Solar Wind/Magnetosphere Drivers of Space Weather

D. N. Baker
Laboratory for Atmospheric and Space Physics
University of Colorado, Boulder

I. Introduction

II. Examples of Space Environmental Effects

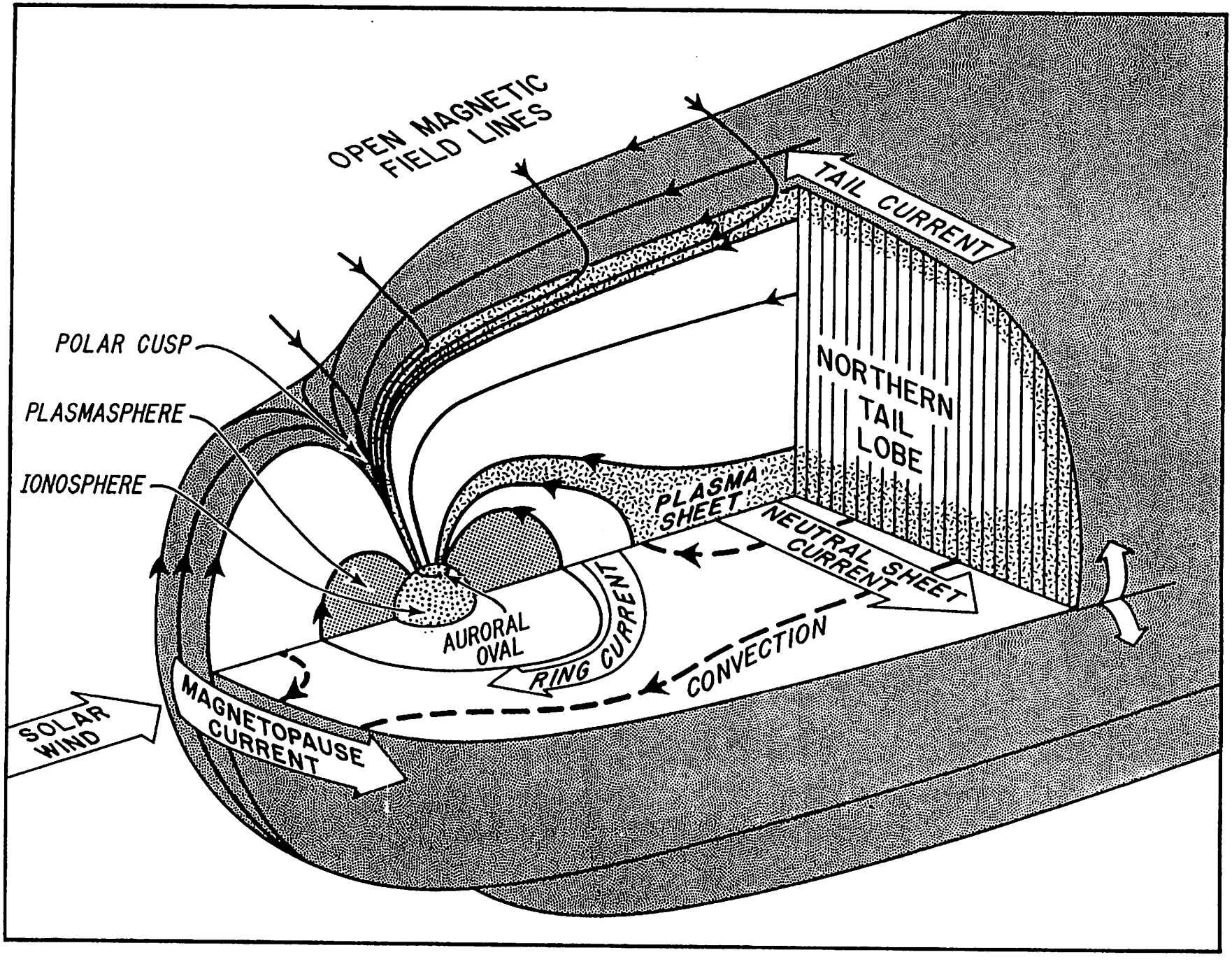
- Galactic cosmic rays
- Trapped magnetospheric particles
- Geomagnetic storms (Nonrecurrent)
- Geomagnetic storms (Recurrent)
- Magnetospheric substorms

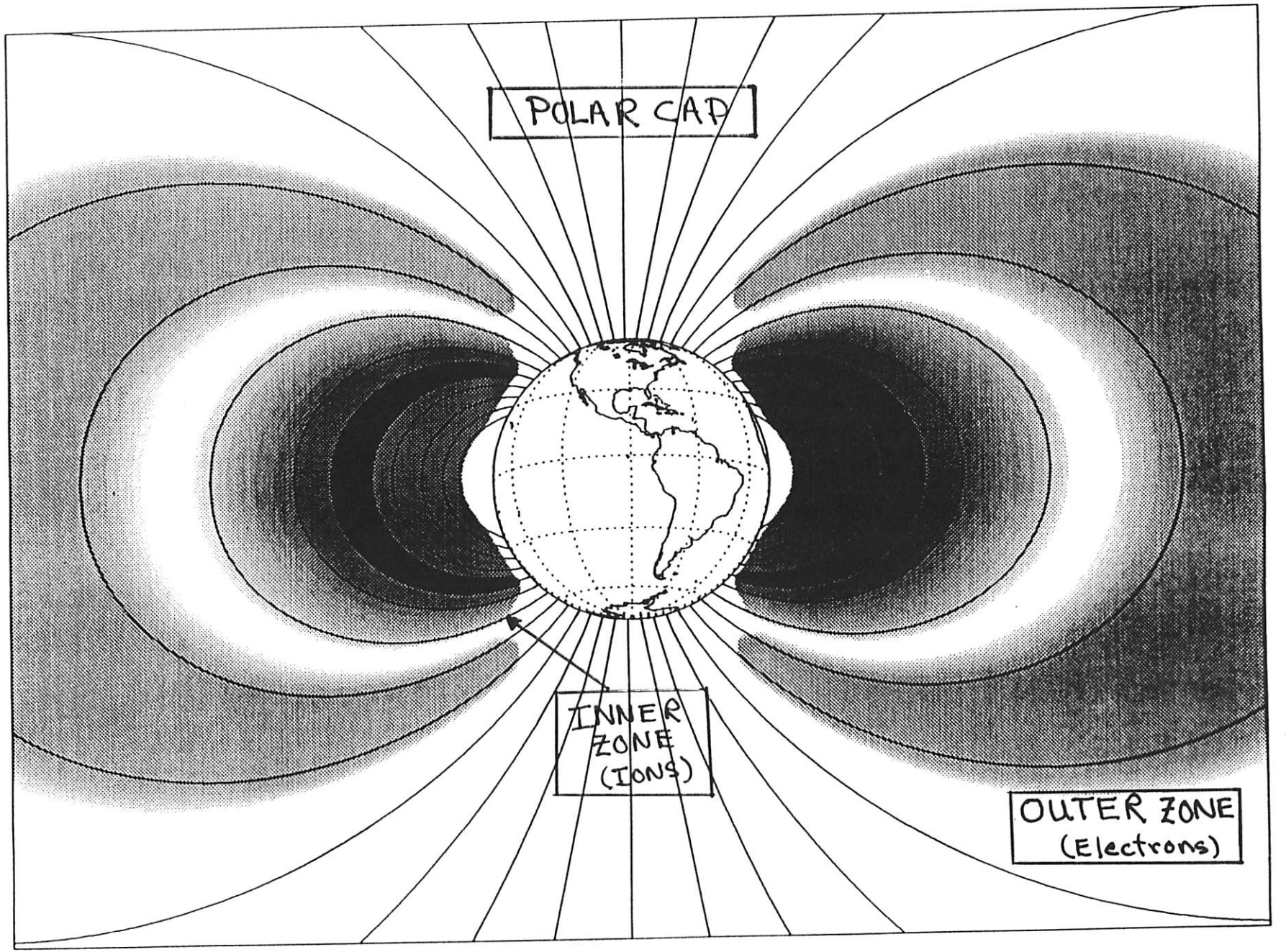
III. Prediction of Space Weather

- Solar/Heliosphere forecasts
- Upstream solar wind monitors
- Magnetosphere/ionosphere predictions

IV. Summary and Future Directions

Presented at CEDAR Workshop
27 June 1995


OPEN MAGNETIC FIELD LINES
TAIL CURRENT
POLAR CUSP
PLASMASPHERE
IONOSPHERE
NORTHERN TAIL LOBE
PLASMA SHEET
NEUTRAL SHEET CURRENT
AURORAL OVAL
RING CURRENT
CONVECTION
SOLAR WIND
MAGNETOPAUSE CURRENT


POLAR CAP
INNER ZONE (IONS)
OUTER ZONE (Electrons)

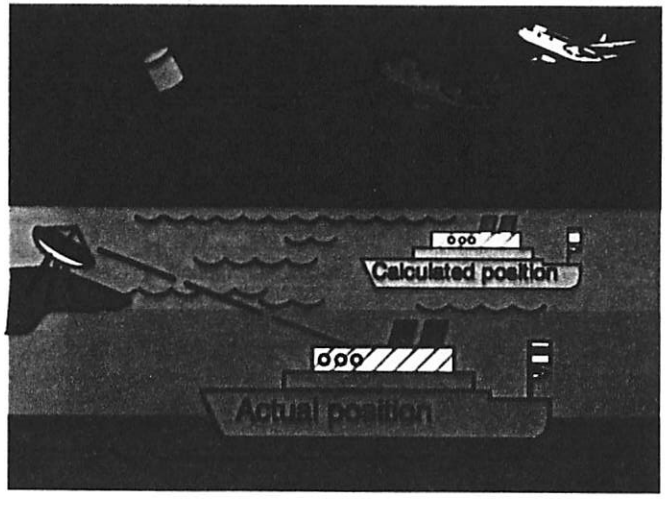
"Space Weather" refers to conditions on the sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and endanger human life and health. Adverse conditions in the space environment can cause disruption of satellite operations, communications, navigation, and electric power grids, leading to a panoply of socio-economic losses.

- National Space Weather Program
Strategic Plan (March 1995)

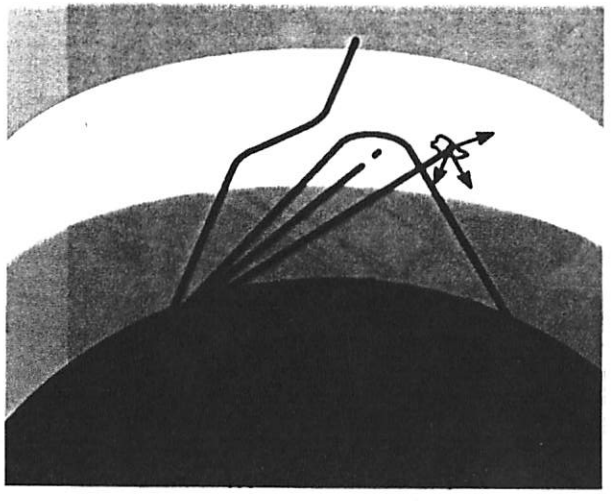
EFFECTS OF SOLAR-TERRESTRIAL DISTURBANCES

Astronauts can be exposed to serious radiation hazard during major solar activity.

Electronic navigation can be in error due to shifting of radio waves

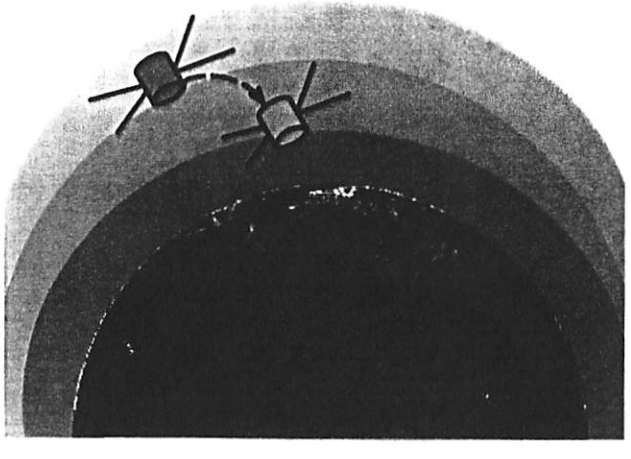


Radio waves that bounce off the atmosphere go astray.

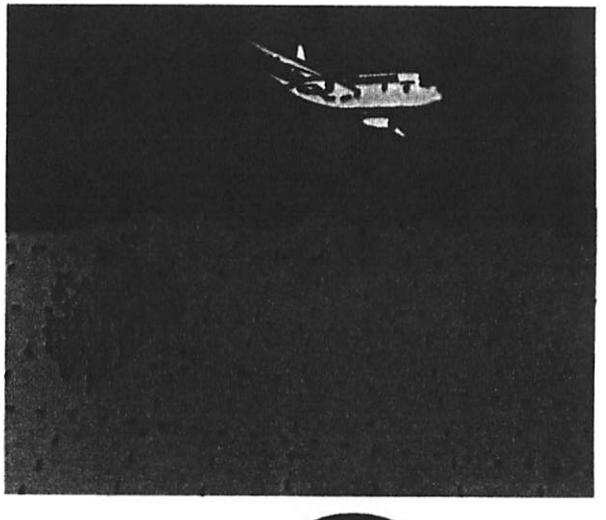


Power grids overload during large geomagnetic storms.

Satellites are "aged" and tend to fall to Earth prematurely. Their electronics also can be damaged.



Measurements from magnetic and electrical surveys often are incorrect during geomagnetic storms.



Space Environment Laboratory

Single Event Upset Mechanism
Direct Ionization

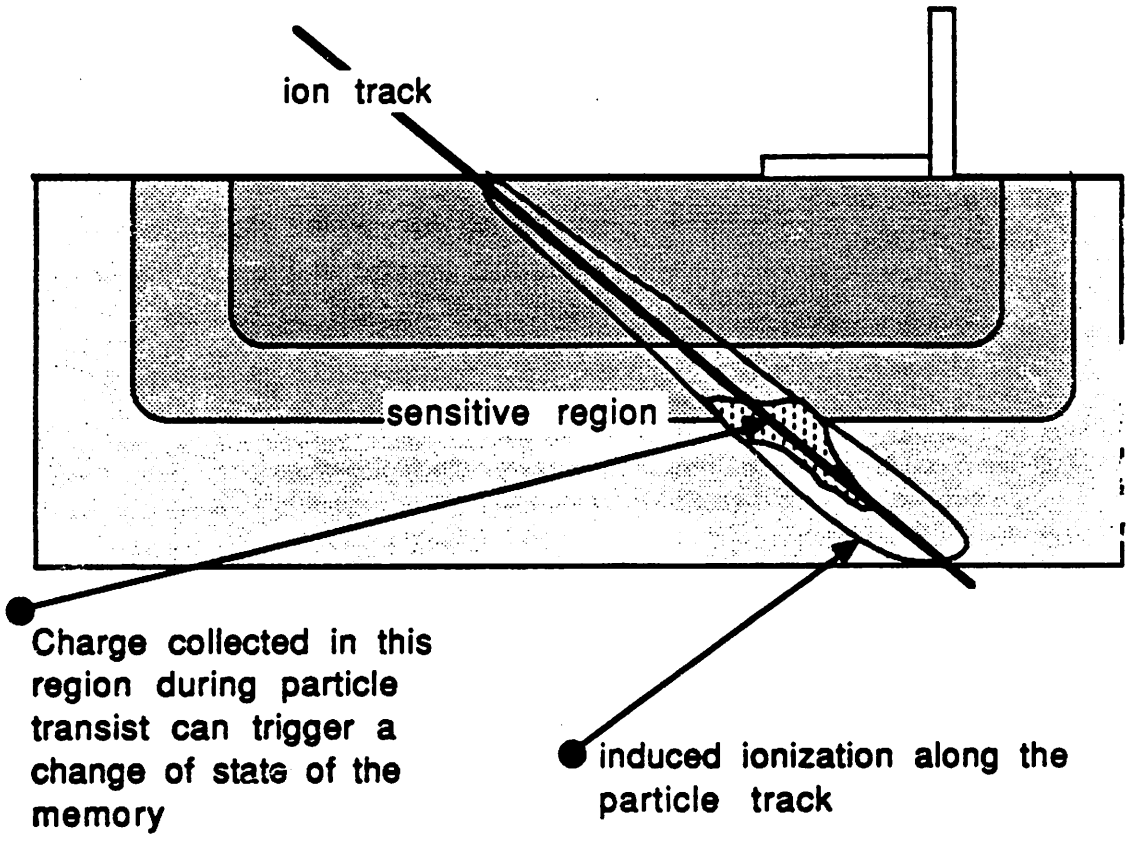
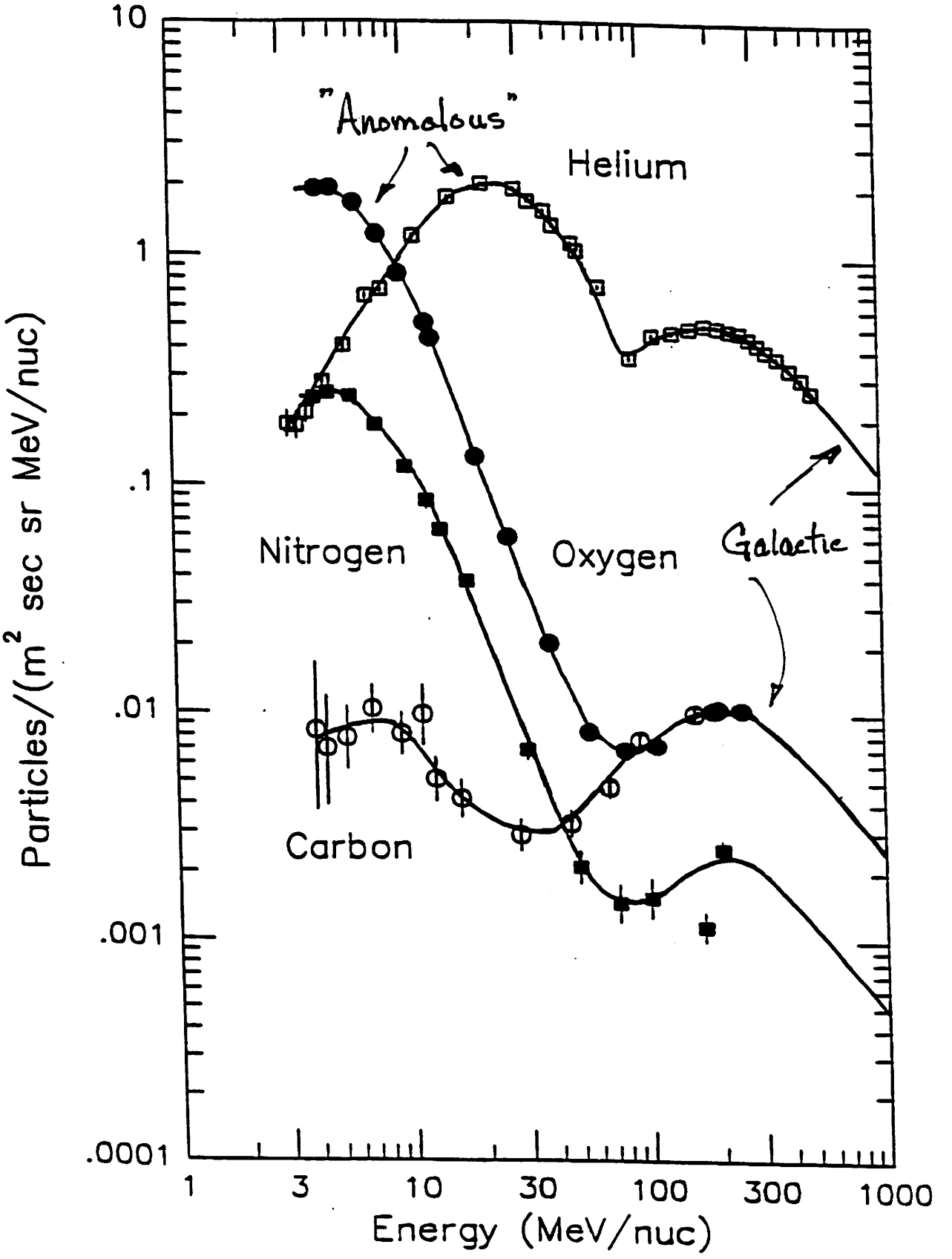
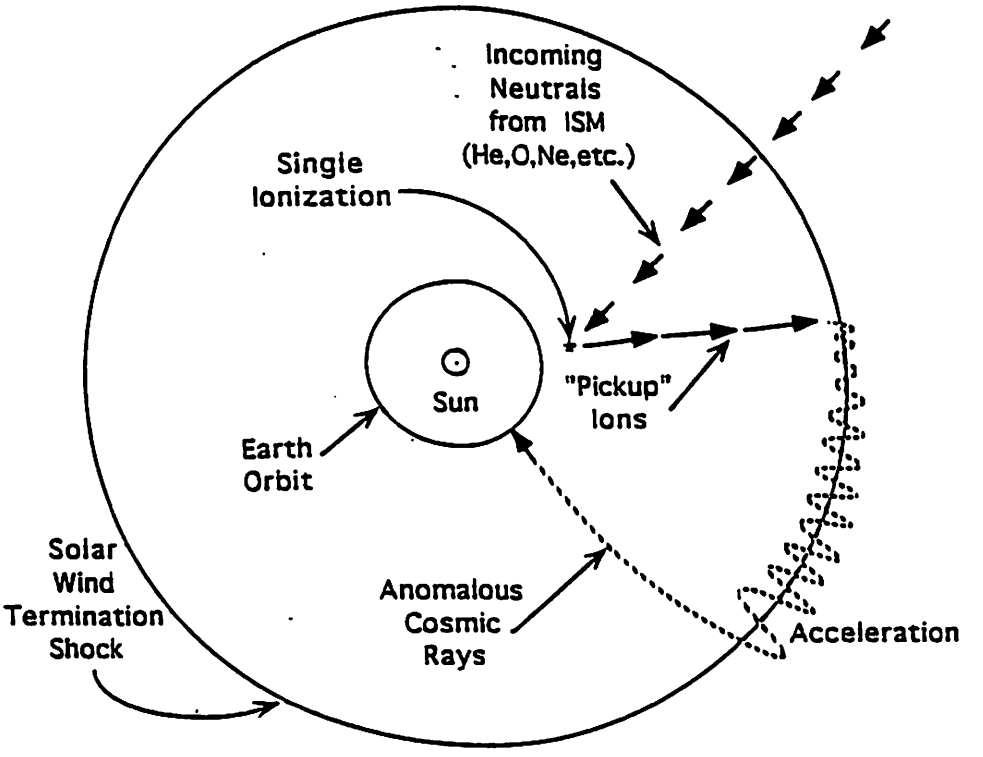


