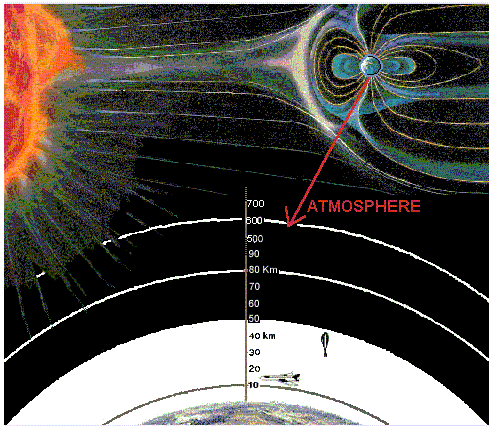
Modelling the outer radiation belt as a complex system in a self-organised critical state

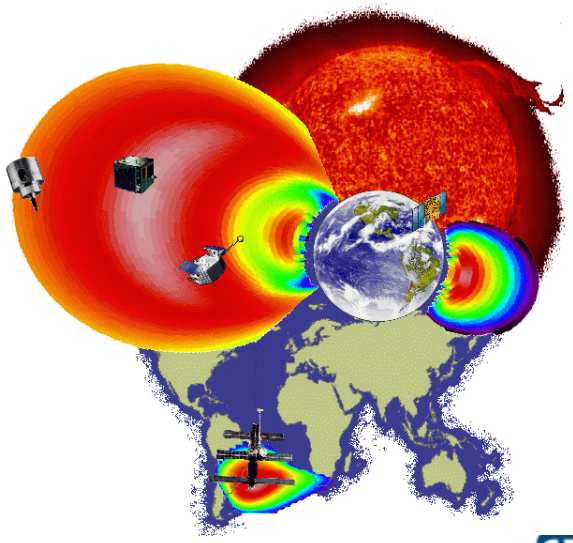
Norma B. Crosby

Belgian Institute for Space Aeronomy
Ringlaan-3-Avenue Circulaire, 1180 Brussels, Belgium



Self-Organized Criticality and Turbulence, ISSI Team Meeting 1, Bern, Switzerland, 15-19 Oct. 2012

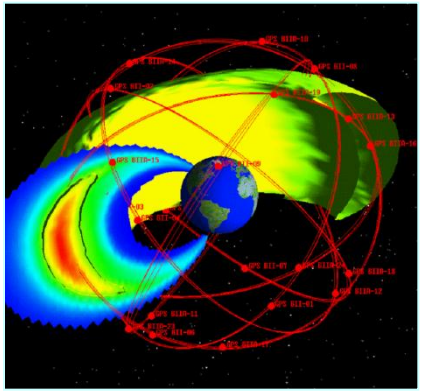
When a method has been applied successfully on one part of the Sun-Earth Scenario (e.g. solar corona) one can investigate if it can also be applied successfully on another part (e.g. Earth's magnetosphere).



