Acceleration and Precipitation of Relativistic Electrons

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Observations and Questions

Electron Precipitation observed to relativistic energies (>1 MeV).

- What do we know about these electrons?
- What mechanisms precipitate relativistic electrons?
- What is the relationship of precipitation and acceleration?

These questions are of importance to Space Weather and RBSP.

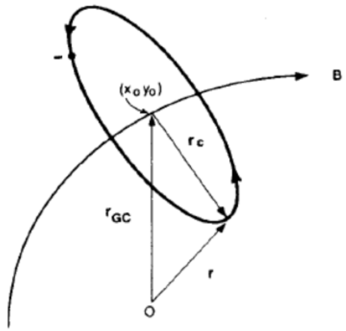
Organization:

1. Introduction
2. Microburst precipitation on the dayside
3. Relativistic precipitation on the dusk side
4. Future Measurements about relativistic precipitation

Time Scales of Electrons at L=4-6

Cyclotron period

T_c~10^{-3} s

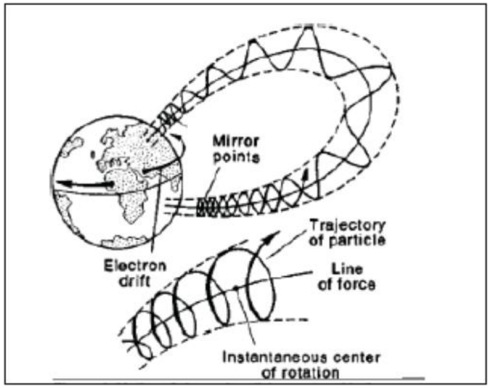


Bounce period

40 keV, T_B ~1s

1 MeV, T_B ~0.04s

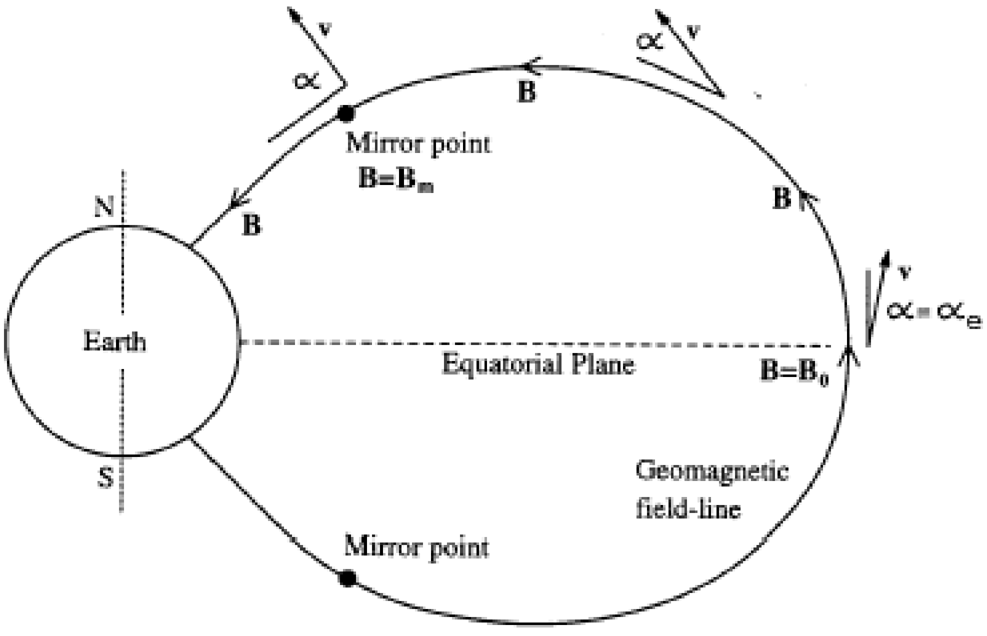
Drift period in dipole field (averaged over bounce)



40 keV, T_D ~ 2 hours

1 MeV, T_D ~5 minutes

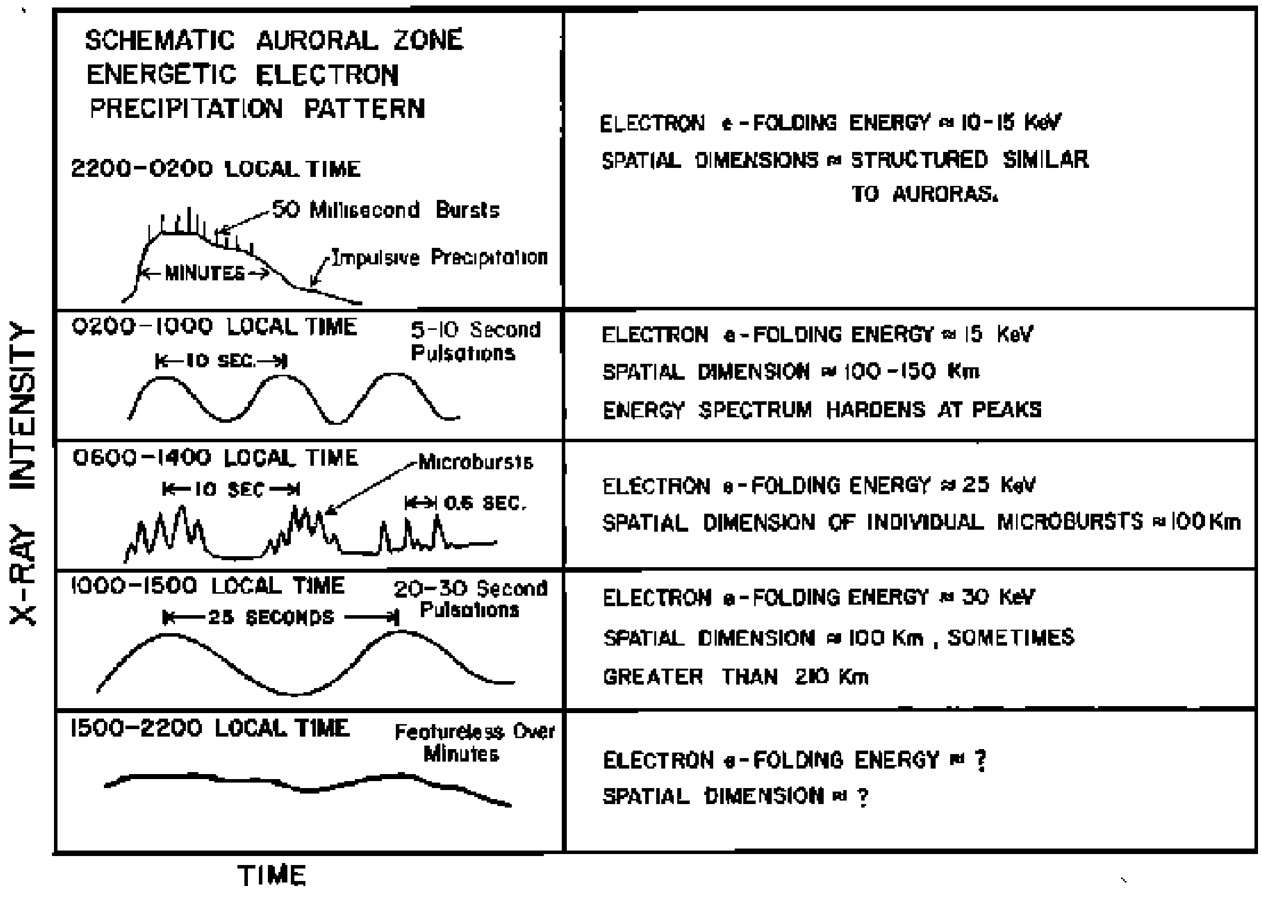
Loss cone and Precipitation



$$\frac{\sin^2 \alpha_1}{B_1} = \frac{\sin^2 \alpha_2}{B_2}$$

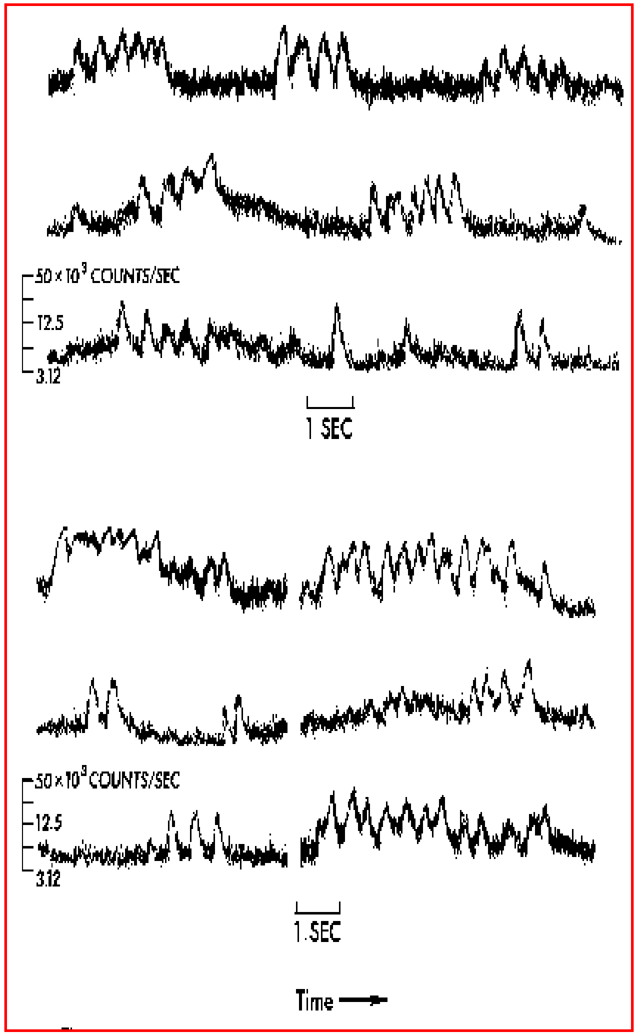
- For L=6 Equatorial loss cone ~3° (dipole geometry).
- Particles mirror at B_{90} =100 km are precipitated.
- Independent of mass, energy and charge.

