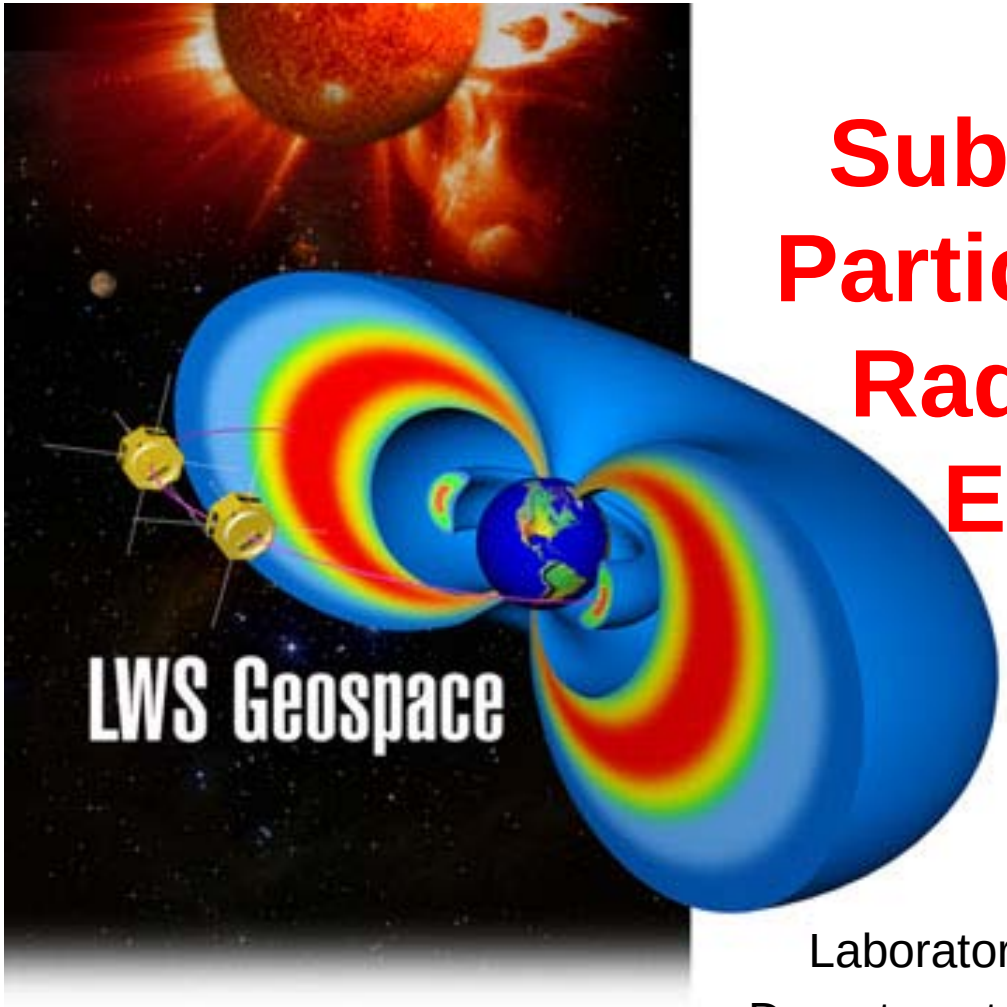

Substorm Energetic Particle Injections and Radiation Belt Flux Enhancements

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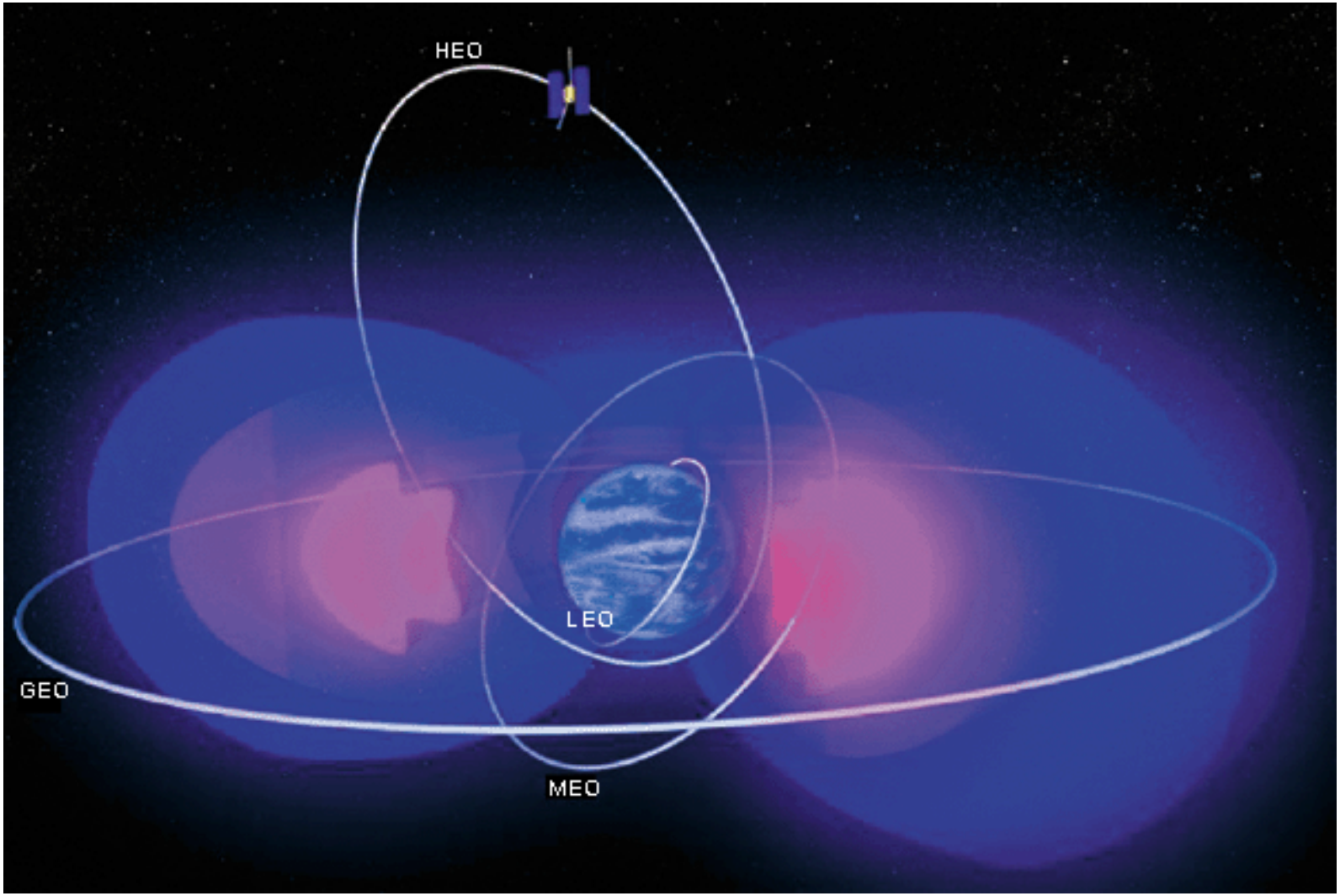
Laboratory for Atmospheric and Space Physics
Department of Astrophysical and Planetary Sciences
Department of Physics
University of Colorado - Boulder

Topics of Discussion

- Historical Overview
- Substorm Electron Events at GEO
- Geomagnetic Storms and SW Streams
- Overall Rad Belt Electron Energization
- Ion (proton) Injections and Transport
- Discussion

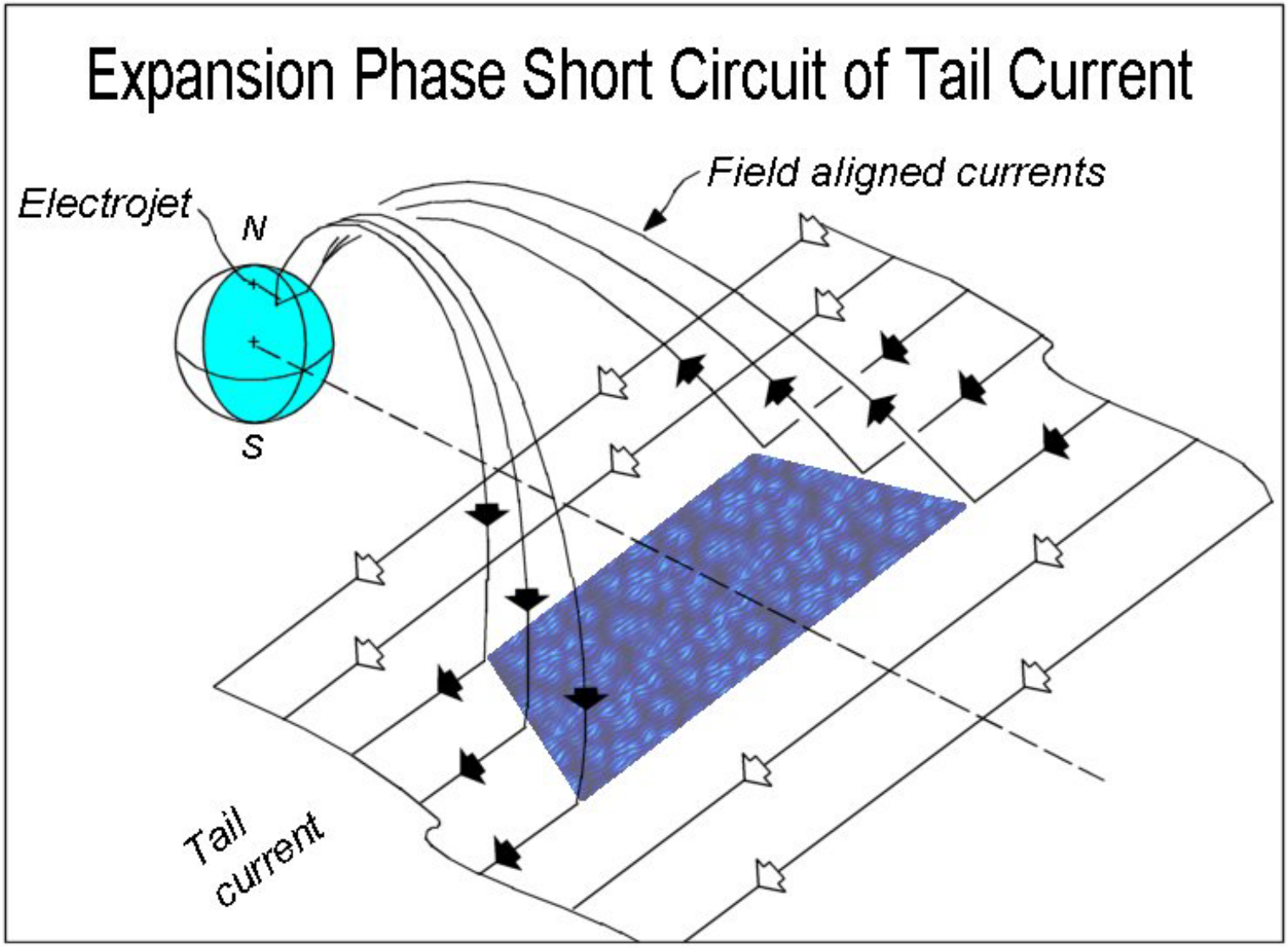
Geosynchronous Orbit – In Context



Early GEO Studies of Substorms

- Arnoldy, R.L., and K.W. Chan, Particle substorms observed at the geostationary orbit, J. Geophys. Res., 74, 5019-5028, 1969.
- Bogott, F.H., and F.S. Mozer, Equatorial proton and electron angular distributions in the loss cone and at large angles, J. Geophys. Res., 76, 7690, 1971.
- Bogott, F.H., and F.S. Mozer, Nightside energetic particle decreases at the synchronous orbit, J. Geophys. Res., 78, 8119, 1973.
- DeForest, S.E. and C.E. McIlwain, Plasma clouds in the magnetosphere, J. Geophys. Res., 76, 3587, 1971.
- Lanzerotti, L. J., A. Hasegawa, and C. G. Maclennan, Drift Mirror Instability in the Magnetosphere: Particle and Field Oscillations and Electron Heating, *J. Geophys. Res.*, 74(24), 5565–5578, 1969
- Lezniak, T.W., R.L. Arnoldy, G.K. Parks, and J. Winckler, Measurement and intensity of energetic electrons at the equator at 6.6 R_E, Radio Sci., 3, 710, 1968.
- Parks, G.K., R.L. Arnoldy, T.W. Lezniak, and J.R. Winckler, Correlated effects of energetic electrons at the 6.6 R_E equator and the auroral zone during magnetospheric substorms, Radio Sci., 3, 715, 1968.
- Pfitzer, K.A., and J.R. Winckler, Intensity correlations and substorm electron drift effects in the outer radiation belt measured with the OGO 3 and ATS 1 satellites, J. Geophys. Res., 74, 5005, 1969.

The Substorm Current Wedge



McPherron et al.,1973

GEO Substorm Observations - Next

- Walker, R.J., K.N. Erickson, R.L. Swanson, and J.R. Winckler, Substorm-associated particle boundary motion at synchronous orbit, J. Geophys. Res., 81, 5541, 1976.
- Belian, R. D., D.N. Baker, P.R. Higbie, and E.W. Hones, High-Resolution Energetic Particle Measurements at 6.6 R_E, 2, High-Energy Proton Drift Echoes, JGR, 83, 4857, 1978
- Baker, D. N., P.R. Higbie, E.W. Hones, and R.D. Belian, High-Resolution Energetic Particle Measurements at 6.6 R_E, 3. Low-Energy Electron Anisotropies and Short-Term Substorm Predictions, JGR, 83, 4863, 1978

Charged Particle Analyzer - LANL

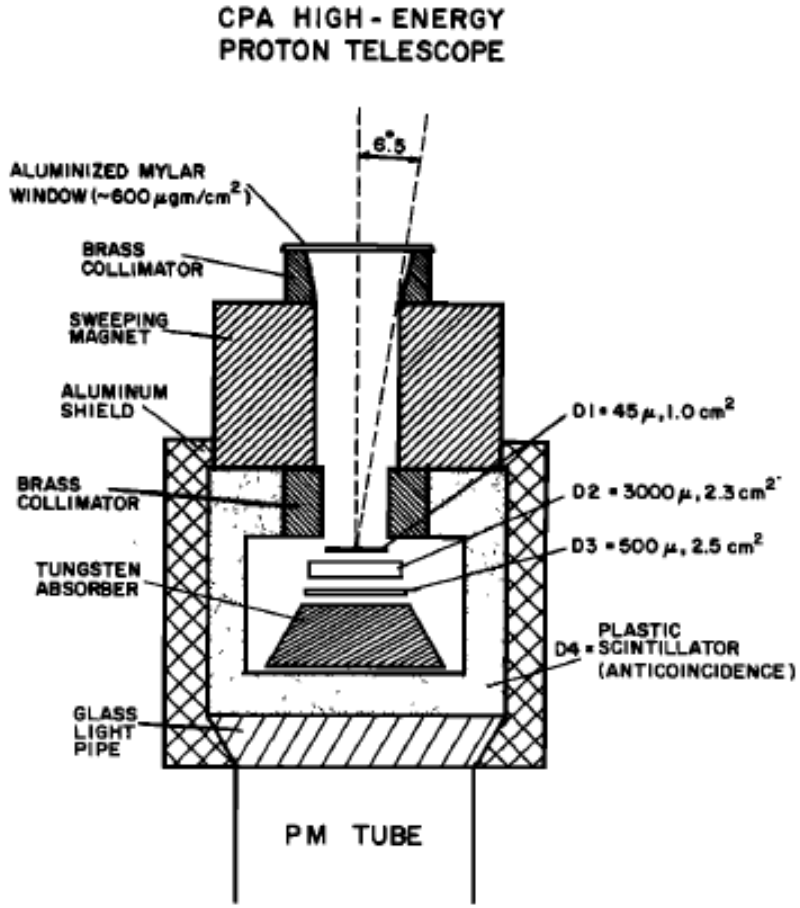
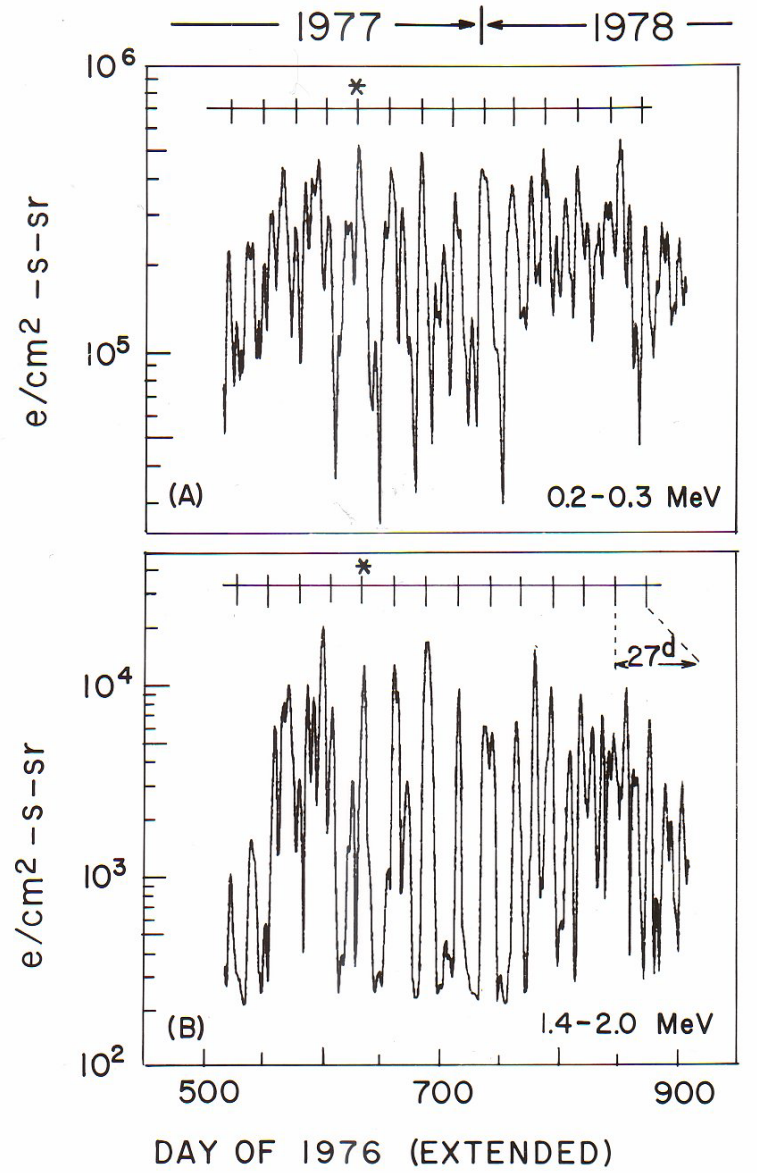


Fig. 1*b*. Illustration showing the main features of the CPA high-energy proton telescope on spacecraft 1976-059A.

LoE: 30 – 300 keV
HiE: 0.2 – 2 MeV
LoP: 0.1 – 0.6 MeV
HiP: 0.4 – 150 MeV

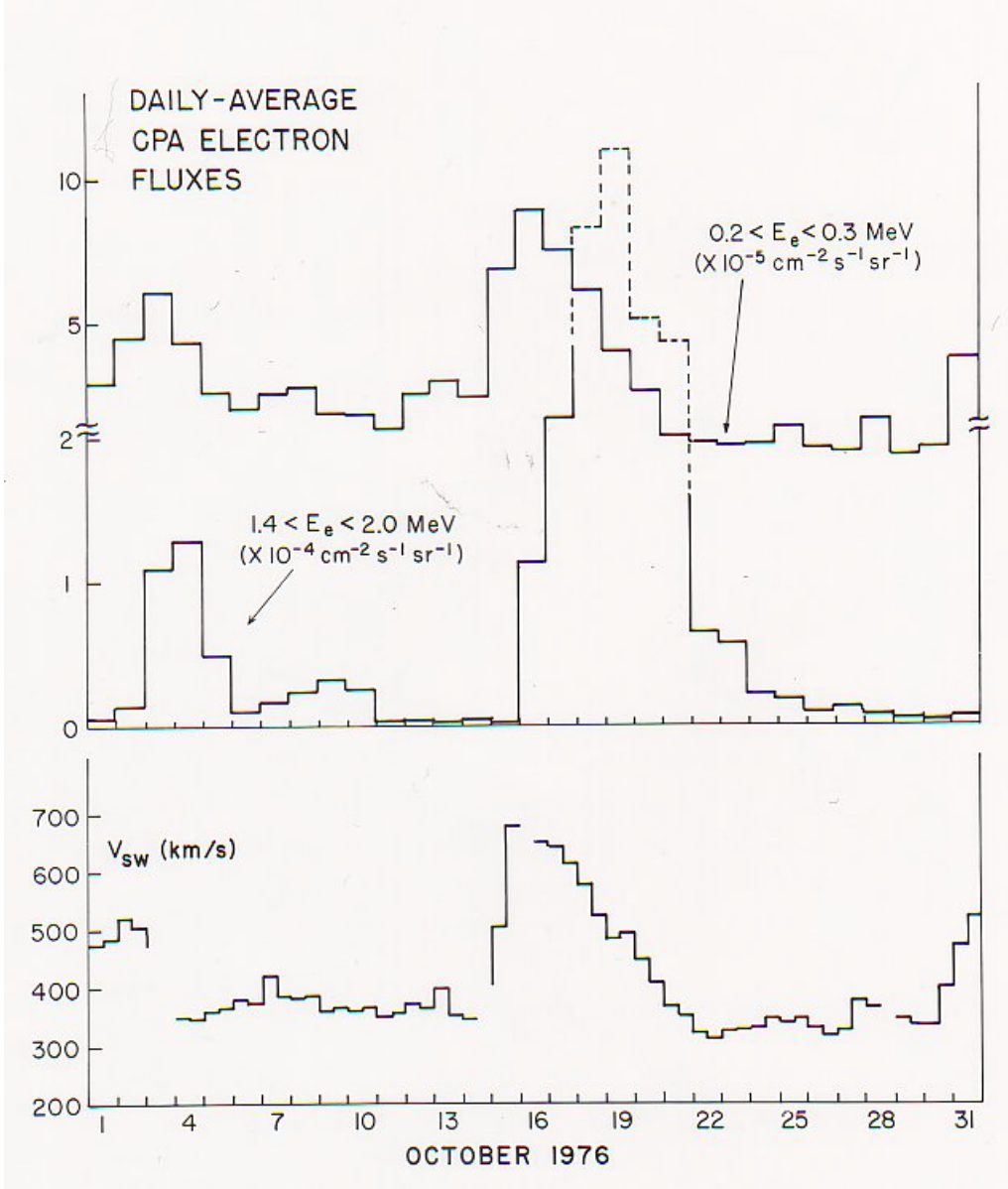
[Baker et al., 1979]

Electron Recurrence: 27-day Periods



Many cite Paulikas & Blake [1979] as the authors who first "discovered" solar wind stream control of MeV electrons at GEO. Concurrently we (GRL,1979; JGR, 1979) published papers that showed not only relativistic electron response to V_{SW}, but also low-energy electron responses (at GEO) as well as proton responses over a wide range of energies (> 1-2 MeV).