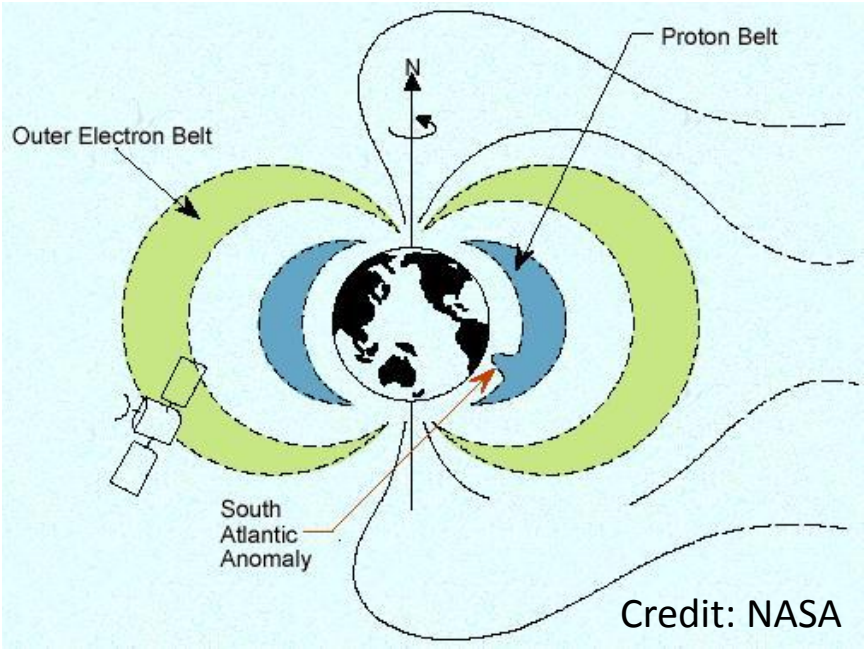
FREQUENCY DISTRIBUTIONS
FREQUENCY DISTRIBUTIONS

EARTH'S RADIATION BELTS

Trapped particle populations



Courtesy of U.S. Air Force
Phillips Laboratory



Proton Belt: 1.3 R_E

Electron Inner Belt: 1.5 - 2.5 R_E
Electron Outer Belt: 3-9 R_E

Protons: Tens keV – couple of hundreds of MeV

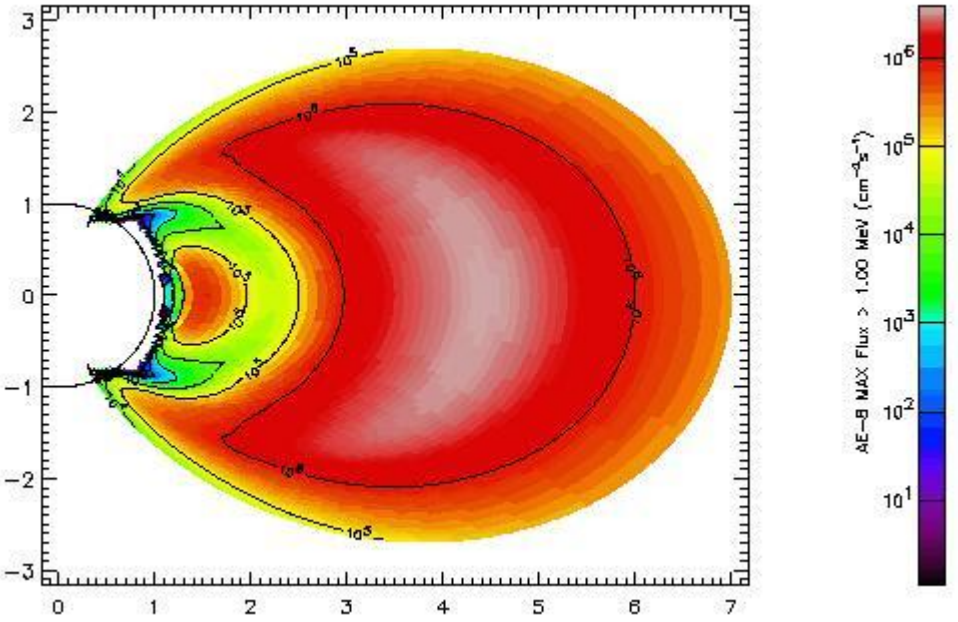
Electrons: Tens keV – several MeV

EARTH'S ELECTRON RADIATION BELTS

from STATIC MODELS to Dynamic Behaviour (on all spatial- and time-scales)

L-shell, L-value, or McIlwain L-parameter (McIlwain, 1961):

Motions of low-energy charged particles in the Earth's magnetic field can be usefully described in terms of McIllwain's (B,L) coordinates [B: magnitude (or length) of the magnetic field vector].



Invariant coordinate map of the AE-8 MAX integral electron flux >1 MeV. The semi-circle represents the surface of the Earth, distances are expressed in Earth radii.

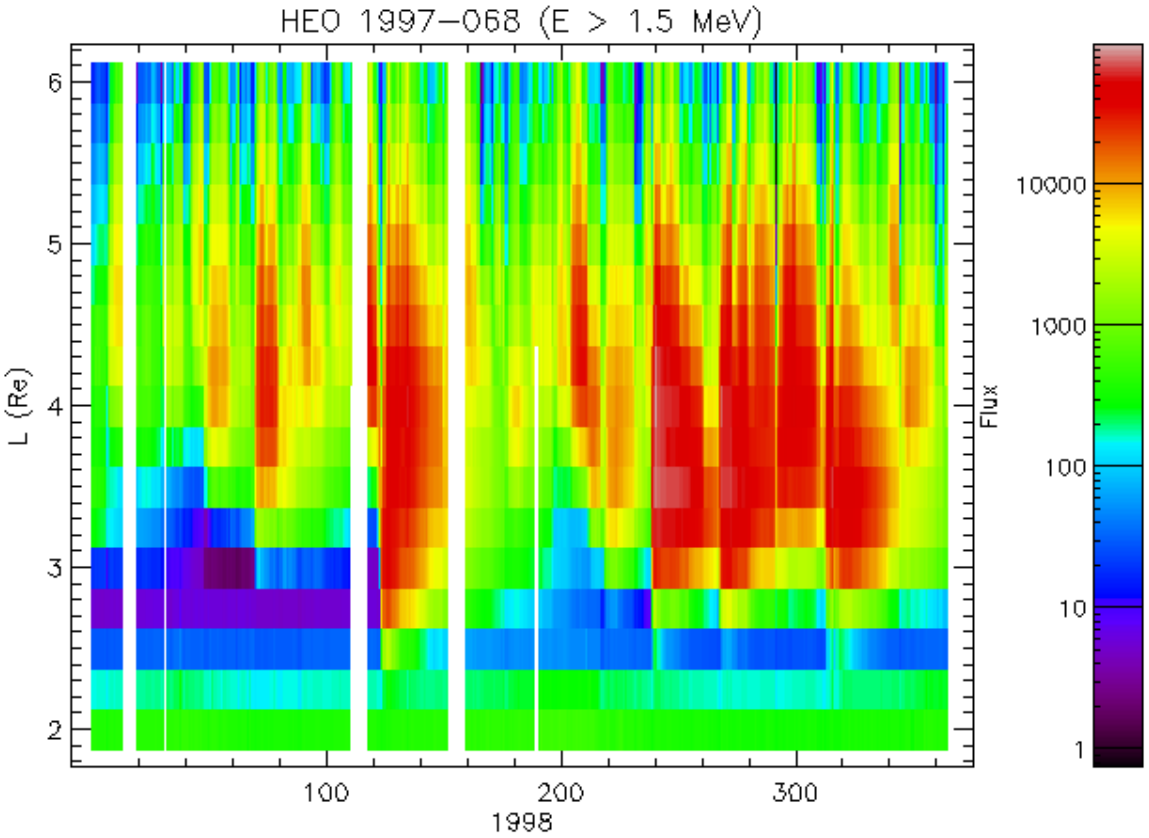
Courtesy of SPENVIS (http://www.spenvis.oma.be/)

aeronomie.be

.be

Outer electron radiation belt is highly variable.