Electron Temporal Forms vs Local Time



Parks et al., 1968

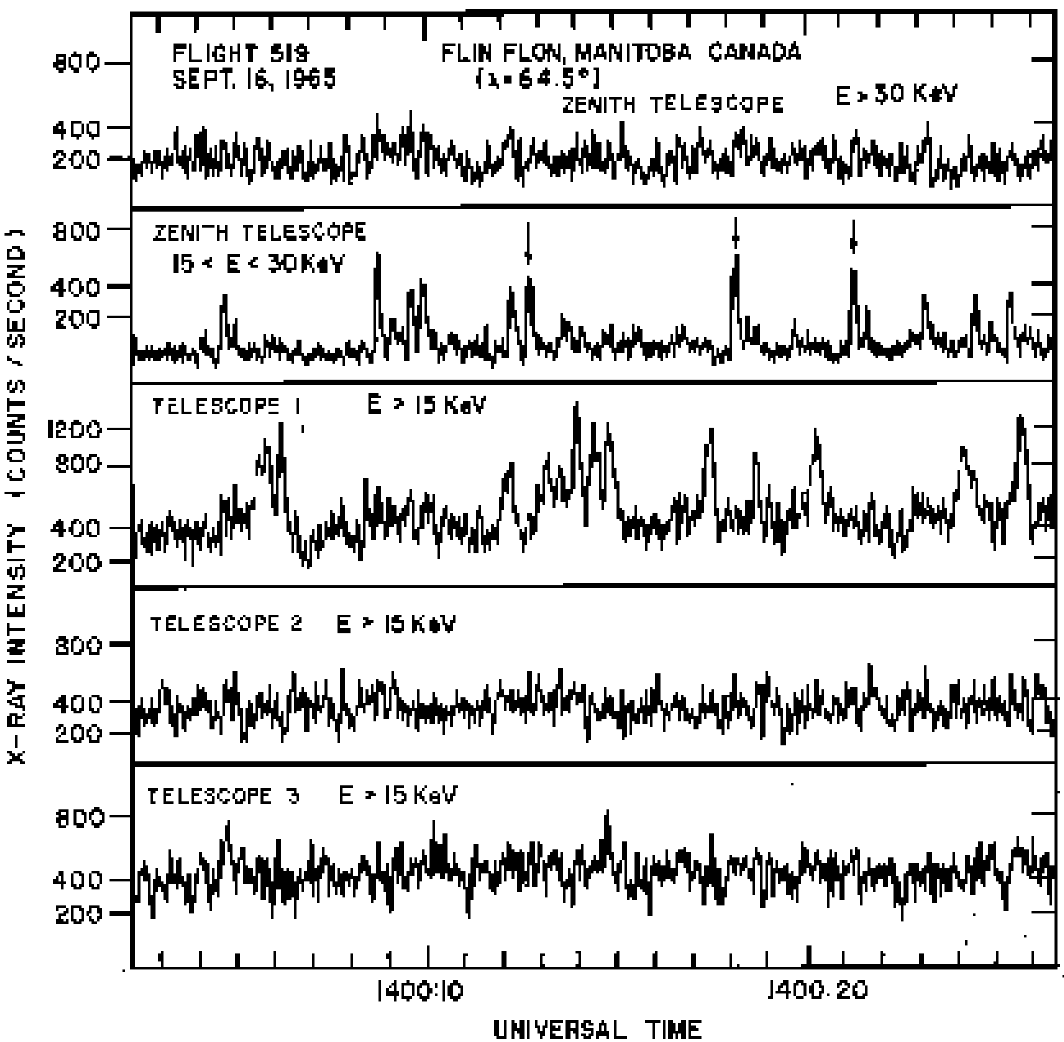
Microbursts

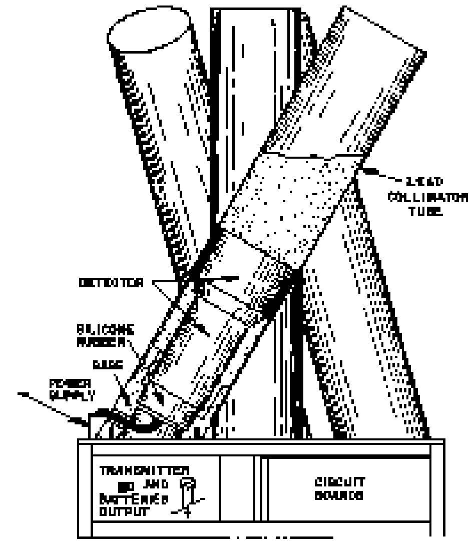


- X-rays, $h\nu > 20$ keV
- Impulsive, duration ~ 0.25s
- Single or Multiple
- Precipitation periodic, ~0.6 -1.2s

Anderson and Milton, 19
64

Microburst Size (at 100 km altitude)



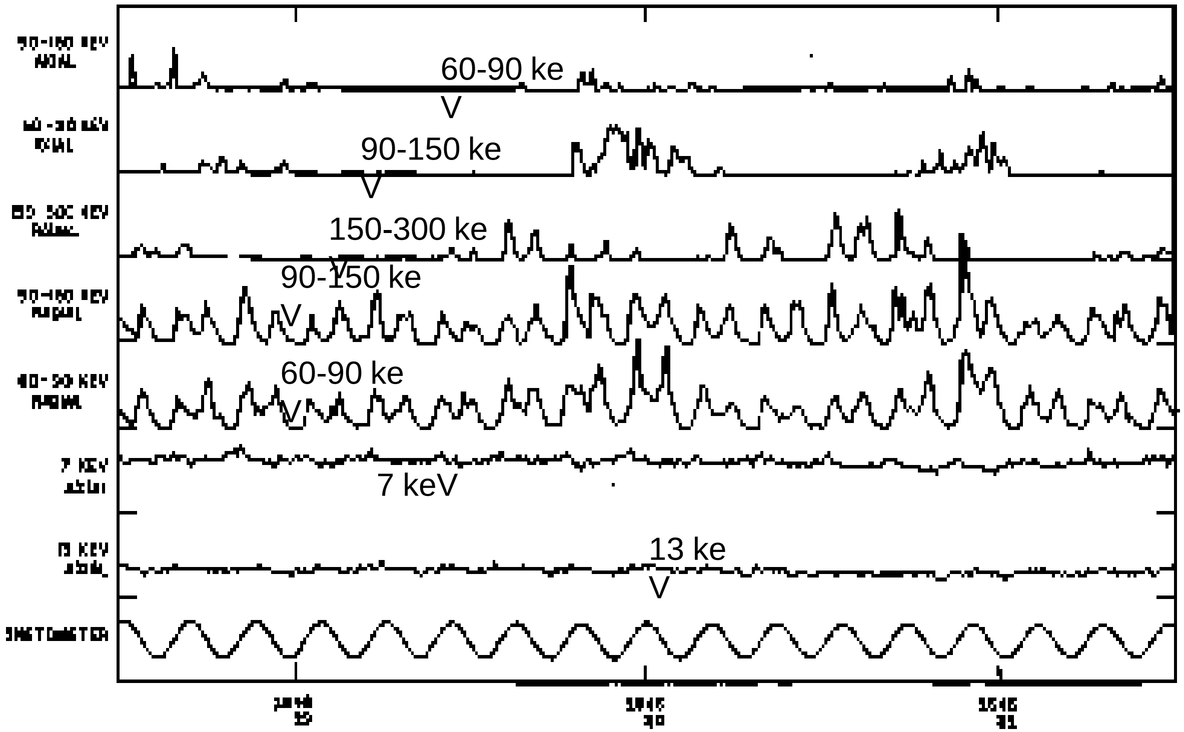


DIRECTIONAL DETECTOR
ASSEMBLY
1965

- Size as small as ~15 km.
- Average ~100 km
- Precipitation region thousands of km.

