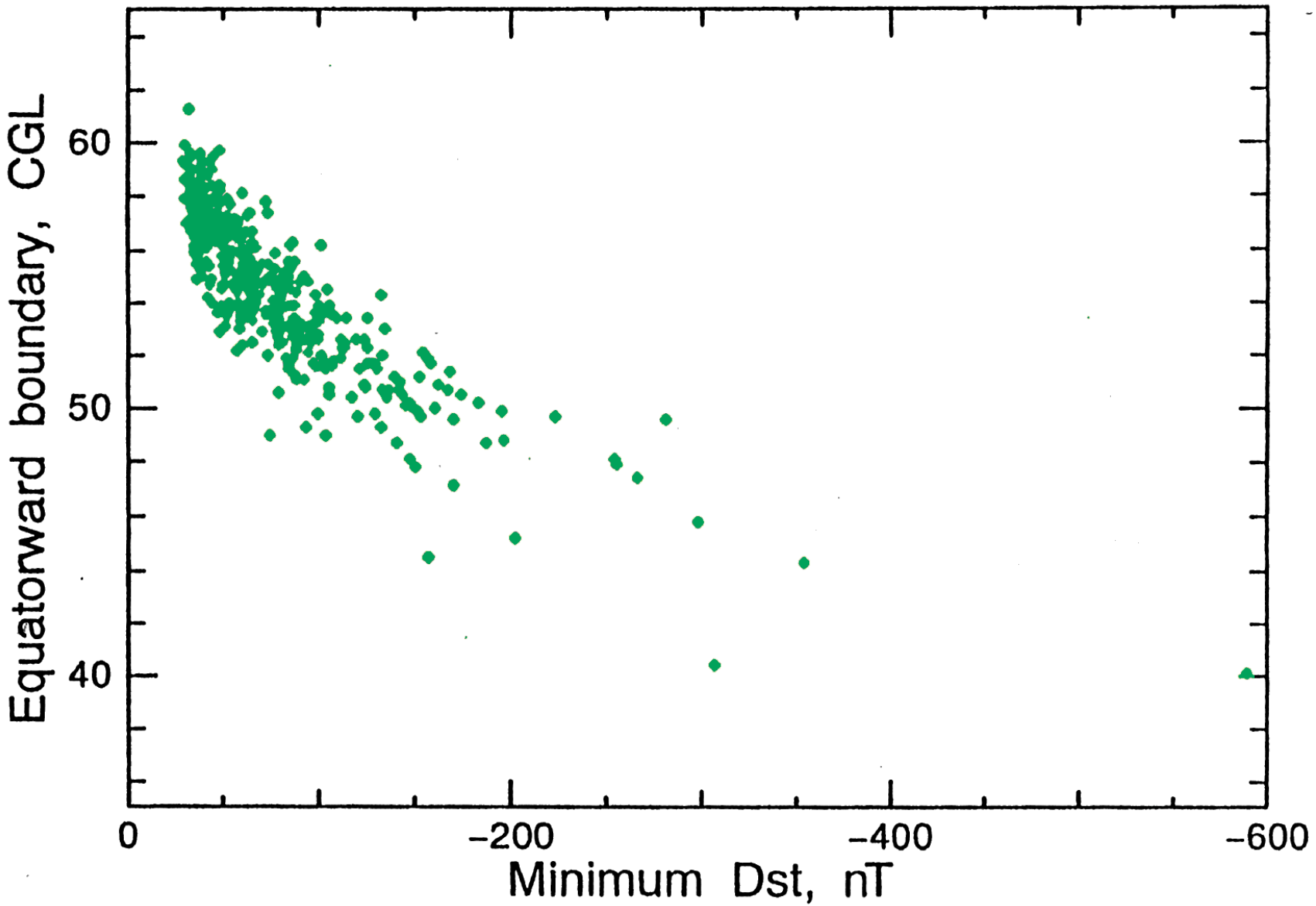

0
−100
−200
Dst (nT)
0
20
40
60
Normalized time (hrs)
X = 6.4 hrs
T = 3.3 hrs
Y = 7.6 hrs
t_r = 52.8 hrs
0
−20
−40
−60
−80
Dst (nT)
0
20
40
Normalized time (hrs)
X = 3.7 hrs
T = 1.9 hrs
Y = 4.0 hrs
t_r = 42.7 hrs
0
−20
−40
Dst (nT)
0
20
Normalized time (hrs)
X = 3.2 hrs
T = 2.3 hrs
Y = 3.4 hrs
t_r = 24.4 hrs