L= Earth's Radius
= 6371 km



Daily Averaged Electron Outer Radiation Belt
Count Rate Data

HEO data courtesy of The Aerospace Corporation

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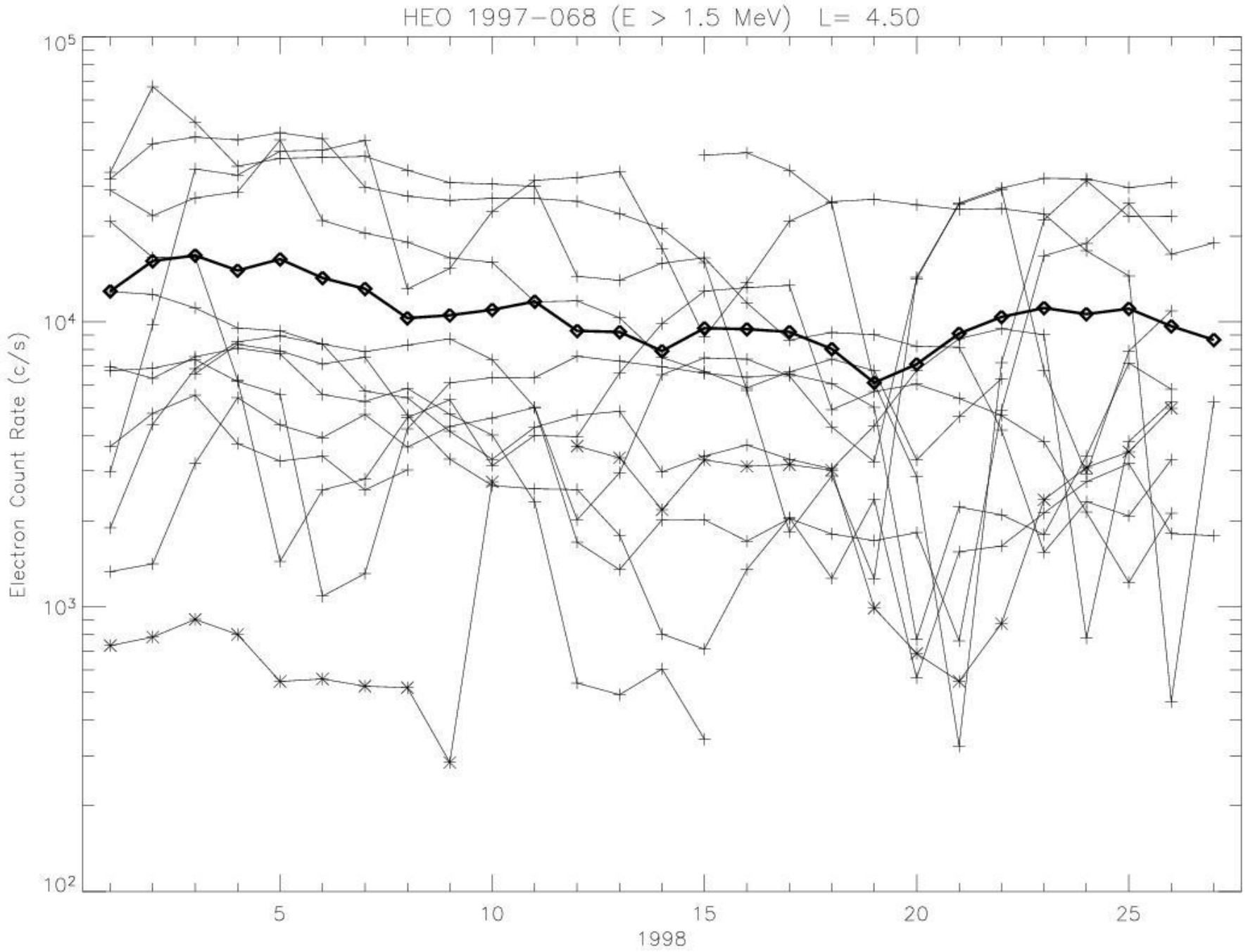
HEO 1997-068 (E > 1.5 MeV) L= 4.50
Electron Count Rate (c/s)
10^5
10^4
10^3
10^2
5
10
15
20
25
1998

Theories of electron acceleration include shock acceleration, classical radial diffusion, ULF enhanced radial diffusion, large- and small-scale recirculation, direct substorm injection, and Landau and cyclotron res

Any successful model should be able to explain [or at least to reproduce] the results of statistical studies performed on the data.

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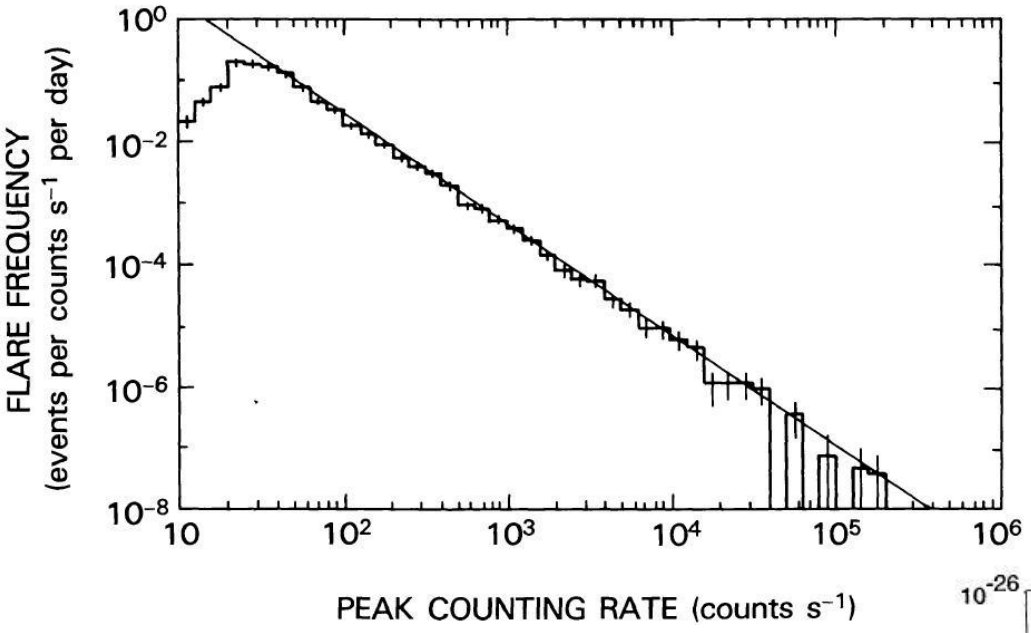
database and LANL-GEO geosynchronous satellites.