Parks, 1967

First Measurement of Microbursts on a Rocket



Axial

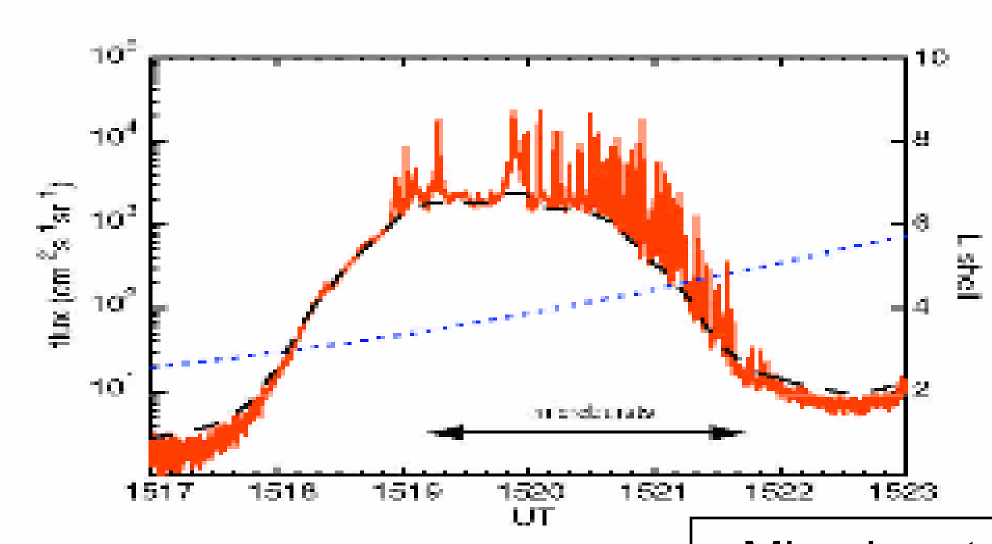
Radial

ESA

No Microbursts at 7 and 13 ke
V

Lampton, 1968

Relativistic Microbursts (>1 MeV)

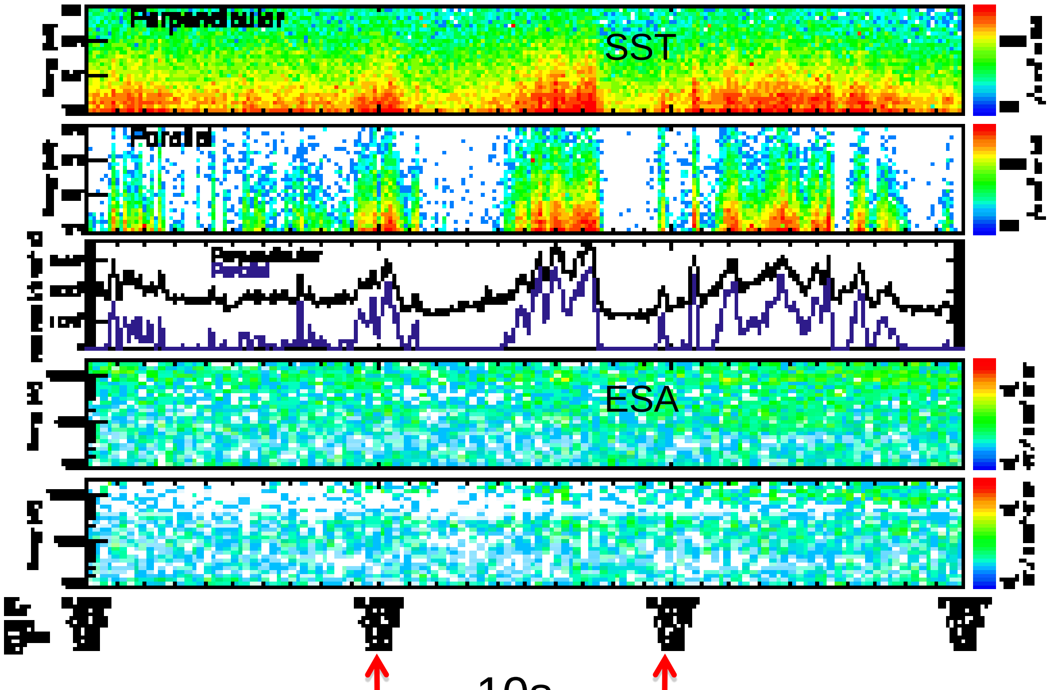


- Microbursts = Impulsive precipitation, < 1s.
- Imhof (1992) called “Relativistic Microbursts.”
- Extensively studied by SAMPEX

(Blake et al., 1996; Lorentzen et al., 2001)

Microbursts on First Korean Scientific Satellite

E ~ 170-360 keV

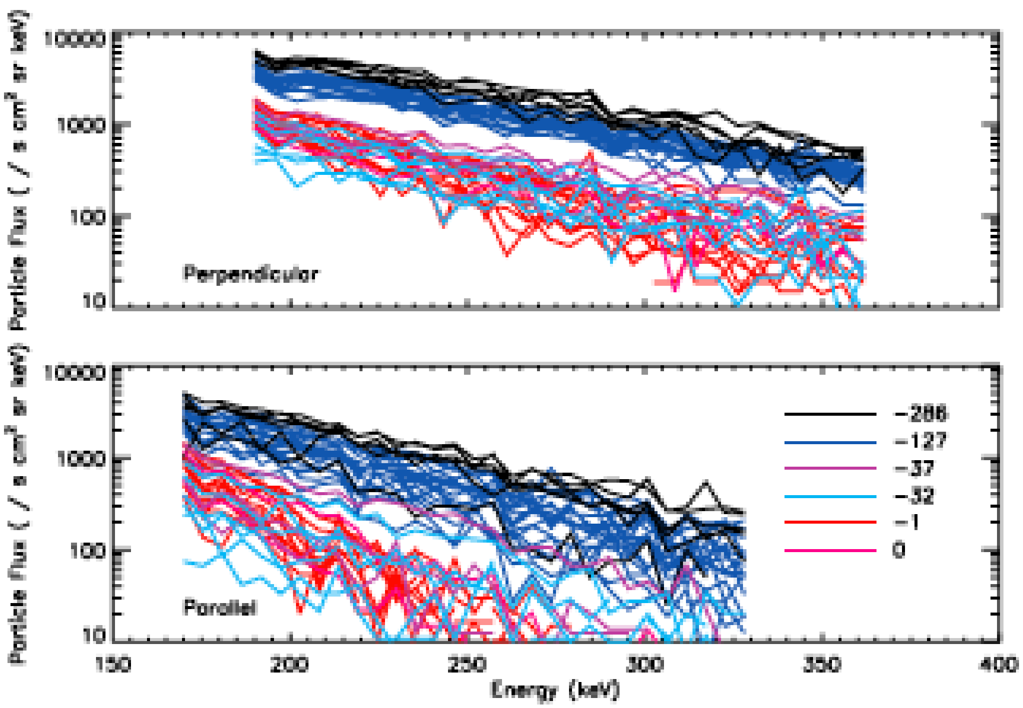


Lee et al., GRL, 200
5

- Loss cone 680 km ~60 o.
- Loss cone empty exce pt when microbursts precipitate
- Perp > Para fluxes by a
factor of ~2
- No microbursts: 100 e V – 20 keV
- 10 Nov2004, Kp = 5, D st -125

(Recovery of 8Nov stor m, Dst-286)

Energy Spectra of Microbursts

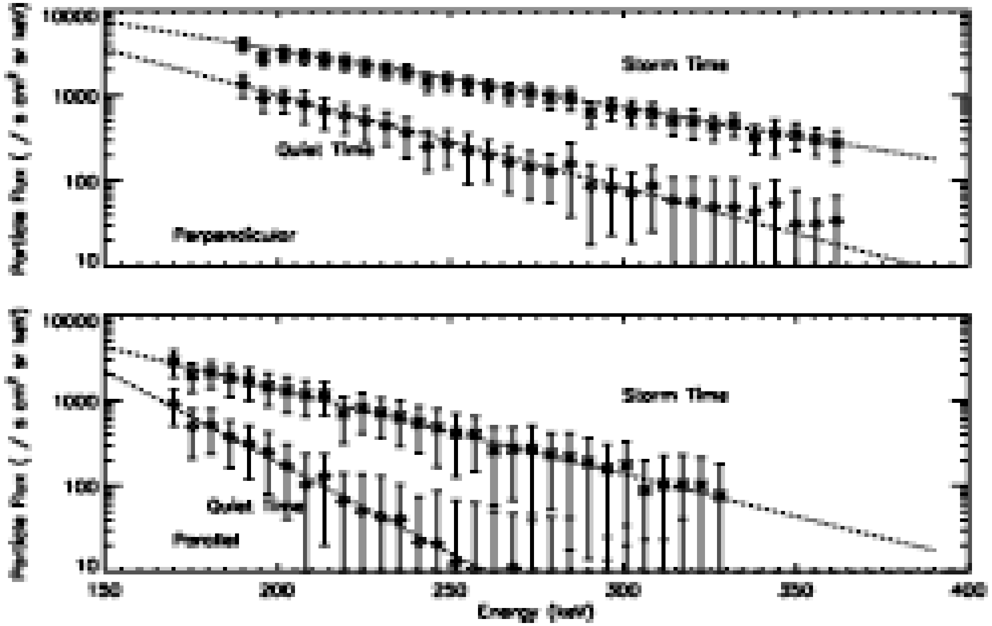


- Energy spectra of individual microbursts from 6 passes
- Organized by Dst (color)
- Measurements to ~350 keV
- 07-10 MLT
- L=3.5-6.9
- Dst = 0 - -286