Figure 1-6. Direct Ionization SEU. Sensitive region is typically the depletion region, although charge can be collected a considerable distance from the depletion region.

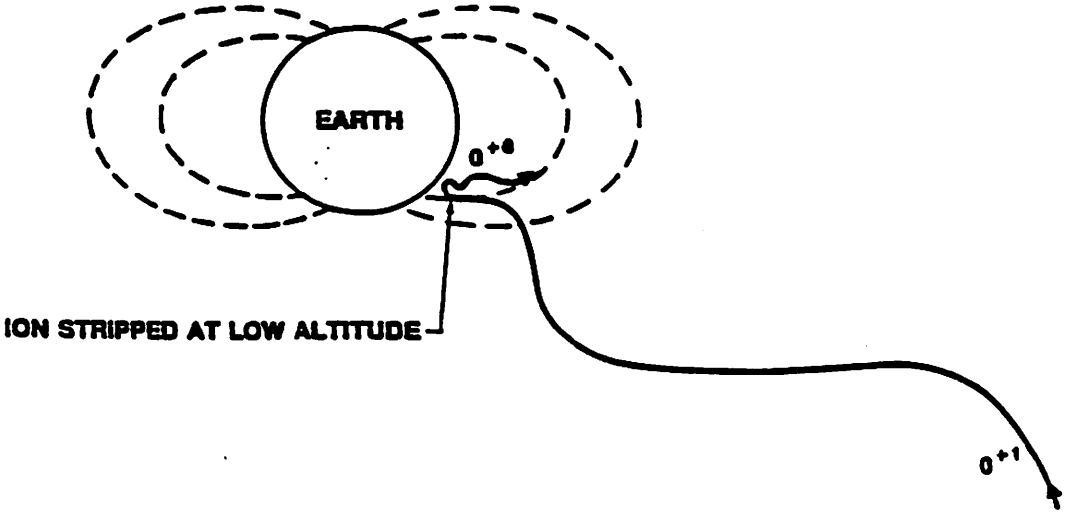


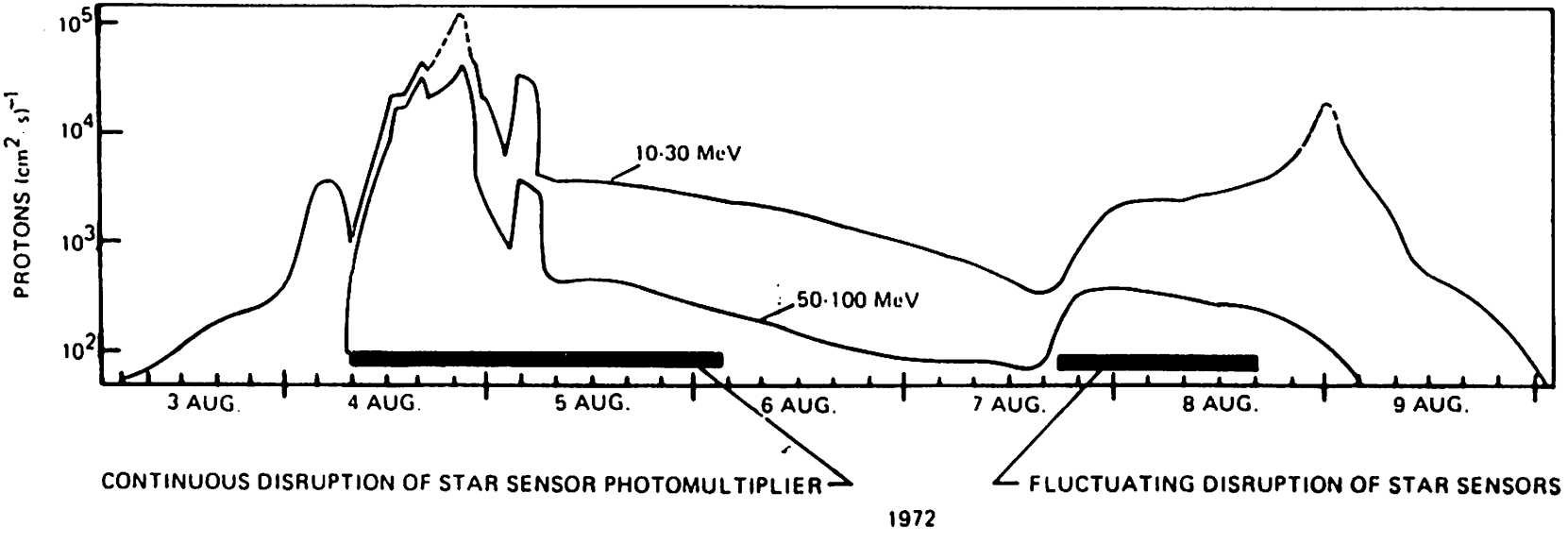
Voyager data from Cummings and Stone

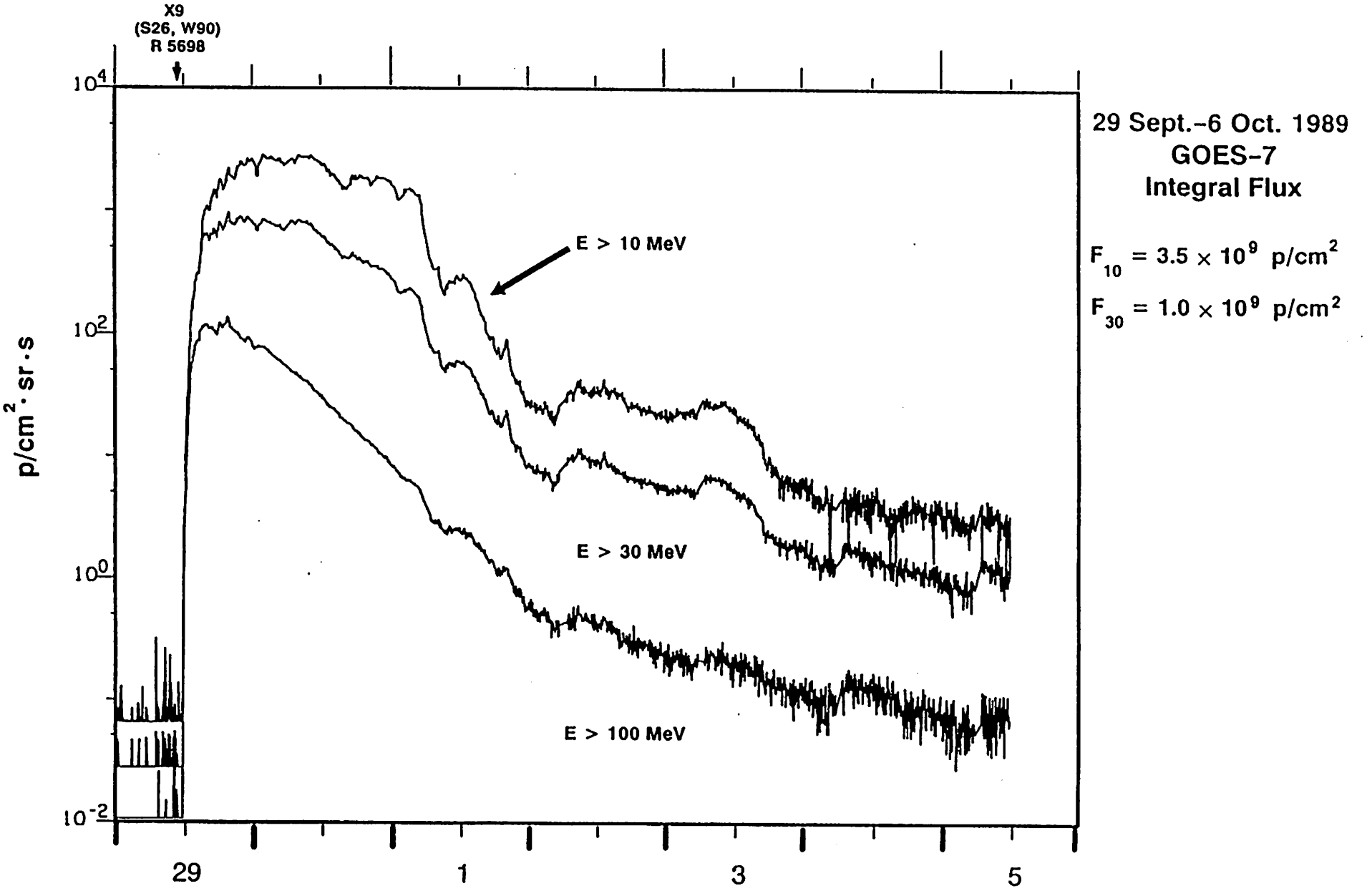
Origin of Anomalous Cosmic Rays



Trapping of an Anomalous Cosmic Ray




PROTONS (cm^2 · s)$^{-1}$
10^5
10^4
10^3
10^2
10-30 MeV
50-100 MeV
3 AUG.
4 AUG.
5 AUG.
6 AUG.
7 AUG.
8 AUG.
9 AUG.
CONTINUOUS DISRUPTION OF STAR SENSOR PHOTOMULTIPLIER
FLUCTUATING DISRUPTION OF STAR SENSORS
1972



This event contains the largest GLE seen since Solar Cycle 19

Figure 4

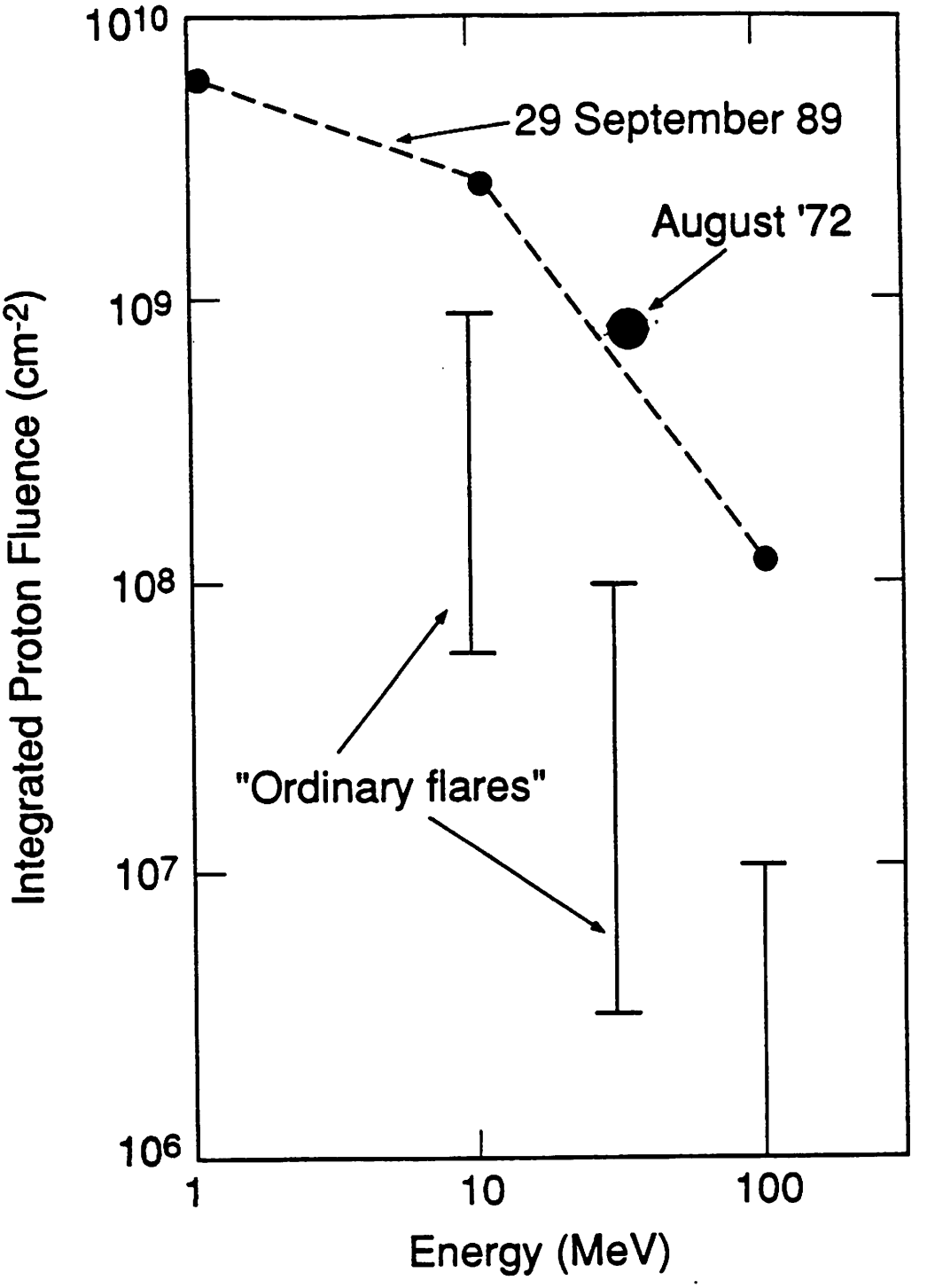
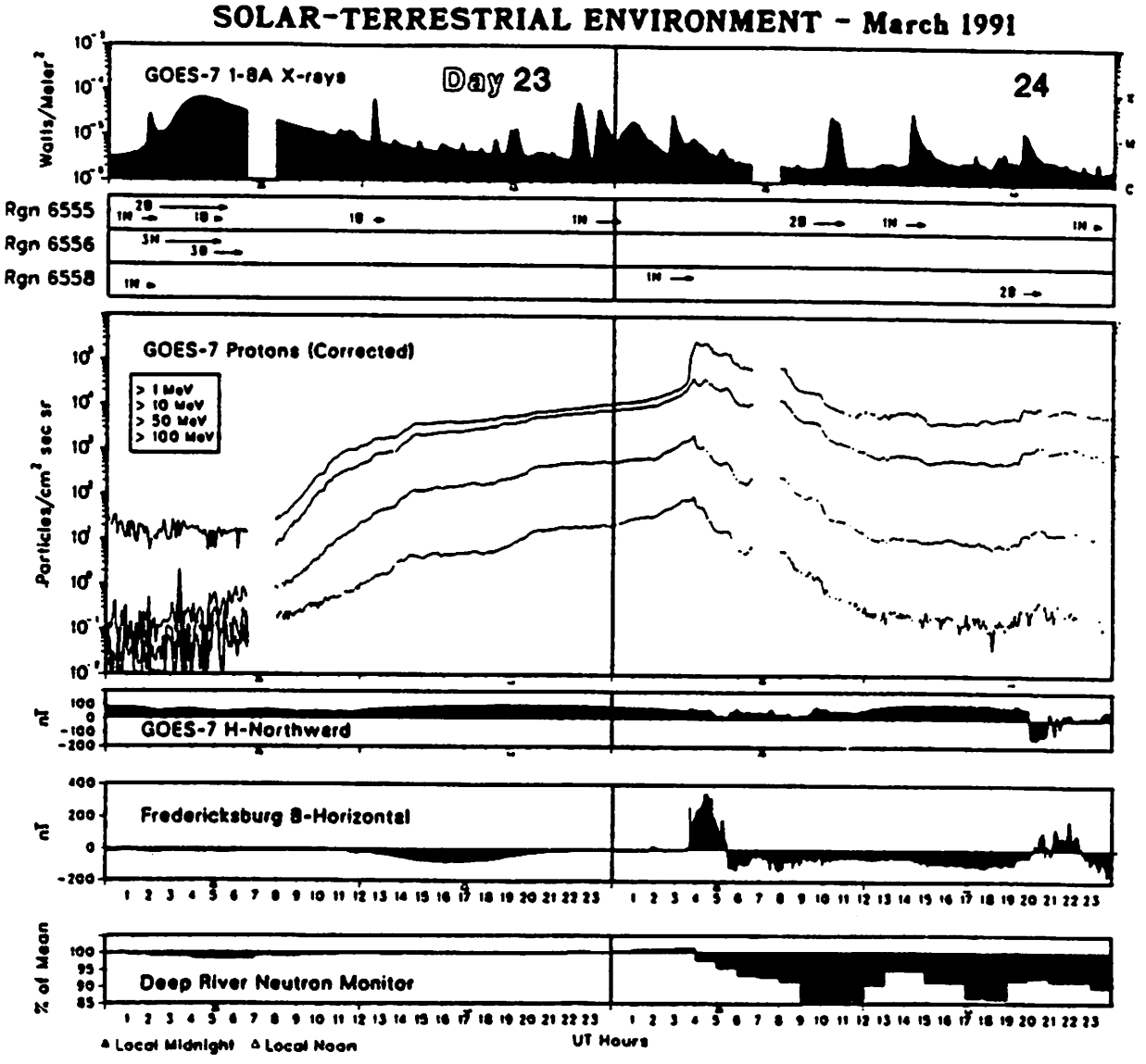

10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
Integrated Proton Fluence (cm^{-2})
29 September 89
August '72
"Ordinary flares"
1
10
100
Energy (MeV)

Figure 1



Panel Degradation

Geosynchronous SEUs

Radiation Belt Modification

SWF High-Latitude Communication Disruption

Low-Latitude Communication Disruption

Hydro-Quebec Power Surges

Ground-Induced Currents

Magnetic Survey Disruption

E.G. Mullen, M.S. Gussenhoven, K. Ray and M. Violet

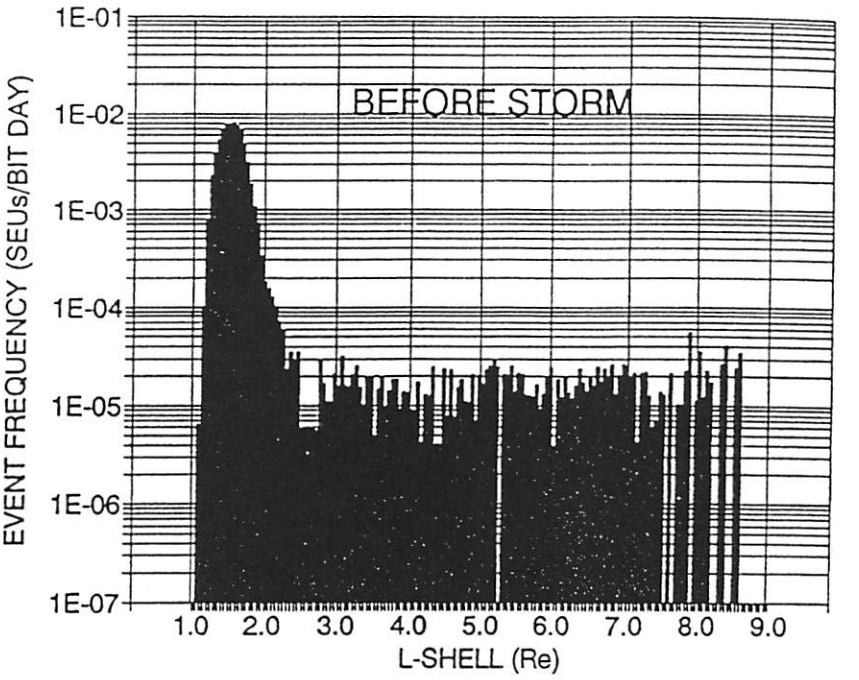


Figure 5

SEU frequency in SEUs/Bit-Day for 35 proton sensitive devices for the first 585 orbits (July 25, 1990 to March 22, 1991) of the CRRES mission as a function of L-shell in Earth Radii. The peak at an L-value of 1.5 coincides with the heart of the inner radiation belt.