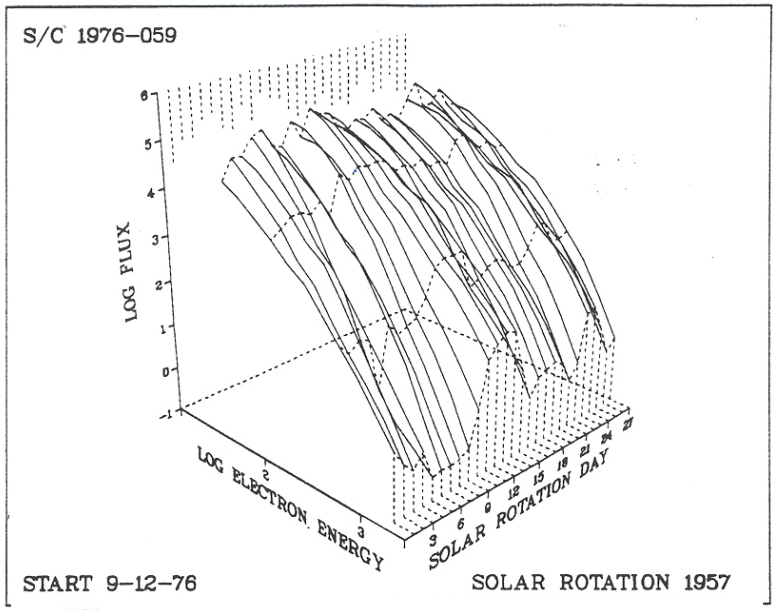
Low- vs. High-Energy Electron Responses

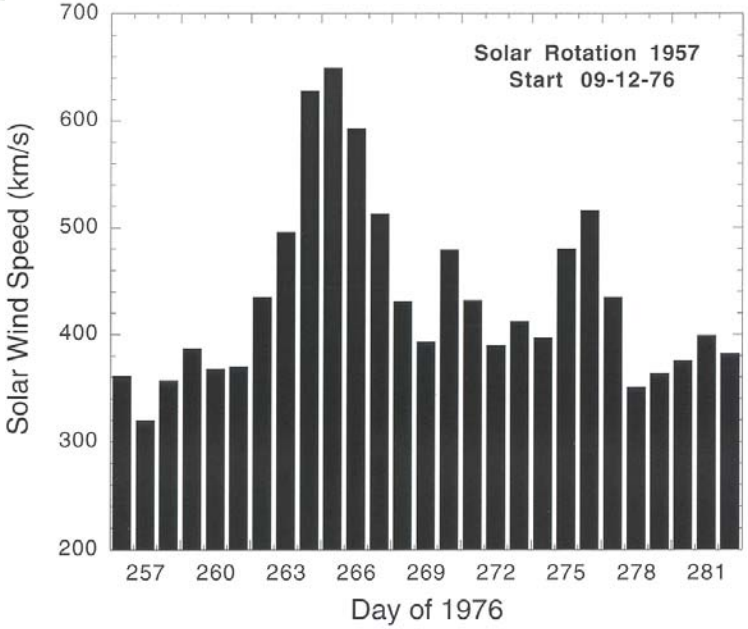


It was found that electrons from E ~ 30 keV to E ~ 300 keV (at geostationary orbit) were closely related to solar wind speed variations.

On the other hand, electrons with E > 1 MeV were found to be delayed in relation to solar wind stream profiles.

Geostationary Orbit Electron Spectra and Solar Wind Speeds



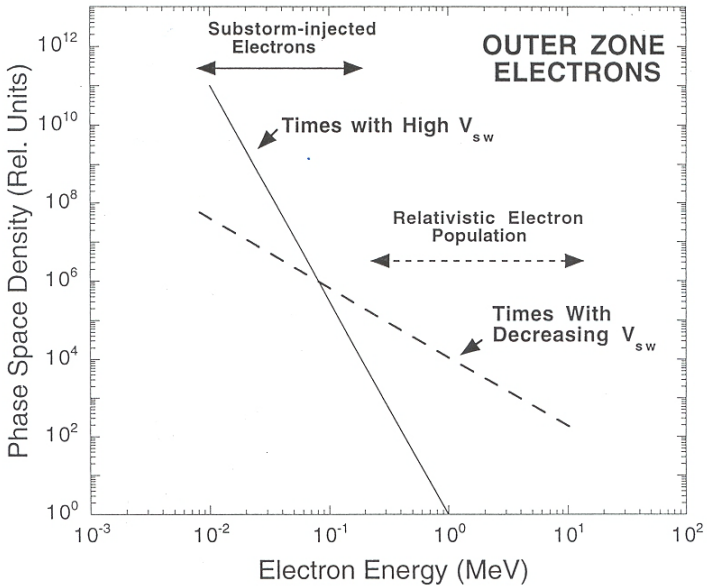


[Baker, et al, 1987;1998]

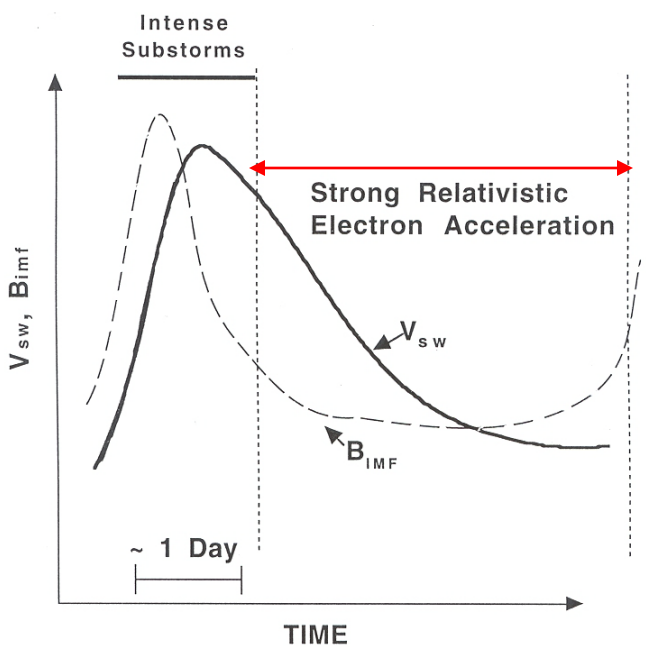
* Prompt low-energy electron acceleration

* Delayed relativistic electron production

The Role of High-Speed Solar Wind Streams



[Baker et al.,1986]

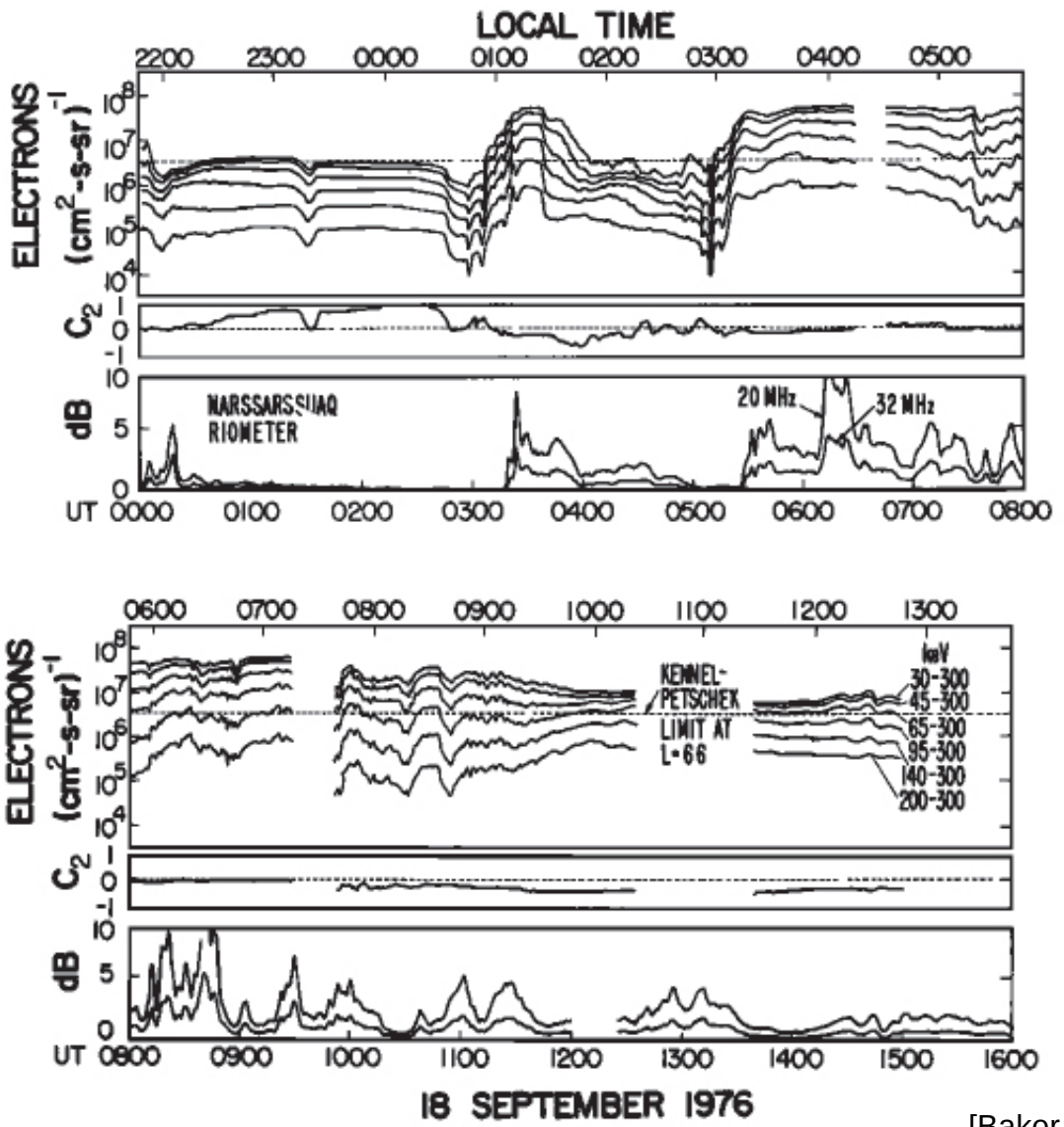


[Baker, et al, 1997]

*** Prompt substorm acceleration of electrons < 300 keV**

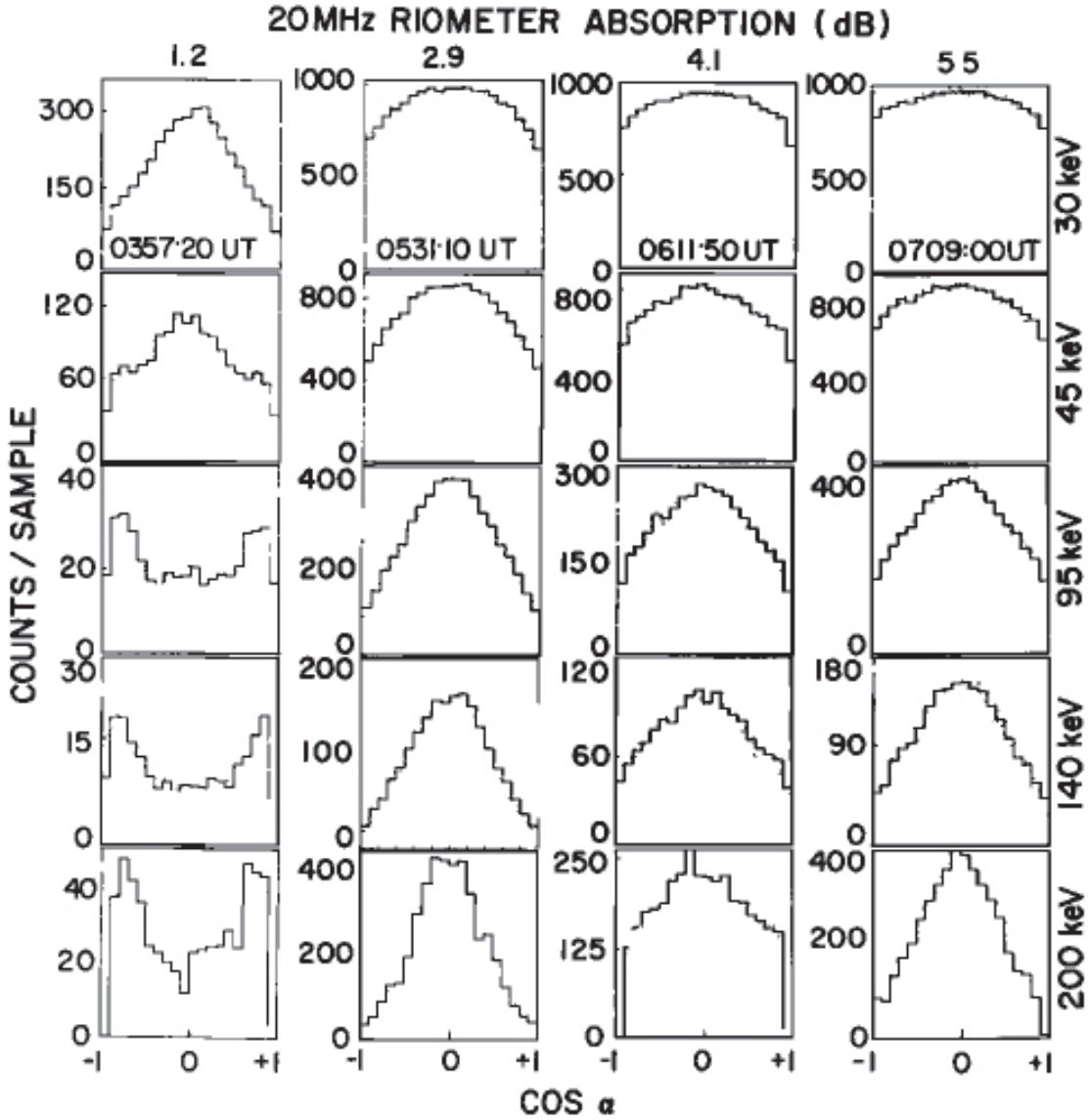
*** Delayed relativistic electron acceleration (2-3 days)**

Electron Flux and Riometer Comparisons

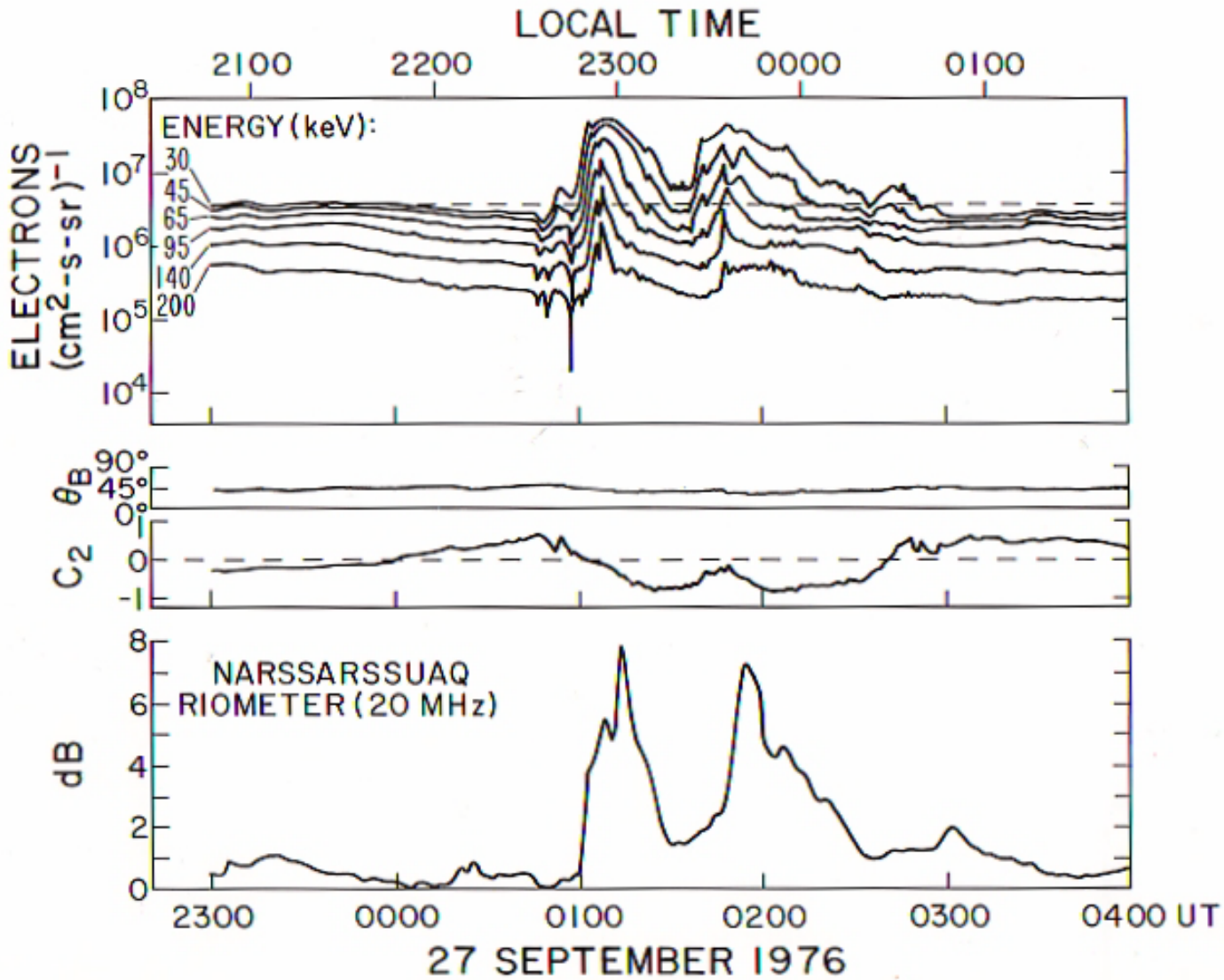


[Baker et al., GRL, 1979]