dJ/dE = Aexp-(E/E_o

E_o ~20 – 77 keV

Average Energy Spectra of Microbursts

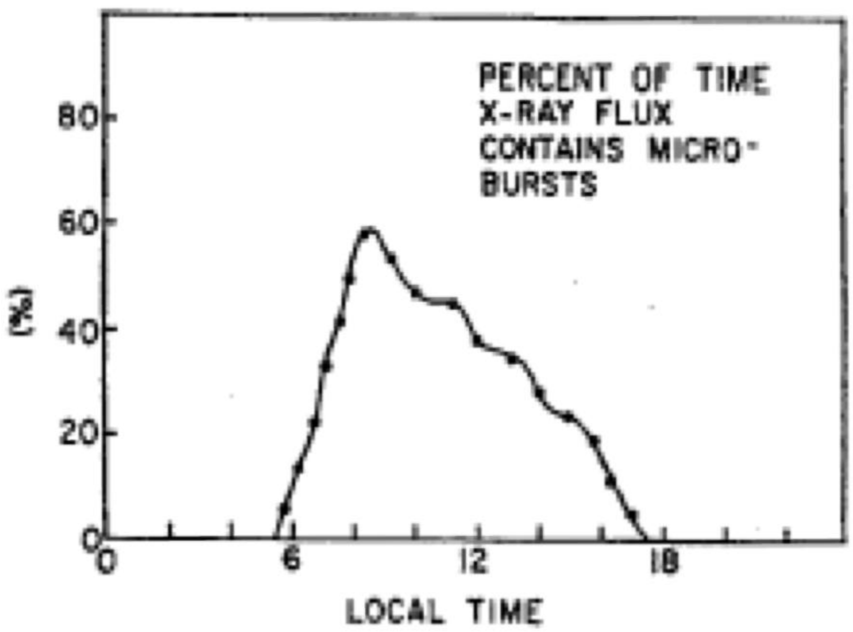


- E_o increased as Dst decreas ed
- Spectra harder during storms
- ~43 - 65 keV (perp)
- ~20 - 40 keV (para)

Requirements for producing Microburst

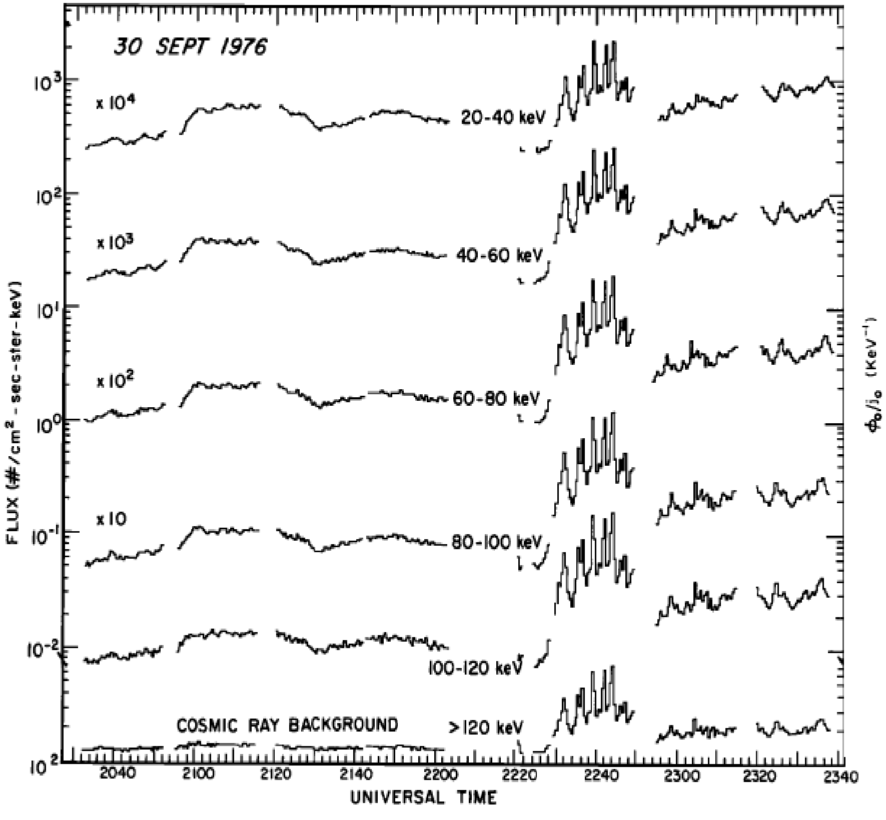
- For STSAT-1 microbursts, the equatorial loss cone ~3.7^{o} (IGRF model) and L = 5.7.
- Observations: Loss cone fills < 50 ms (time resolution).
- Wave-particle interaction suggested for Microburst precipitation (scattering of electrons by Chorus waves).
- *Challenge to Theorists*: Prompt appearance of microbursts on STSAT-1 indicate diffusion coefficient ~3.5×10^{-2} rad^2/s (Lee et al., 2005).

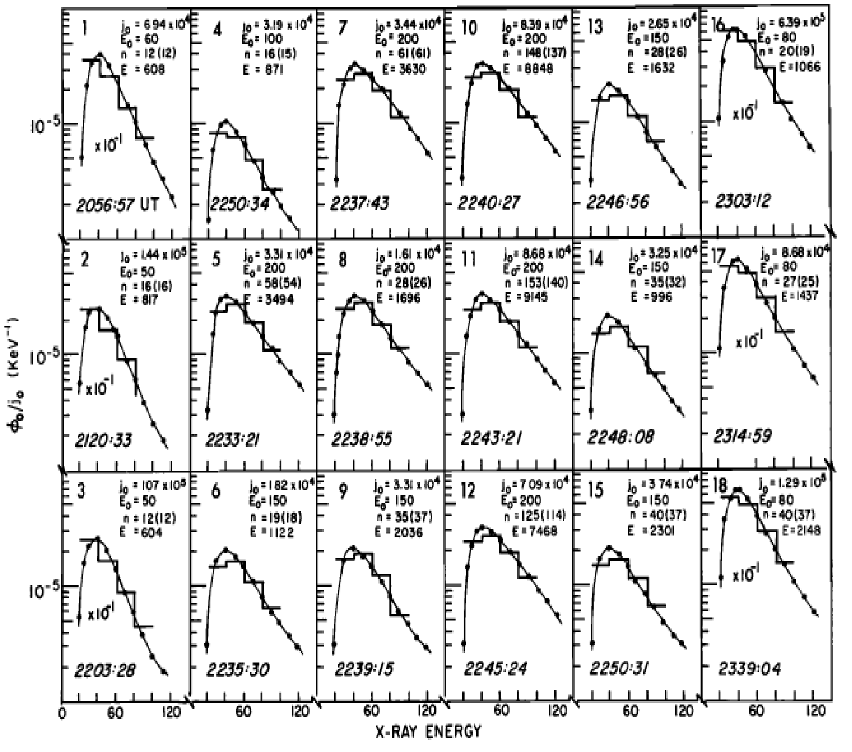
Unanswered Questions about Microbursts



- What mechanism precipitates microbursts?
- Why no microbursts <20 keV.
- Relationship between *low* energy and *relativistic* microbursts?
- Are relativistic microbursts precipitation of pre-accelerated relativistic electrons?
- Why Relativistic Energy Microbursts *Not seen* on Balloons?

Relativistic Electron Precipitation (Dusk side)



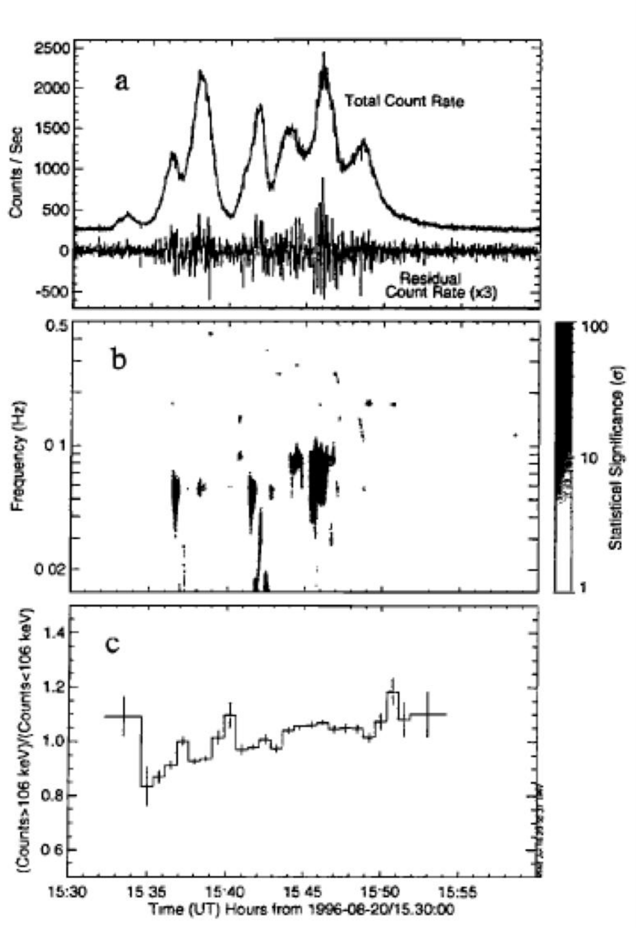


• e-folding energy, ~200 keV

• ~few minutes variations;