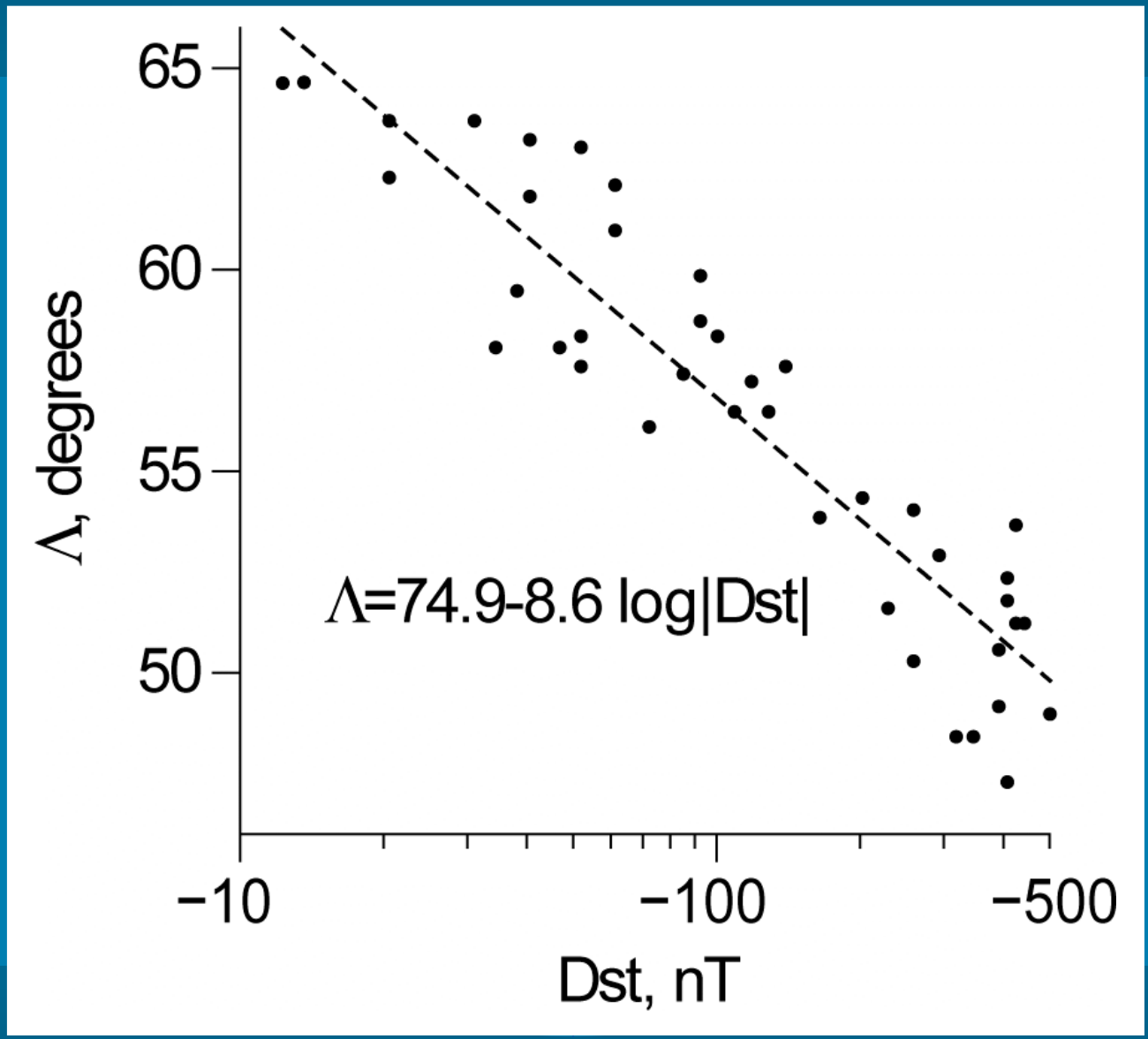

Interplanetary Magnetic Field
Type 1
Bz (nT)
20
10
0
-10
-20
-20
0
20
40
60
80
Normalized Time (hrs)
Type 2
Bz (nT)
20
10
0
-10
-20
-20
0
20
40
60
80
Normalized Time (hrs)