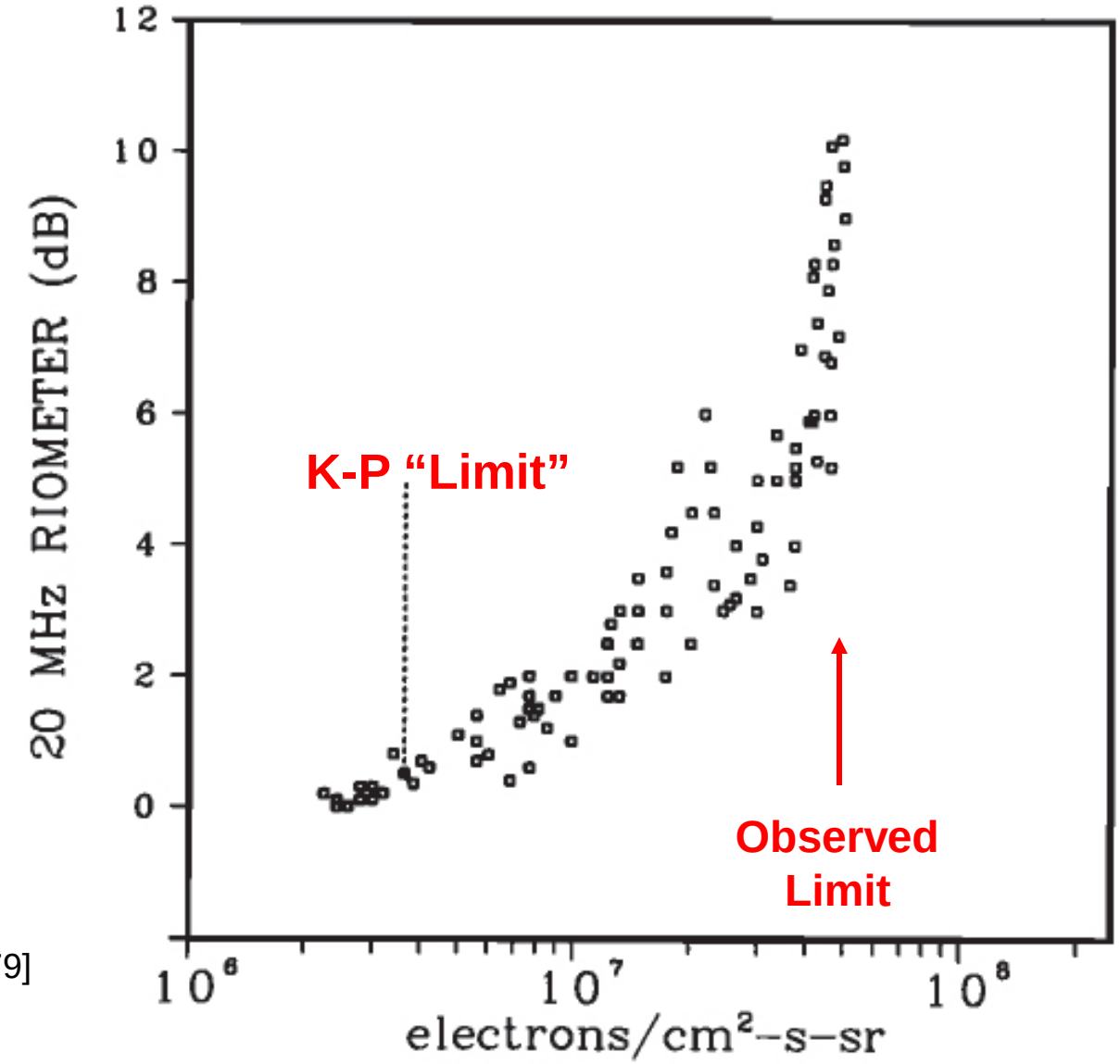
Pitch Angle Evolution



Flux and Riometer Comparison

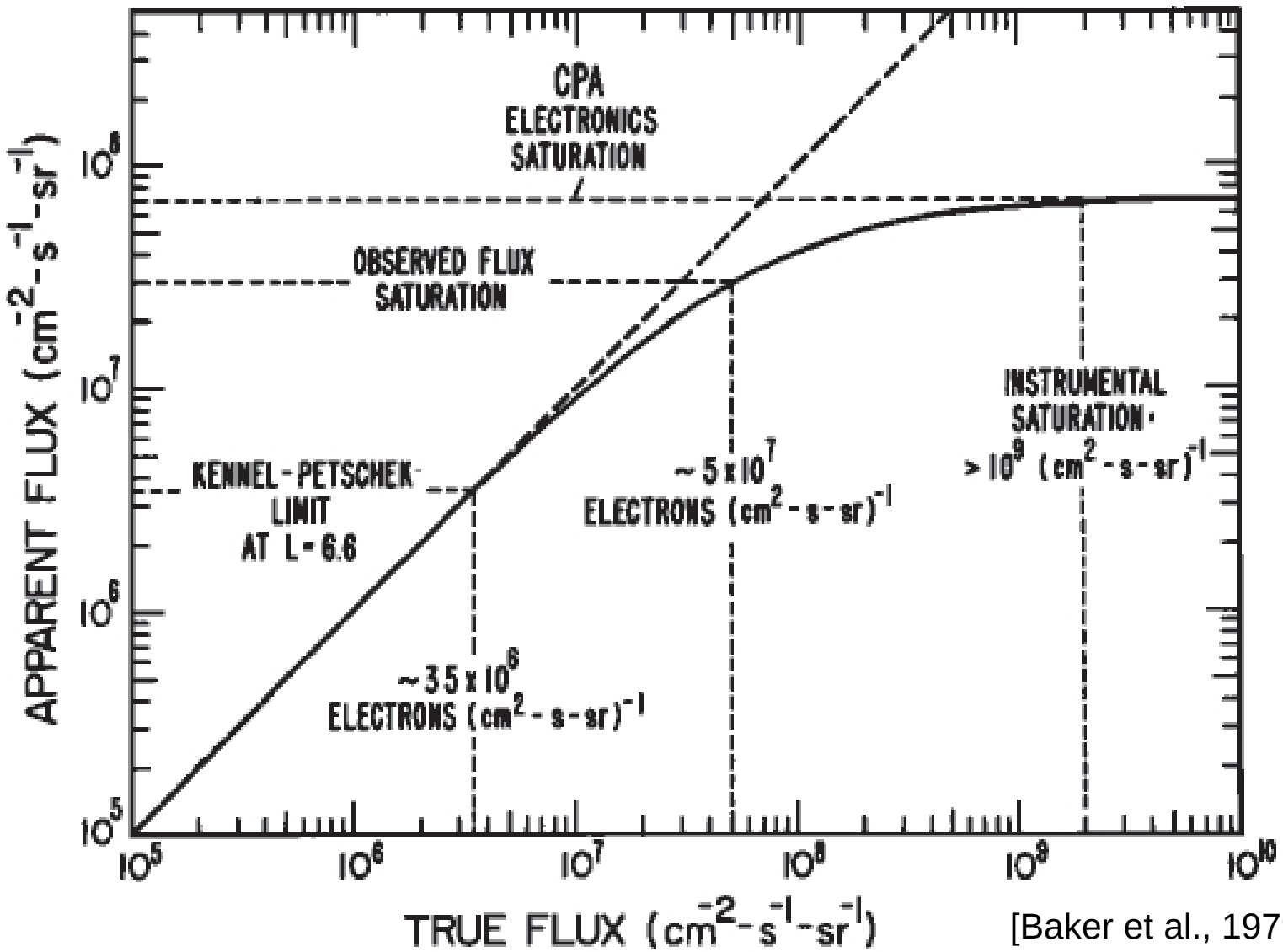


Peak Fluxes vs. Riometer Intensity



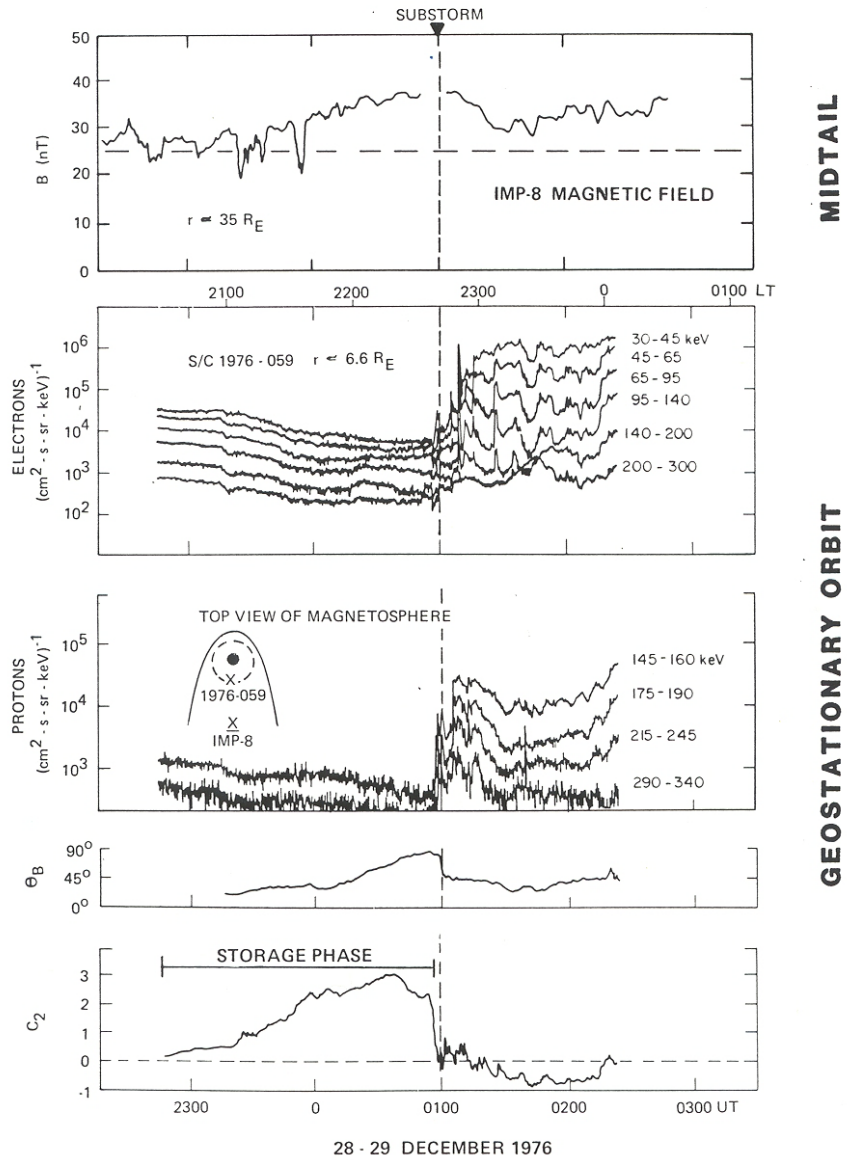
[Baker et al., 1979]

Summary of Flux Limits



[Baker et al., 1979]

Substorm Particle Injection



Magnetic energy increase in magnetotail

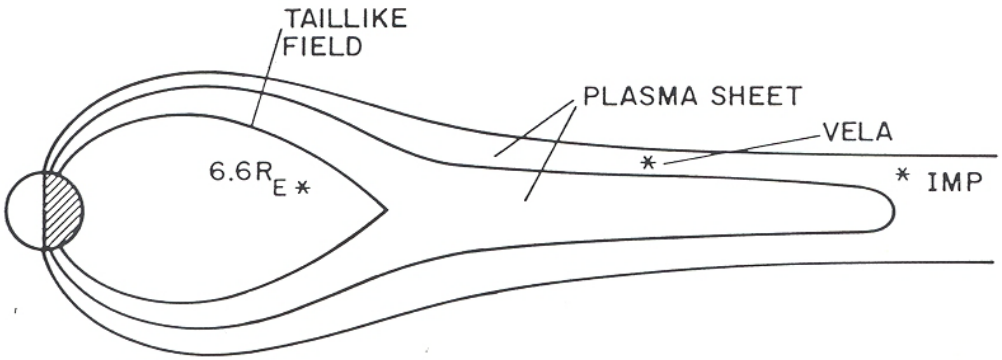
30 - 300 keV particle enhancements near geostationary orbit

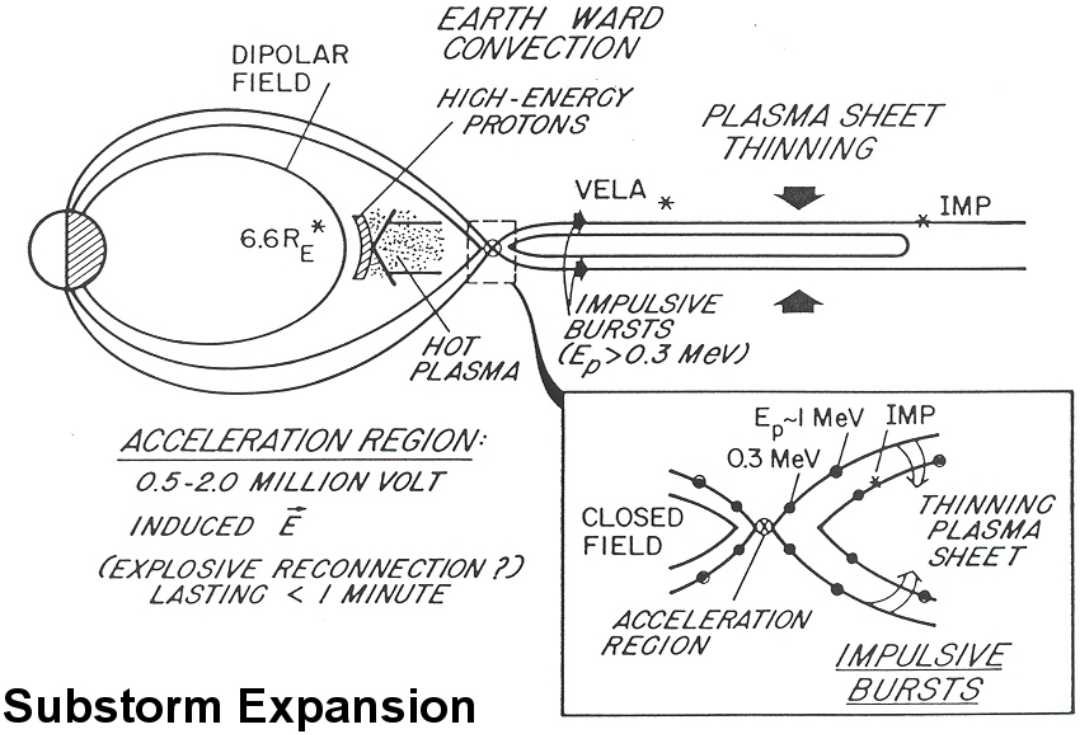
Magnetic field “dipolarization” near GEO orbit

[Baker et al., 1981]

Energetic Particle Acceleration During Magnetospheric Substorms

Substorm Growth Phase





Substorm Expansion

[Baker et al., 1979;1981]

CDAW-2 Substorm Studies

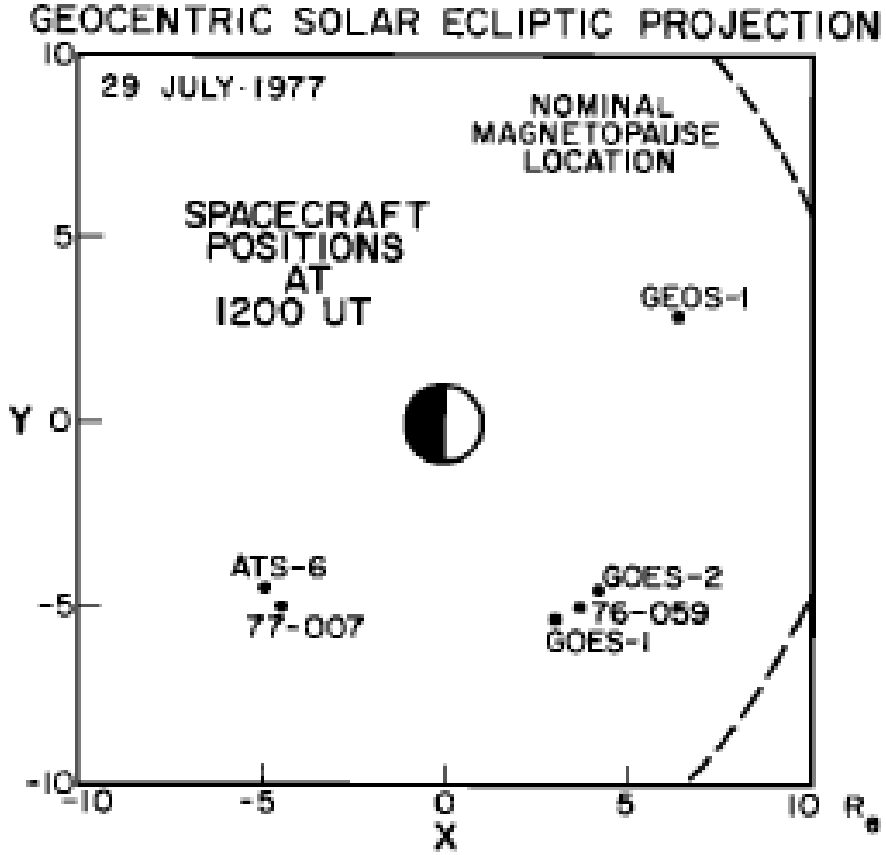


Fig. 1. Positions of the geostationary and near-geostationary (GEOS-1) spacecraft used in this study. The nominal magnetopause location in this solar ecliptic projection is also shown.

[Baker et al., 1982]

CDAW-2 Substorm Injection

BAKER ET AL.: CDAW 2 ENERGETIC PARTICLES

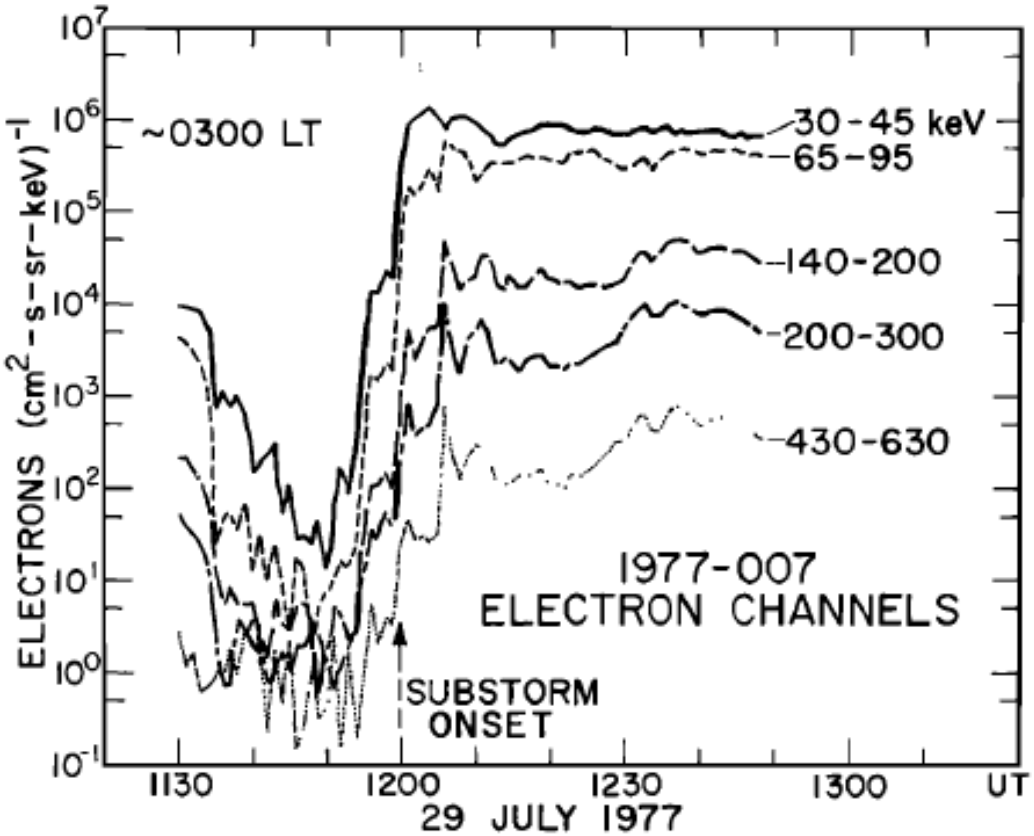
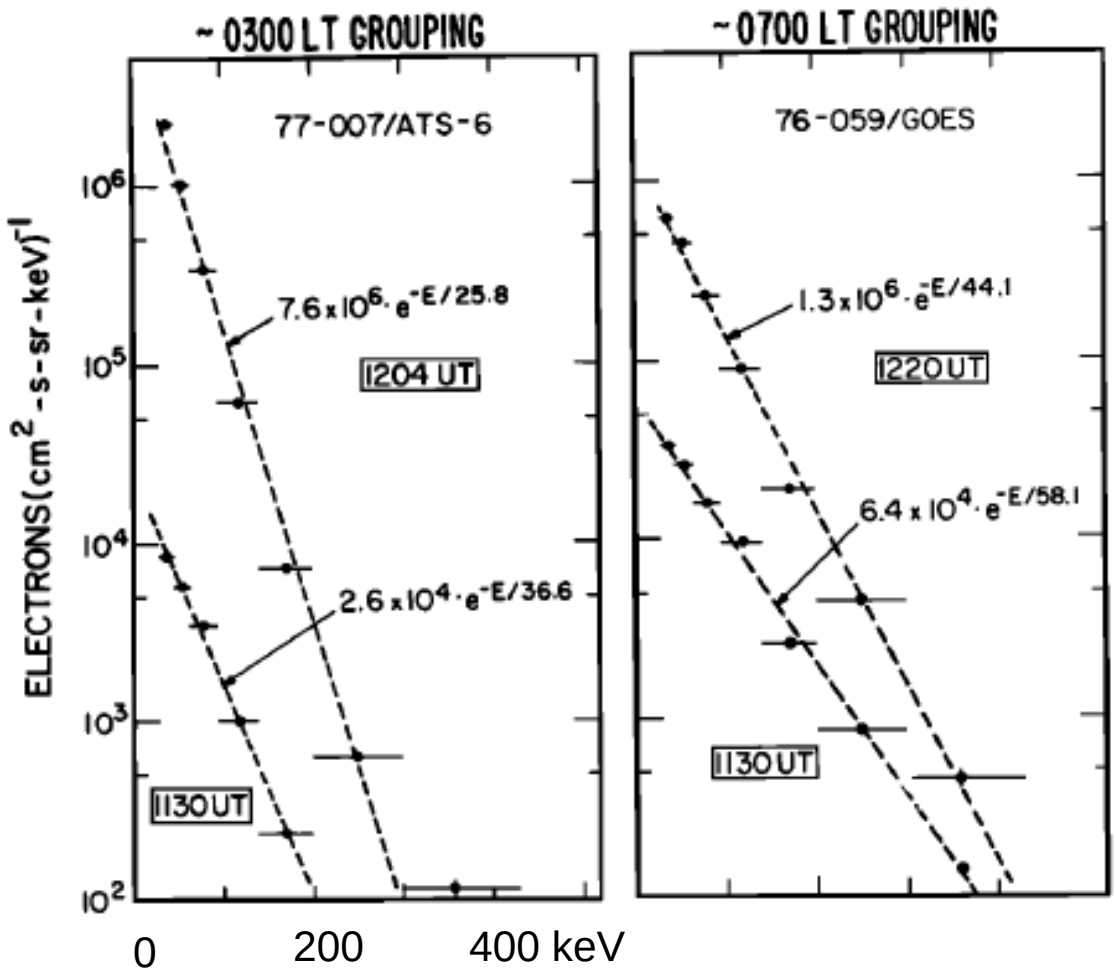


Fig. 3. Representative differential energetic electron flux profiles for the period 1130–1300 UT on July 29, 1977, at the 0300 LT spacecraft position.