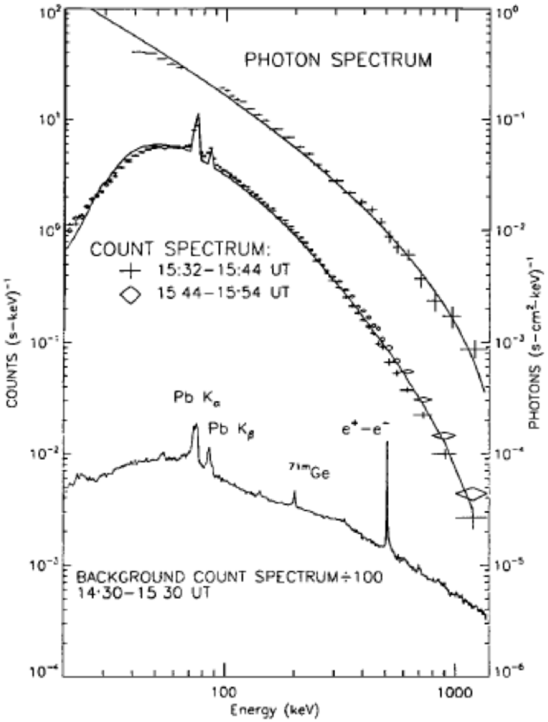
Parks et al, 1979

Relativistic electron precipitation (Dusk side)



Foat et al., 1998

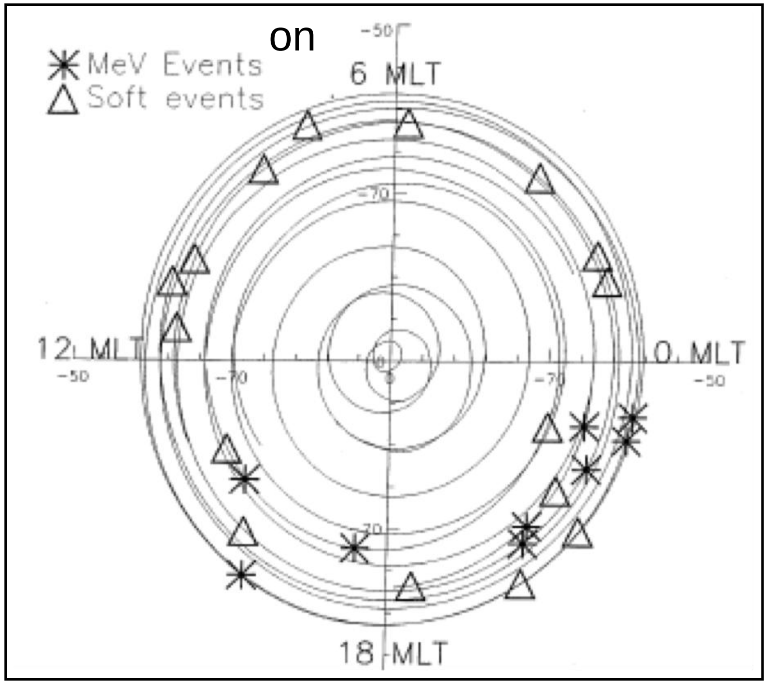
• ~few minutes variations



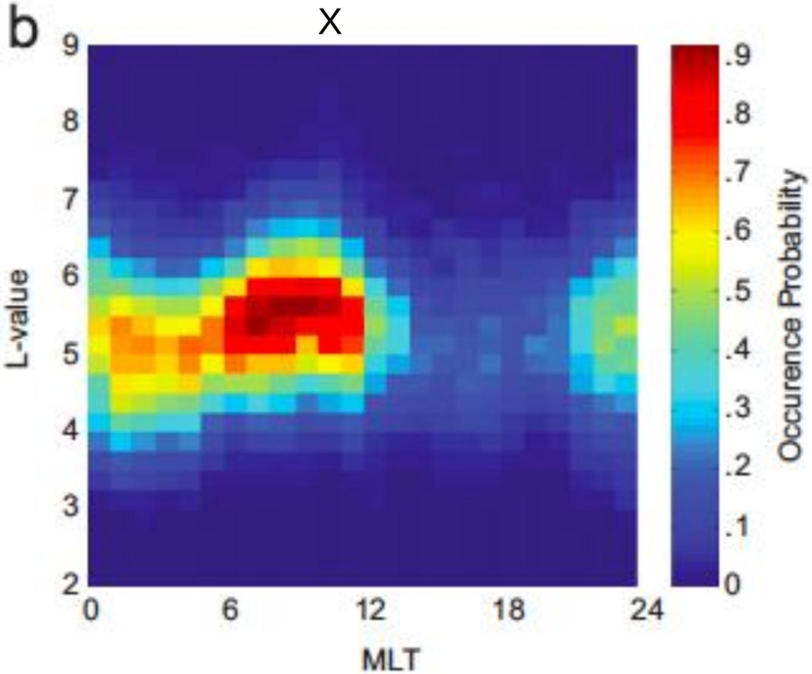
• e-folding ~300 keV

Relativistic Electron Precipitation

Ballo
on



SAMPE
X



14-23 LT

0-12 L
T

Milan, 2002

Milan and Thorne, 200
7

Future Measurements

- *RBSP* includes a variety of electron detectors to study the relativistic electrons, including *microbursts.*

- *Comparisons* to BARREL and SAMPEX extremely important.

- *Energy spectra* obtained with high resolution to several MeV.

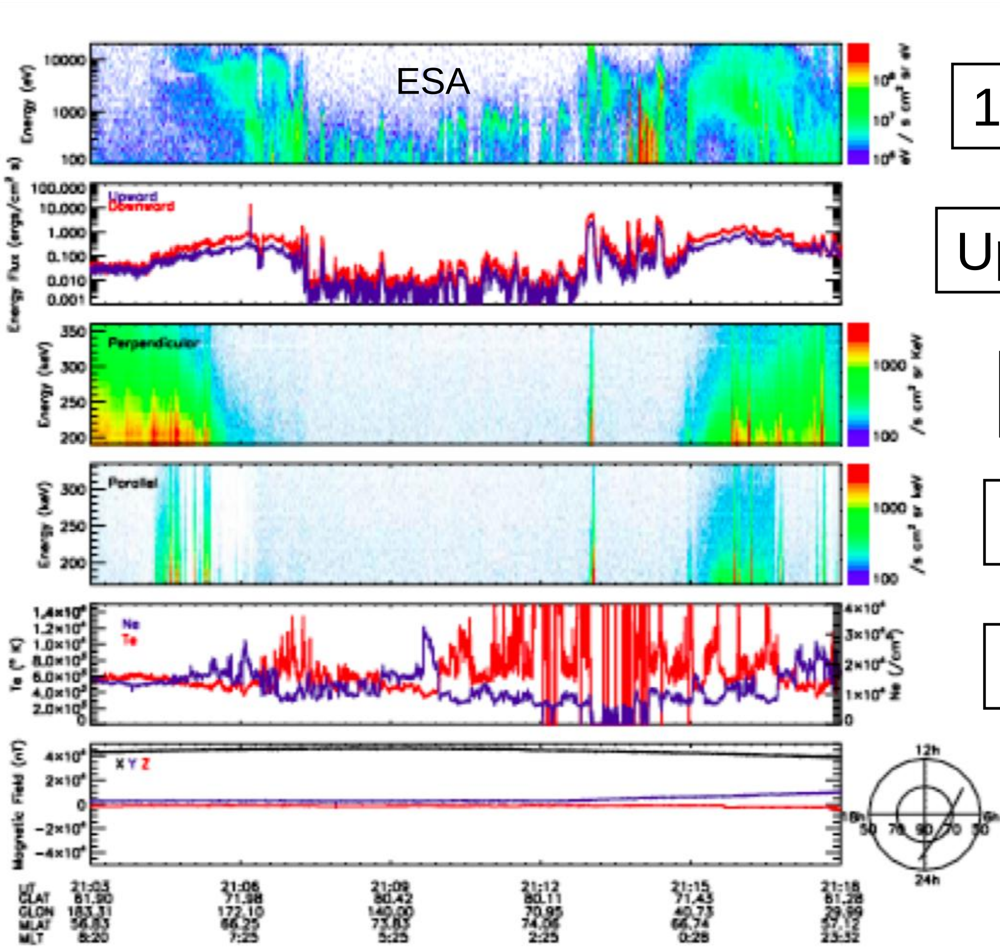
- *Detailed Pitch-angle measurements* in and near the loss cone only possible at ionospheric altitudes (loss cone as large as ~90^{o}).

- *DSX* (*Demonstration and Science Experiment*) has capability to measure loss cone electrons (*Loss Cone Imager*).

- These correlated measurements will *answer* many questions about microbursts and Relativistic Precipitation Useful to Space Weather.

