Substorm Energetic Particle Injections and Radiation Belt Flux Enhancements

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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

[Image: A diagram illustrating geosynchronous orbit (GEO), low Earth orbit (LEO), medium Earth orbit (MEO), and high Earth orbit (HEO) in the context of Earth's orbit and atmosphere.]
Early GEO Studies of Substorms

The Substorm Current Wedge

Expansion Phase Short Circuit of Tail Current

Electrojet

Field aligned currents

Tail current

McPherron et al., 1973
GEO Substorm Observations - Next

Charged Particle Analyzer - LANL

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

[Baker et al., 1979]

Fig. 1b. Illustration showing the main features of the CPA high-energy proton telescope on spacecraft 1976-059A.
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 $E \sim 30$ keV to $E \sim 300$ 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

* Prompt low-energy electron acceleration

* Delayed relativistic electron production

The Role of High-Speed Solar Wind Streams

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

[Baker et al., 1986]

Electron Flux and Riometer Comparisons

[Baker et al., GRL, 1979]
Pitch Angle Evolution
Flux and Riometer Comparison
Peak Fluxes vs. Riometer Intensity

[Graph showing the relationship between peak fluxes and riometer intensity, with a note on the K-P "Limit" and observed limit.

[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

[ACCELERATION REGION: 0.5-2.0 MILLION VOLT INDUCED $\vec{E}$ (EXPLOSIVE RECONNECTION ?) LASTING < 1 MINUTE]

[Baker et al., 1979;1981]
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]
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

~ 0300 LT GROUPING

77-007/ATS-6

7.6 x 10^6 \cdot e^{-E}/25.8

1204 UT

~ 0700 LT GROUPING

76-059/GOES

1.3 x 10^6 \cdot e^{-E}/44.1

1220 UT

Electrons (cm^2 \cdot s \cdot sr \cdot keV)^{-1}

0 200 400 keV

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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

PHASE SPACE DENSITY

$\text{ELECTRONS cm}^{-6} \text{s}^{-3} \times 10^{30}$

$\mu = 1 \text{ MeV/G}$

$\mu = 10$

$\mu = 100$

$\sim 0300 \text{ LT}$

1200 1300 UT

[Baker et al., 1982]
Substorm Injection Model

ACCELERATION REGION:
0.5-2.0 MILLION VOLT
INDUCED E
(EXPLOSIVE RECONNECTION ?)
LASTING < 1 MINUTE

Substorm Expansion

[Baker et al., 1979;1981]
Spectrometer for Energetic Electrons (SEE)

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.

[Baker et al., 1986]
SEE Results: 1979-1984

[Baker et al., 1986]
Observing the Radiation Belts

Key Platforms

**SAMPEX**
- LEO orbit \( \approx 600 \text{ km} \)

**POLAR**
- Elliptical 2x9 \( R_E \) Orbit

**GEO**
- Geostationary Earth Orbit – 6.6 \( R_E \)
White arrows indicate 27-day recurrent events: High-speed solar wind streams

1994 – High Speed Stream Control

Strong electron acceleration in the approach to sunspot minimum

SAMPEX: electrons; 2.0 - 6.0 MeV
Electron Flux Scaled to the Maximum Amplitude

[Presicci et al., 2011]
MeV Electrons & Geomagnetic Storms

- 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

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

[Baker et al., 1998]
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
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 $\rightarrow$ 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

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

- 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

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

Energetic Electron Spectra

- March 1991 (CRRES L=4)
- March 2001 (SAMPEX L=4)
- November 1993 (High Speed Stream L=6.6)
- November 2003 (Polar L=2.5)
- NASA AE-8 Model (L=3.5)

Electron Energy (MeV) vs. Electron Count/cm² - s-sr
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>]

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Fig. 13. Proton phase space density variations for the 1200 UT substorm period. Densities at constant first invariant values ($\mu$, 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?
Relativistic Electron-Proton Telescope (REPT): $1 < E_e < 20 \text{ MeV} \; ; \; 15 < E_p < 200 \text{ MeV}$

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