CDAW-2 Energy Spectra



CDAW-2 Magnetic Field Values

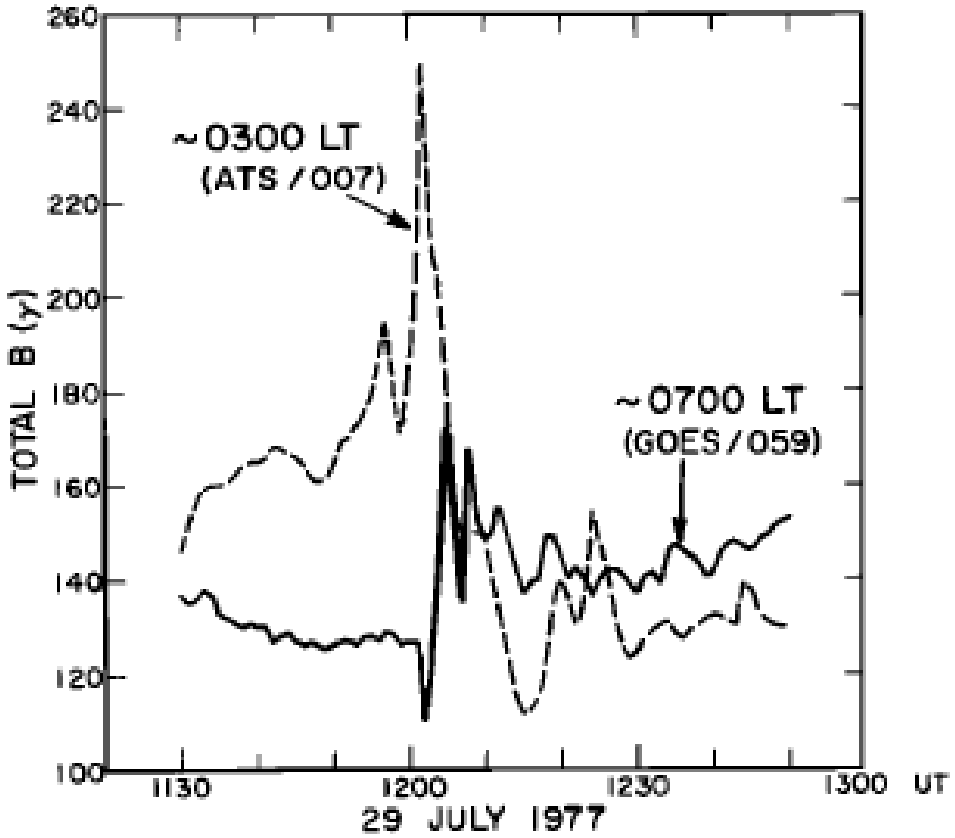
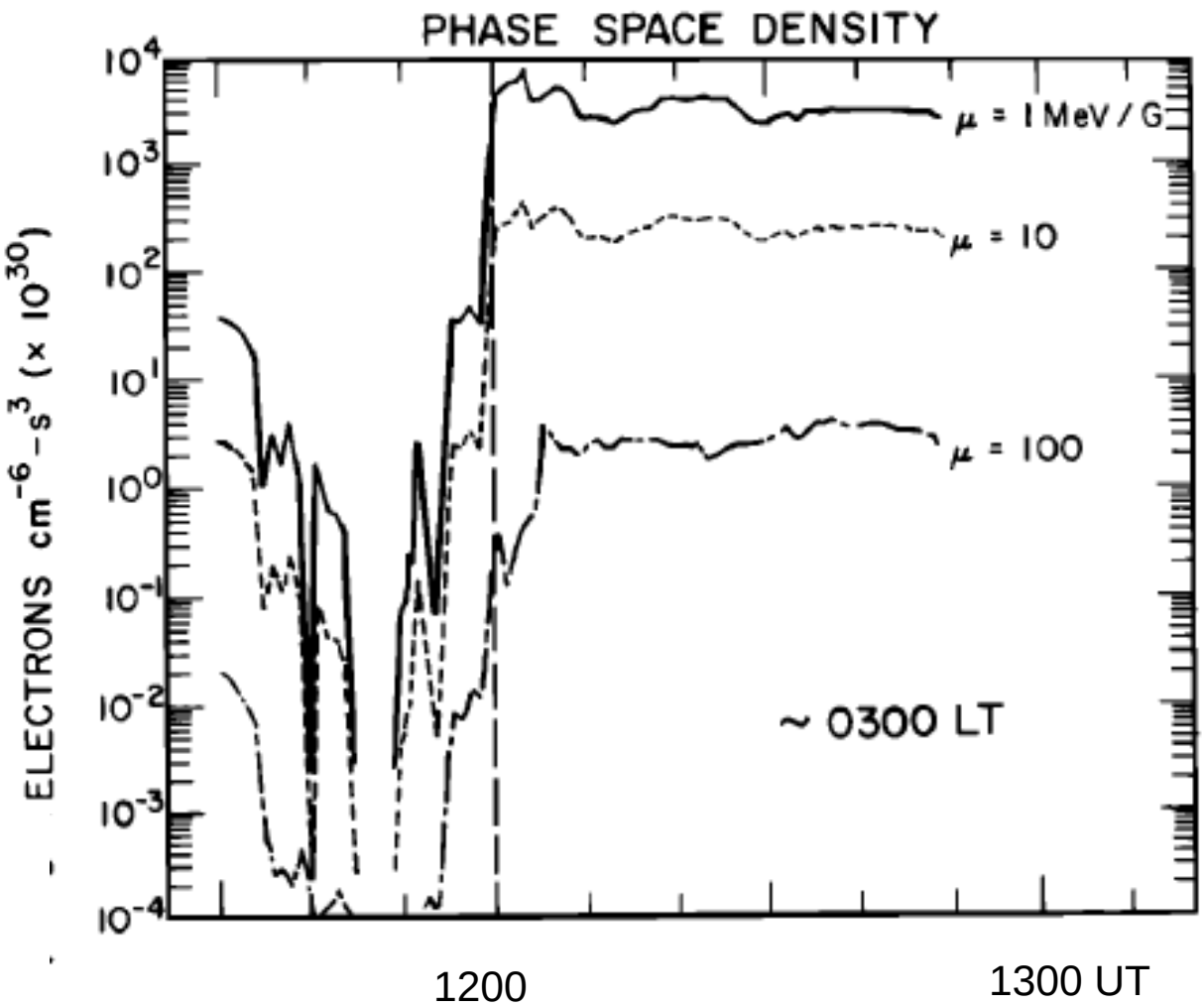


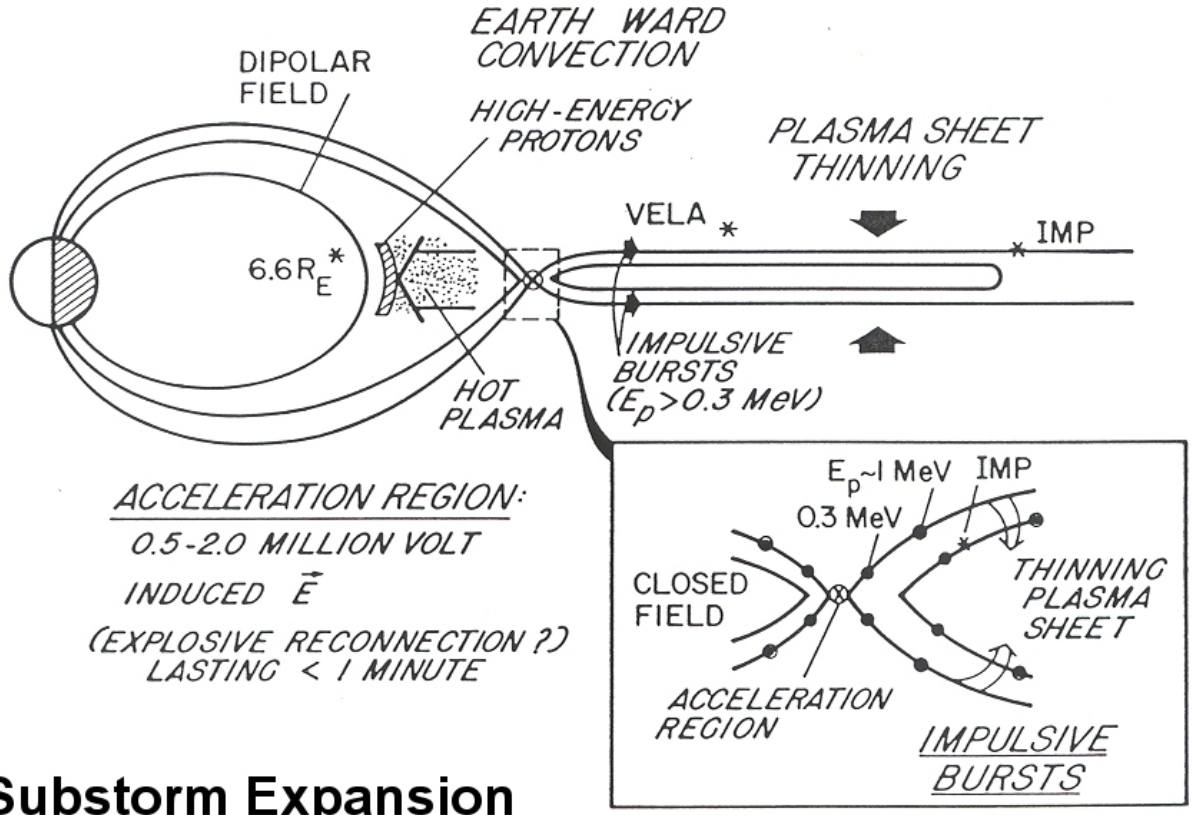
Fig. 11. Total magnetic field strength variations for the 1200 UT substorm at the 0300 and 0700 local time grouping positions studied in this paper.

CDAW-2 Electron PSD



[Baker et al., 1982]

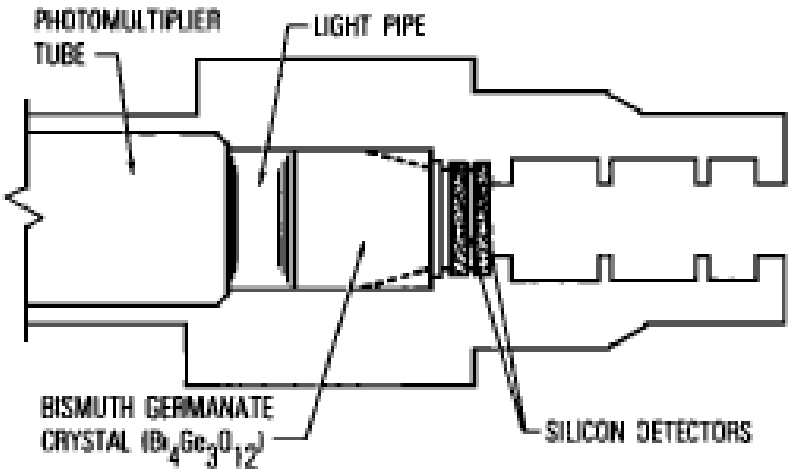
Substorm Injection Model



Substorm Expansion

[Baker et al., 1979;1981]

Spectrometer for Energetic Electrons (SEE)

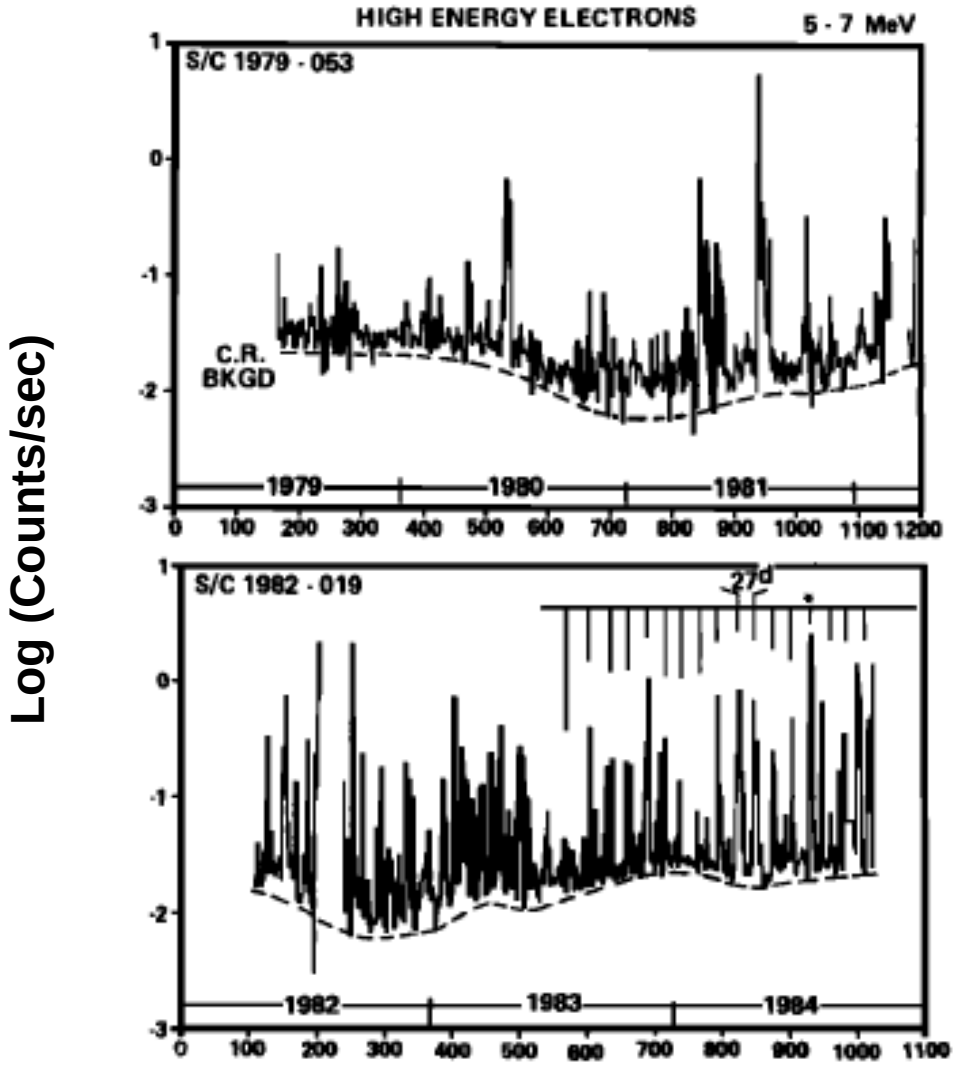


[Baker et al., 1986]

G = 0.15 cm^2-sr

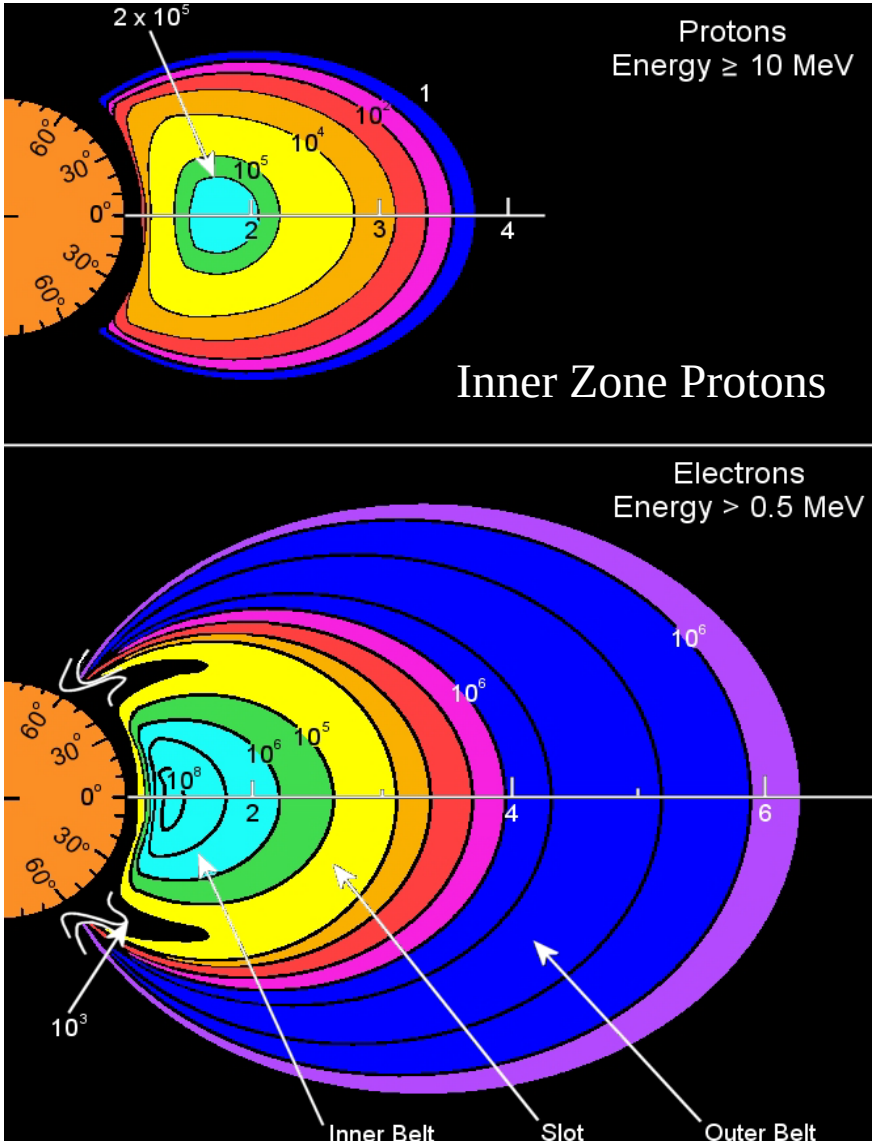
Fig. 2. Schematic illustration (in cross section) of the spectrometer for energetic electrons (SEE). The essential features include the collimator structure to the right, the silicon solid-state detectors (operated in parallel), and the BGO analyzer crystal. The sensor has a geometric factor of 0.15 cm^2 sr; in addition to the illustrated structure there is a shielding of 0.34 g/cm^2 of Al at the opening end of the collimator.

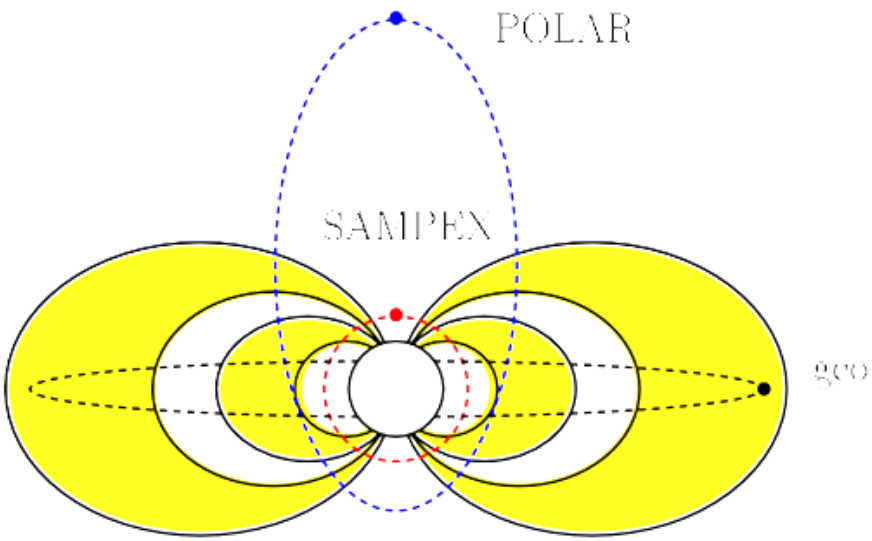
SEE Results: 1979-1984



[Baker et al., 1986]