The End (Talk about Wave-Particle Interactions)

Korean Scientific Satellite (STAT-1) Detects Microbursts



100 eV - 20 keV

Upward and downward fluxes

Perpendicular: 190 – 360 keV

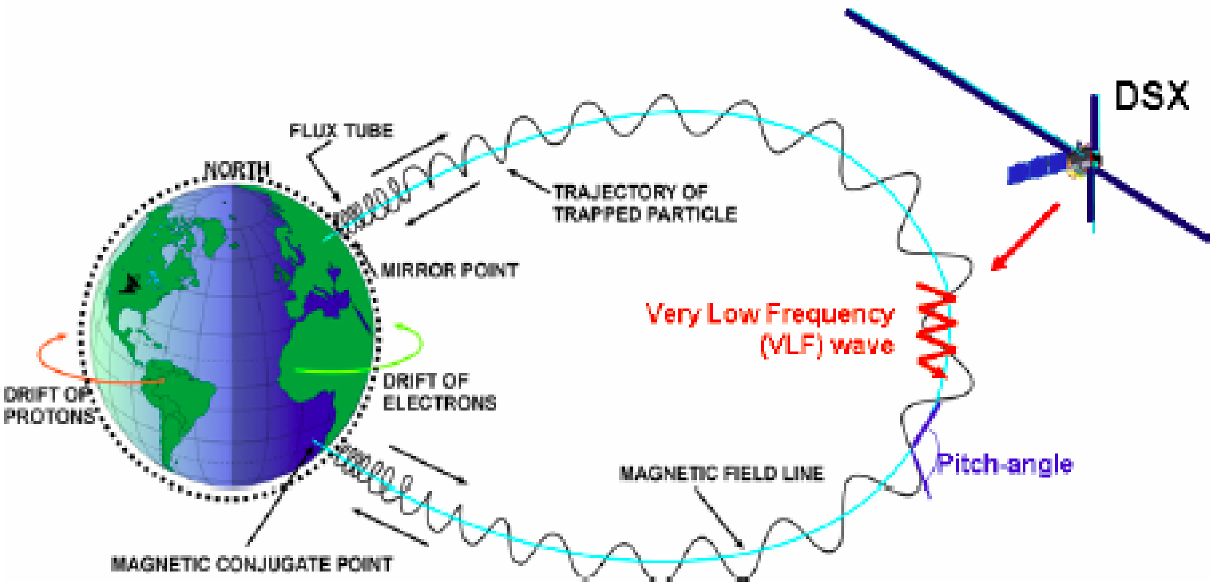
Upward: 170-330 keV

Ne and Te (Langmuir probe)

B-field

Demonstration and Science Experiment (DSX)

Orbit: 6000-12,000 km.



Has Loss Cone Imager!

Mechanisms of Relativistic Electrons

- What mechanism accelerates electrons to relativistic energies?
- What is the relationship between acceleration and precipitation?
- Role of Cyclotron interaction with large-amplitude Whistlers?
- Electron Acceleration to relativistic energies on the *dusk side*?
- Role of Ion cyclotron waves (EMIC)?

DSX Science Instruments

1. Vector magnetometer
2 Wave-induced precipitation of electron radiation (WIPER)

   Transmitter (3-50 kHz) and Receiver (0.1-50 kHz)
3. *Loss cone Imager* (LCI); 3 sensors, two rotating sensor heads, with ±180^{o} motorized articulation capability; Use B to point sensors. Third sensor 0.1 cm^2-str along B (HST), obtain 100 cnts/cm^2-str in the loss cone.
4. LEESA 100 eV – 50 keV); ESA.
5. HEPS (High Energy Proton Spectrometer); 1.5-400 MeV.
6. HIPS (High Energy Imaging Particle Spectrometer) 1-10 MeV
7. LIPS (Low Energy Imaging Particle Spectrometer) 20 keV-1 MeV

RBSP Instruments

1. Energetic Particle, Composition, and Thermal Plasma (ECT) Instrument Suite [1]; PI: Harlan Spence, UNH. LANL, SWRI, Aerospace, LASP

2. Electric and Magnetic Field Instrument Suite and Integrated Science (EMFISIS); PI: Craig Kletzing, UIowa.

3. Electric Field and Waves Instrument (EFW); PI: John Wygant UM, UCB,

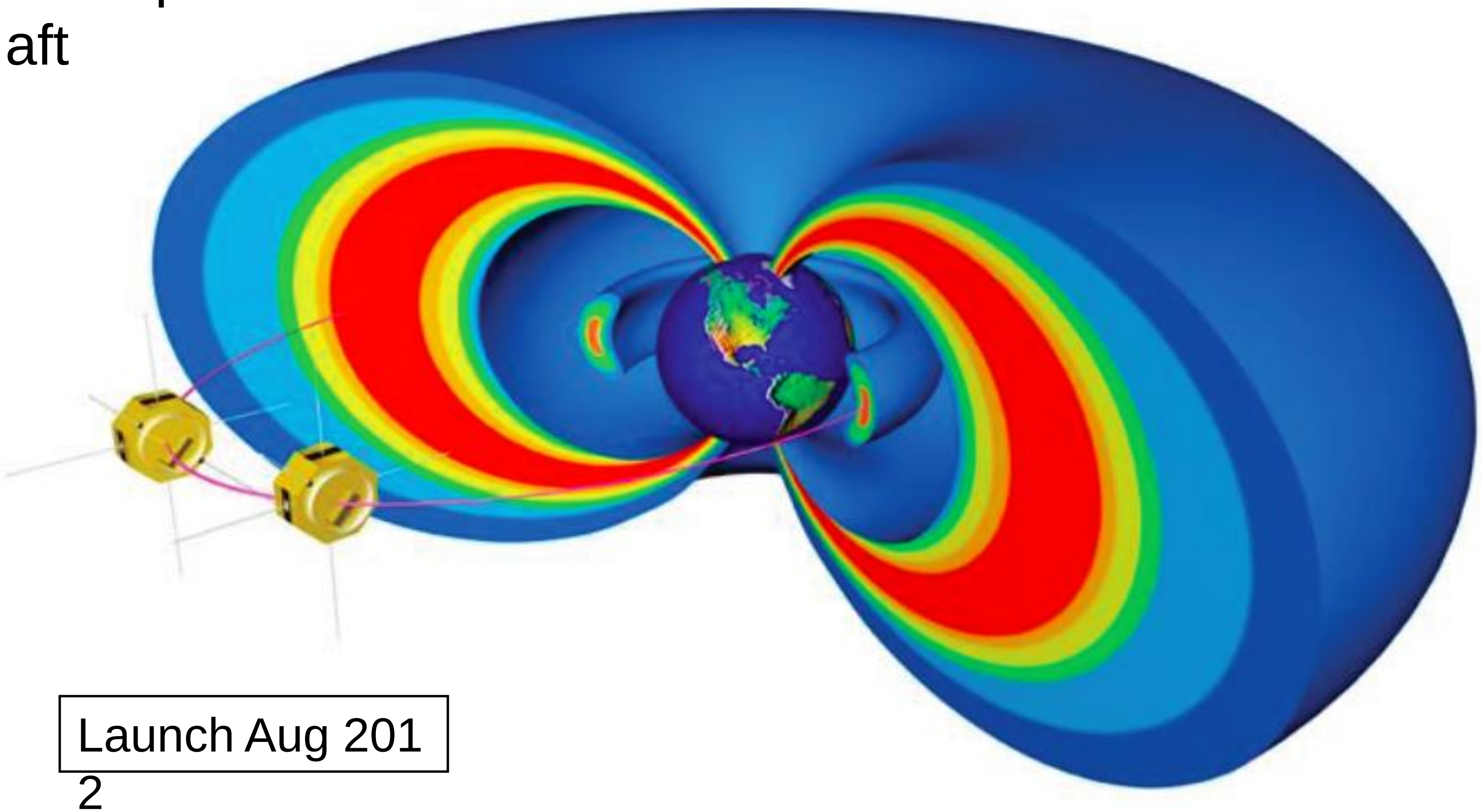
   U of Col, Boulder.

4. Radiation Belt Storm Probes Ion Composition Experiment (RBSPICE); PI: Lou Lanzerotti, New Jersey Institute of Technology, APL.