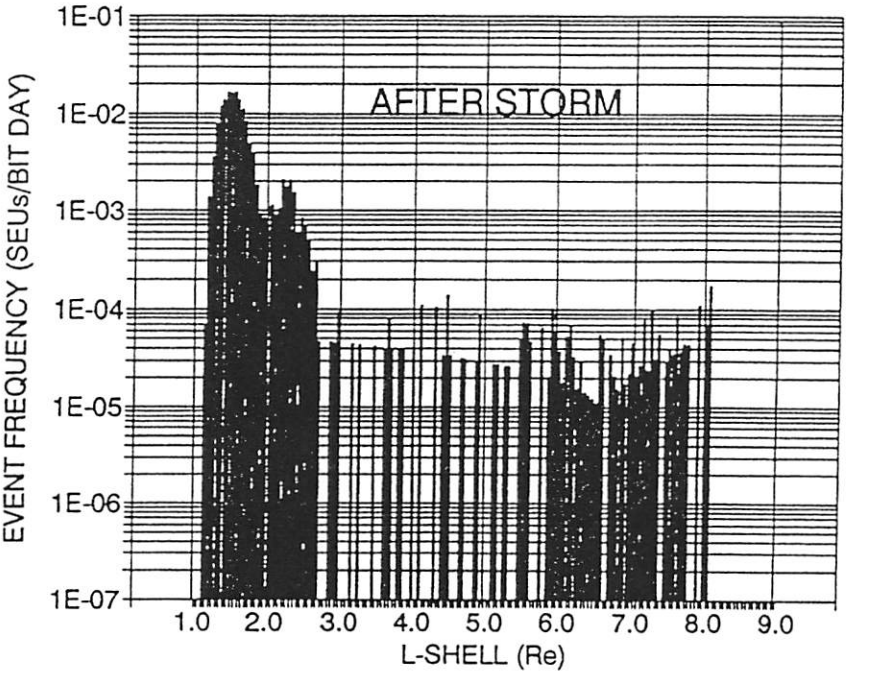
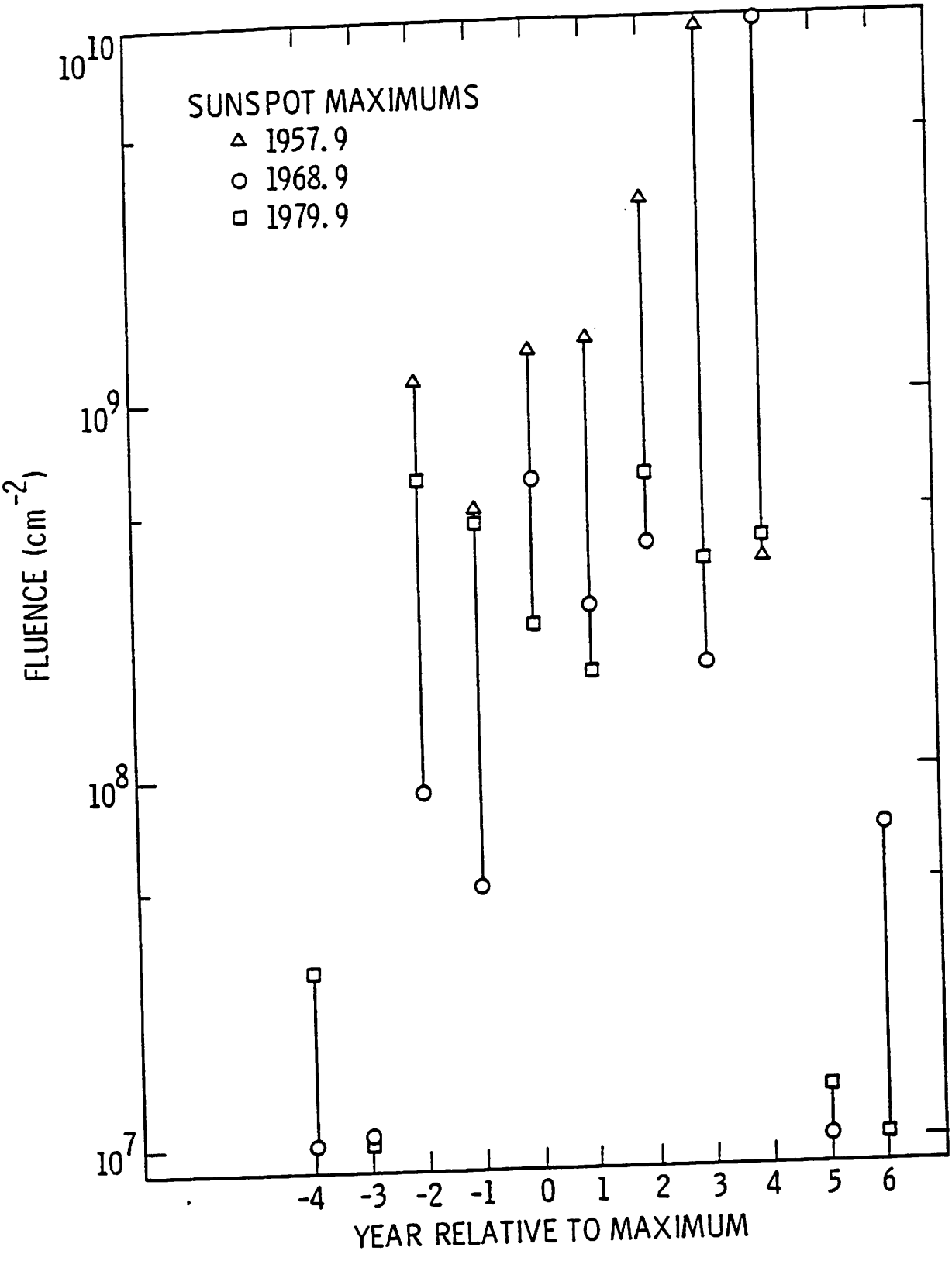


Figure 6

SEU frequency in SEUs/Bit-Day for 35 proton sensitive devices for the 141 orbits (March 29,1991 to May 25, 1991) following the solar proton event of March 1991. The double belt proton structure is clearly evident in the double-peaked SEU frequency. The dropouts at higher L-values are due to poor statistics.

YEARLY FLUENCES (>30 MeV)



ENERGETIC ION RADIATION DAMAGE IN SPACE

Trapped (Van Allen) Ions

- Peak Flux : J (> 10 MeV) ~ 3 x 10^5 p/cm^2-s
- Persistently present
- J $\leq$ 1 cm^{-2}-s^{-1} for r $\geq$18000 km

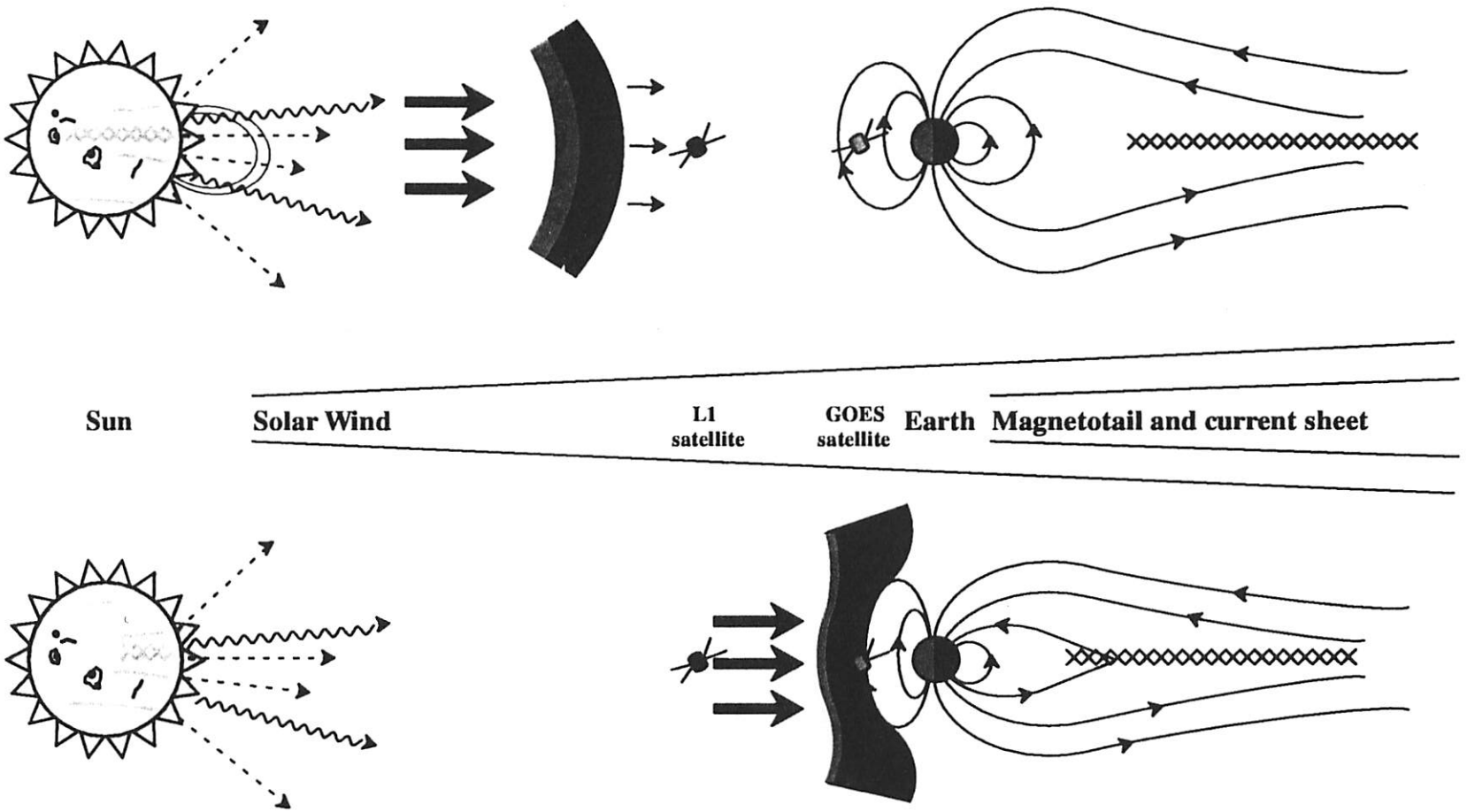
Galactic Cosmic Rays (GCR)

- Composition : p, α, CNO, Z $\geq$ 20
- "Anomalous" Component
- Kinetic Energy : 0.01-10 GeV/n
- Strong 11-year Solar Cycle Modulation
- J (E > 100 MeV) ~ 1 p/cm^2-s

Solar Energetic Particles (SEP)

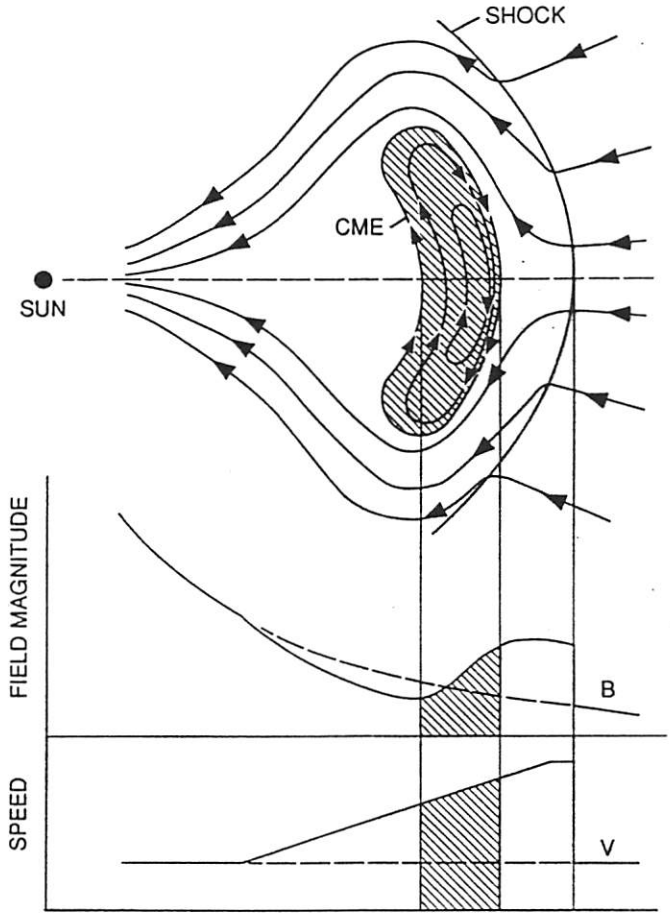
- Kinetic Energy : 10 keV/n ~ 300 MeV/n
- Source : Solar Flares and Shocks
- Highest Occurrence at Sunspot Max
- J (E > 10 MeV) ~ 100 p/cm^2-s
- Duration : 1-7 days

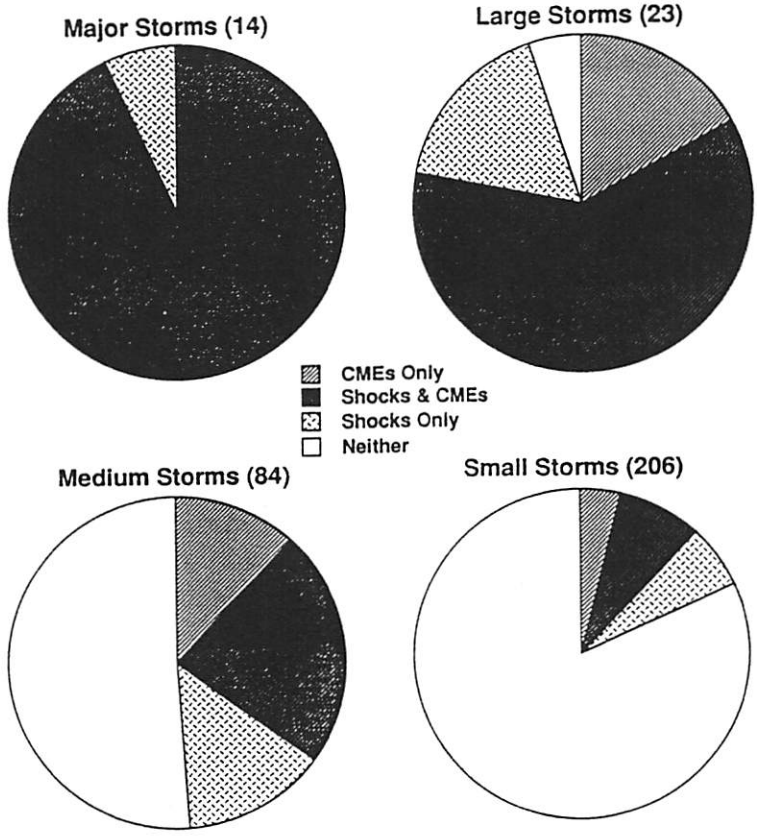
Compression of the Magnetosphere during a Severe Geomagnetic Storm

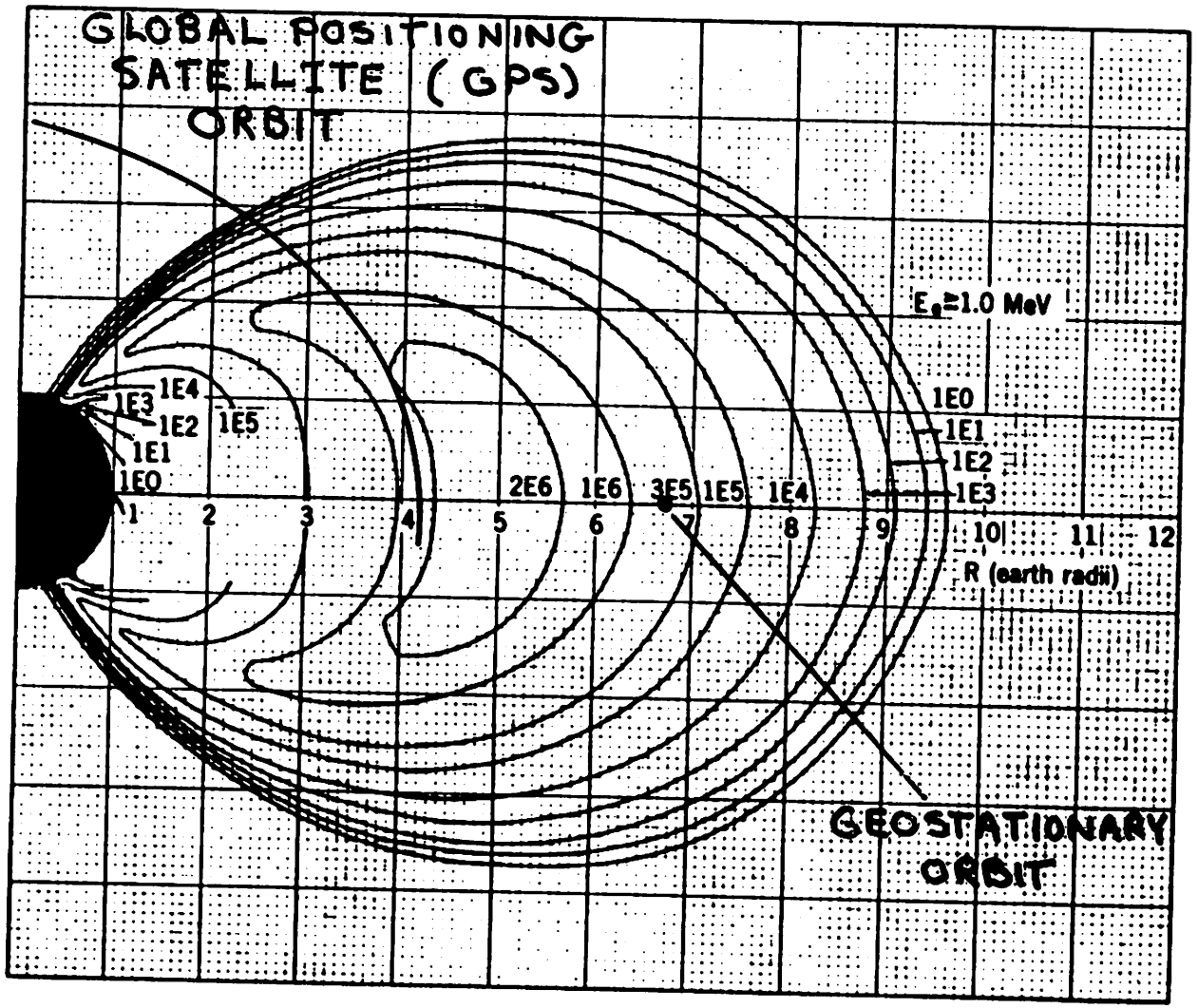


(Not to Scale)