"The findings support a model whereby solar wind velocity drives convective transport of source and seed electrons, to the inner magnetosphere, where local acceleration and subsequent radial diffusion is responsible for the enhanced fluxes."

SOLAR FLARES [HXRBS/SMM]



Frequency distribution of the peak counting rate for solar flares covering 1980-1985.

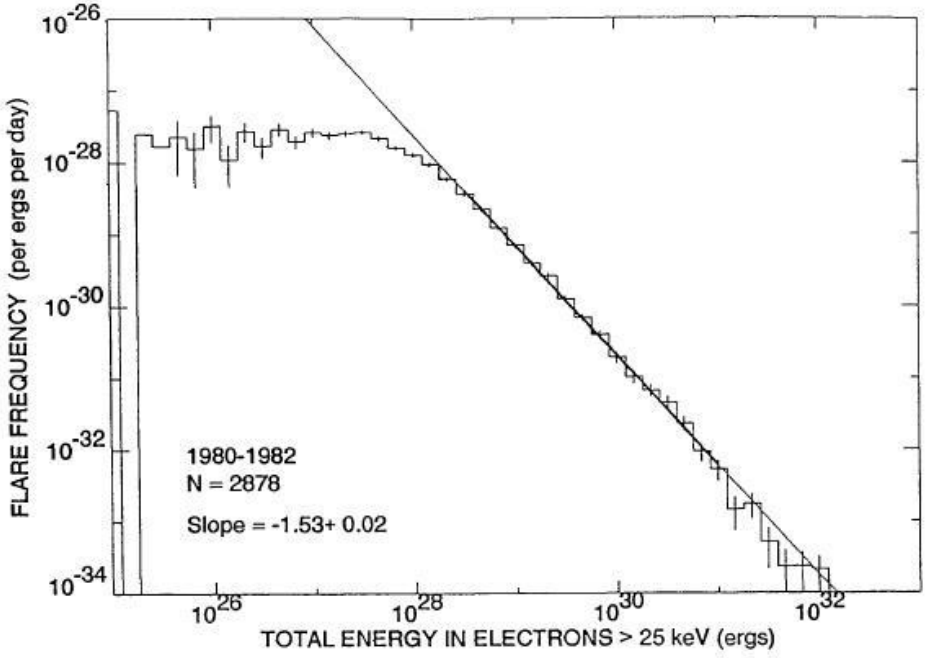
$\alpha = -1.8$

(Dennis, *Solar Physics*, 100, 465, 1985)

Frequency distribution of the total energy in electrons above 25 keV calculated by integrating the thick-target energy over the flare duration (1980-1982).

$\alpha = -1.53$

(Crosby, Aschwanden, Dennis, *Solar Physics*, 143, 275, 1993)



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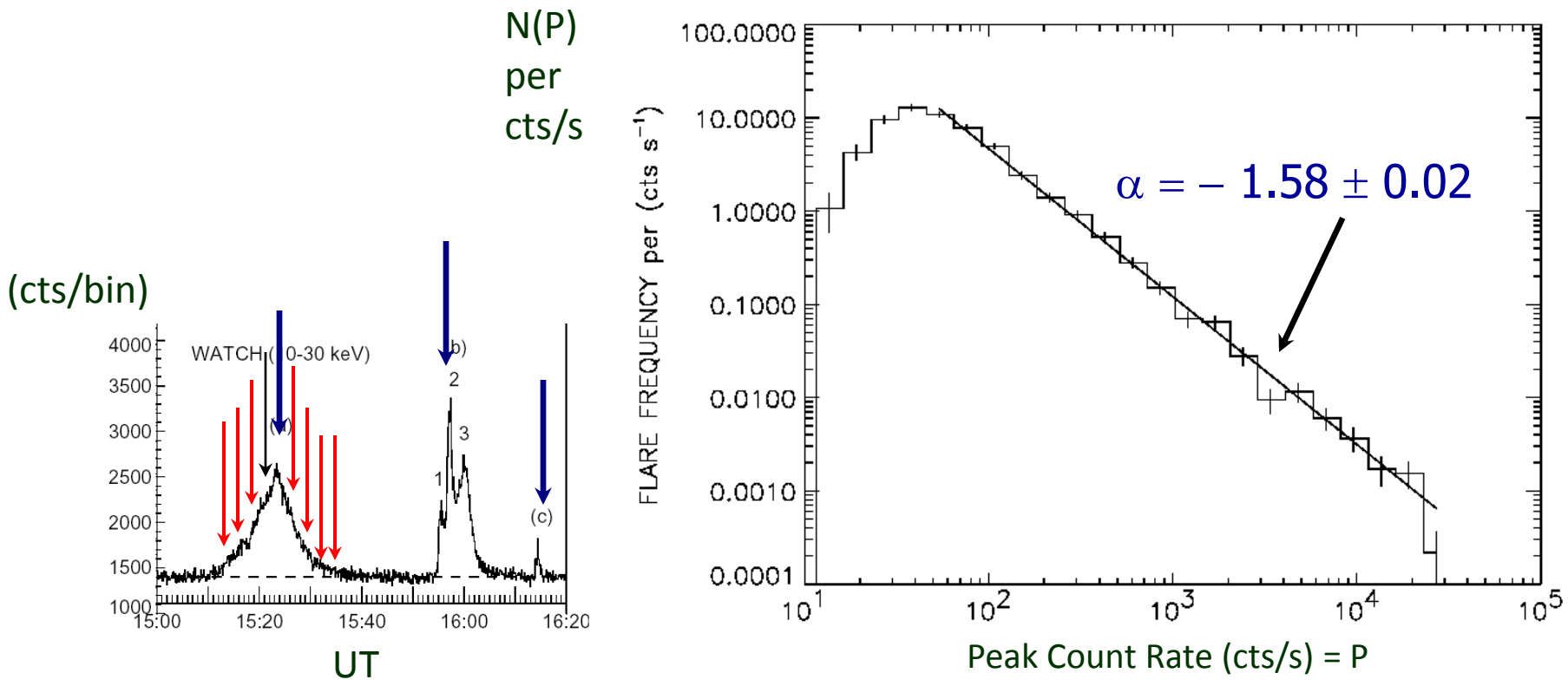
SOLAR FLARES [WATCH/GRANAT]