Observing the Radiation Belts





Key Platforms

SAMPEX

-LEO orbit ≈ 600 km

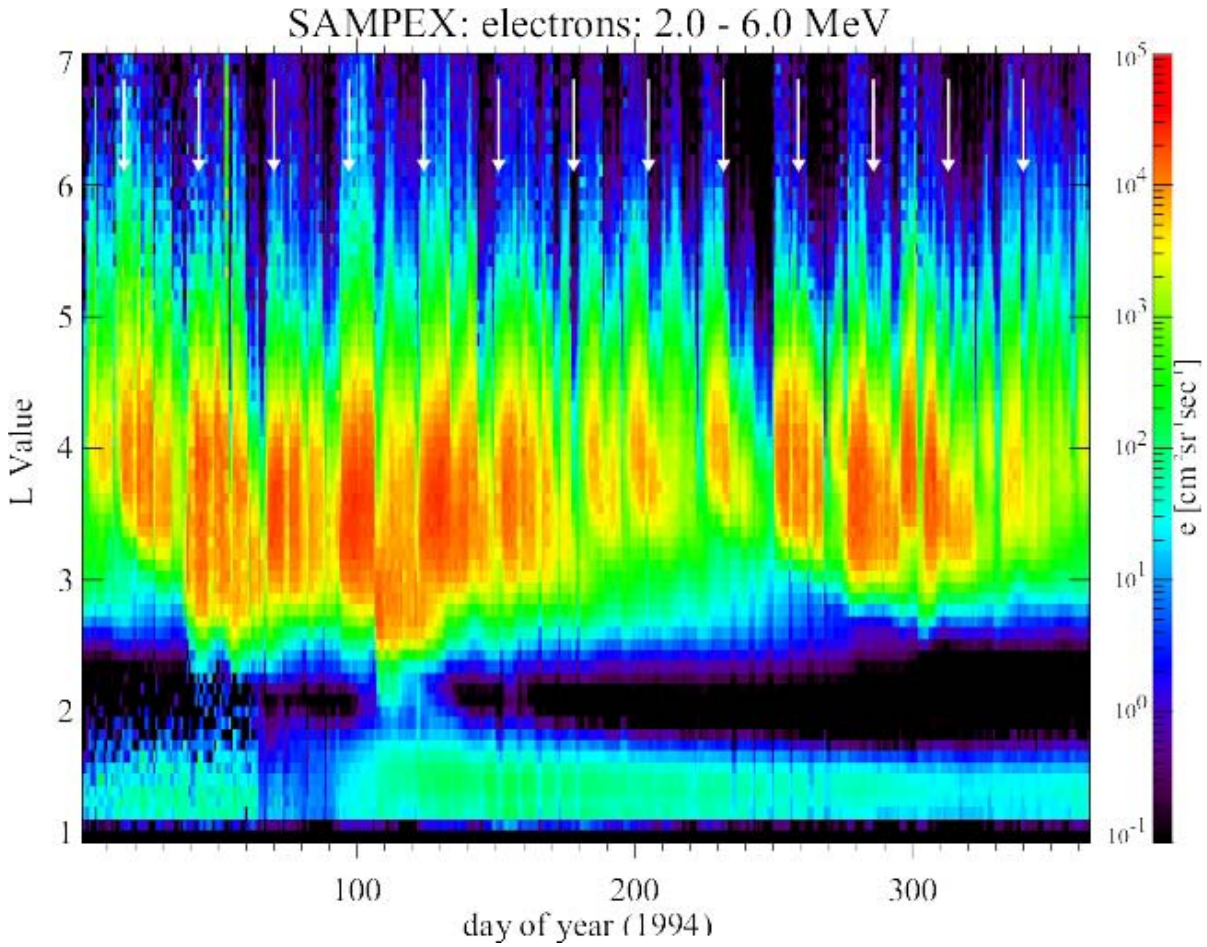
POLAR

-Elliptical 2x9 R_E Orbit

GEO

-Geostationary Earth Orbit – 6.6 R_E

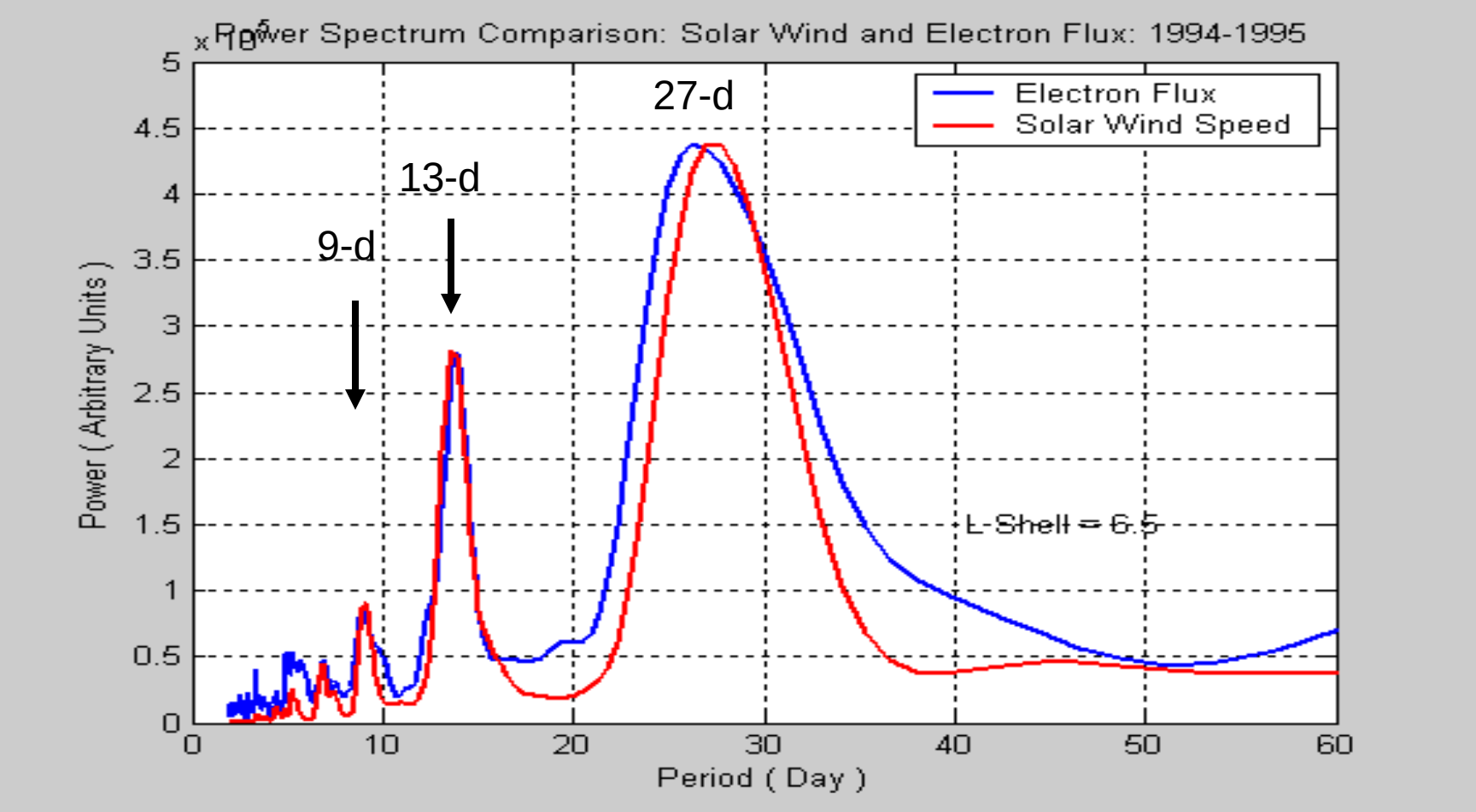
1994 – High Speed Stream Control



Strong electron acceleration in the approach to sunspot minimum

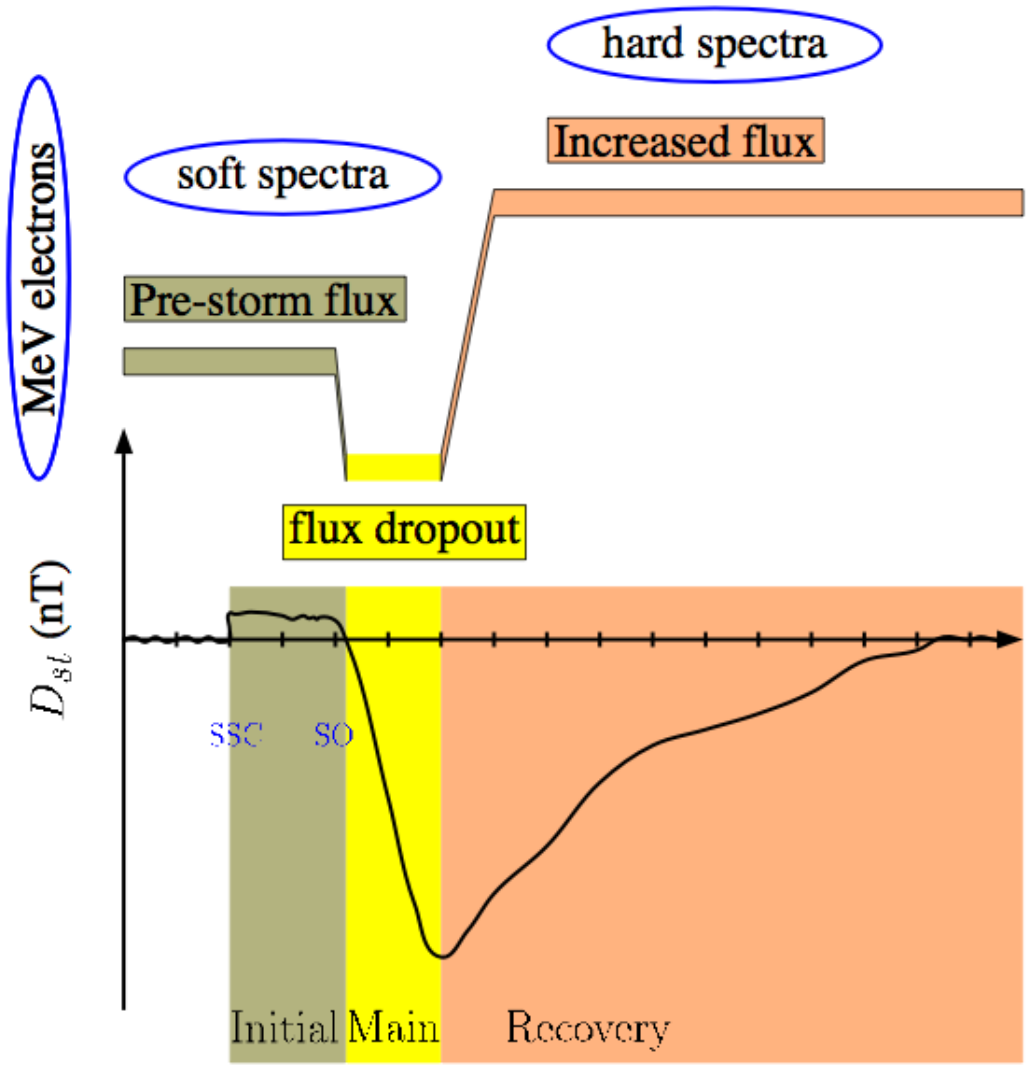
White arrows indicate 27-day recurrent events: High-speed solar wind streams

Electron Flux Scaled to the Maximum Amplitude



[Presicci et al., 2011]

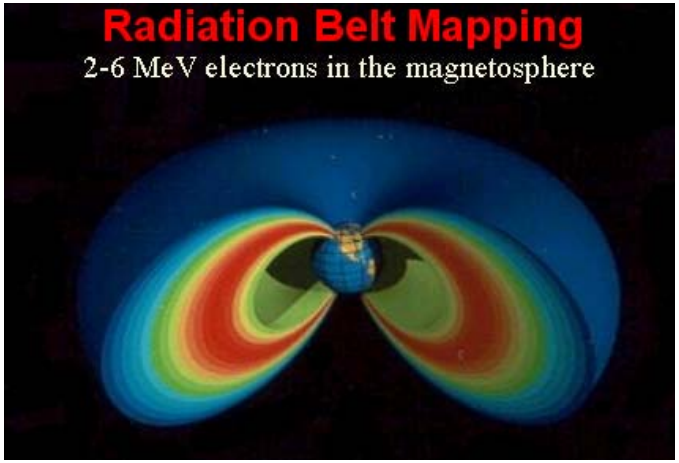
MeV Electrons & Geomagnetic Storms

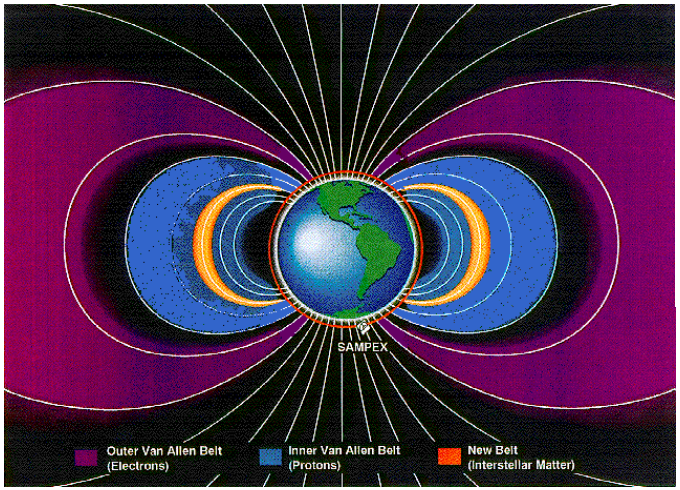


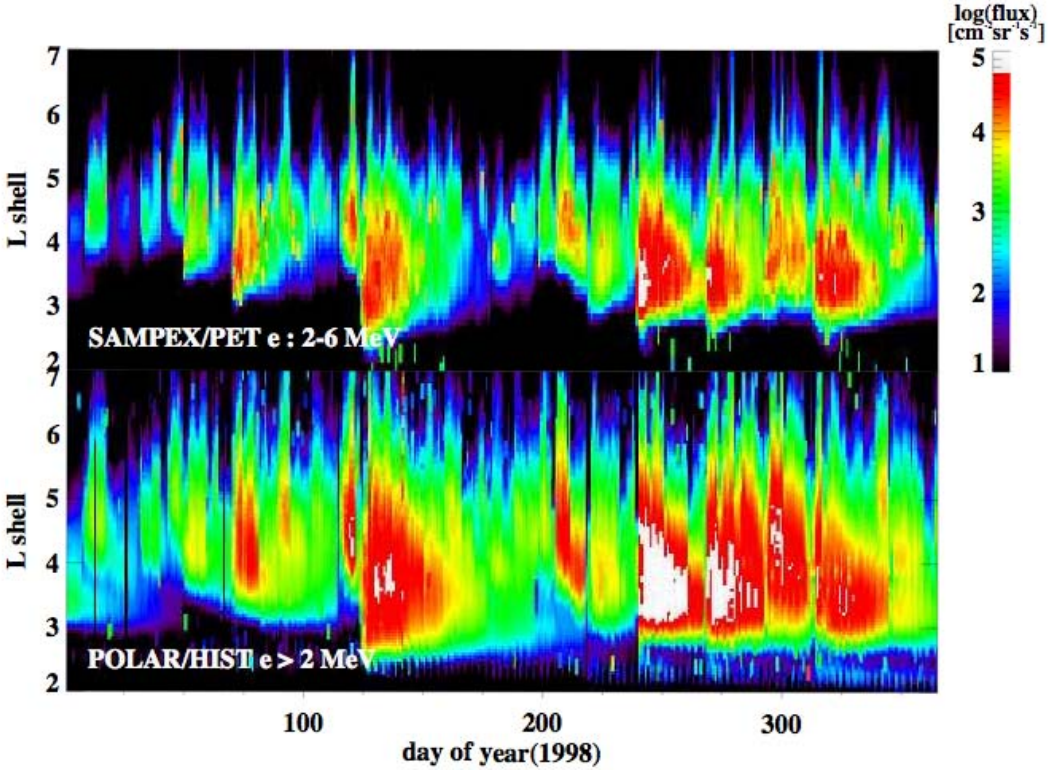
[See Kanekal et al., 2004; Reeves et al., 2003]

- Recovery phase
  - Increased PSD
  - Broad L range
- Main phase
  - Flux dropout
  - Adiabatic field changes and particle loss
- Flux changes
  - Decrease or no change in about 50% of storms - GEO data

Multiple spacecraft study of acceleration



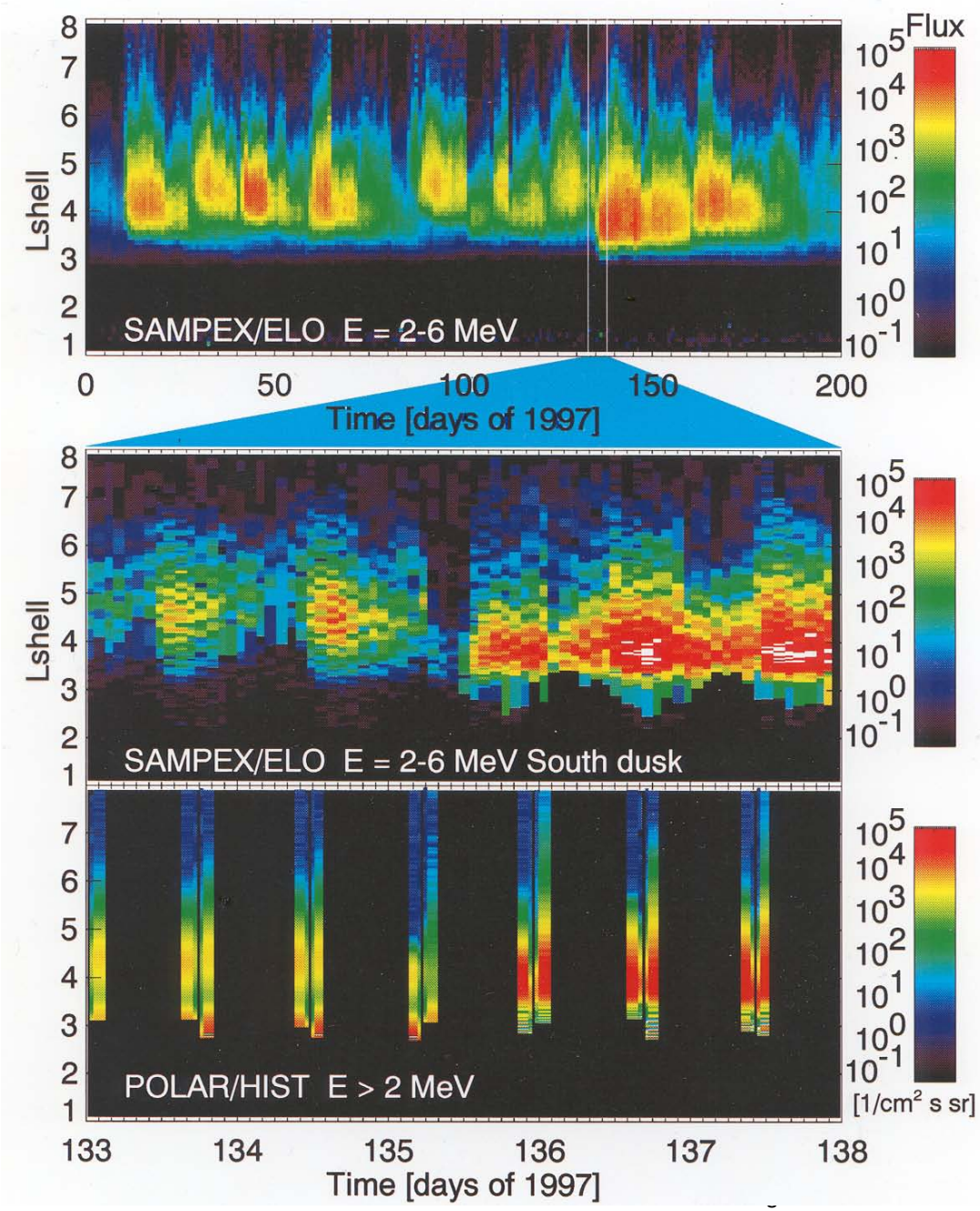




Radiation belt electrons show

"remarkable global coherence"

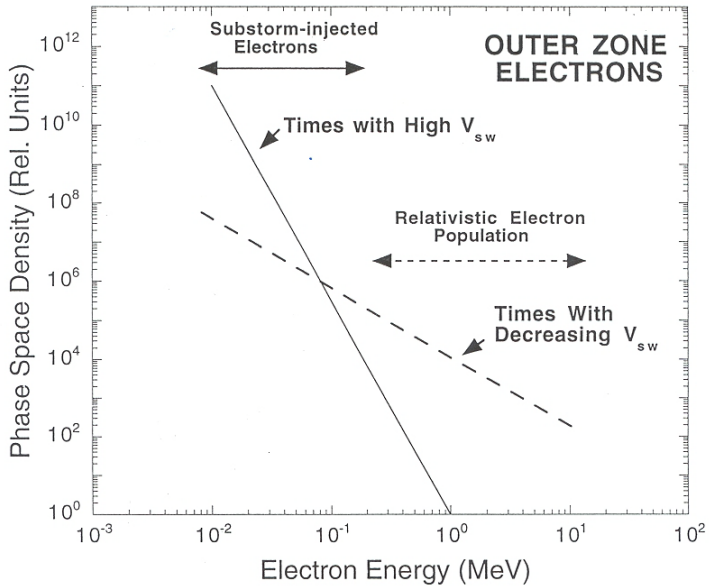
Kanekal et al. (JGR, 2001)