Space Environment Laboratory

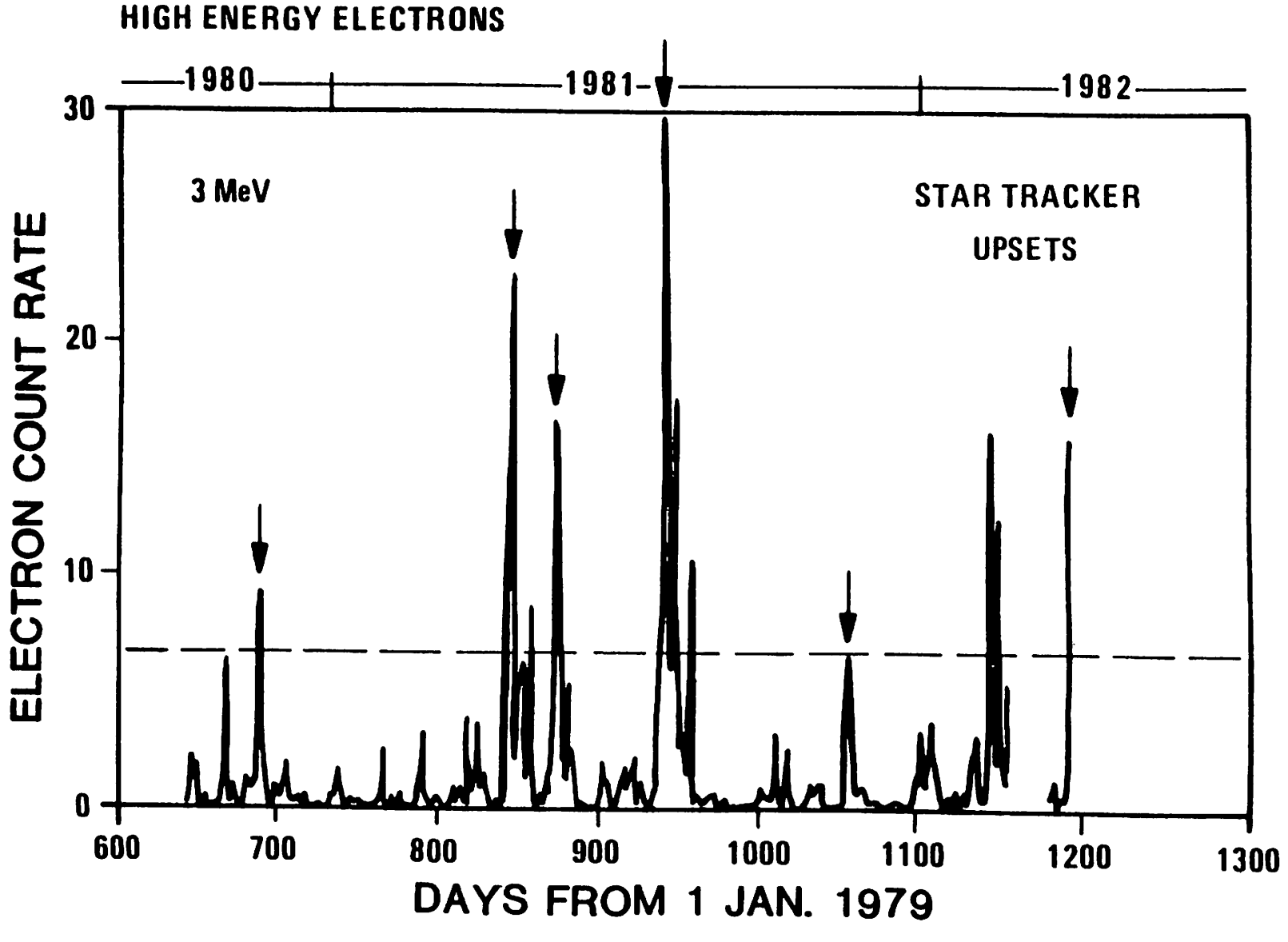

SHOCK
CME
SUN
FIELD MAGNITUDE
B
SPEED
V

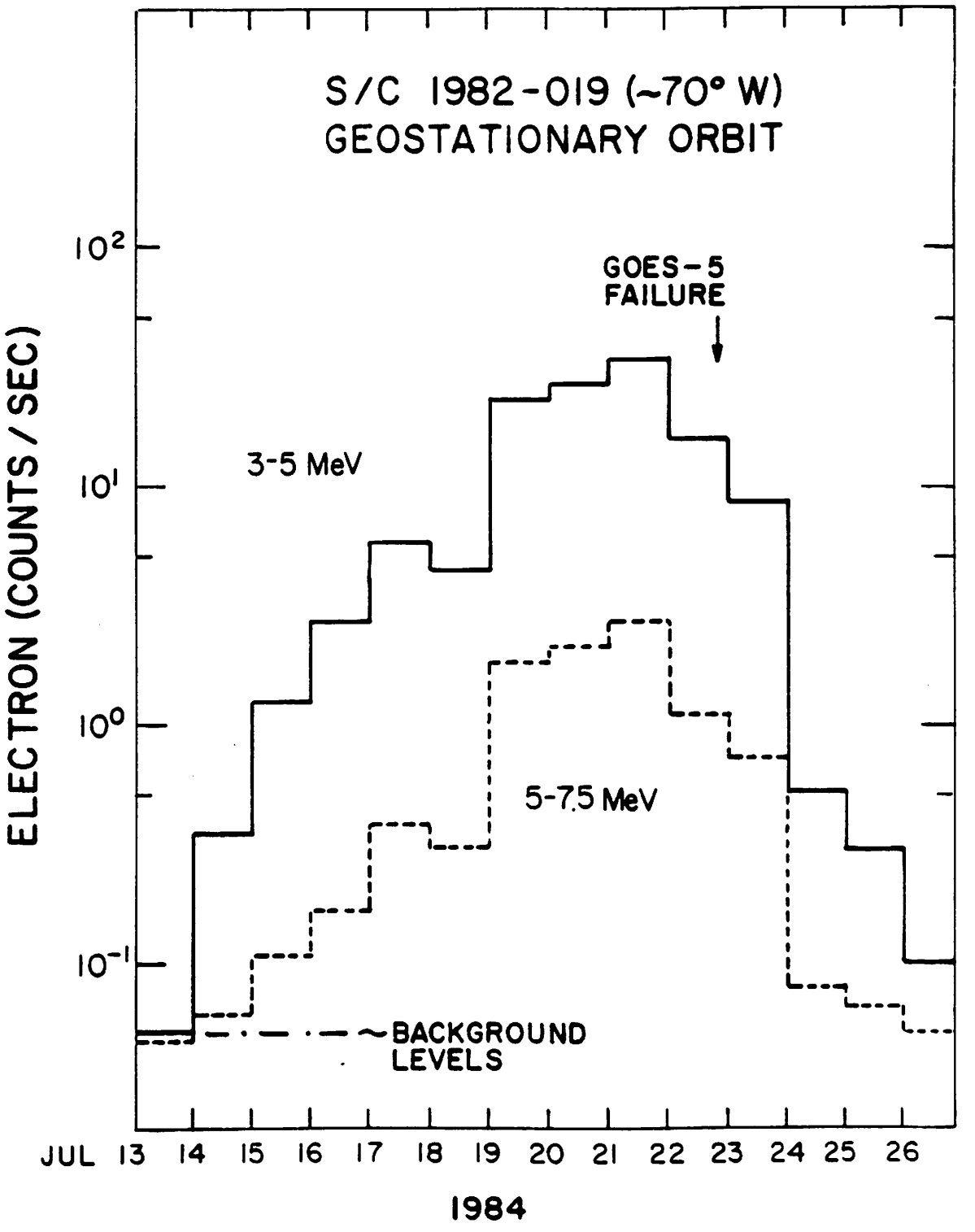

Major Storms (14)
Large Storms (23)
CMEs Only
Shocks & CMEs
Shocks Only
Neither
Medium Storms (84)
Small Storms (206)



R-λ Map of AE-4 Electron Fluxes for Epoch 1964, Threshold Energy 1.0 MeV

Baker et al. (1987)




S/C 1982-019 (~70° W)
GEOSTATIONARY ORBIT
GOES-5
FAILURE
3-5 MeV
5-7.5 MeV
~BACKGROUND
LEVELS
ELECTRON (COUNTS / SEC)
10^2
10^1
10^0
10^{-1}
JUL 13 14 15 16 17 18 19 20 21 22 23 24 25 26
1984

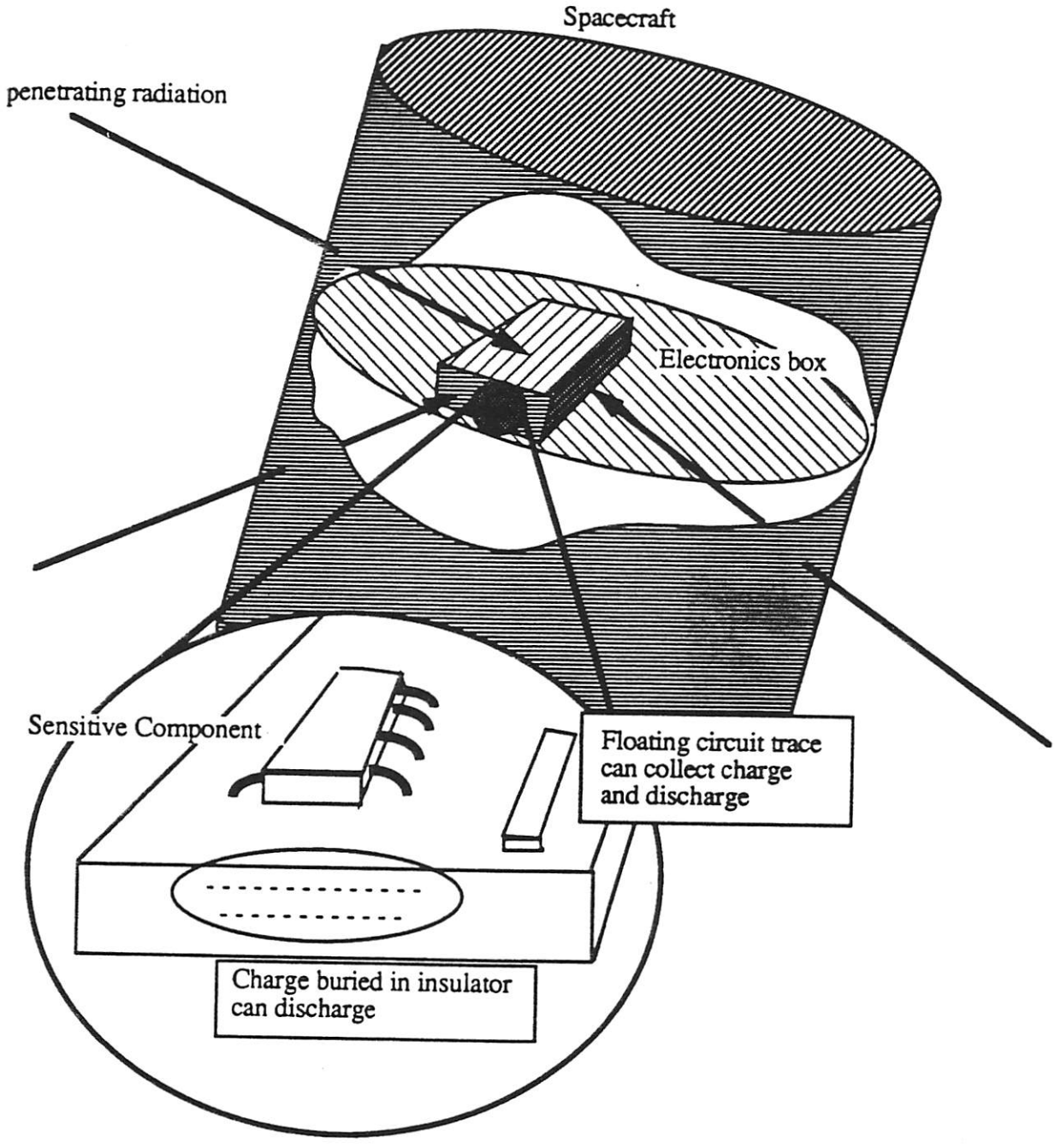


Figure 1-4. Internal Discharges Result From Charges Deposited Directly On or In Well Insulated Regions Inside the Spacecraft

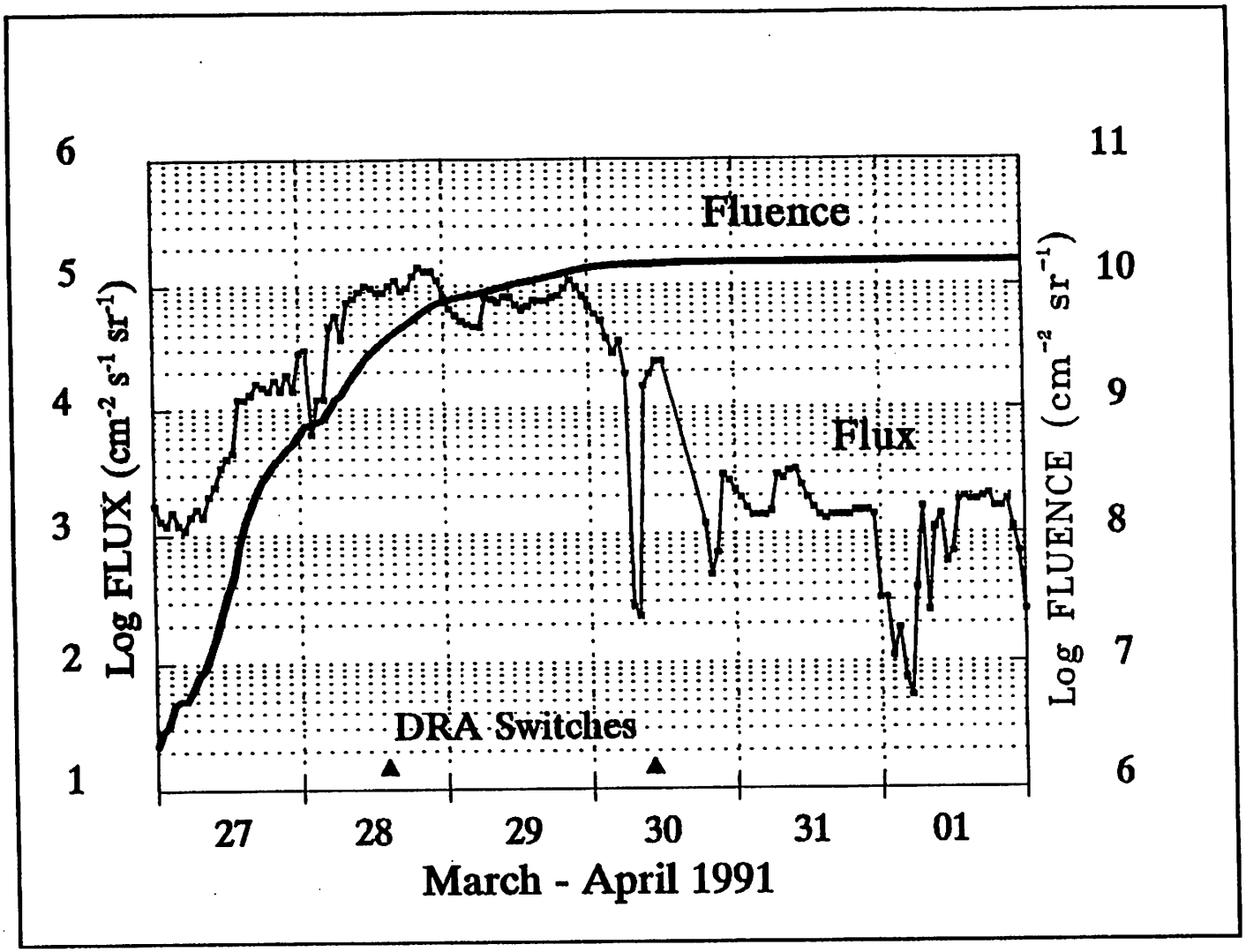


Fig. 6 Flux and fluence of > 2 MeV electrons measured at GOES-7 during 6 days in March-April 1991; times of the first two *DRAδ* ATC/IFC switches are shown.

The Hamilton Spectator

ıry 21, 1994

Established 1846 • Mon-Fri 47¢ + 3¢ GST

assion

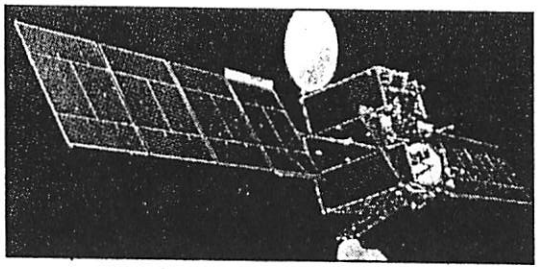
,an
it'
ecurity
burner
ıy says

ISCHER
News

Liberal govern-
ted so much to
estore hope and
Canadians, Hu-
Minister Lloyd
erday.
ıate Commons
ned at Reform
MPs pushing for
ction measures,
nised to fight for
ınge to bring so-
e into line with
or, unemployed

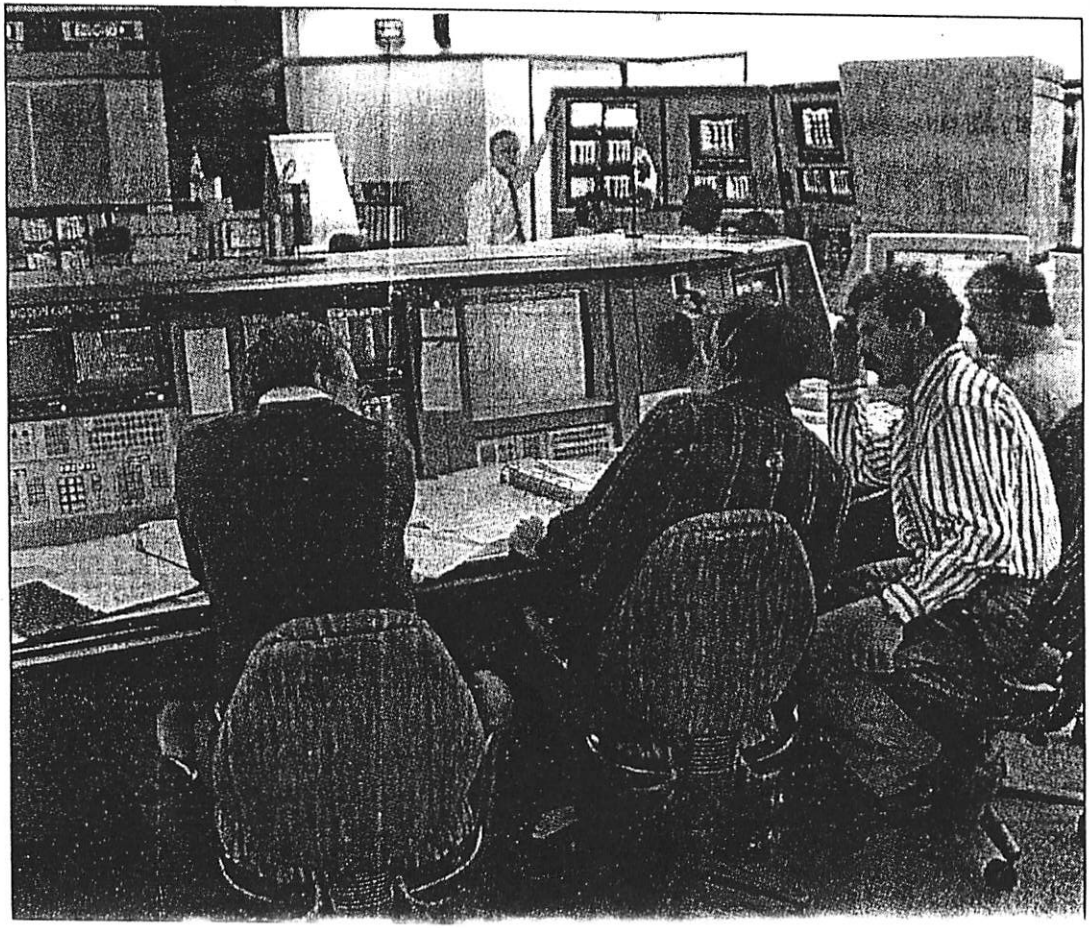
f talk about fis-

P-ANIK!