1990, April-Dec.1991, Jan.-April, July 1992



Crosby N., Vilmer N., Lund N., Sunyaev R., *Astron. Astrophys.*, 334, 299, 1998

THE ANALOGY – PART 1

Count rate frequency distribution of more than 5000 hard X-ray structures (less than 1 s) detected in 640 solar flares was found to be well-represented by a power-law with a slope of −1.84 (Aschwanden et al., 1995).

This is identical with what was found for the global frequency distribution behaviour of solar flare hard X-rays (e.g. Dennis, 1985; Crosby et al., 1993).

From a scale-invariant model like the avalanche model one would expect that the individual pulses that make up an “avalanche” would also show power-law behaviour and that the slope values would be similar.

THE ANALOGY – PART 2

Even though there are no individually defined “avalanches” in the outer radiation belt, as there are, for example, in the case of the solar corona (e.g. solar flares), one can imagine that the outer radiation belt acts as one individual system “one flare”.

The analogy is that the pulses that make up the outer radiation belt are identical with the burst structures making up a flare “individual avalanche”.

Bearing this in mind and the fact that the outer electron radiation belt is indeed dynamical on all spatial and temporal scales, one can speculate if perhaps the outer electron radiation belt also exhibits power-law behavior and thus exibiting itself as a candidate for SOC behaviour.

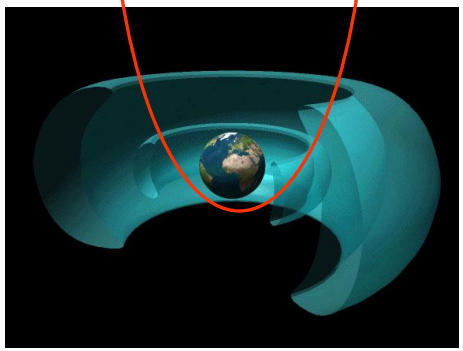
Cold Ion Detector STRV-1a satellite

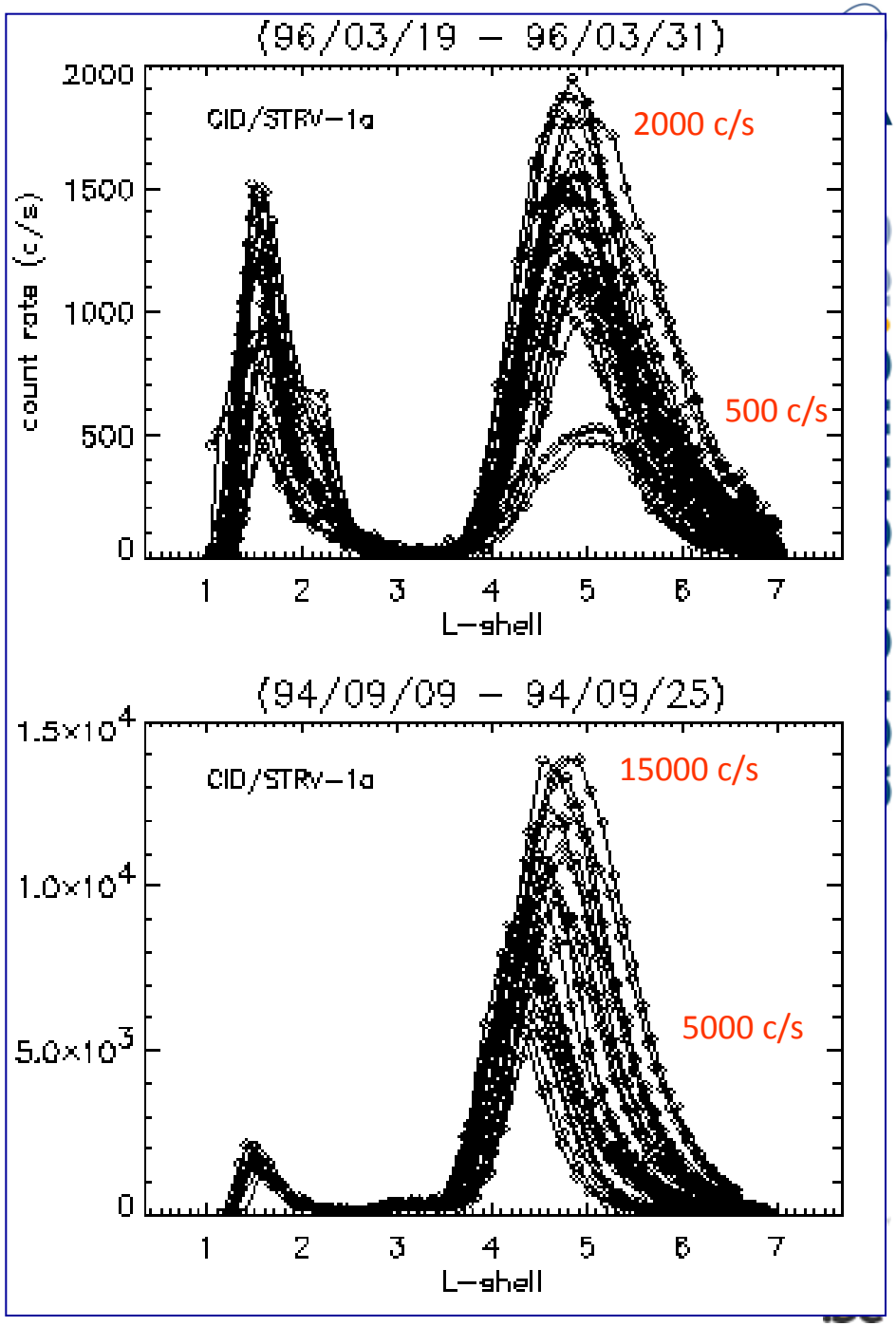
[measures electrons > 750 keV]