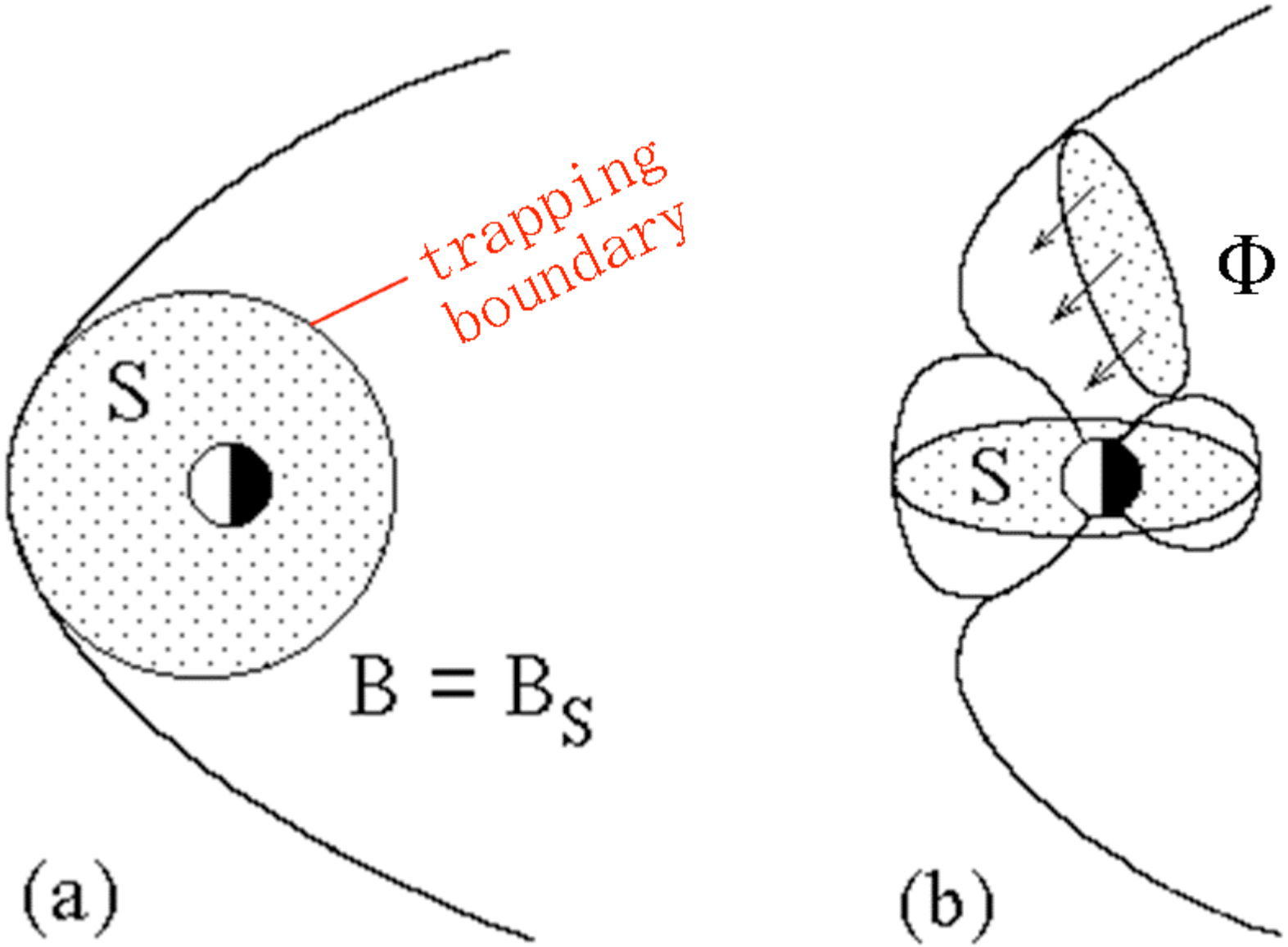
Classification of geomagnetic storms into two types