High-tech chaos as satellites spin out of control

Plug pulled on phones, TV, radio, papers



OTTAWA — Telesat Canada was facing some tough questions today as it tries to explain how its two main communication satellites tumbled out of control, interrupting TV, radio, newspaper and telephone signals across the country.

After struggling for more than eight hours to bring the wobbly Anik E-1 under control, Telesat technicians thought they had the problem licked late yesterday.

The were only half right.

Shortly after 9 p.m. EST, as Anik E-1 settled back into position, Telesat's primary broadcasting satellite, Anik E-2, also got a bad case of the shakes.

CBC Newsworld and other national specialty cable channels, including MuchMusic, TSN, Vision and the Weather Channel, were knocked off the air. Partial service, with signals carried by fibre-optic cable, was later restored in some major centres, including Toronto.

In Hamilton local cable companies and police communications were unaffected. The Mt. Hope weather office had minor disruptions.

"We don't know how it was brought about," said Chris Frank-

Drug use rebounding among kids survey find

OTTAWA — A 14-year trend ward lower drug use among O rio students halted abruptly year, a provincewide survey by Toronto-based Addiction Resea Foundation suggests.

A survey of more than 3,500 dents at 165 schools around province late last year found increases in drug use outnumbe declines for the first time s 1979.

And some of the most alarm findings were at the grade 7 l with significant increases in ab

"Between 1991 and 1993 the m important change has been abrupt halt in the decline of d use," says the study, which cove 17 drugs.

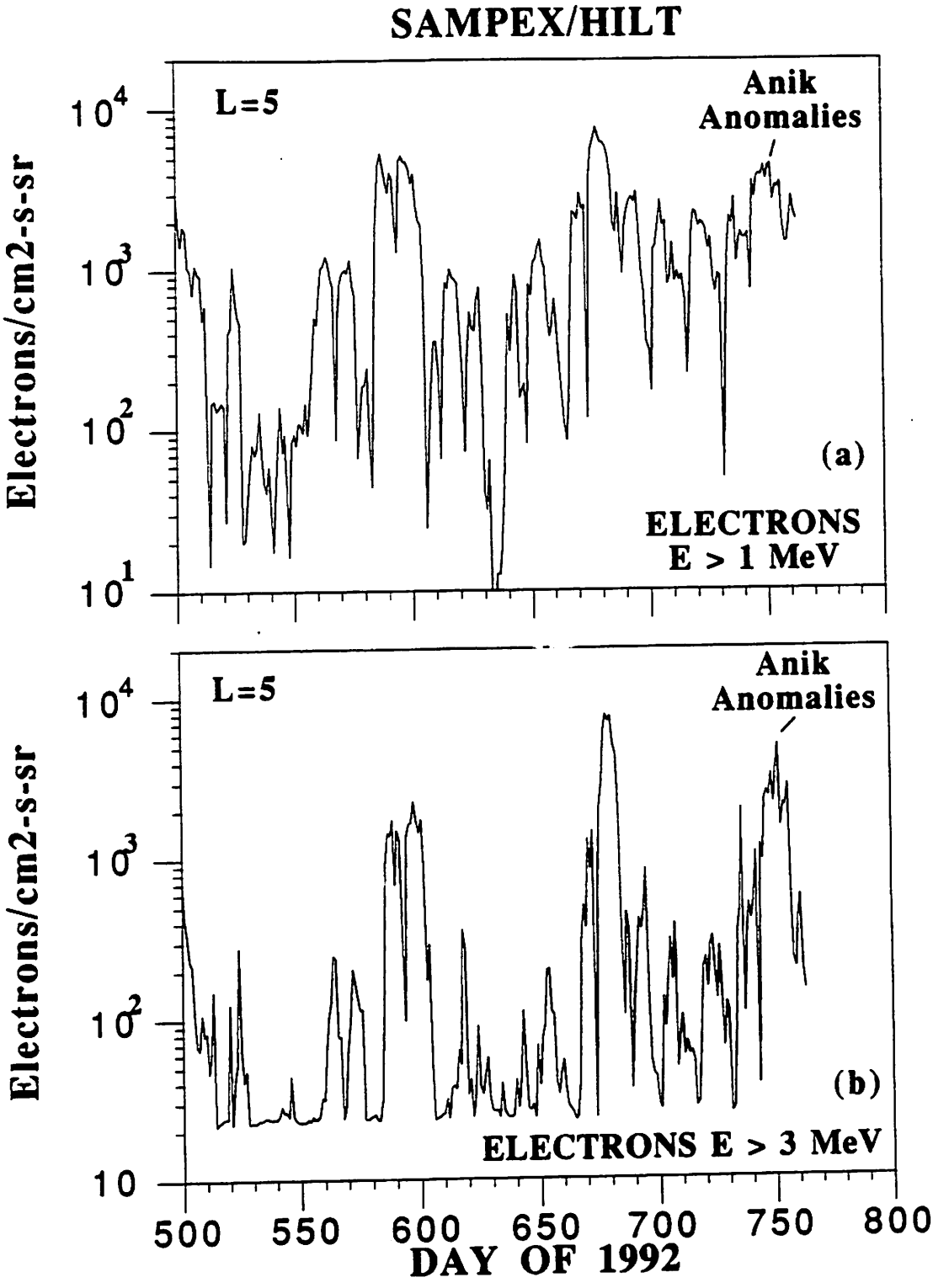
Trend

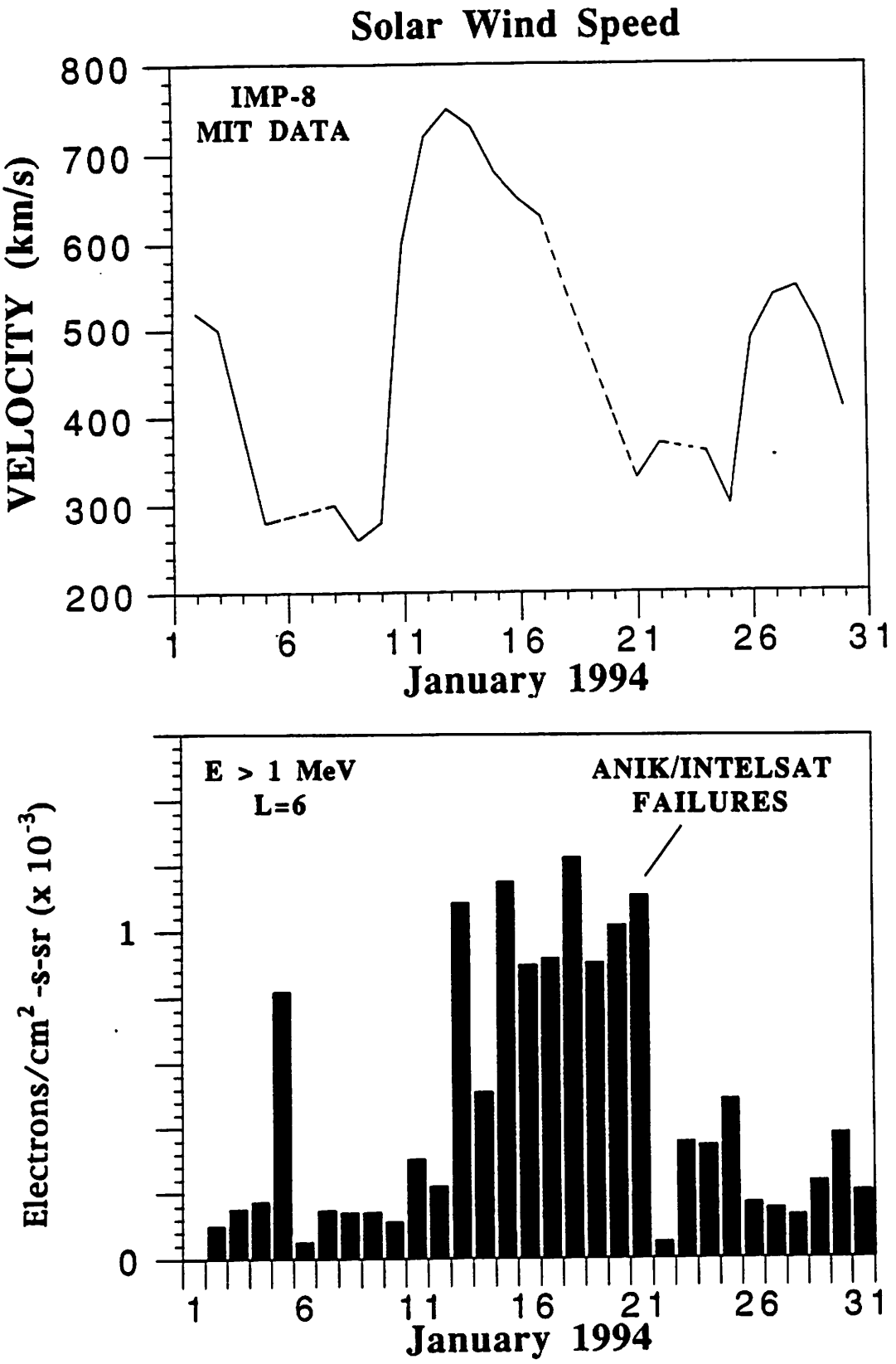
The foundation's regular surv comprise the longest-running st of student drug use in Canada. tailed data are not availabl other provinces, but researc say the Ontario findings may cate a national trend.

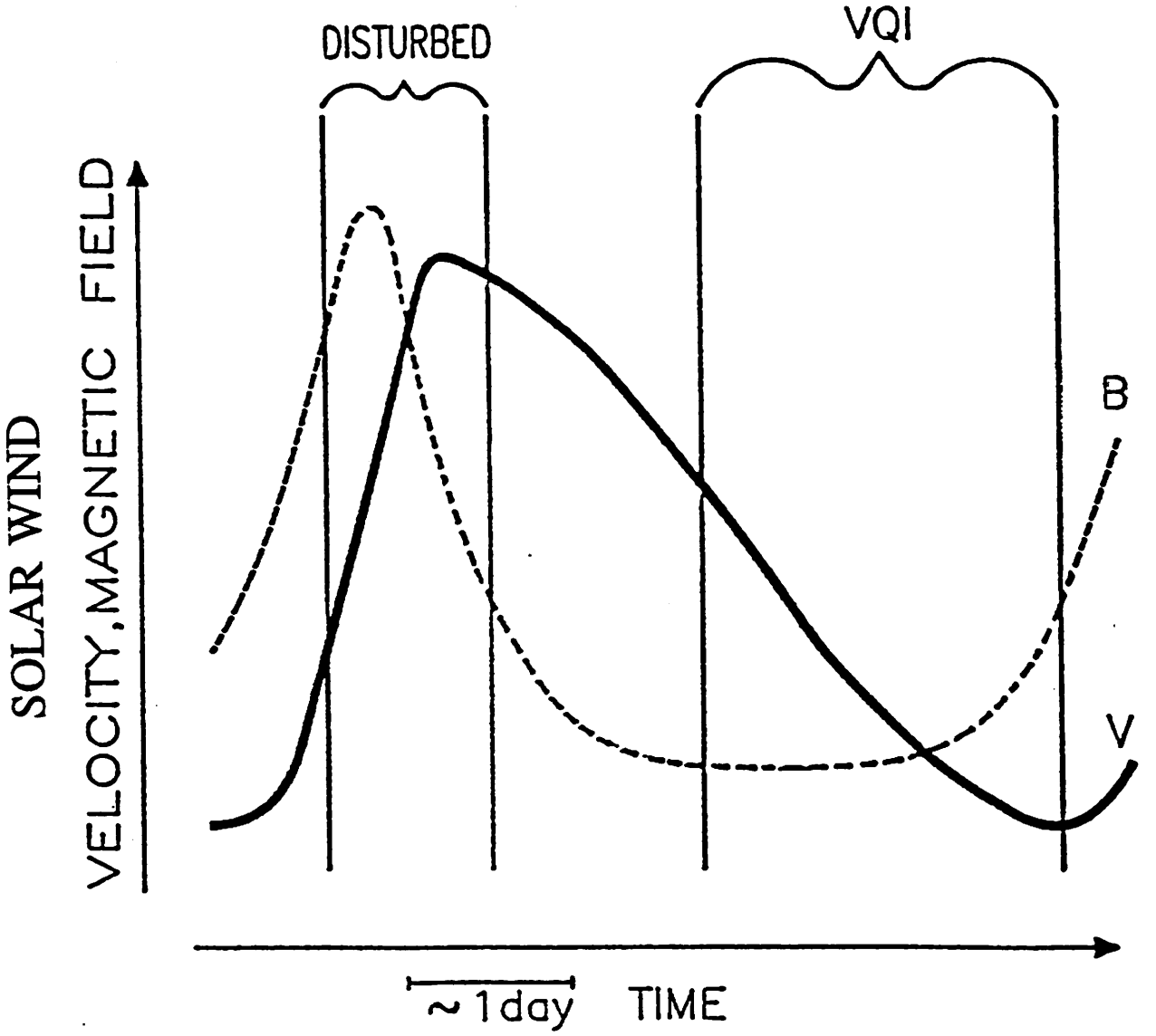
"Historically we do typic find that trends we find in Ont do tend to occur nationwide," Edward Adlaf, the researcher led the survey.

"It's a little early to know wh er this trend that we found indicates that the declines stopped or whether possibl might mean the beginning o upswing in drug use."

The most disturbing increase were the grade 7 level, where dents reported increasing us

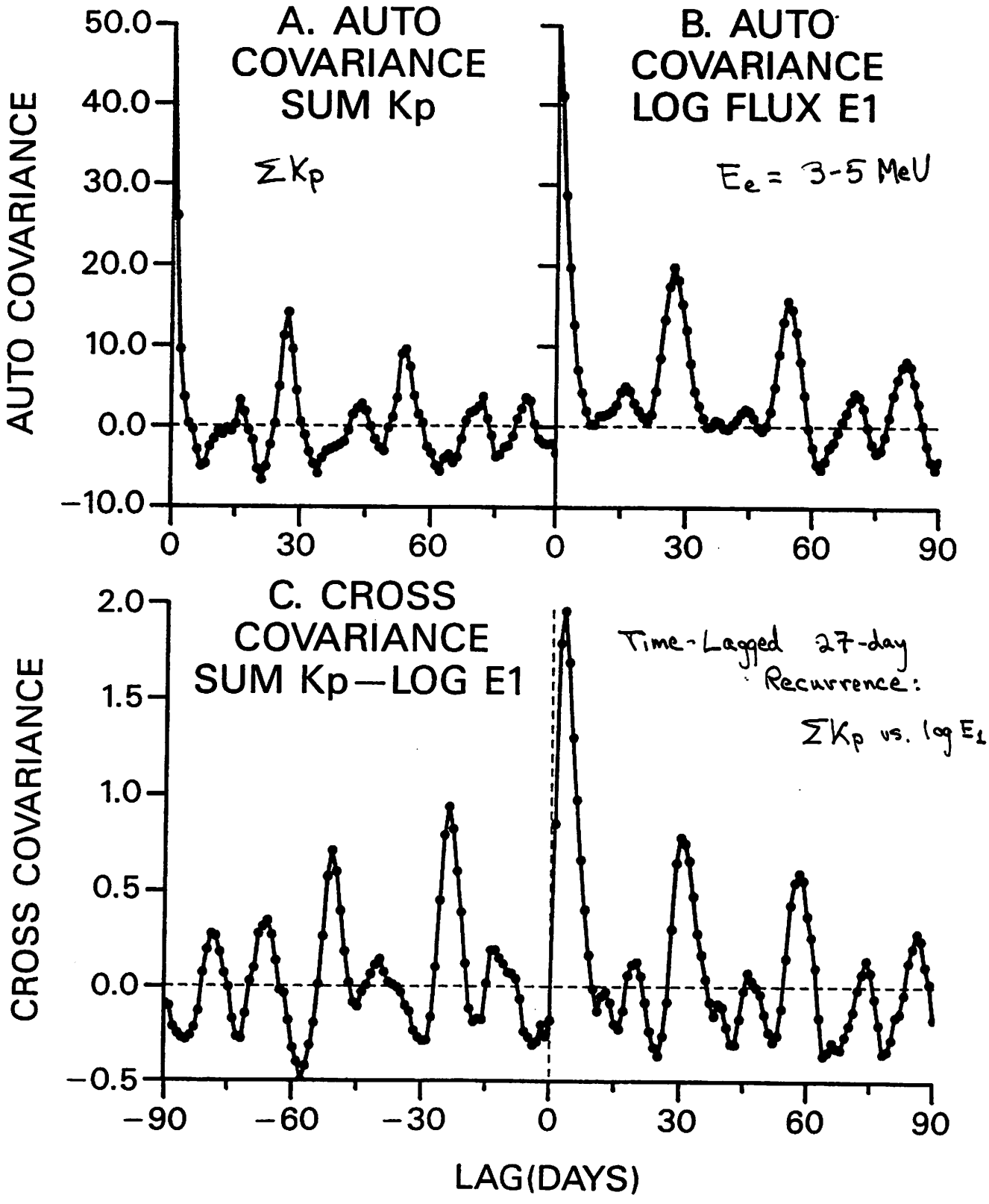

SAMPEX/HILT
L=5
Anik
Anomalies
(a)
ELECTRONS
E > 1 MeV
Electrons/cm2-s-sr
10^4
10^3
10^2
10^1
L=5
Anik
Anomalies
(b)
ELECTRONS E > 3 MeV
Electrons/cm2-s-sr
10^4
10^3
10^2
10
500
550
600
650
700
750
800
DAY OF 1992