Apogee: 35795 km

Sept. 1994
through
March 1998

Perigee: 200 km





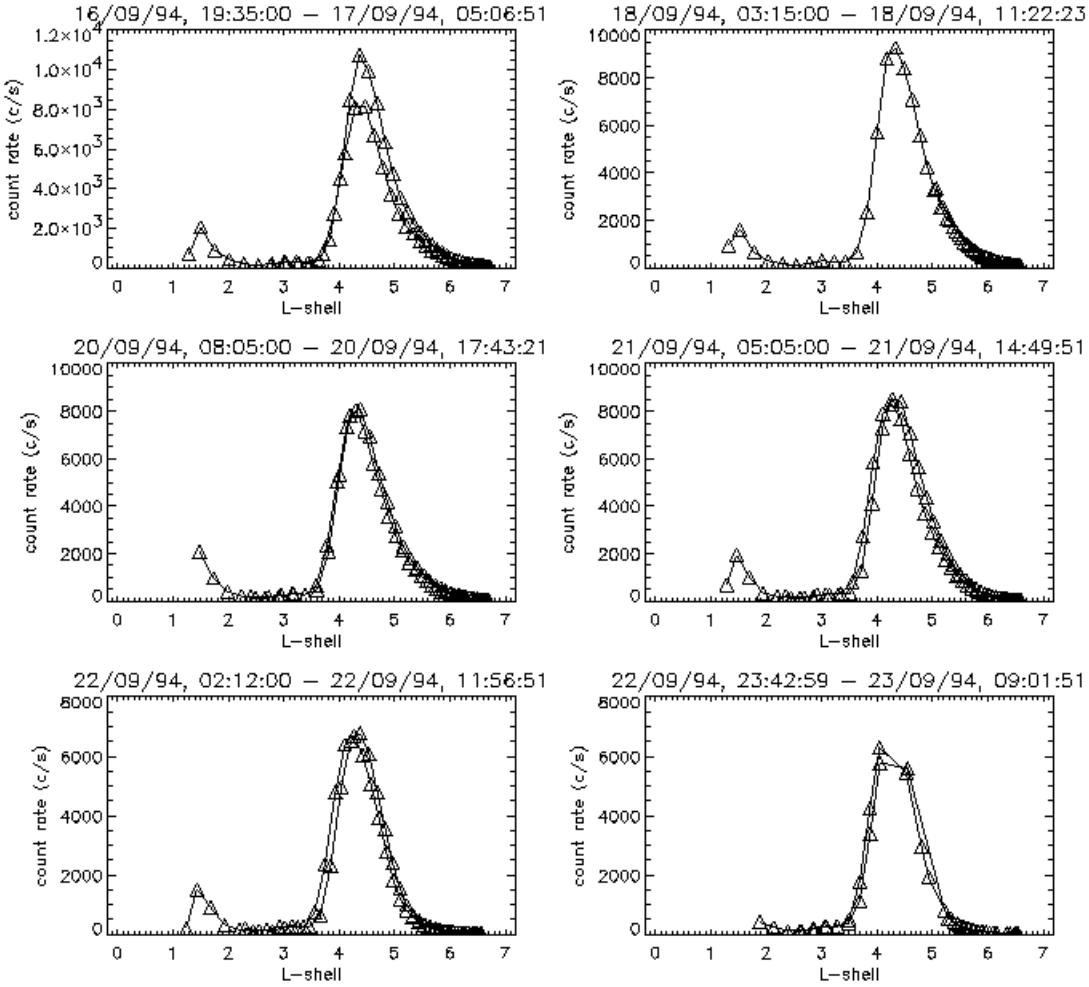
UCL MSSL

CID/STRV-1a
(individual orbit plots)

Count rate (cts/s)

Count rate (cts/s)

Count rate (cts/s)