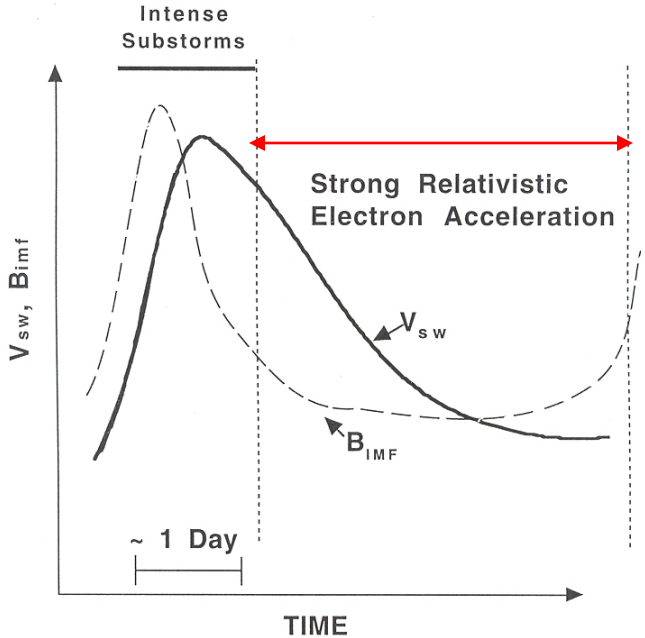


May 1997 Magnetic Cloud Event

* Powerful relativistic electron acceleration

* Deep penetration into outer radiation belt

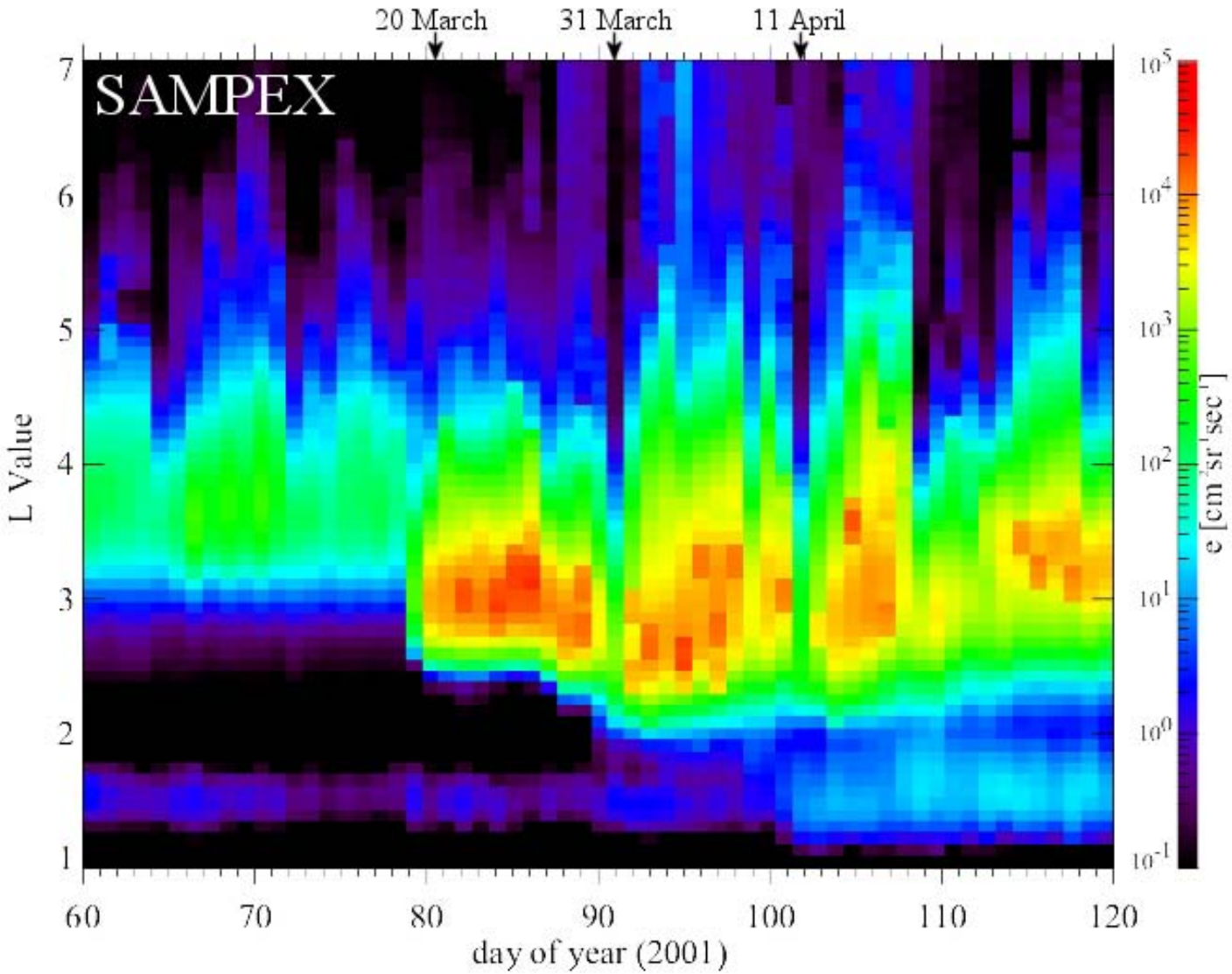


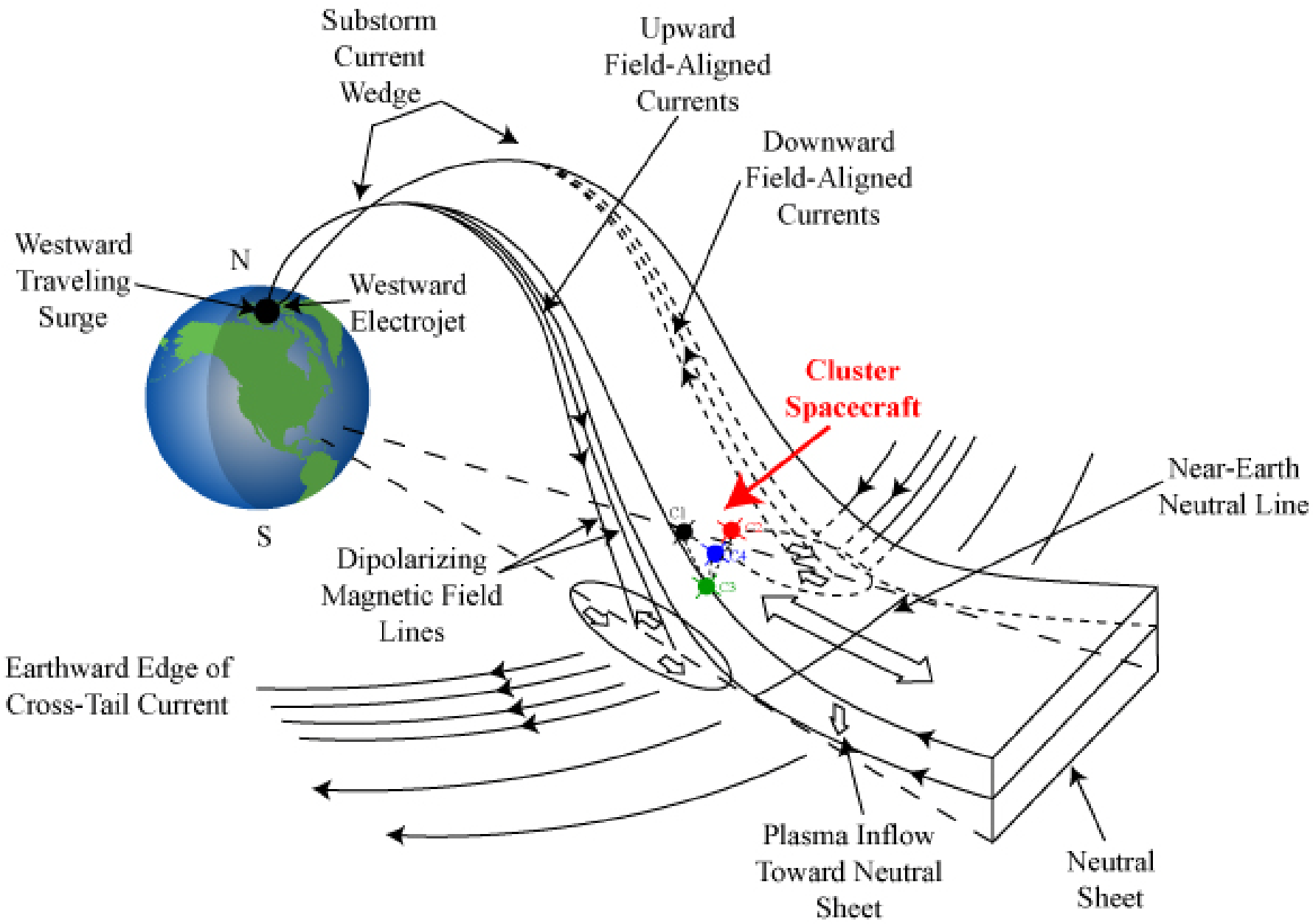


The Role of Substorms Even in Nonrecurrent Storms…

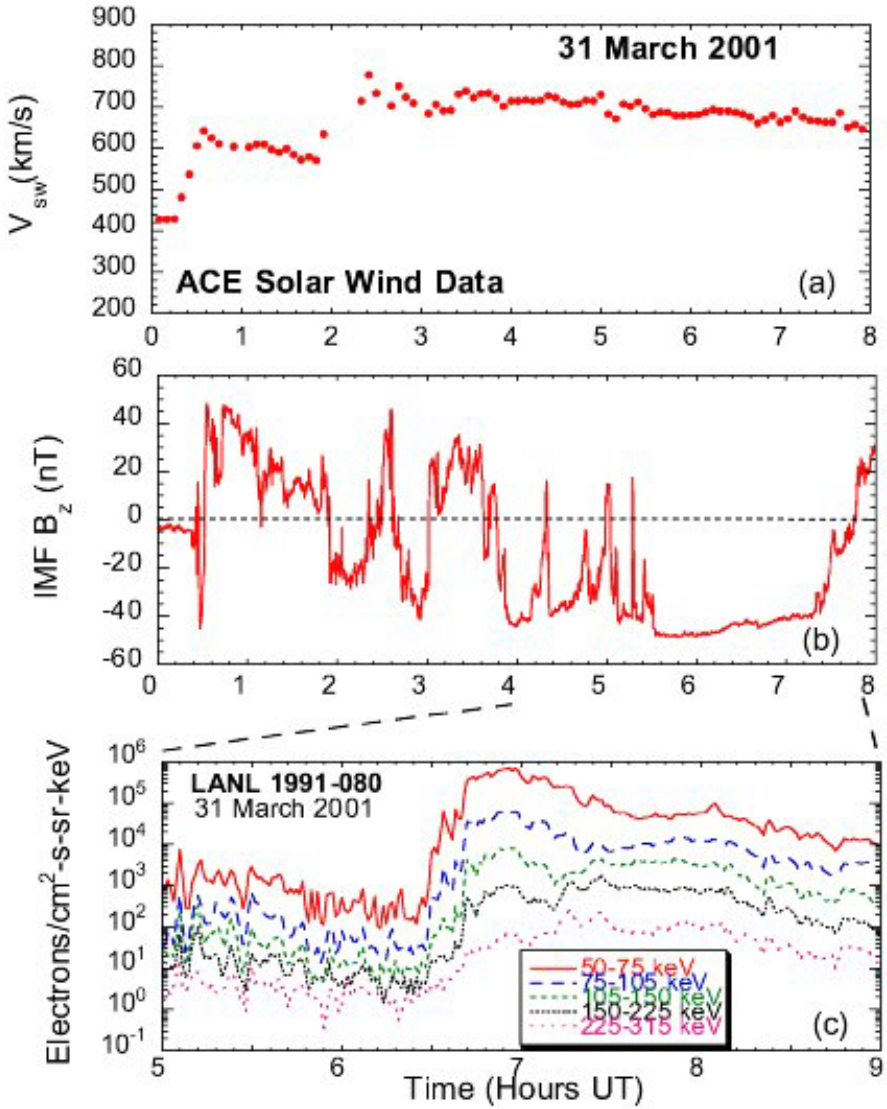
- Prompt substorm acceleration of electrons < 300 keV
- Delayed relativistic electron acceleration (2-3 days)

SAMPEX Radiation Belt Electrons: 2-6 MeV




Substorm
Current
Wedge
Upward
Field-Aligned
Currents
Downward
Field-Aligned
Currents
Westward
Traveling
Surge
N
Westward
Electrojet
Cluster
Spacecraft
Near-Earth
Neutral Line
S
Dipolarizing
Magnetic Field
Lines
Earthward Edge of
Cross-Tail Current
Plasma Inflow
Toward Neutral
Sheet
Neutral
Sheet

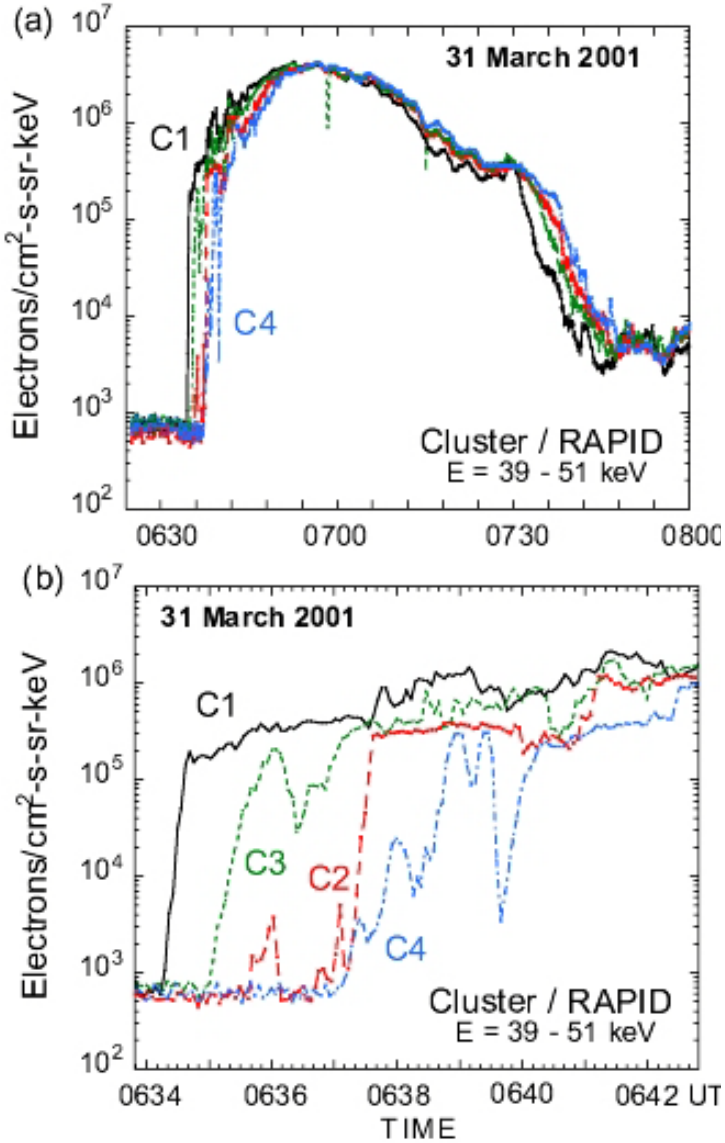
LANL Geosynchronous Orbit Data

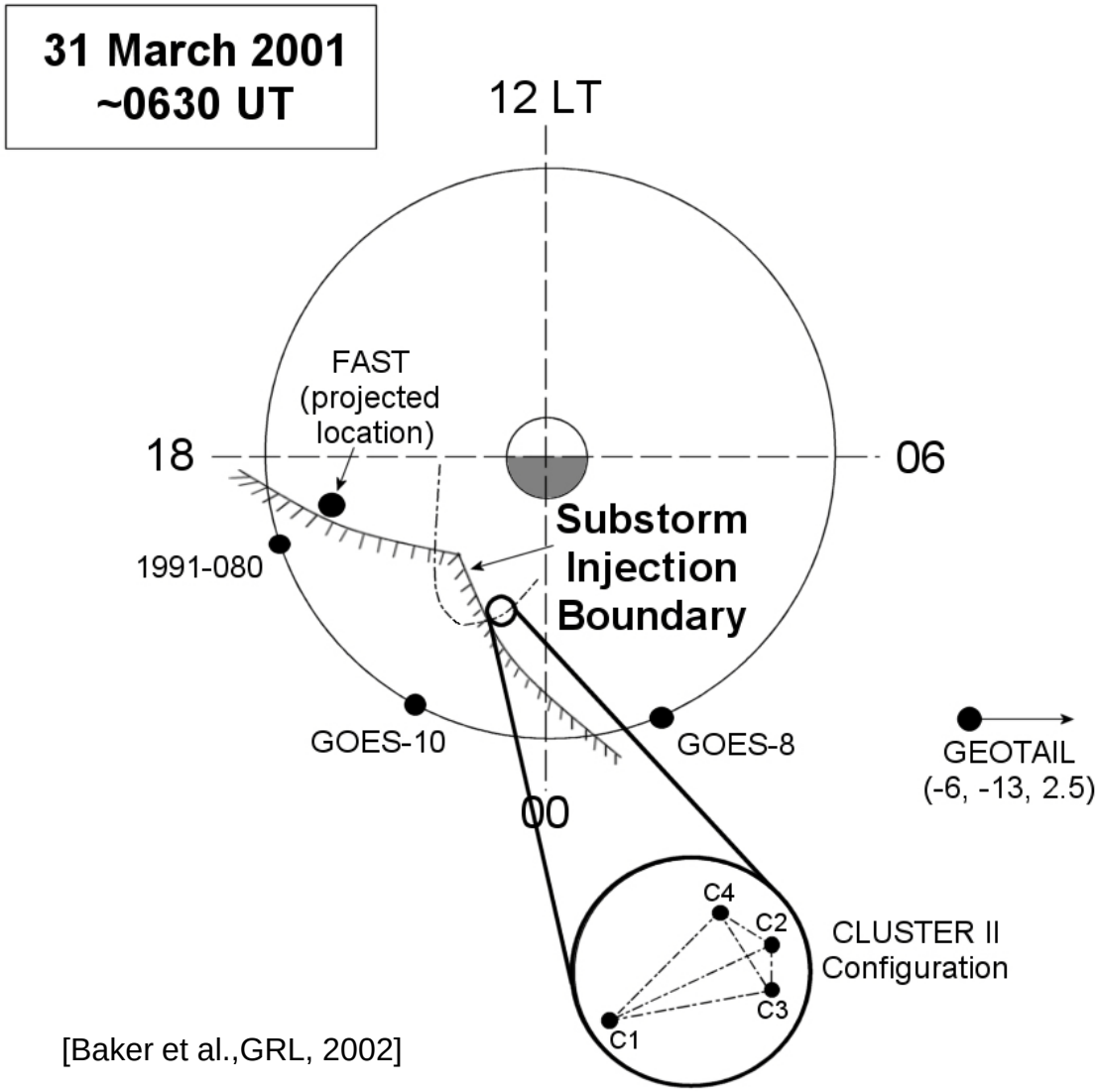


ACE solar wind data (magnetospheric drivers)

Los Alamos National Laboratory particle measurements at GEO

Near-Earth Substorm Injection

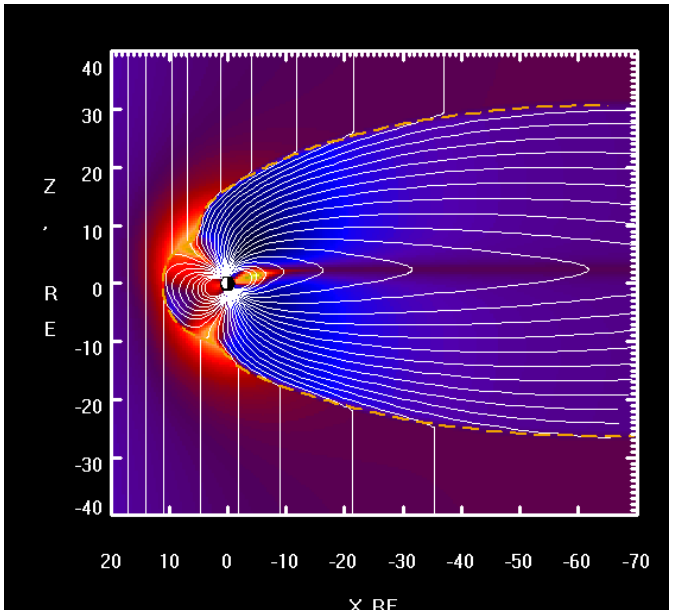




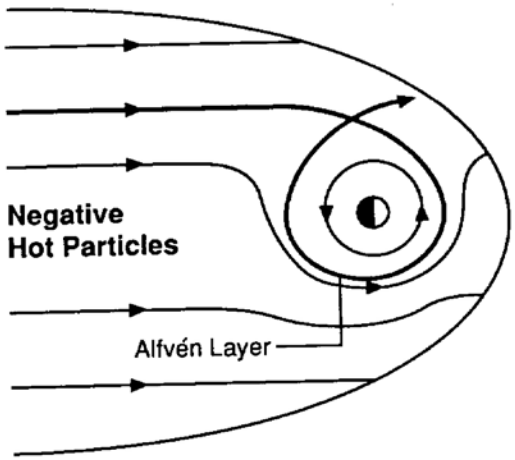
[Baker et al.,GRL, 2002]

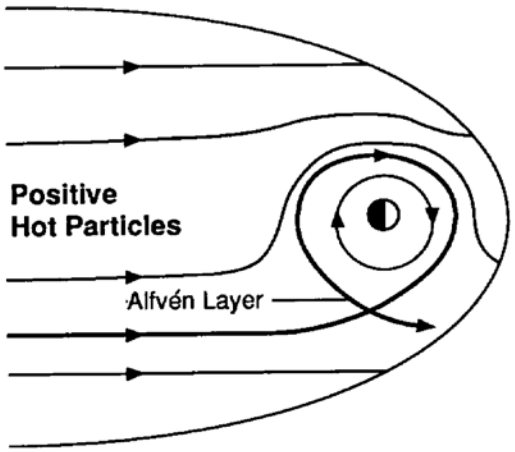
Boundary Conditions: The Plasma Sheet as an Outer Boundary Source?