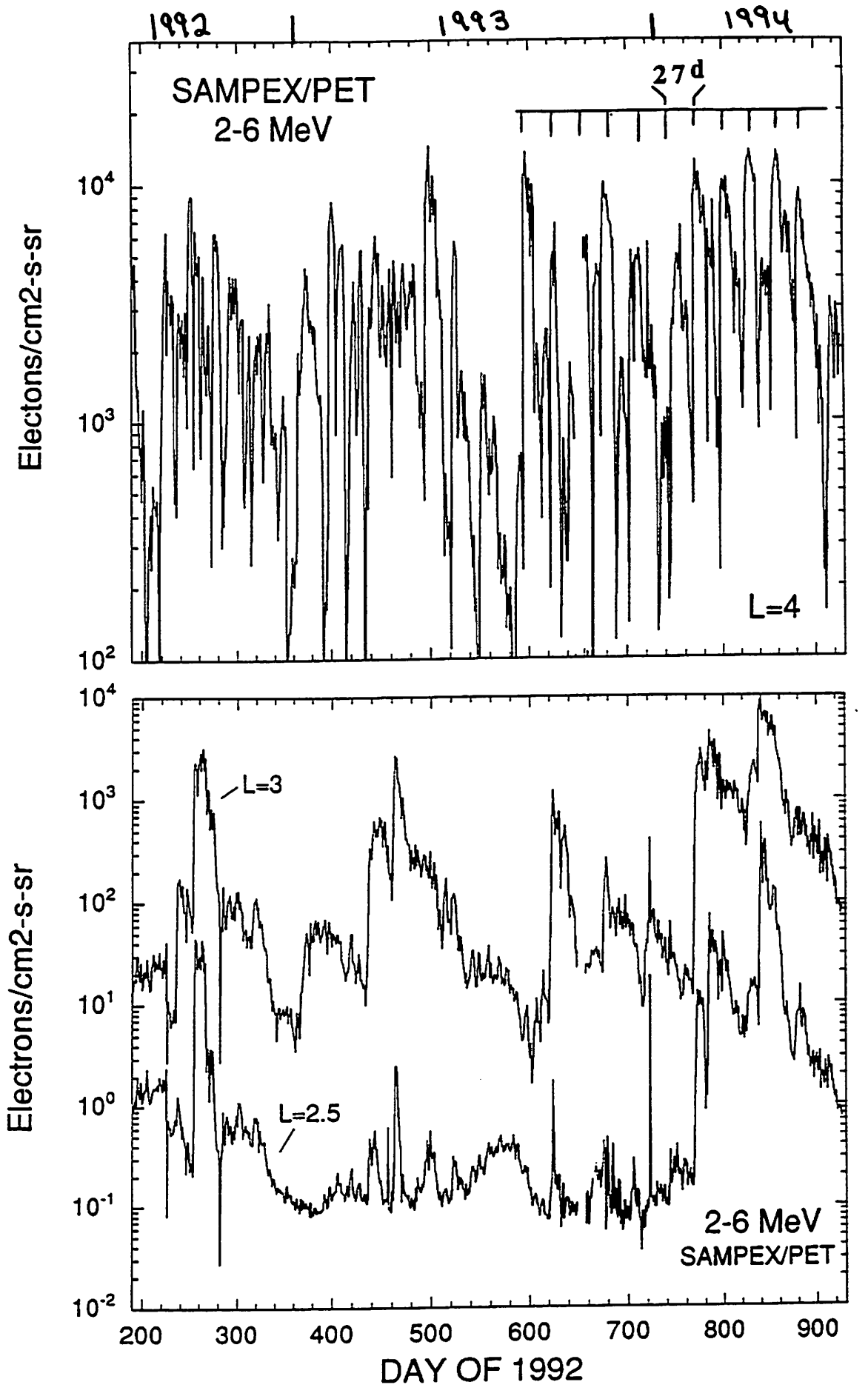

Solar Wind Speed
IMP-8
MIT DATA
VELOCITY (km/s)
800
700
600
500
400
300
200
1
6
11
16
21
26
31
January 1994
E > 1 MeV
L=6
ANIK/INTELSAT
FAILURES
Electrons/cm^2-s-sr (x 10^{-3})
1
0
1
6
11
16
21
26
31
January 1994

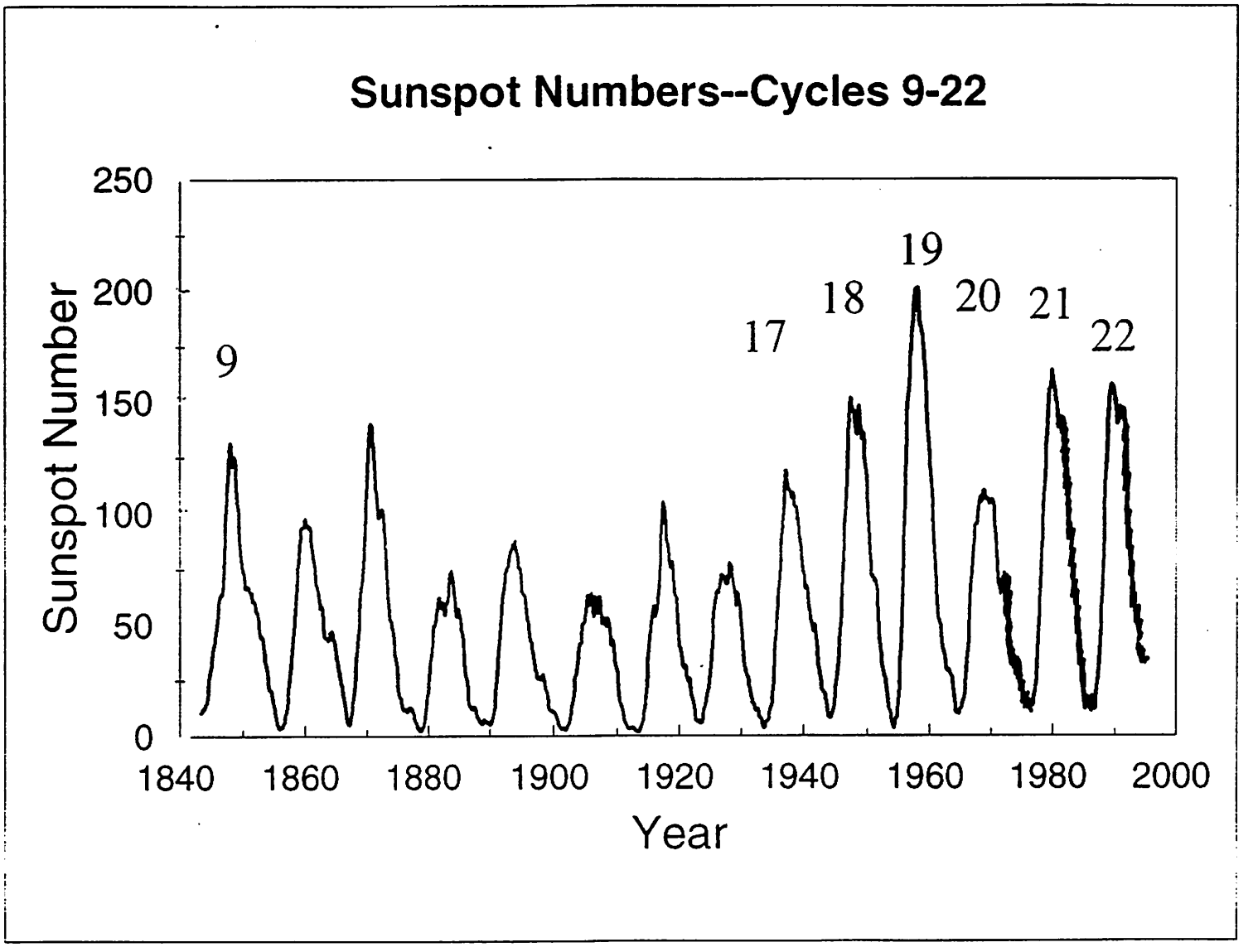

DISTURBED
VQI
SOLAR WIND
VELOCITY, MAGNETIC FIELD
B
V
~1day
TIME

Baker, McPherron, Cayton, Klebesadel (199

1982-85

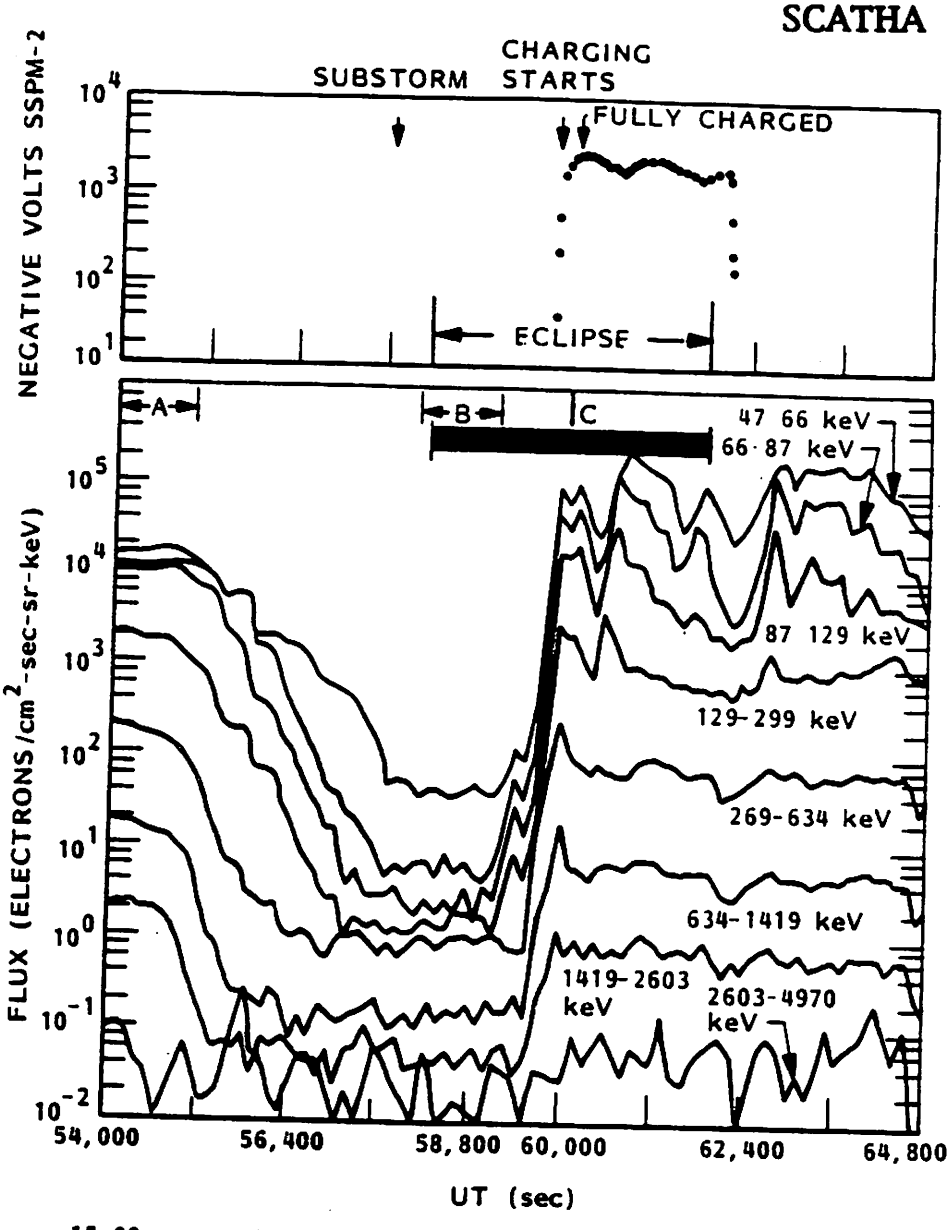



1992
1993
1994
SAMPEX/PET
2-6 MeV
27d
Electons/cm2-s-sr
10^4
10^3
10^2
L=4
Electrons/cm2-s-sr
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
L=3
L=2.5
2-6 MeV
SAMPEX/PET
200
300
400
500
600
700
800
900
DAY OF 1992


Sunspot Numbers--Cycles 9-22
Sunspot Number
250
200
150
100
50
0
1840
1860
1880
1900
1920
1940
1960
1980
2000
Year
9
17
18
19
20
21
22

Reagan et al. (1980)

SCATHA



UT	15.00	15.67	16.33	16.67	17.33	18.00
LT	21.90	22.74	23.52	23.89	0.59	1.25
MLT	21.79	22.65	23.46	23.85	0.58	1.26

28 March 1979

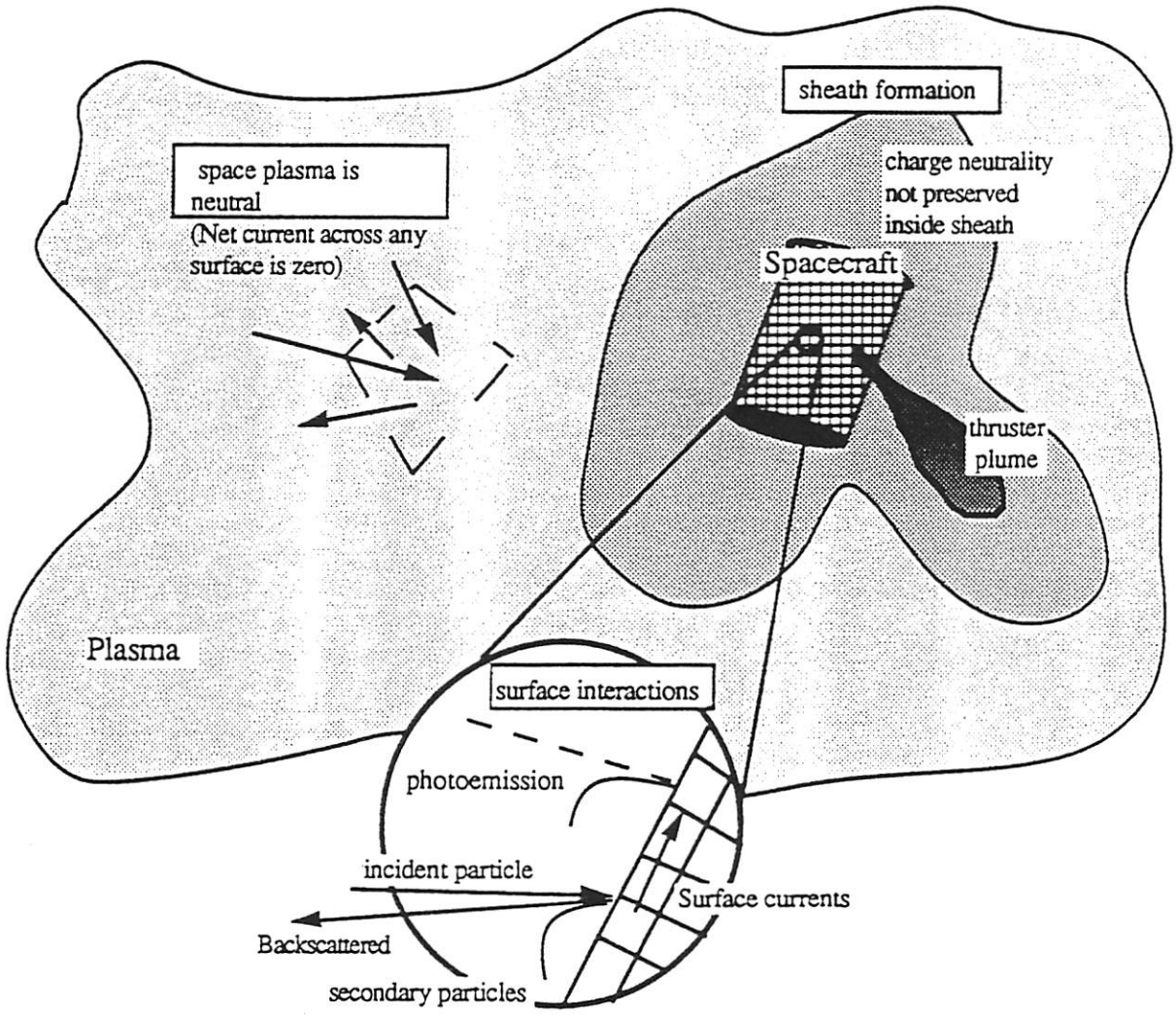
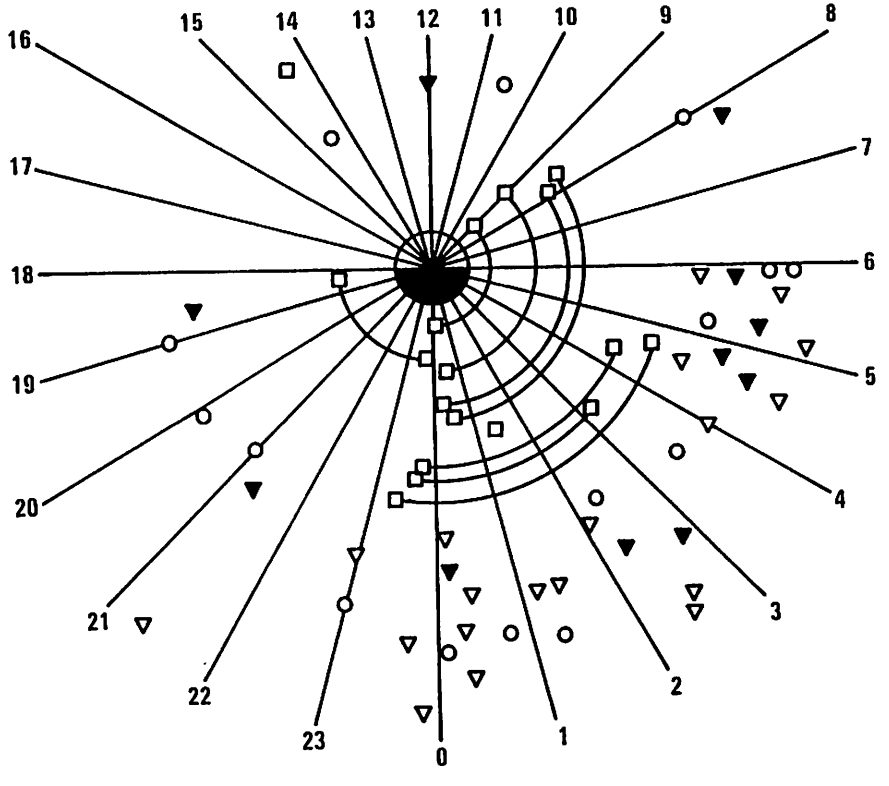


Figure 1-2. Surface Discharges Result From Charge Built Up on the Surface of the Spacecraft.