L-shell L-shell

Crosby N., Meredith N.,
Coates A., Iles R., NPG, 12,
993, 2005

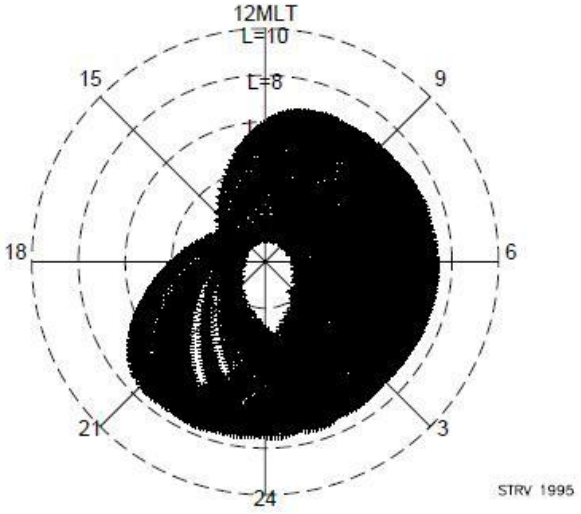


Fig. 2. 1995 STRV orbit (function of L-shell and MLT).

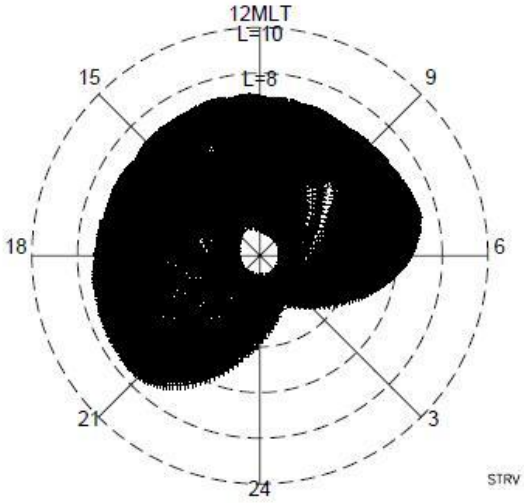


Fig. 3. 1996 STRV orbit (function of L-shell and MLT).

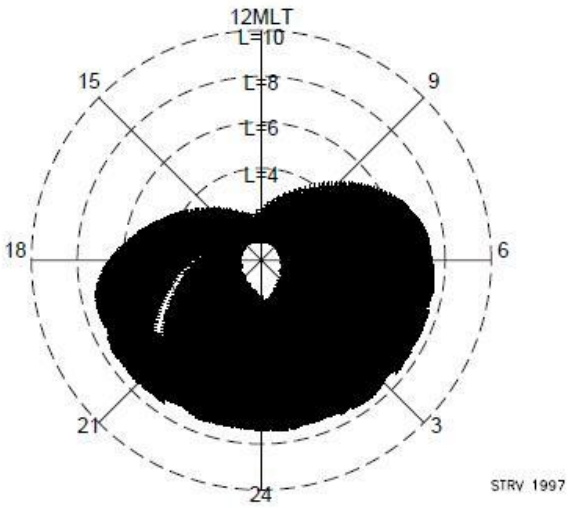


Fig. 4. 1997 STRV orbit (function of L-shell and MLT).

Table 2. Characteristics of the electron count rate (CR) frequency distributions for different MLT intervals for 1995–1997.

MLT	4.1–7.7 interval	4.1–7.7 slope	4.4–5.5 interval	4.1–5.5 slope	5.5–7.7 interval	5.5–7.7 slope
0–6	[60,12079]	−1.674±0.007	[150,12079]	−1.517±0.015	[60,7609]	−1.959±0.015
6–12	[60,11837]	−1.522±0.007	[150,11837]	−1.319±0.014	[60,5345]	−1.705±0.010
12–18	[60,9500]	−1.540±0.010	[150,9500]	−1.476±0.019	[60,4456]	−1.824±0.018
18–24	[60,8611]	−1.803±0.010	[150,7815]	−1.819±0.019	[60,8611]	−2.234±0.017

OUTER ELECTRON RADIATION BELT

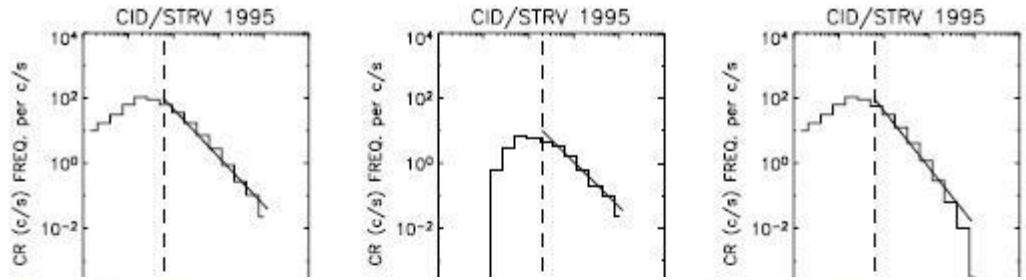
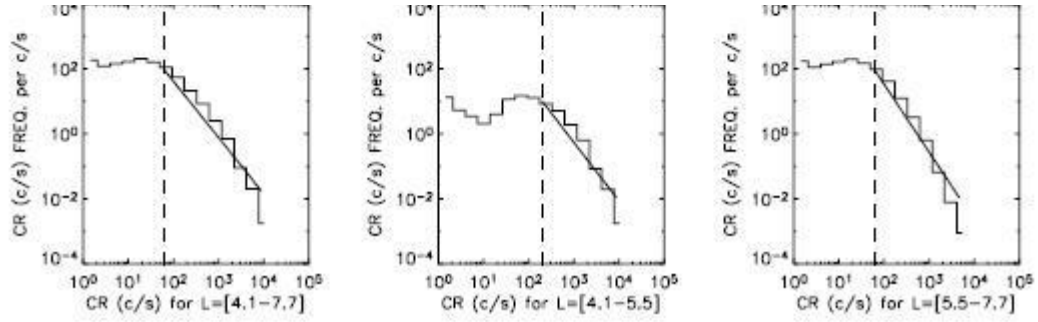


Table 1. Characteristics of the electron count rate (CR) frequency distributions for different years and L-shell intervals.