- keV electrons in the plasmasheet convect inward: *W* increases → more grad-*B* drift
- Alfven layer marks boundary between open and closed trajectories; r_0 increases with *M*, decreases with convection *E*
- Investigate whether and when plasma sheet electrons may act as a source of MeV radiation belt particles



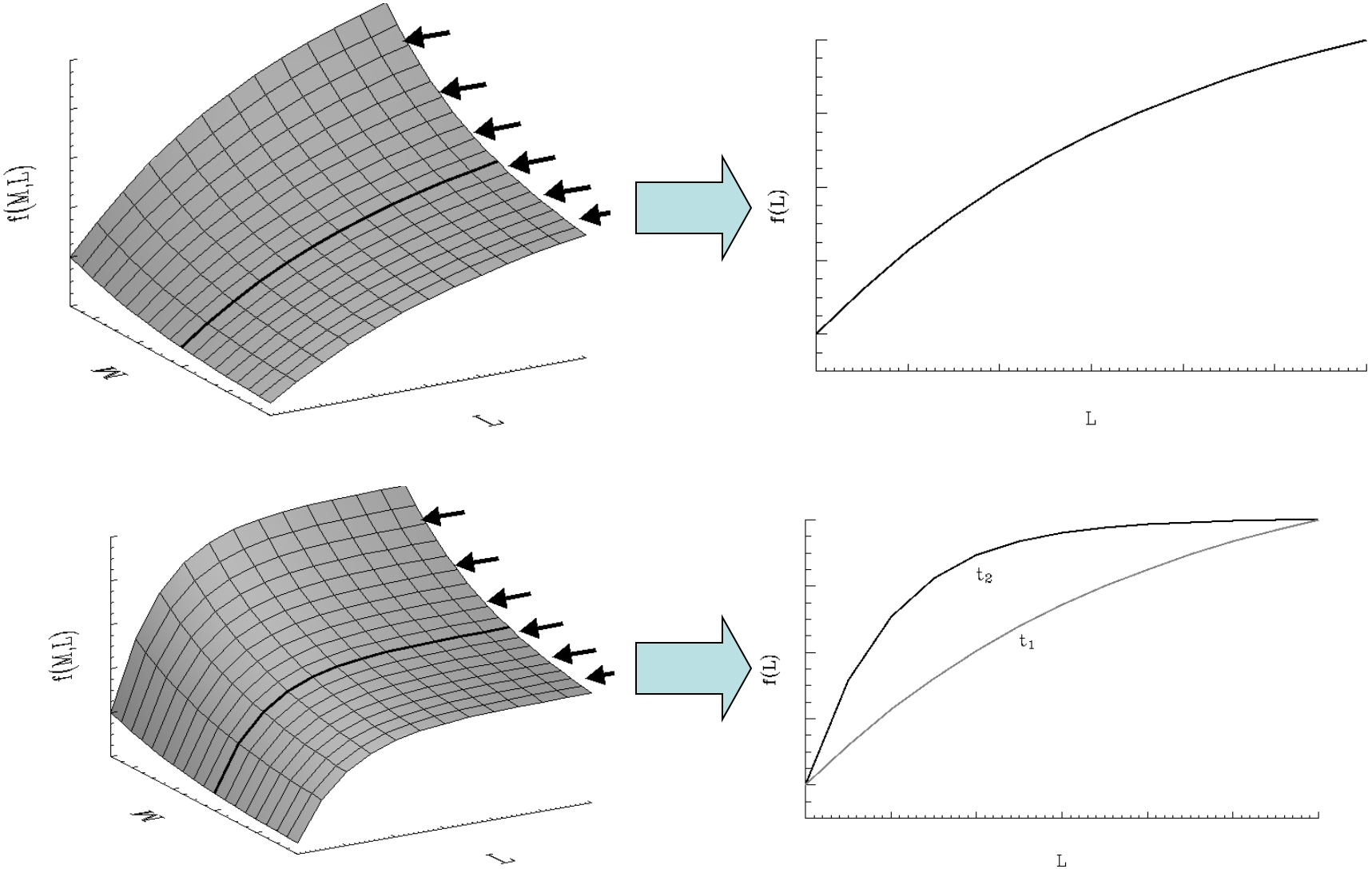
N. Tsyganenko
http://nssdc.gsfc.nasa.gov/space/model/magnetos/data-based/modeling.html



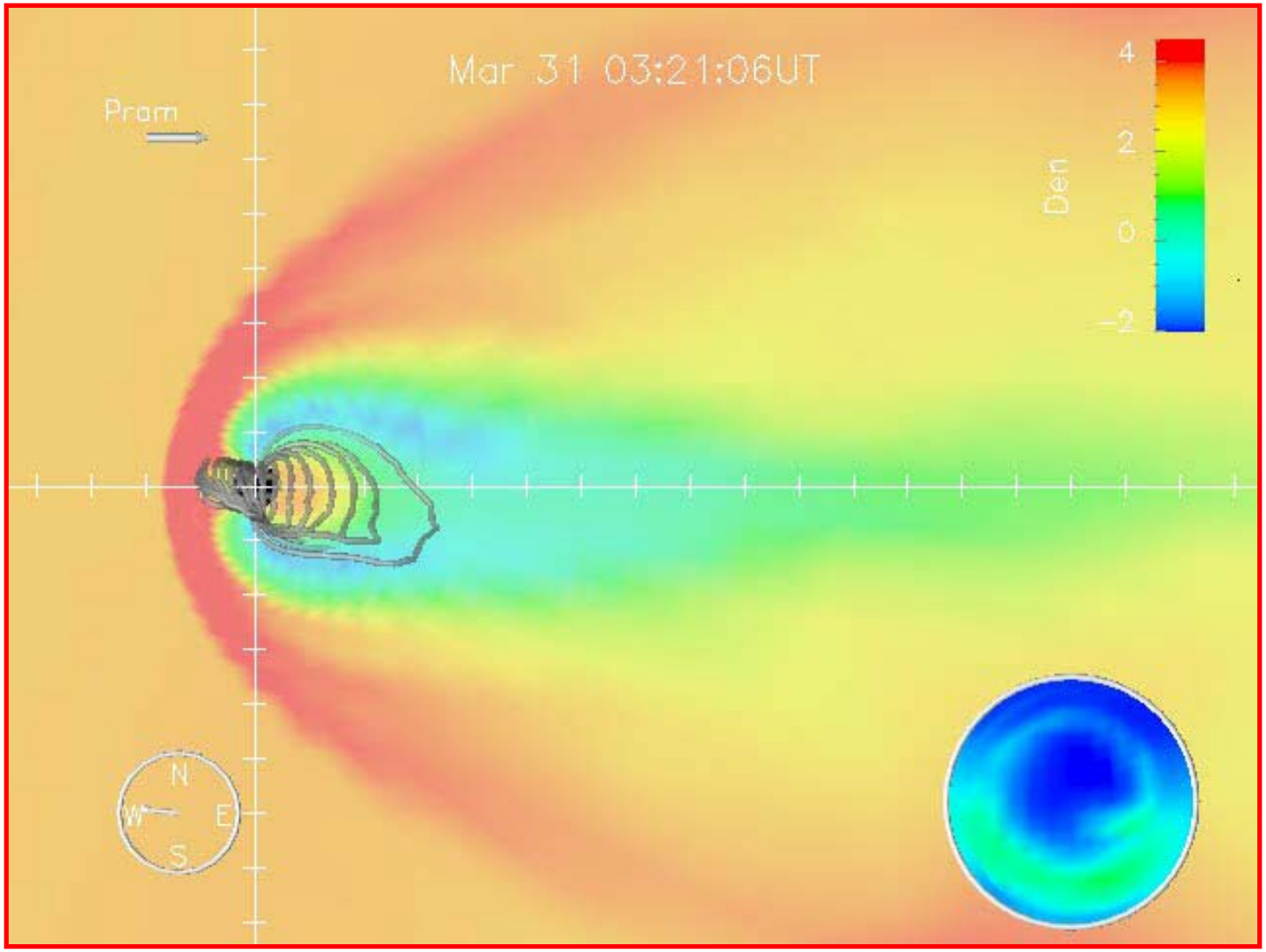


Elkington et al. (JASTP, 2004)

Transport in *L*: Radial Transport



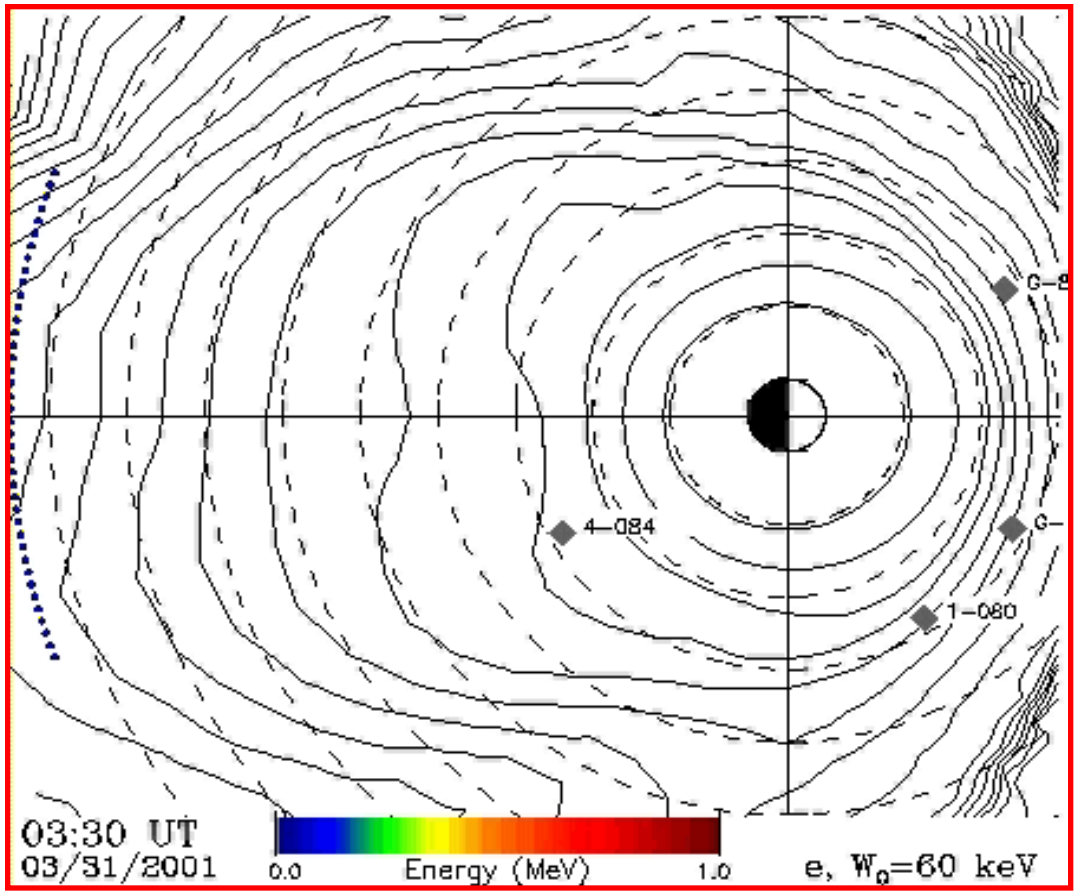
MHD Simulation of a Strong Storm



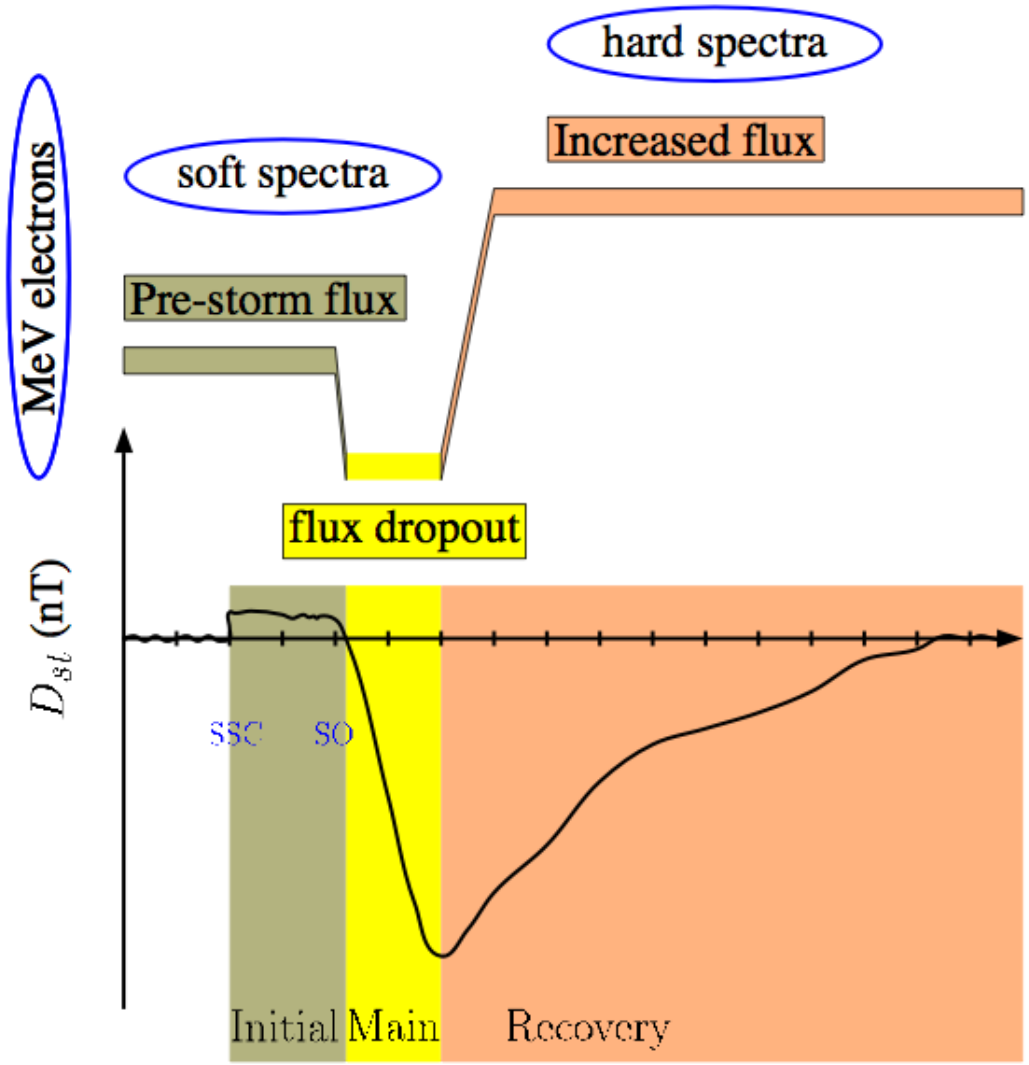
[Courtesy M. Wiltberger]

MHD/Particle Simulations of Energetic Electron Trapping

- 60 keV test electrons, constant *M*
- Started 20 R_E downtail, 15s intervals
- Evolves naturally under MHD *E* and *B* fields
- Removed from simulation at magnetopause
- Color coded by energy

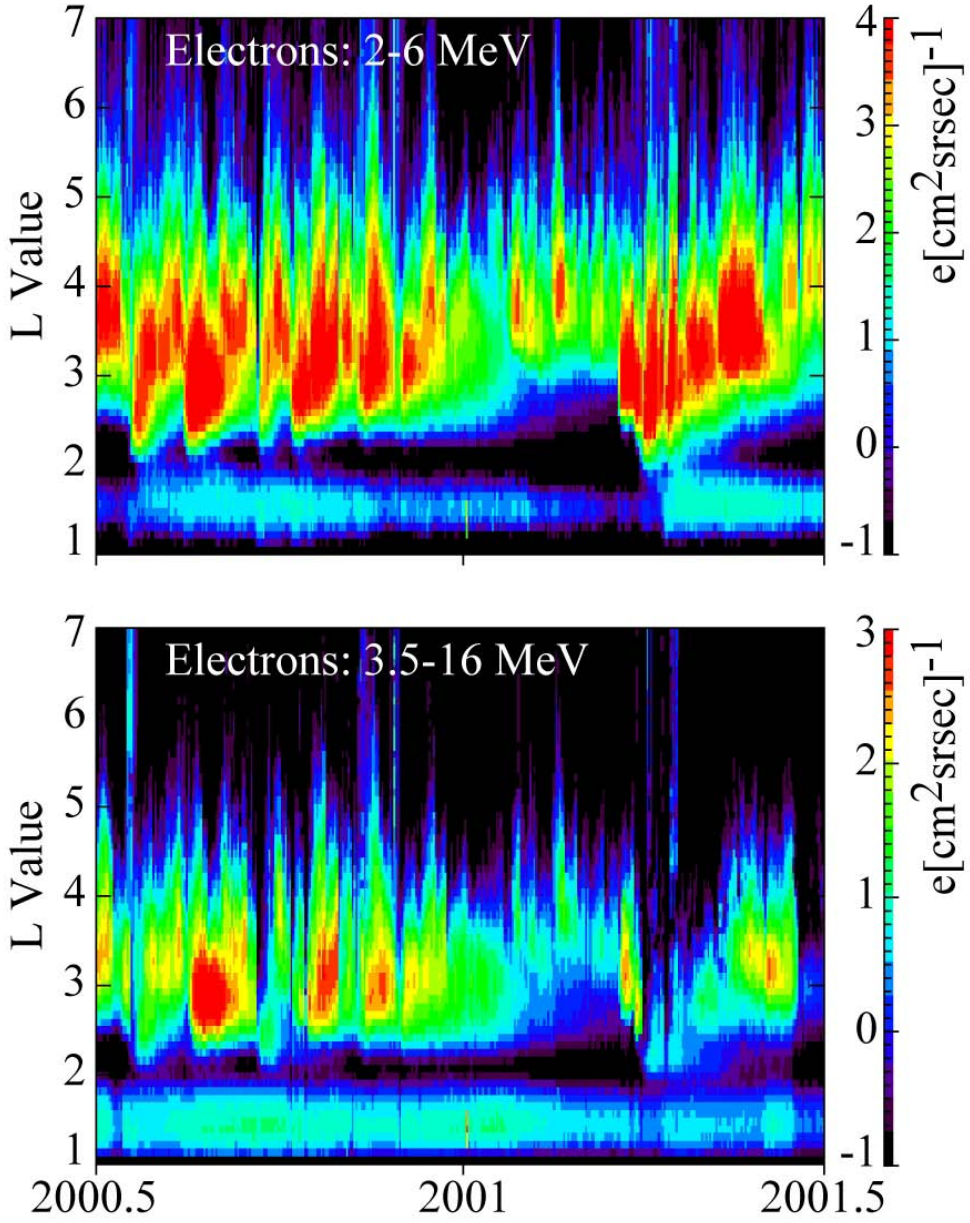


Relativistic Electrons & Geomagnetic Storms



[See Kanekal et al., 2004; Reeves et al., 2003]

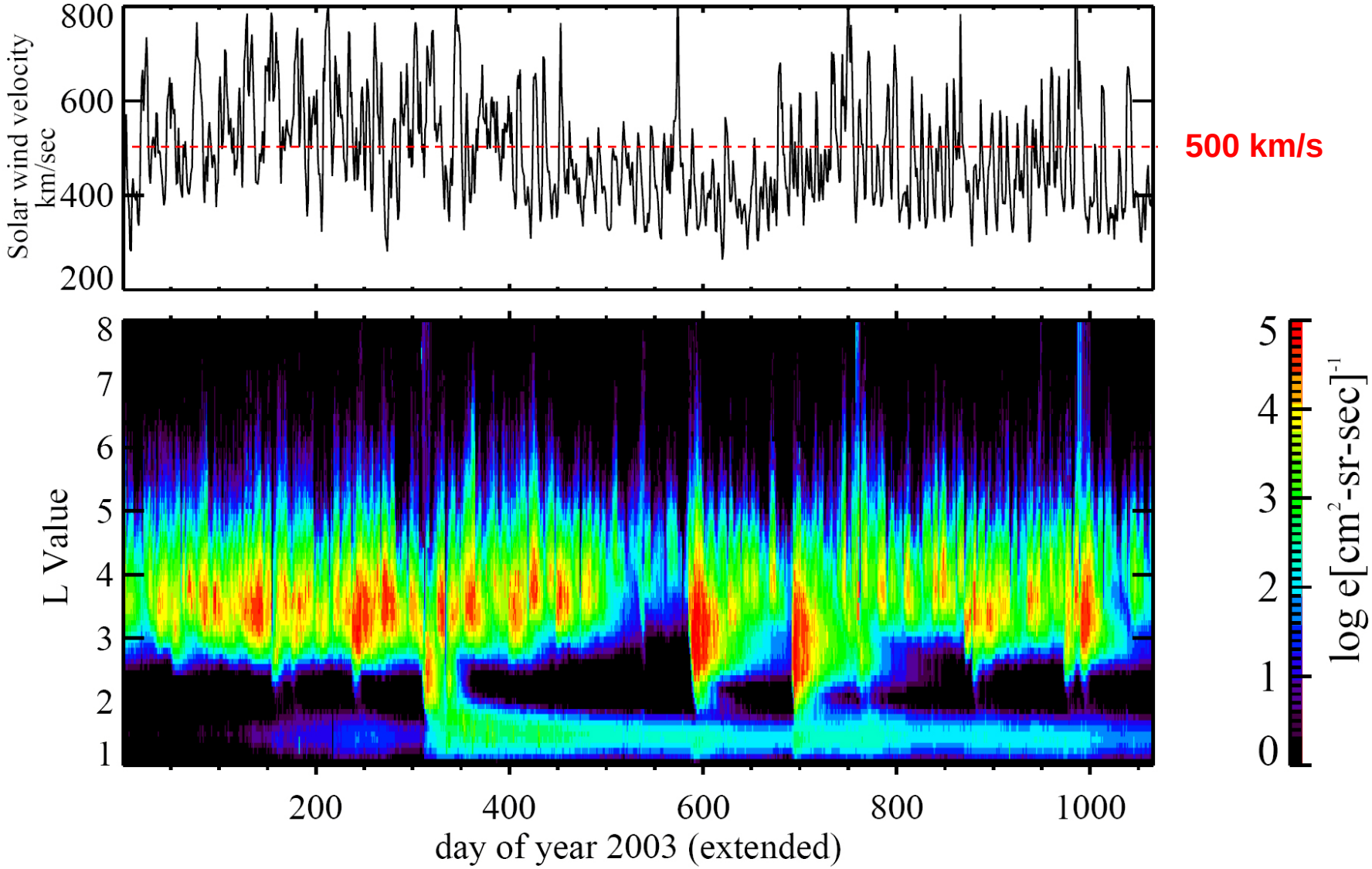
- Recovery phase
  - Increased fluxes
  - Energization
- Main phase
  - Flux dropout
  - Adiabatic field change & particle loss
- Flux changes
  - Decrease or no change in about 50% of storms - GEO data



Acceleration events:

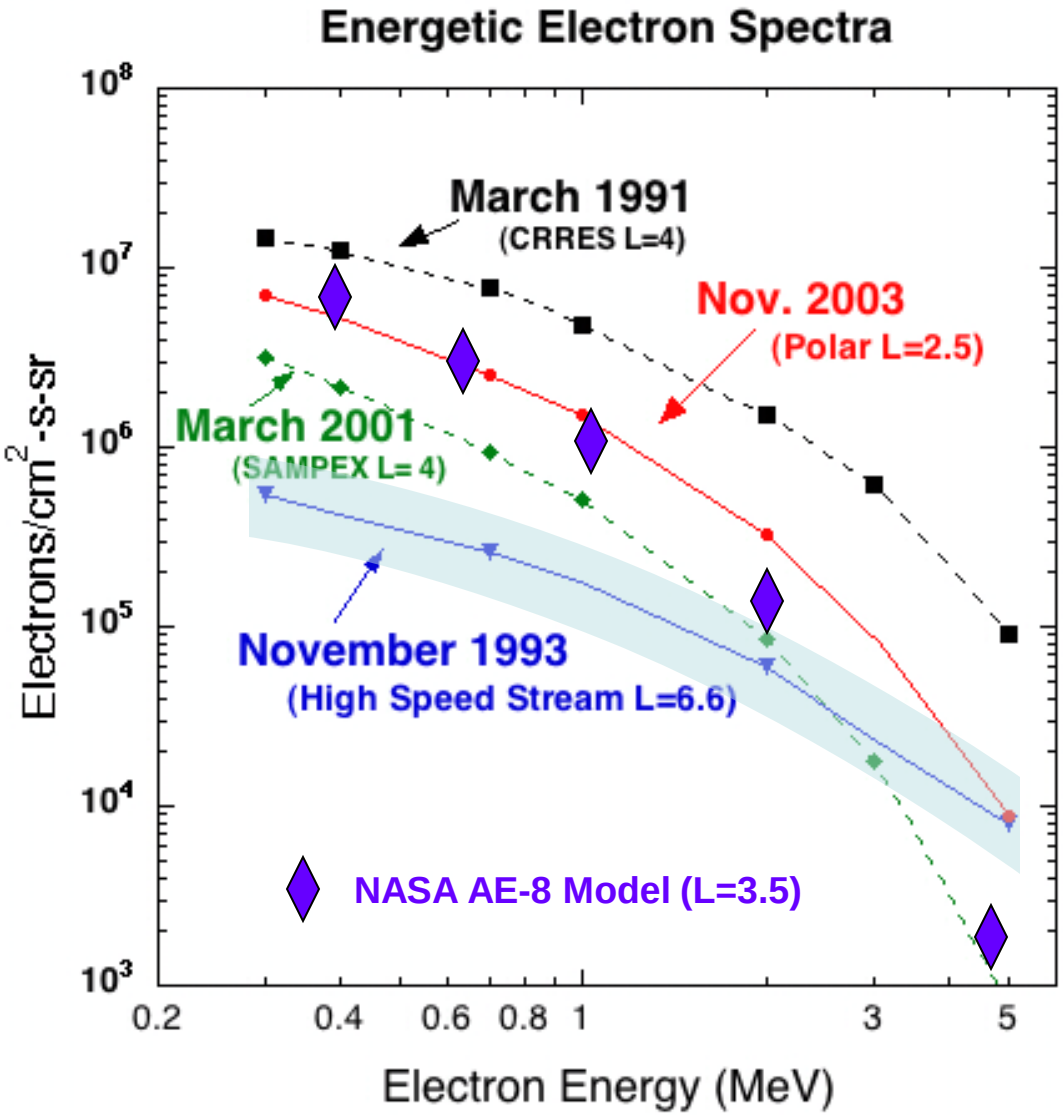
- Some spectrally "hard" episodes
- Some very "soft" intervals--Why?