▽ DSP LOGIC UPSETS
□ DSCS II RGA UPSETS
▼ INTELSAT IV
○ INTELSAT III

LOCAL TIME PLOT OF VARIOUS SATELLITE DISRUPTIONS AND ANOMALIES

Blanchard
+ McPherron (1992)

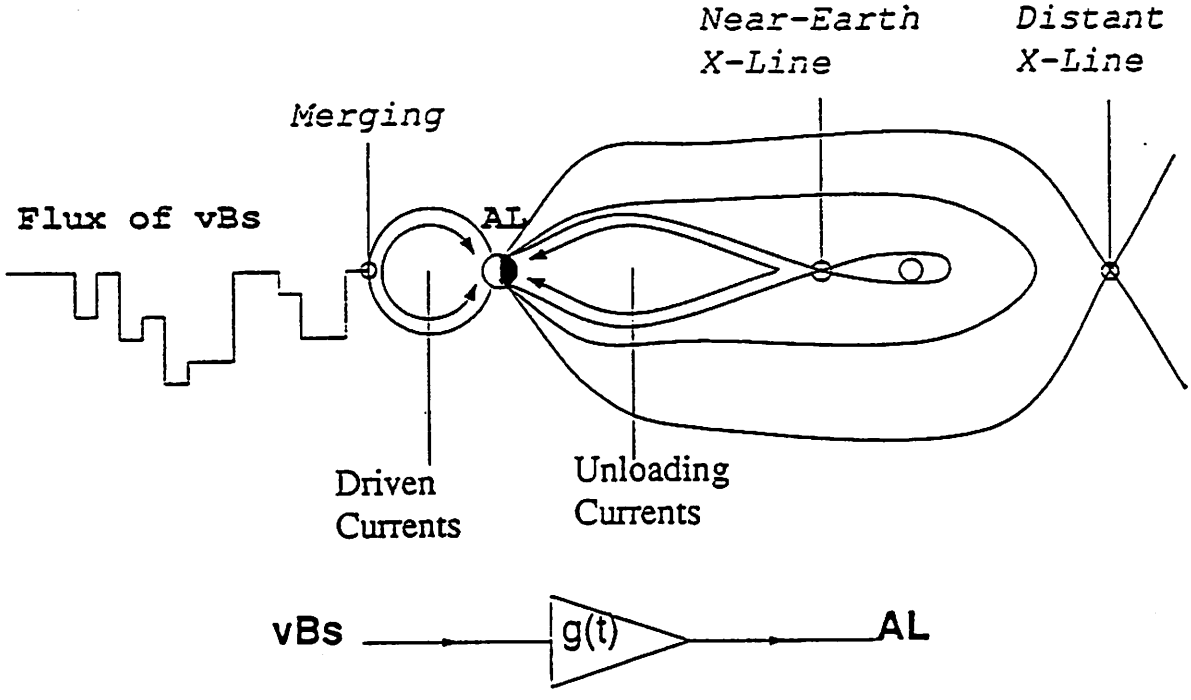
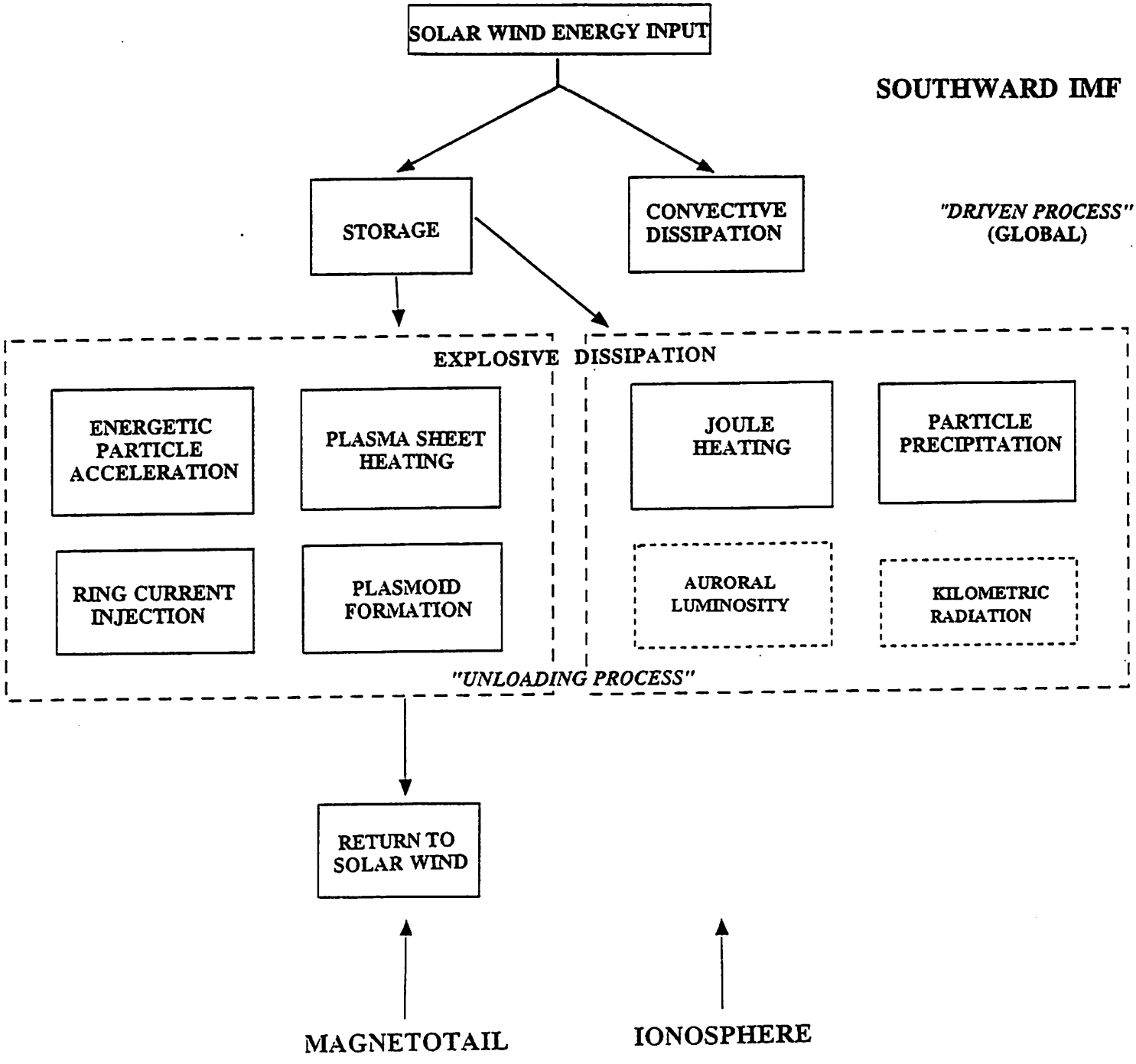


Fig. 2

THE SUBSTORM ENERGY DISSIPATION SEQUENCE



GEOSPACE ENERGY BUDGETS

ENTRY	
Incident Solar Wind	10^{13}-10^{14} W
Coupled to Magnetosphere	10^{11}-10^{12}
STORAGE	
Magnetotail	10^{15}-10^{16} J
Ring Current	10^{15}-10^{16}
TRANSPORT AND LOSS	
Ring Current Injection	10^{11}-10^{12} W
Ionospheric Joule Heating	10^{10}-10^{11}
Auroral Precipitation	10^{10}-10^{11}
Auroral Luminosity	10^{9} -10^{10}
Auroral Kilometric Rad.	10^{7} -10^{9}
PLASMOIDS	10^{11}-10^{12}

TOTAL POWER

Substorms	~ 5 x 10^{11} W
Major Storms	> 10^{12} W

State of the Magnetosphere

A set of *global variables* which are sufficient for the description of geomagnetic activity at short time scales.

$$\text{Magnetospheric State } x(t): \quad \left(\begin{array}{ll} \text{Remote Data:} & \begin{pmatrix} AL \\ AU \\ PC \\ \vdots \end{pmatrix} \\ \text{In Situ Data:} & \begin{pmatrix} E_{Tail} \\ T_{PS} \\ F_{GEO} \end{pmatrix} \end{array} \right)_d$$

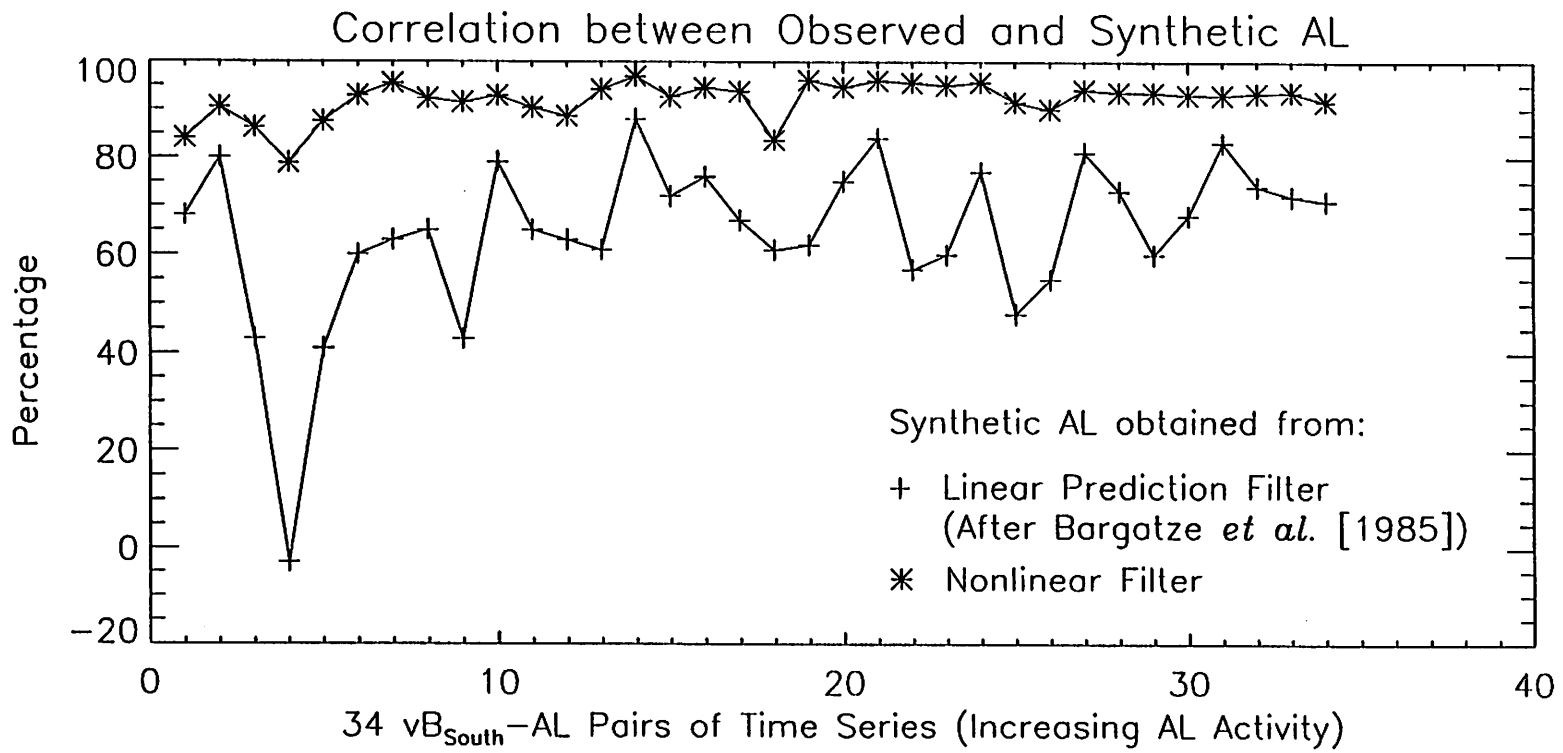
$$\text{Solar Wind Input } u(t): \quad \begin{pmatrix} v \\ B \\ P \end{pmatrix}_{d'}$$

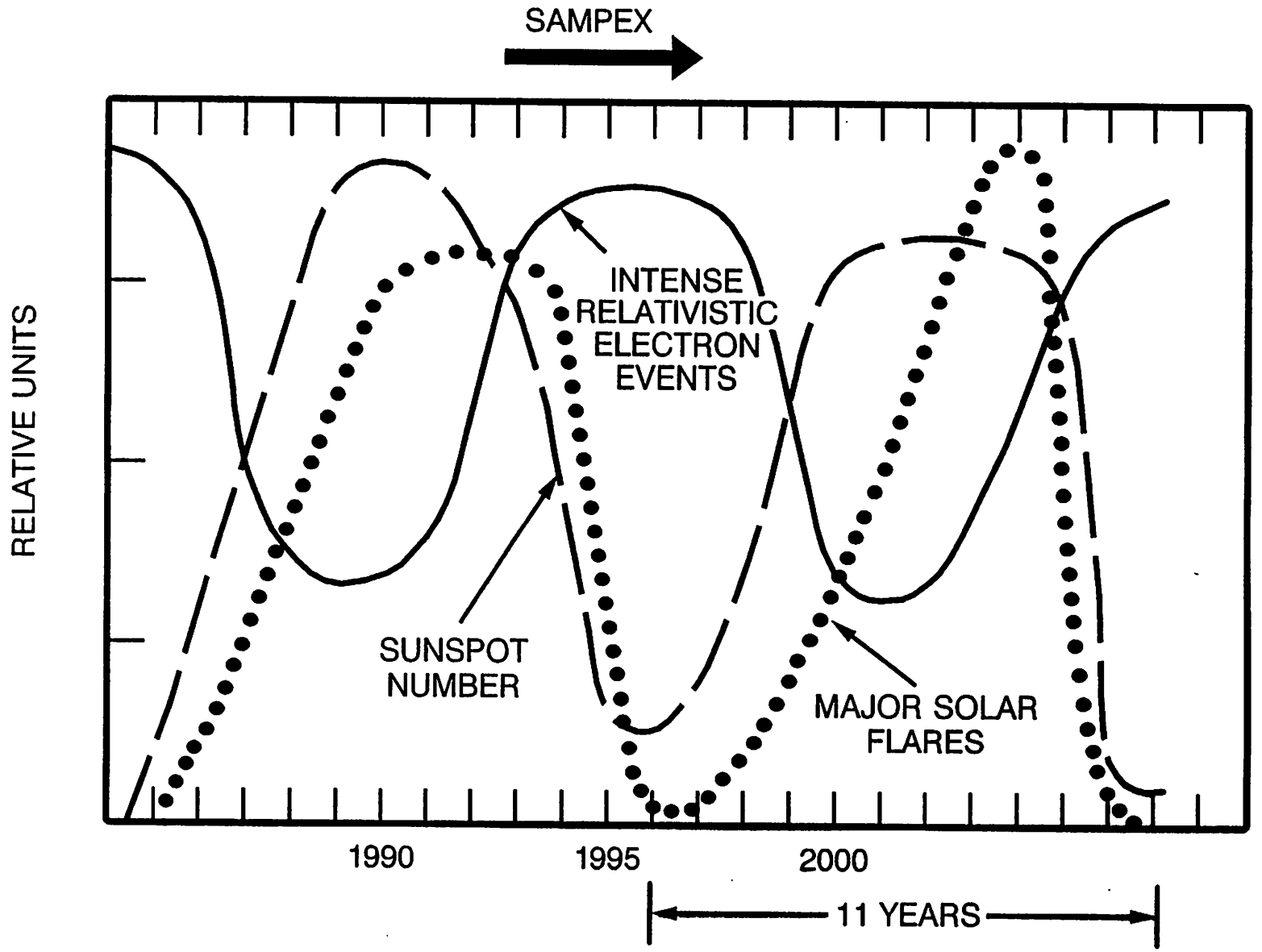
The magnetospheric state evolves according to

$$\frac{dx}{dt} = F(x; u)$$

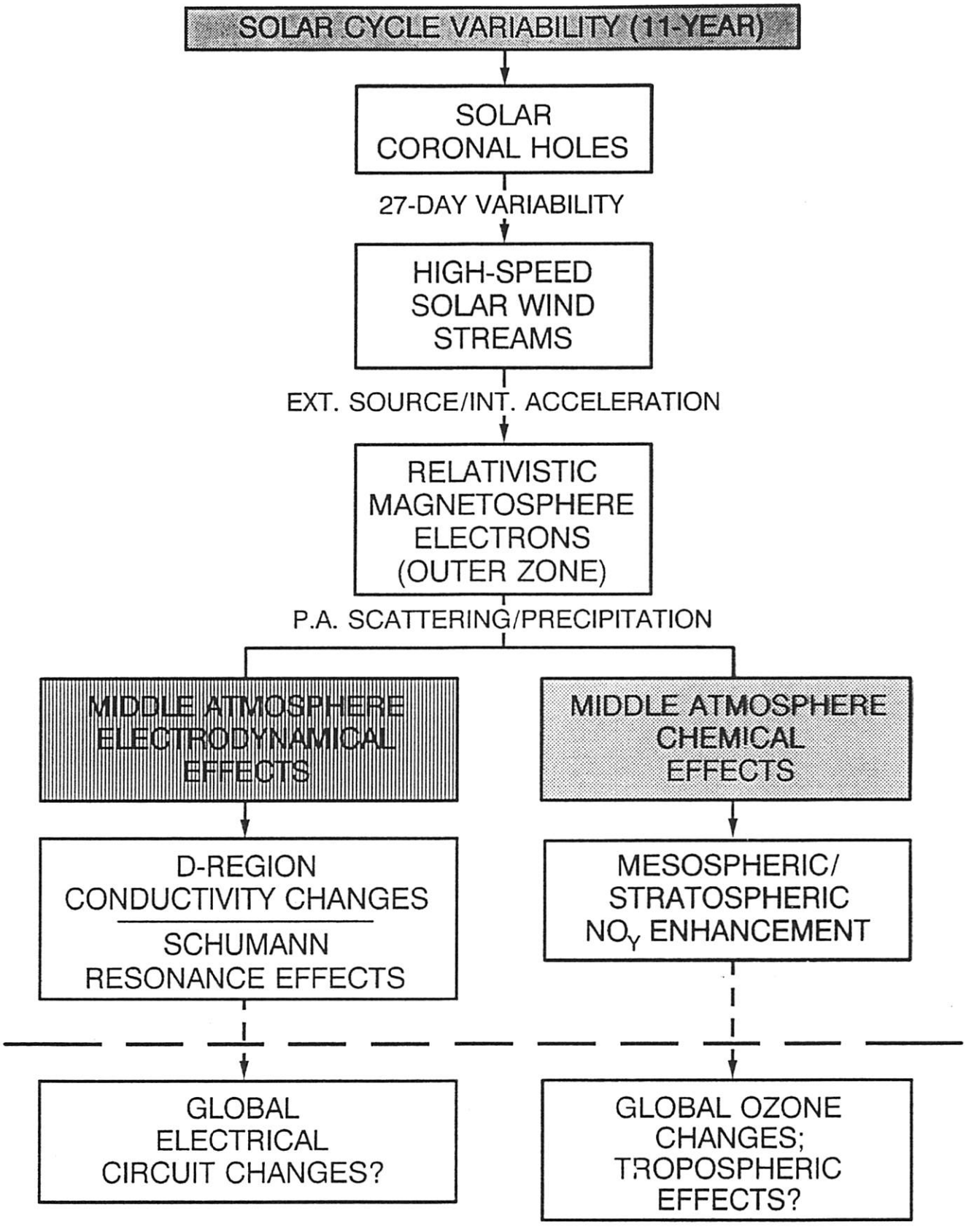
Assumption: The variables x are strongly related to each other so one parameter [e.g., AL(t)] contains adequate information about the state x. Example of equivalent state:

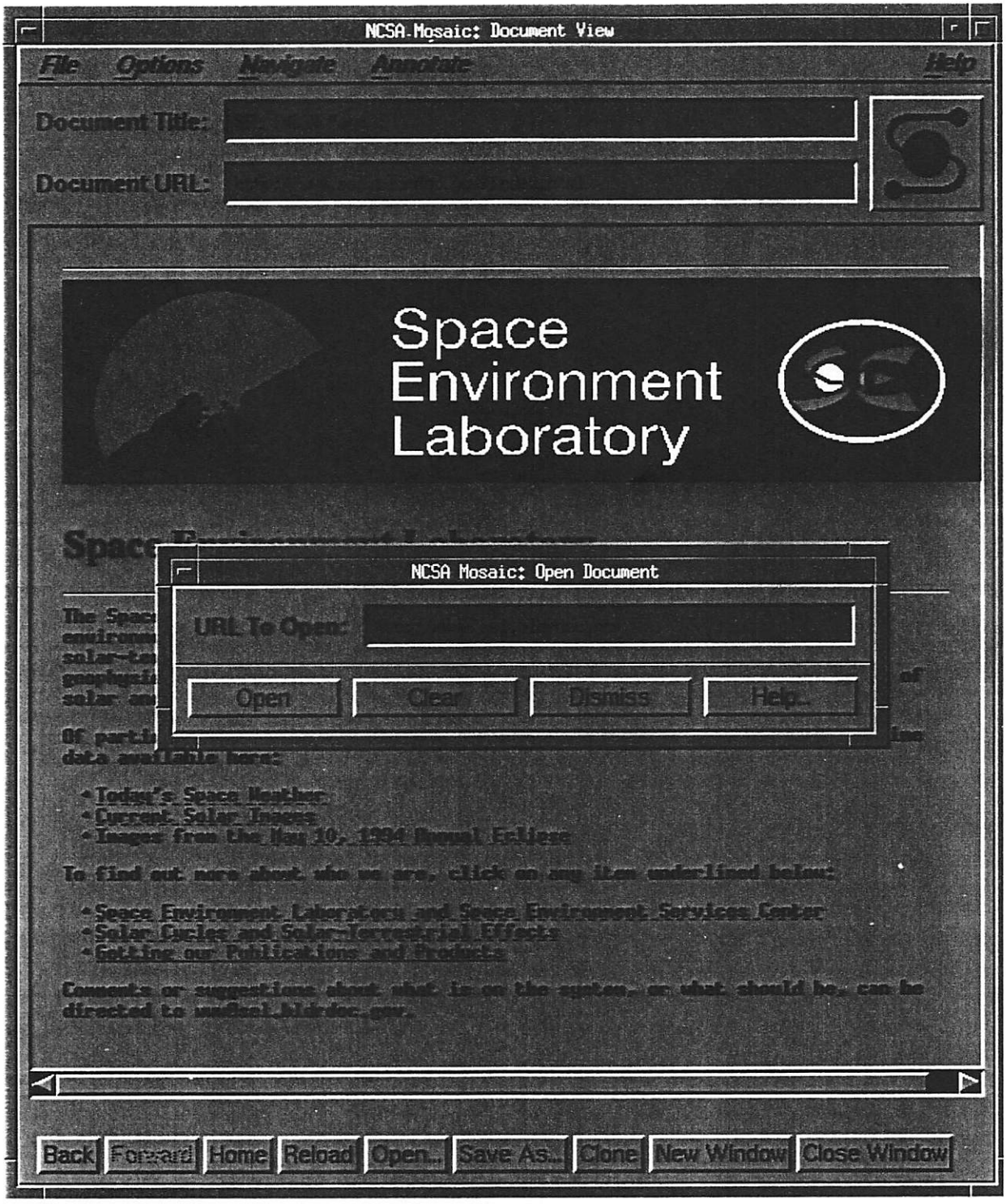
$$X = \begin{pmatrix} AL(t) \\ AL(t-T) \\ AL(t-2T) \\ \vdots \end{pmatrix}_{m \geq d}$$