5. Relativistic Particle Spectrometer (RPS), National Reconnaissance Office

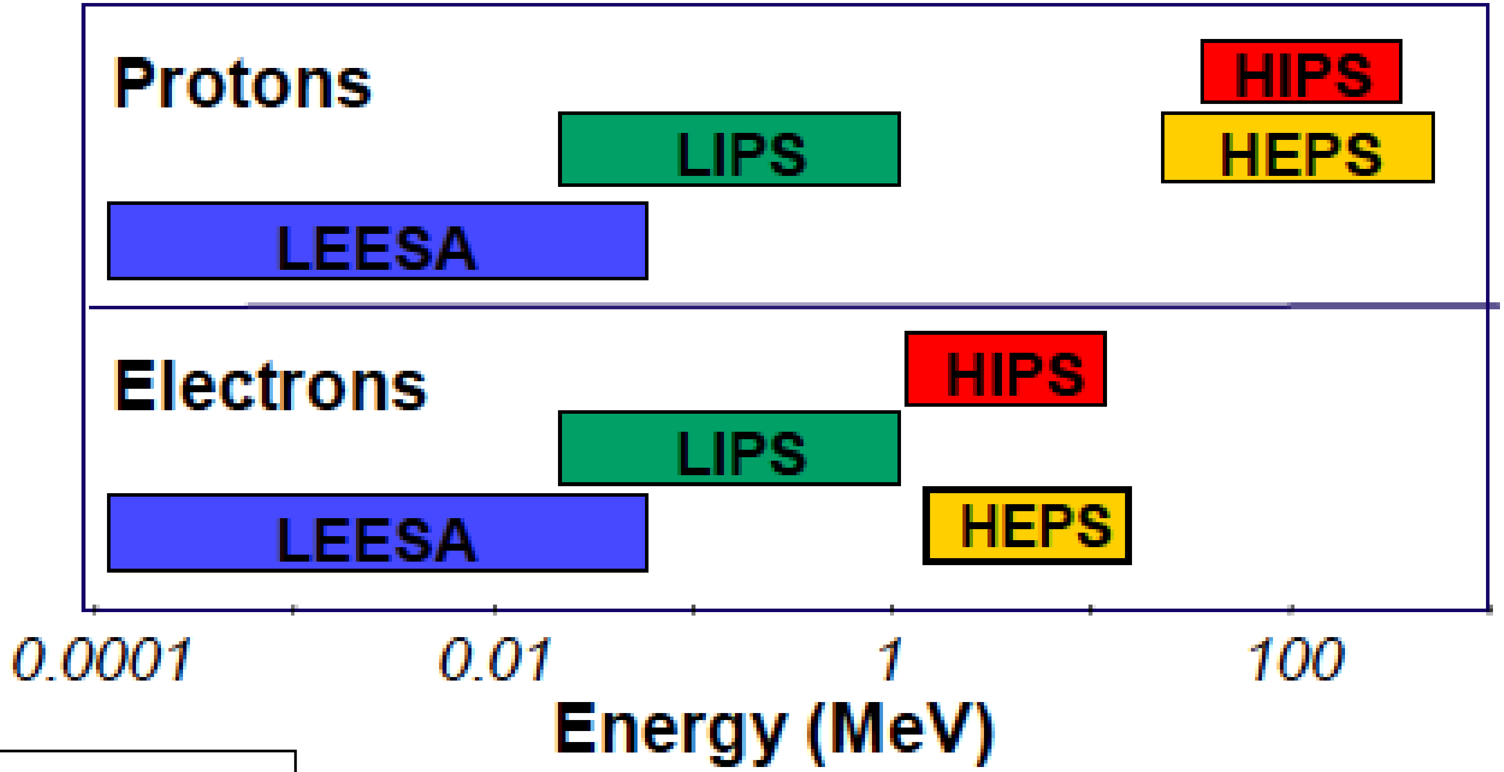
Radiation Belt Storm Probe

Two spacecr
aft



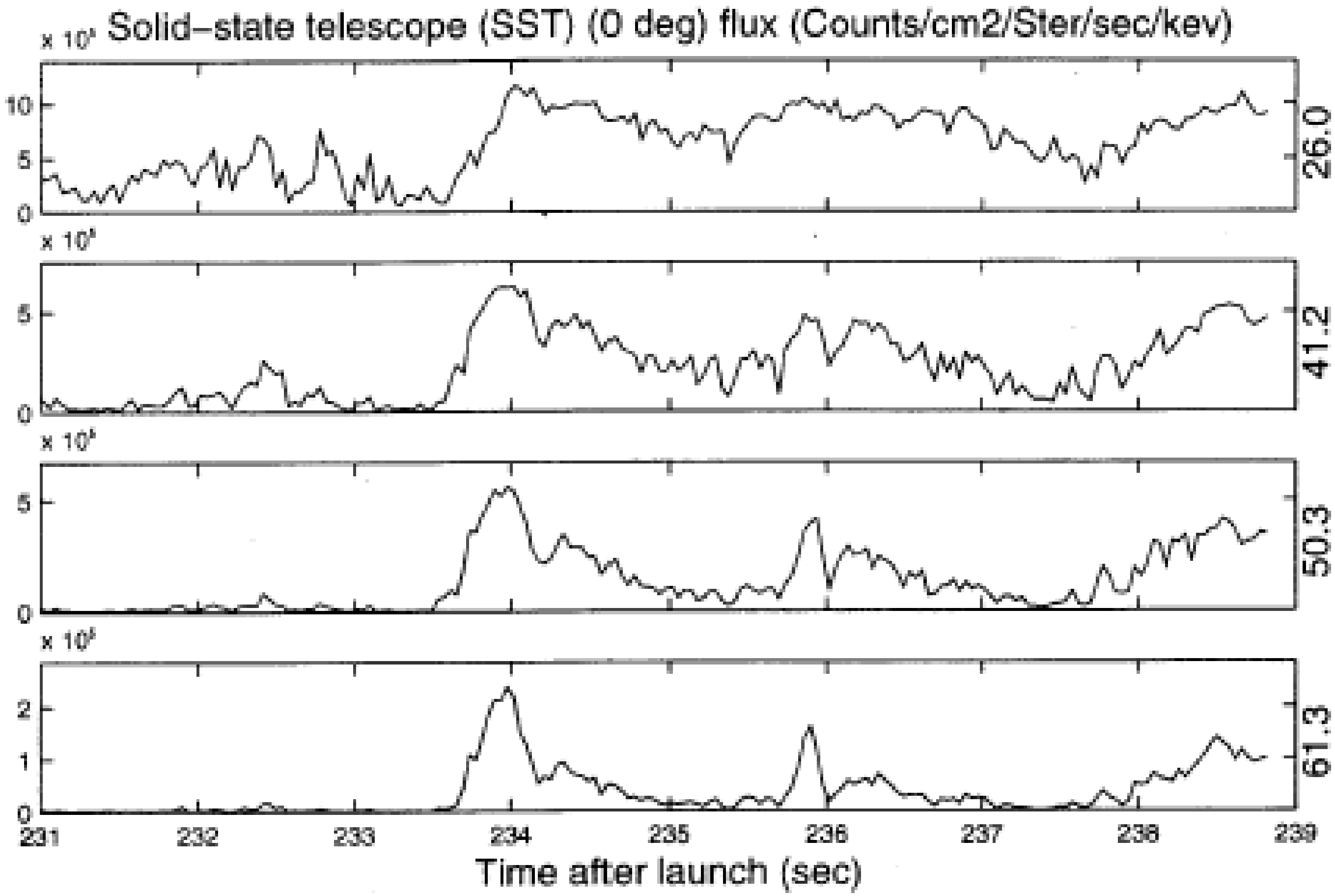
Launch Aug 201
2

Particle Energy Coverage



Launch 2014
?

Microbursts Energy Dependence (Rocket)



Datta et al., 199
7

Wave-particle interaction

- Empty loss cone indicates Velocity space not uniform.
- Loss cone distribution unstable to generating cyclotron waves.

- Kennel and Petschek (1966). Must read paper for anyone working with energetic particles in radiation belts. Pitch-angle diffusion in phase space. Solves a diffusion equation and gets pitch-angle diffusion rates.

- Brice, N. (1964) gives a simple formulation how whistlers and particles can resonate.

Cyclotron Resonance Condition

- Resonance condition for relativistic electrons

$$\omega + k \cos\theta\, v \cos\alpha = s\, \Omega_e/\gamma$$

ω = *wave frequency*

k = *wave number*

θ = *propagation angle relative to B*

v = *electron velocity*

α = *pitch-angle*

s = *integer*

Ω_e = *electron gyrofrequency*

$\gamma = (1 - v^2/c^2)^{-1/}$

Cyclotron Resonance Interaction

- Empty loss cone indicates Velocity space not uniform.
- Loss cone distribution unstable to generation cyclotron waves.
- Whistler mode waves are right-hand circularly polarized waves

$$n^2 = c^2k^2/\omega^2$$
$$= 1 + \omega^2_{pe}/\omega(\Omega_e \cos\theta - \omega)$$

$$v_{||} = \{-\omega k \Omega_e \cos\theta + [\omega^2 k^2 \cos^2\theta + (s^2\Omega_e{}^2 - \omega^2)(k^2\cos^2\theta + s^2\Omega_e{}^2/c^2 \cos^2\alpha]^{1/2}\} (k^2\cos^2\theta + s^2\Omega_e{}^2/c^2 \cos^2\alpha)^{-1}$$