Creation of New Radiation Belt

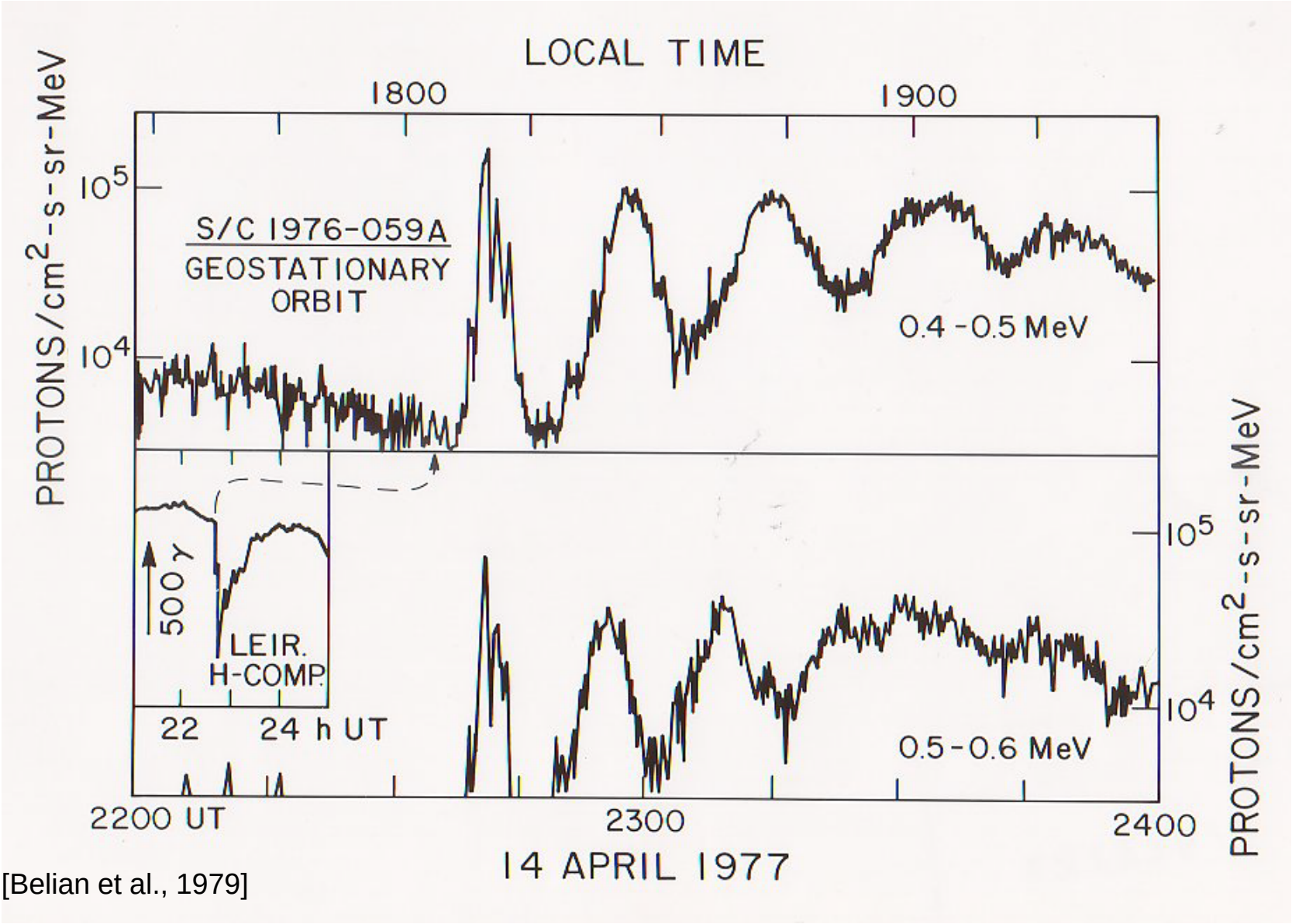


[Baker et al., 2004, 2007]

Electron Acceleration to Highest Energies

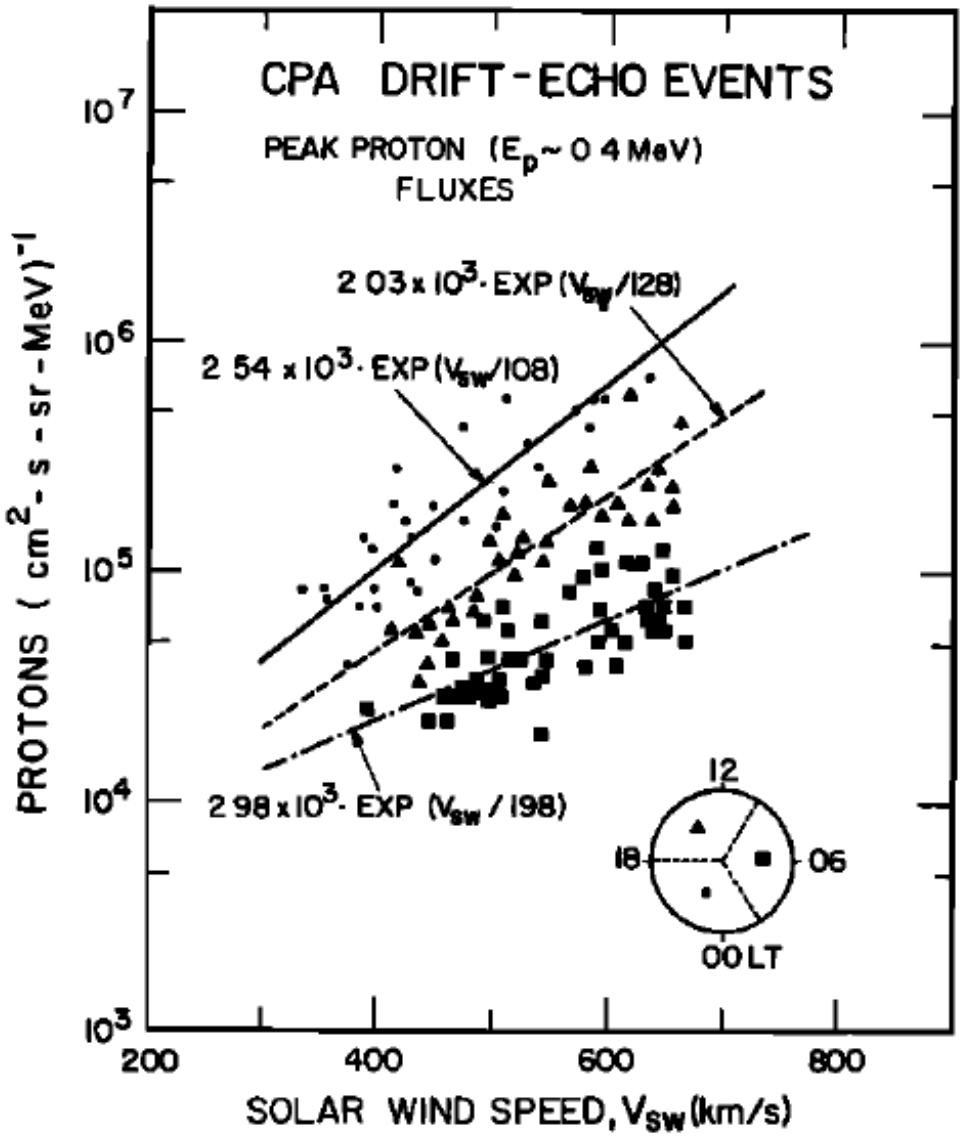


High-Energy Proton Drift Echoes



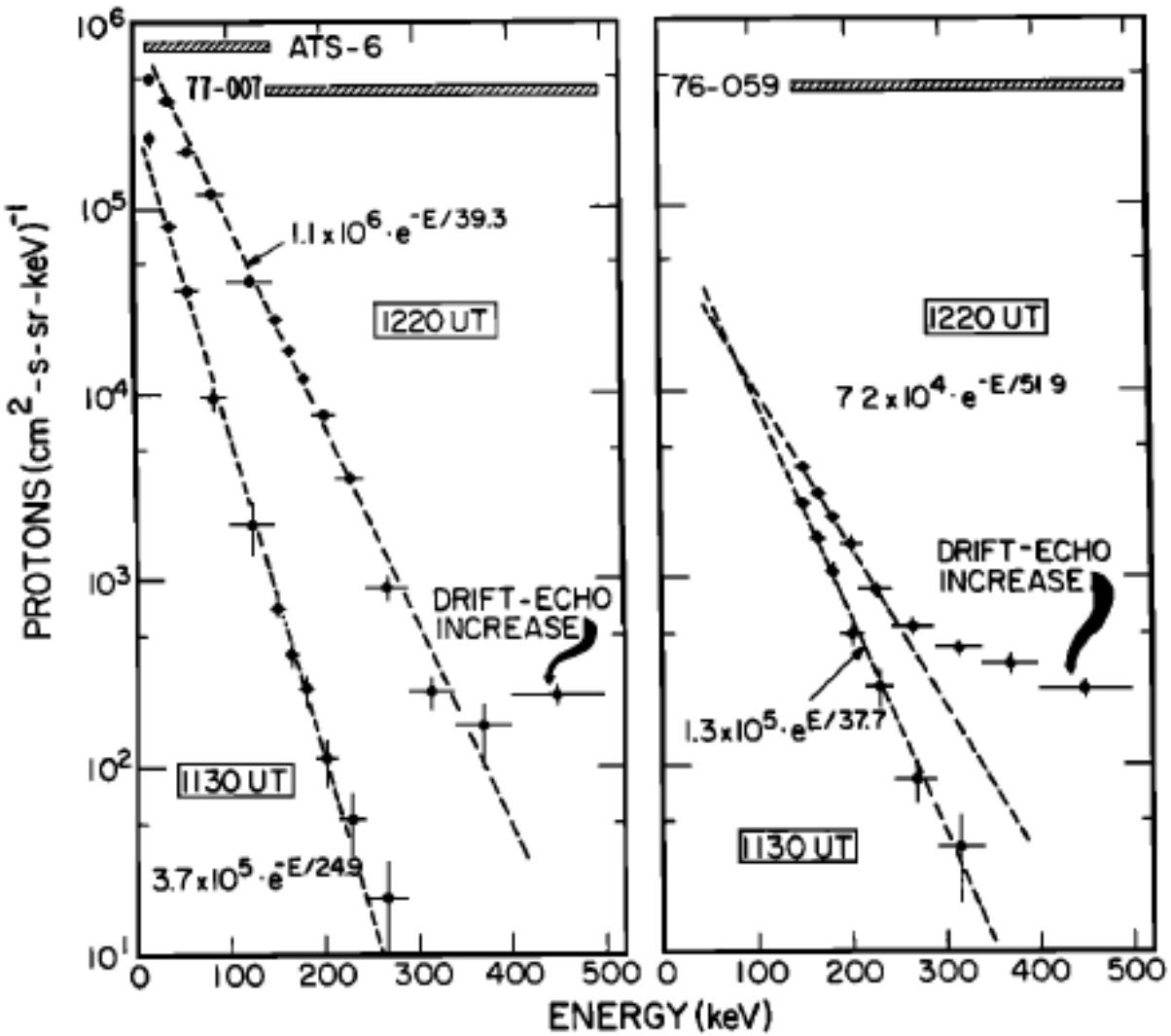
[Belian et al., 1979]

Solar Wind Control of Proton Fluxes



[Baker et al., 1979]

CDAW-2 Proton Spectra



[Baker et al., 1982]

CDAW-2 Proton PSD

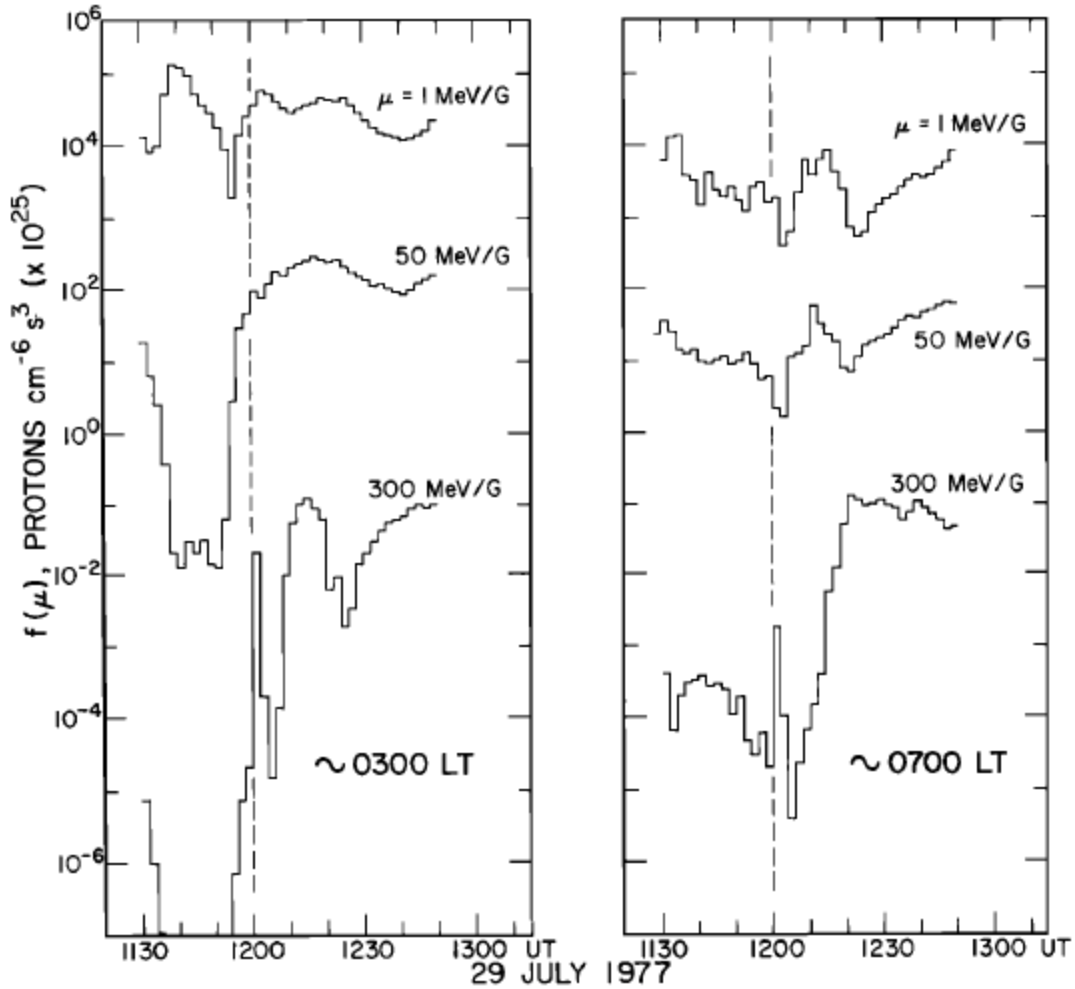


Fig. 13. Proton phase space density variations for the 1200 UT substorm period. Densities at constant first invariant values (μ, as labeled) are plotted.

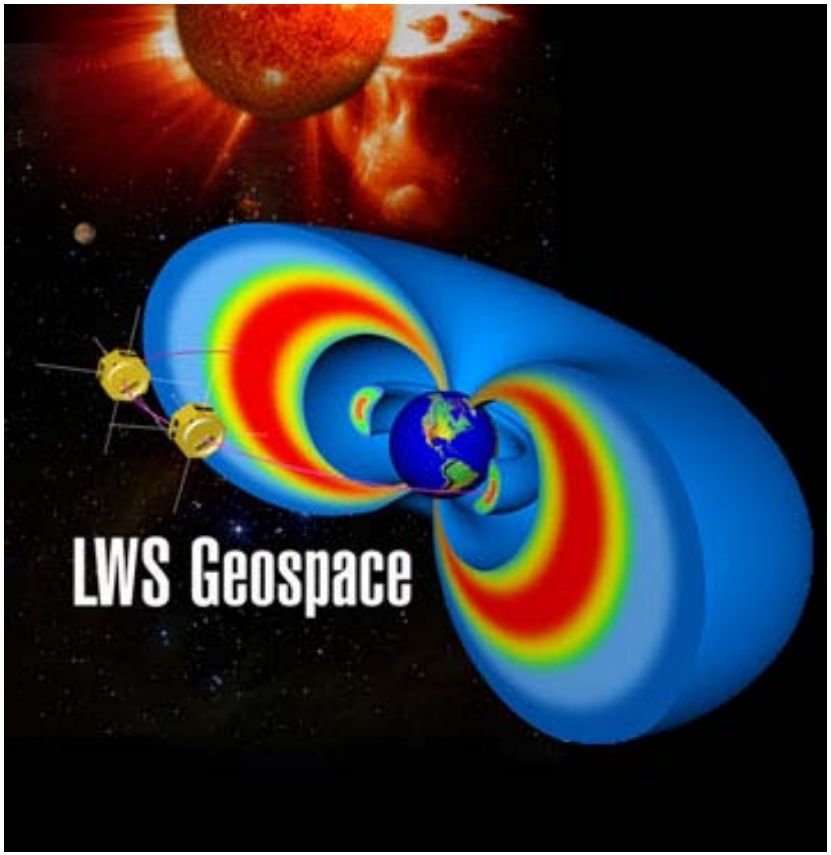
[Baker et al., 1982]

Summary and Conclusions

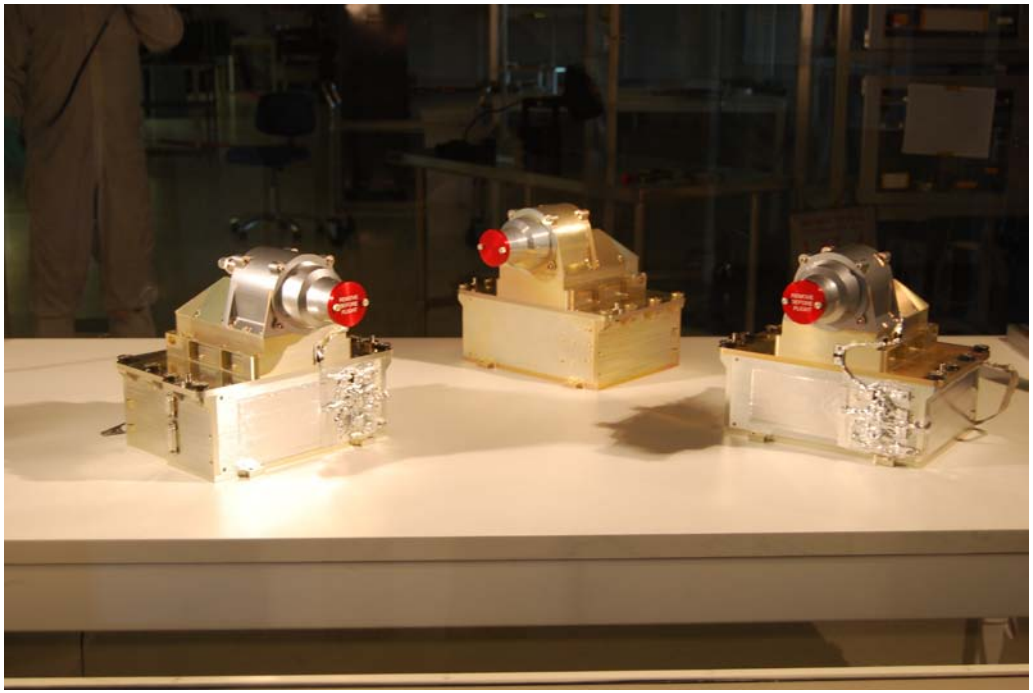
- Radiation belt acceleration and loss constitutes a significant branch in the solar wind-magnetosphere-atmosphere chain
- Acceleration is actively controlled by solar wind speed and related drivers (especially obvious for $V_{SW} > 500$ km/s)
- Radiation belt physical extent is closely correlated with Dst, pps boundary, etc.
- **Substorms play a central role by providing the "seed" population of 30-300 keV electrons**
- Radiation belt enhancements arise from and grow out of substorm injection events in ways that RBSP can study in great detail

Thanks-Questions?

The Radiation Belt Storm Probes (RBSP) program



REPT Flight Units (Right/Left) and EM (Center)



Relativistic Electron-Proton Telescope (REPT): $1 < E_e < 20$ MeV ; $15 < E_p < 200$ MeV

REPT addresses key scientific and programmatic goals of the NASA RBSP (LWS) program.