Correlation between Observed and Synthetic AL
Percentage
100
80
60
40
20
0
−20
0
10
20
30
40
34 vB$_{South}$−AL Pairs of Time Series (Increasing AL Activity)
Synthetic AL obtained from:
+ Linear Prediction Filter
(After Bargatze *et al.* [1985])
✳ Nonlinear Filter


SAMPEX
RELATIVE UNITS
INTENSE
RELATIVISTIC
ELECTRON
EVENTS
SUNSPOT
NUMBER
MAJOR SOLAR
FLARES
1990
1995
2000
11 YEARS

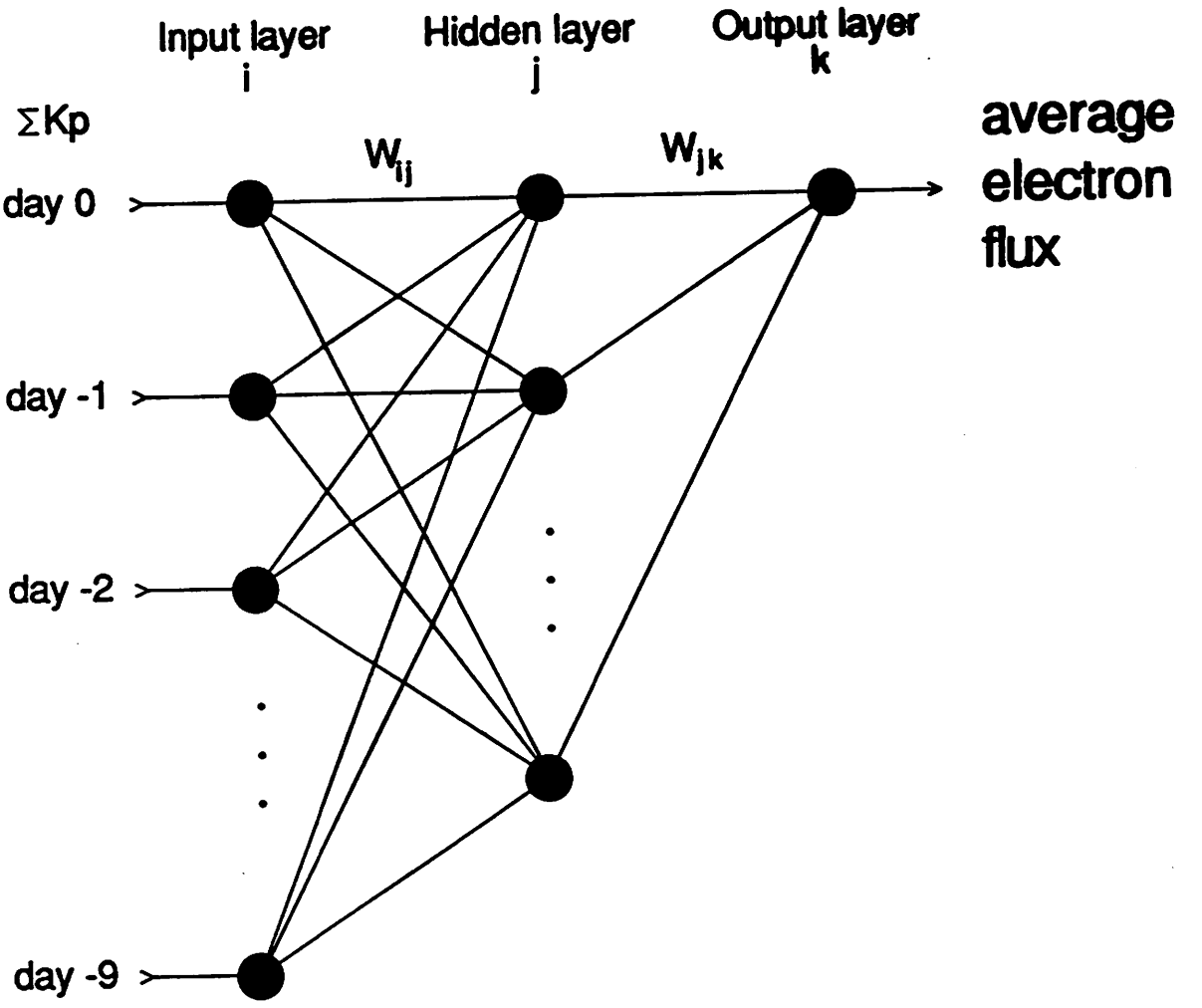
C595.004


SOLAR CYCLE VARIABILITY (11-YEAR)
SOLAR CORONAL HOLES
27-DAY VARIABILITY
HIGH-SPEED SOLAR WIND STREAMS
EXT. SOURCE/INT. ACCELERATION
RELATIVISTIC MAGNETOSPHERE ELECTRONS (OUTER ZONE)
P.A. SCATTERING/PRECIPITATION
MIDDLE ATMOSPHERE ELECTRODYNAMICAL EFFECTS
MIDDLE ATMOSPHERE CHEMICAL EFFECTS
D-REGION CONDUCTIVITY CHANGES
SCHUMANN RESONANCE EFFECTS
MESOSPHERIC/ STRATOSPHERIC NO_Y ENHANCEMENT
GLOBAL ELECTRICAL CIRCUIT CHANGES?
GLOBAL OZONE CHANGES; TROPOSPHERIC EFFECTS?

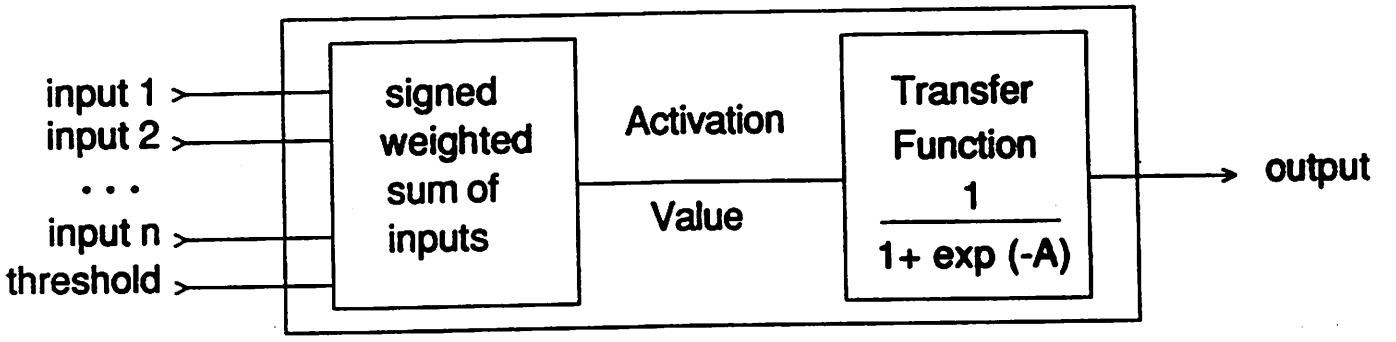

NCSA Mosaic: Document View
File
Options
Navigate
Annotate
Help
Document Title:
Document URL:
Space
Environment
Laboratory
NCSA Mosaic: Open Document
URL To Open:
Open
Clear
Dismiss
Help...
Back
Forward
Home
Reload
Open...
Save As...
Clone
New Window
Close Window

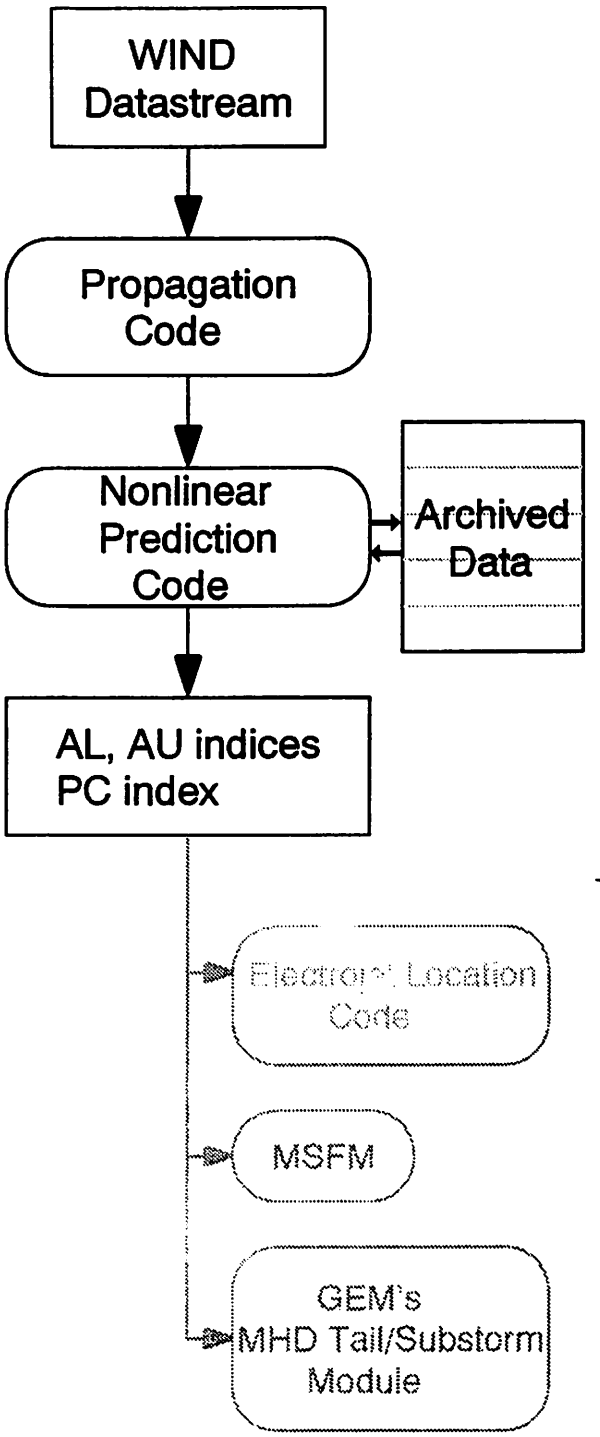
Koons + Gorney (1991)

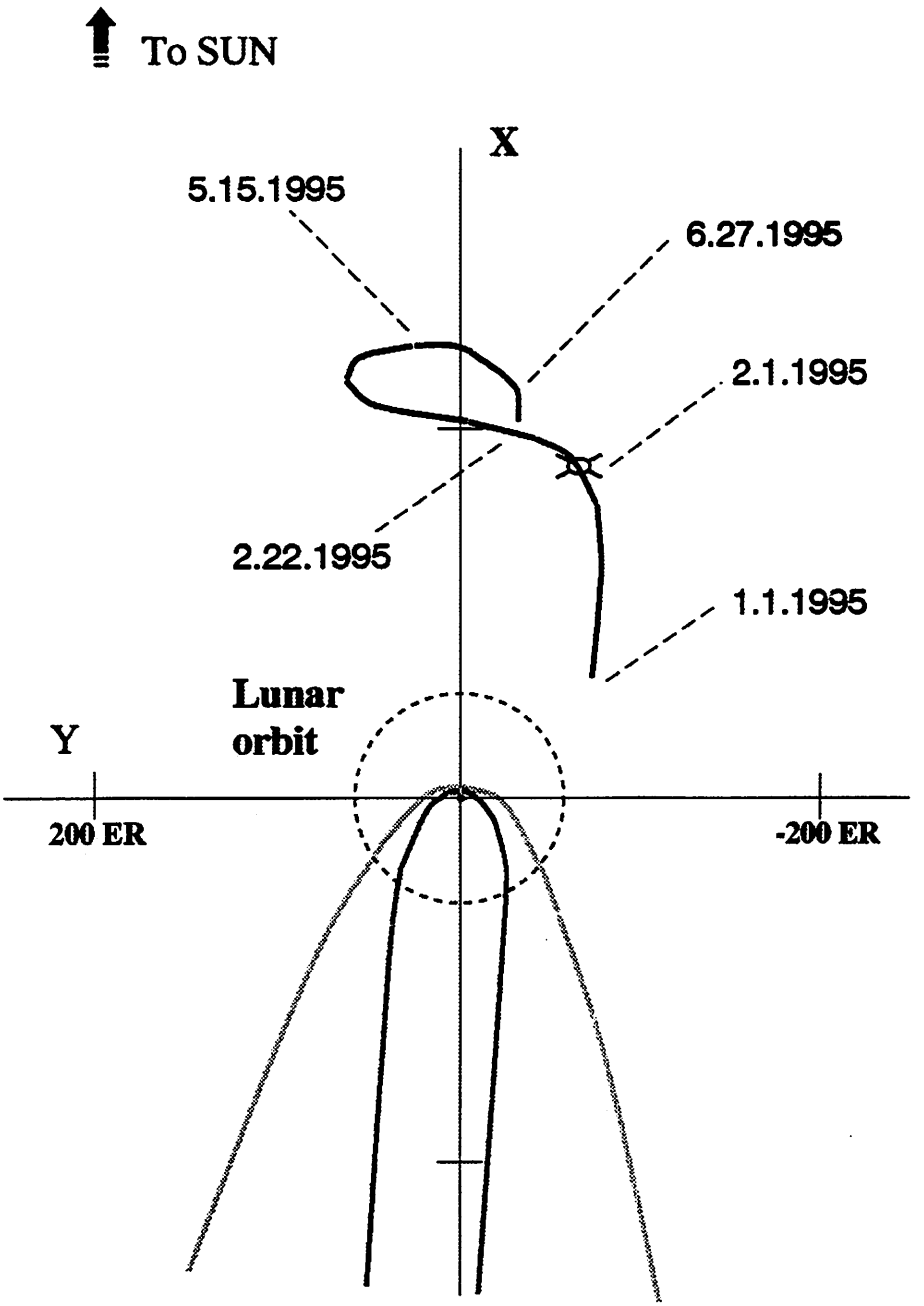
ELECTRON FLUX PREDICTION NETWORK



Typical Neuron





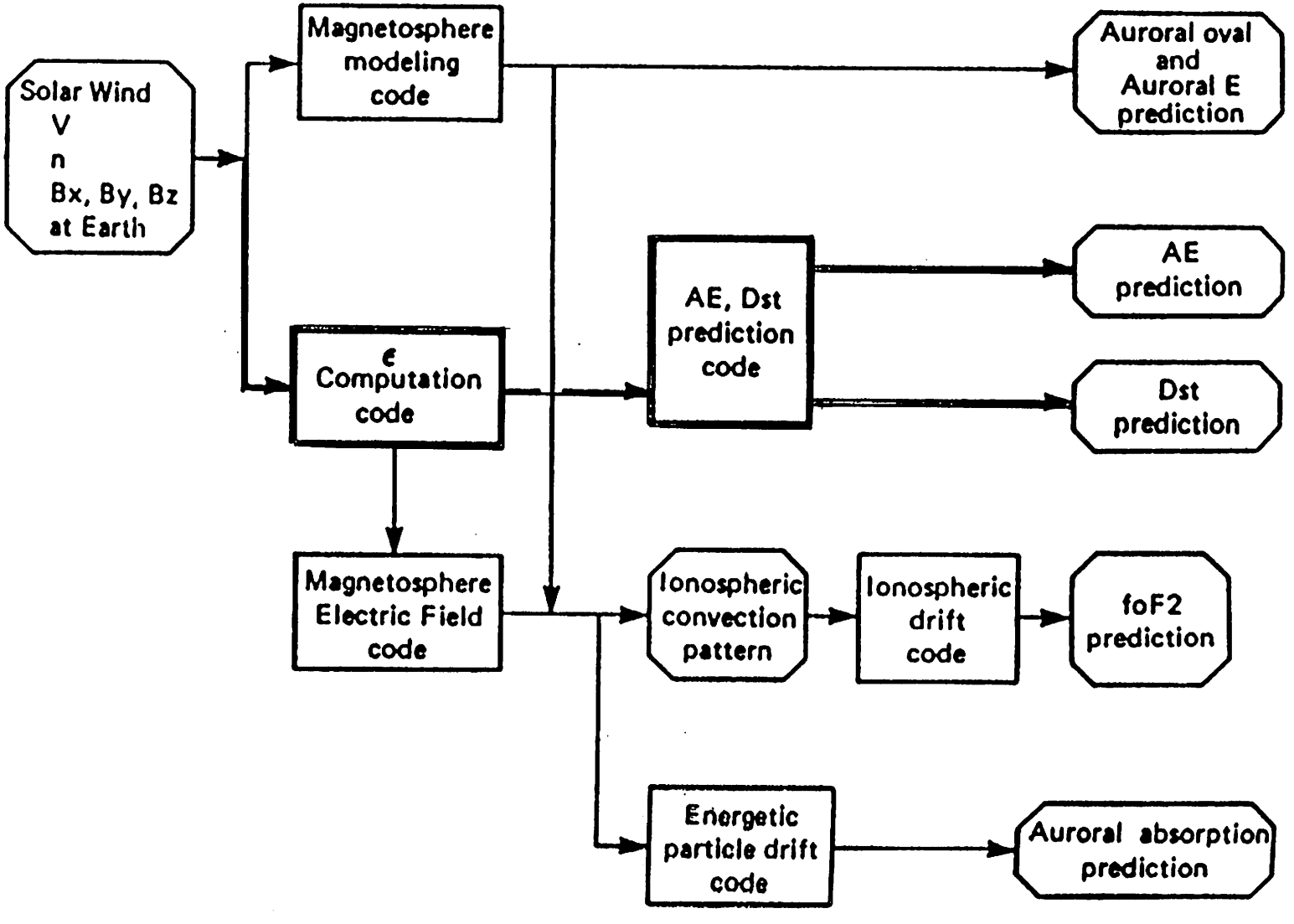


Input: WIND VBs

Prediction Output:

* Auroral geomagnetic activity (AL, AU indices)
* Polar cap geomagnetic activity (PC index)

GEOMAGNETIC ACTIVITY PREDICTION



Relevance to America

Given accurate space weather warnings, system operators could:

satellites	◆ turn off sensitive spacecraft components ◆ increase monitoring of satellite operations for anomalies ◆ calculate best time to adjust a low Earth orbit for drag ◆ delay major changes in vehicle potential from turning on/off components
electric power	◆ reduce load on transmission circuits ◆ confidently reset tripped protective relays on power networks ◆ selectively ground capacitor banks to prevent large potential drops ◆ delay power station maintenance and equipment replacement
communications	◆ look for alternate frequencies; plan means and timing to minimize communications outages
navigation	◆ delay compass calibration on aircraft inertial navigation systems
surveying	◆ delay high-resolution geological surveying, exploration, or other research using GPS ◆ delay high-resolution magnetic surveying degraded by geomagnetic disturbances
radiation	◆ adjust flight altitude on polar routes to minimize health hazard ◆ delay space walk operations