	Type 1	Type 2	Uncertain
Weak	47%	47%	6%
Medium	35	56	9
Intense	29	67	4
All	40	53	6


March 1989
ABI, CGL
70.0
60.0
50.0
40.0
Dst, nT
0
−100
−200
−300
−400
−500
−600
−700
5
10
15
20
25
30
DAY

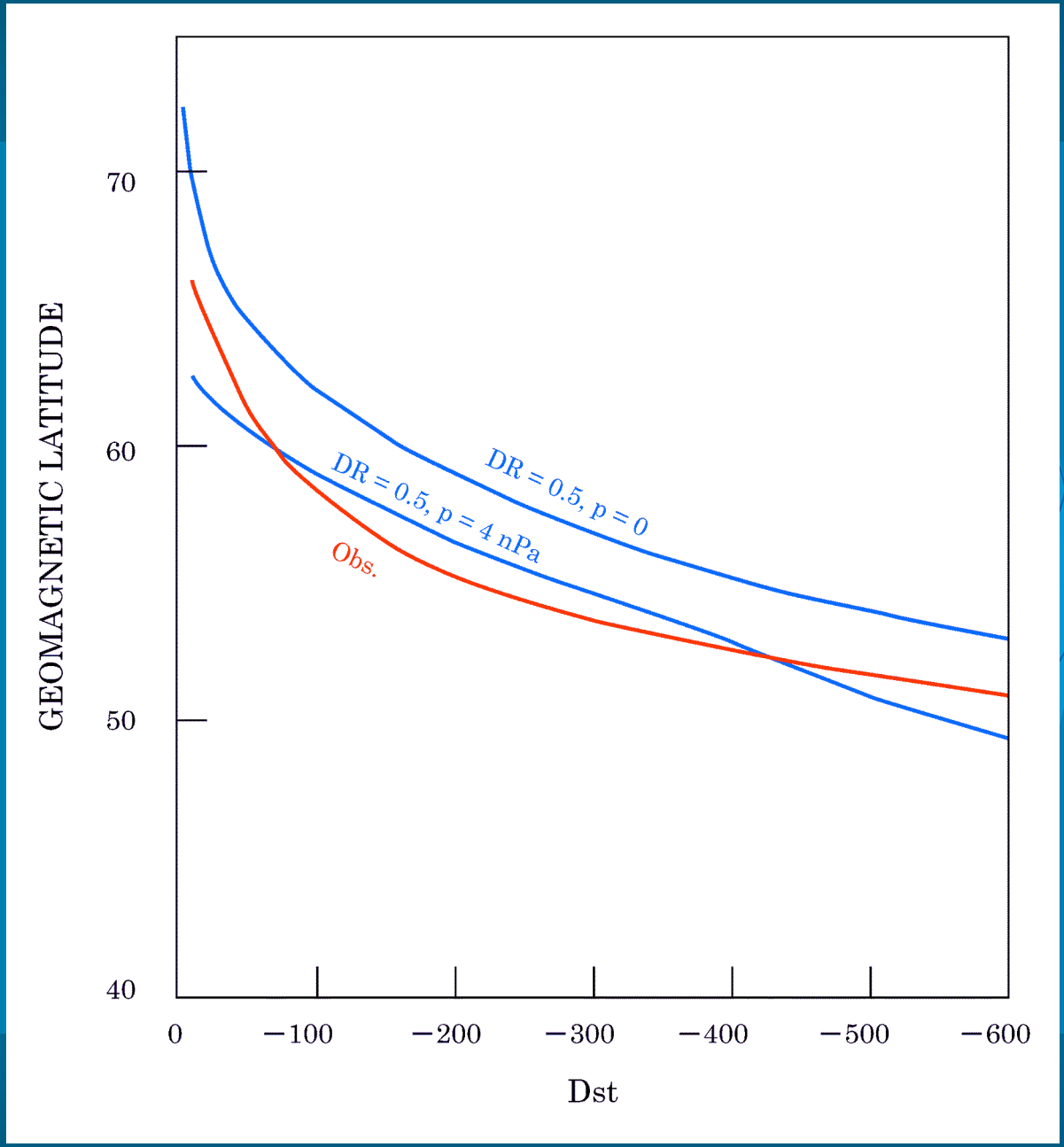

Equatorward boundary, CGL
60
50
40
0
−200
−400
−600
Minimum Dst, nT

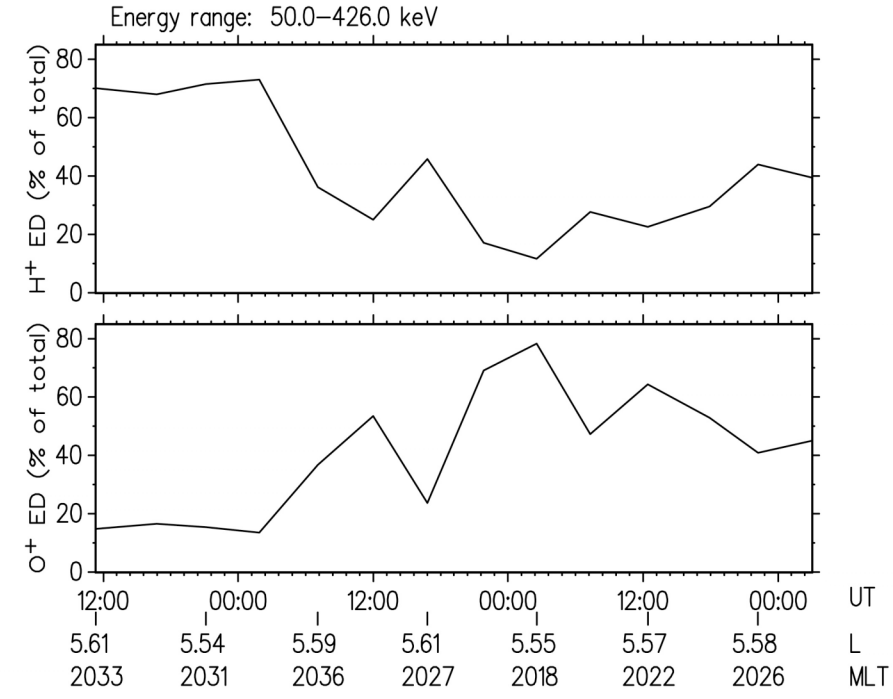

65
60
55
50
Λ, degrees
Λ=74.9-8.6 log|Dst|
−10
−100
−500
Dst, nT


trapping
boundary
S
B = B_S
(a)
Φ
S
(b)

$$B_z = B_m + B_{RC} + B^{ext}$$

$$= \sqrt{2\mu_0 p} + B_{RC} - \Phi/2S$$


GEOMAGNETIC LATITUDE
70
60
50
40
0
−100
−200
−300
−400
−500
−600
Dst
DR = 0.5, p = 0
DR = 0.5, p = 4 nPa
Obs.



March 23-25, 1991

Summary

1. A geomagnetic storm is identified by the development of the ring current in the magnetosphere, which is carried by energetic (10 − 200 keV) ions in $L = 2 - 7$. The growth and decay of geomagnetic storms can be monitored by the *Dst* index.

2. Studies of geomagnetic records with the help from solar and auroral observations were conducted in parallel with discoveries of the important laws of electromagnetism.

3. Most of the *Dst* variance during intense geomagnetic storms can be reproduced by knowledge about changes in large-scale electric fields in the solar wind. A continuing controversy exists, however, as to whether the successive occurrence of substorms plays a direct role in the energization of storm-time ring current particles.

4. CMEs and CIRs are the primary sources leading to major geomagnetic storms. These are dominant near the maximum phase and during the declining phase of the solar cycle, respectively.

5. The increase in the ring current of about 50% of the largest geomagnetic storms goes through two steps at the main phase.

6. Not only the ring current but also the magnetotail current is the main sources to produce storm-time changes in *Dst*.

7. The abundance of ionosphere-origin ions is high and is correlated well with substorm activity during the main phase of geomagnetic storms.