Resonance energy vs frequency

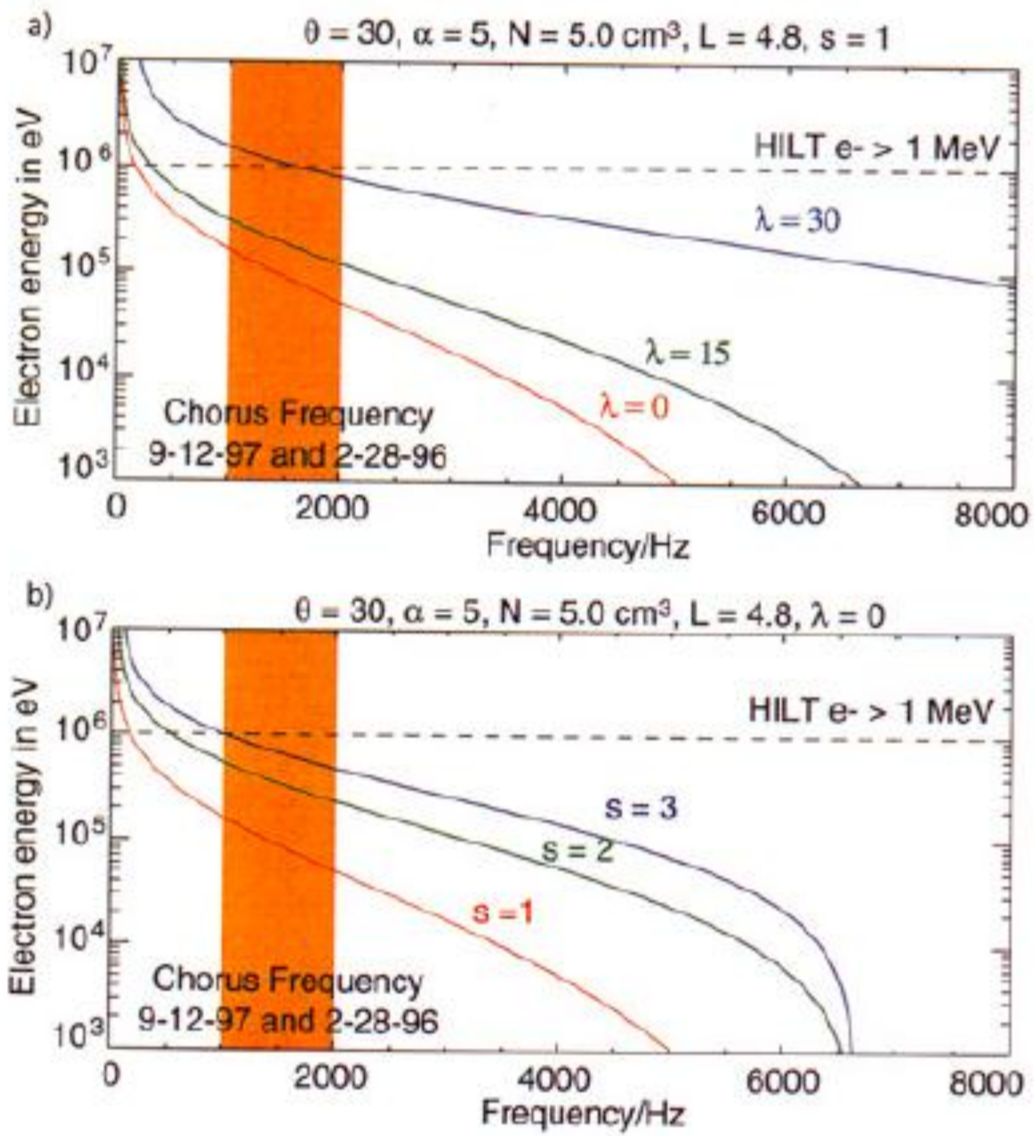
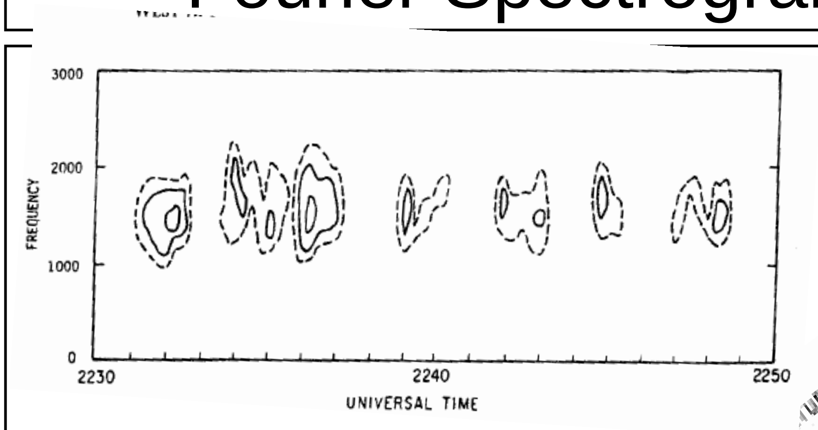
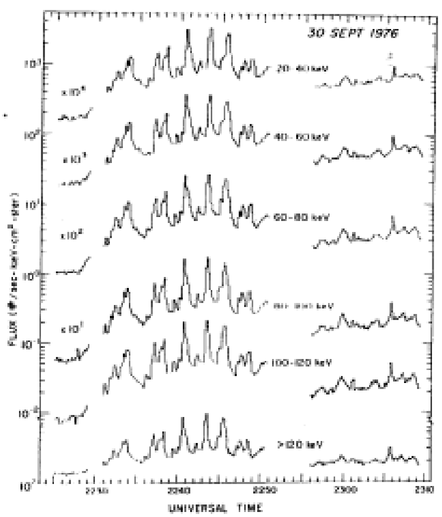


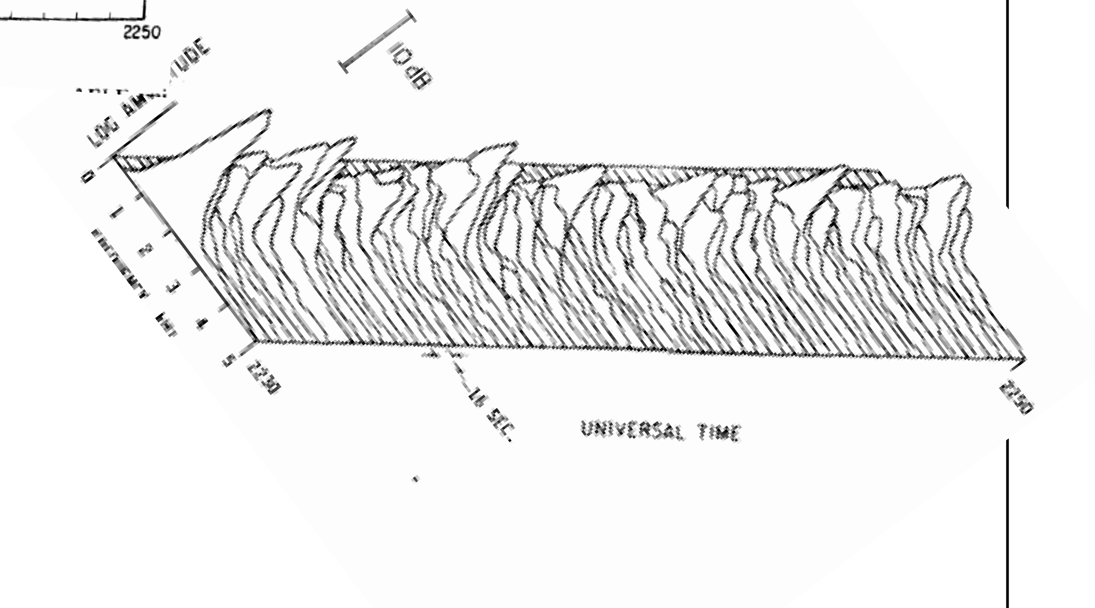
Plate 7. Electron resonant energy versus whistler wave frequency for the conditions observed by Polar and SAMPEX in Plates 2 and 3 for (a) various locations along the field line and (b) various harmonics.

- MeV electrons on equato r resonate waves <200 Hz
- For MeV electrons to interact with 1-2 kHz waves observed, interaction must take place off the equator, at ~30° latitude.
- At this location, loss cone ~7°.• Calculations show s >3.
- Higher harmonics important for obliquely Propagating waves.
- Simulation: Chang and Inan (1983), Inan et al. (1992).

Fourier Spectrogram of Duskside REP

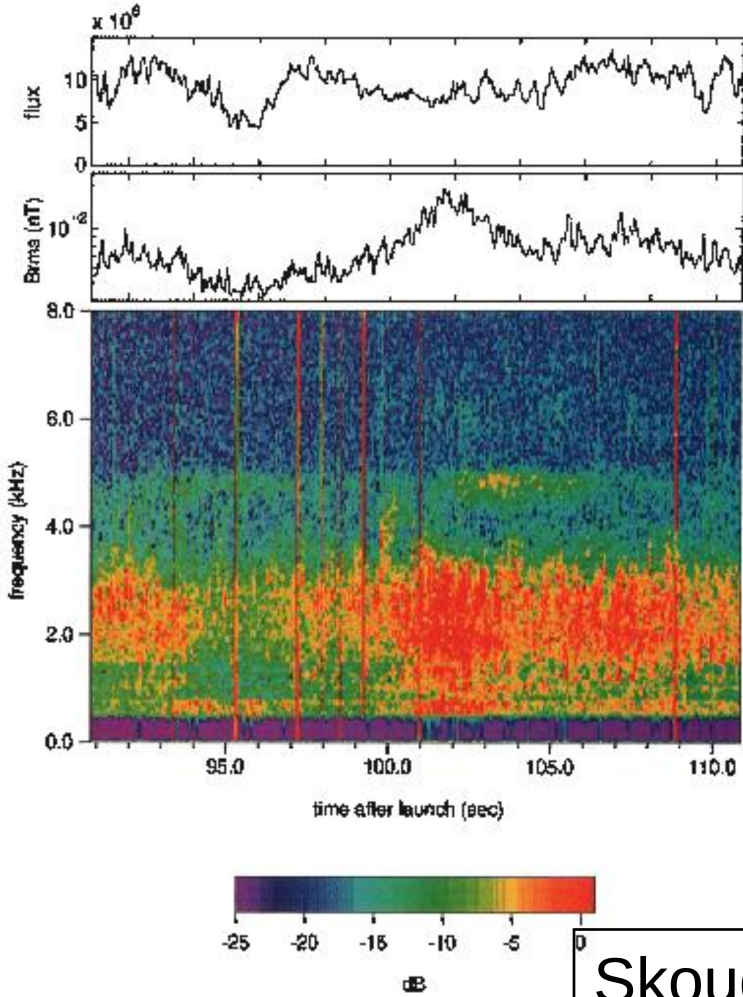






West and Parks, 1978

Chorus and Microbursts



Skoug et al., 1996