Year	4.1–7.7 interval	4.1–7.7 slope	4.1–5.5 interval	4.1–5.5 slope	5.5–7.7 interval	5.5–7.7 slope
1995–1997	[60,12079]	−1.634±0.004	[200,12079]	−1.602±0.009	[60,8611]	−1.911±0.006
1995	[60,12079]	−1.476±0.007	[200,12079]	−1.373 ±0.015	[60,8611]	−1.749±0.011
1996	[60,9500]	−1.655±0.006	[200,9500]	−1.589±0.016	[60,4456]	−1.856±0.010
1997	[60,8842]	−1.728±0.008	[200,8842]	−1.786±0.018	[60,4662]	−2.100±0.014



CR (cts/s) for L= [4.1-7.7]

CR (cts/s) for L= [4.1-5.5]

CR (cts/s) for L= [5.5-7.7]

Crosby N., Meredith N., Coates A., Iles R., NPG, 12, 993, 2005

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Total Relativistic Electron Content (T_{REC})

To take into account the non-symmetric aspect of Earth's magnetic field the Total Relativistic Electron Content (T_{REC}) is computed for the three Years (1995, 1996, 1997):

Count rate data is :

- Initially binned as a function of L by averaging in steps of $\Delta L = 0.2$
- Then approximated by $T(L)=C(L)\times L^2$, where the factor L^2 makes an allowance for the volume occupied between dipolar shells L and $L+\Delta L$

(for more details see Iles R.H.A., Fazakerley A.N., Johnstone A.D., Meredith N.P. and Bühler P, *Ann. Geophys.*, 20, 7, 957-965, 2002)

The T_{REC} is computed as a function of day for the following three radiation belt intervals:

$L=[4.1,5.5]$, $L=[5.5,7.7]$ and $L=[4.1,7.7]$

OUTER ELECTRON RADIATION BELT

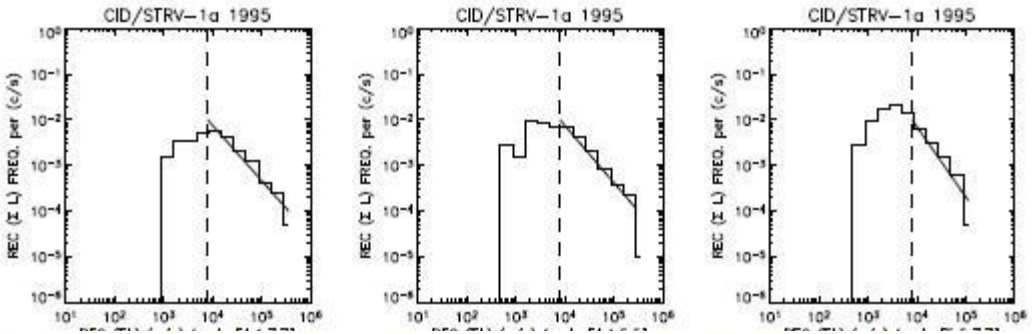
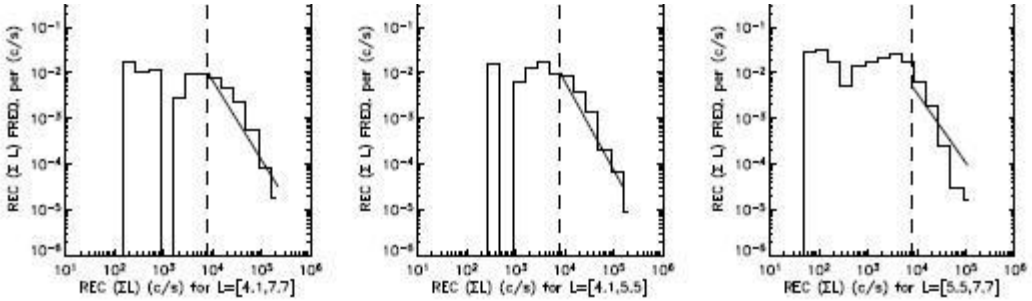


Table 3. Characteristics of the total relativistic electron content (T_{REC}) frequency distributions for different years and L-shell intervals.

Year	4.1–7.7 interval	4.1–7.7 slope	4.1–5.5 interval	4.1–5.5 slope	5.5–7.7 interval	5.5–7.7 slope
1995	[8000,359717]	−1.195±0.060	[8000,274153]	−1.254±0.069	[8000,111914]	−1.548±0.122
1996	[8000,270400]	−1.535±0.082	[8000,199090]	−1.430±0.104	[8000,71309]	−2.074±0.193
1997	[8000,216389]	−1.739±0.092	[8000,160989]	−1.950±0.119	[8000,109188]	−2.675±0.234



Crosby N., Meredith N., Coates A., Iles R., NPG, 12, 993, 2005

T_{REC} ∑L (cts/s) for L= [4.1-7.7]

T_{REC} ∑ (cts/s) for L= [4.1-5.5]

T_{REC} ∑ (cts/s) for L= [5.5-7.7]

EARTH'S OUTER ELECTRON RADIATION BELT SUMMARY

- Results suggest that the modelling of the outer electron radiation belt as a complex system in a self-organized critical state provides a good context to understand the frequency distributions of the electron parameters.

- Evidence for more dynamic control in the outer region of the outer electron radiation belt.

- Entire outer electron radiation belt appears to be affected in the same way.

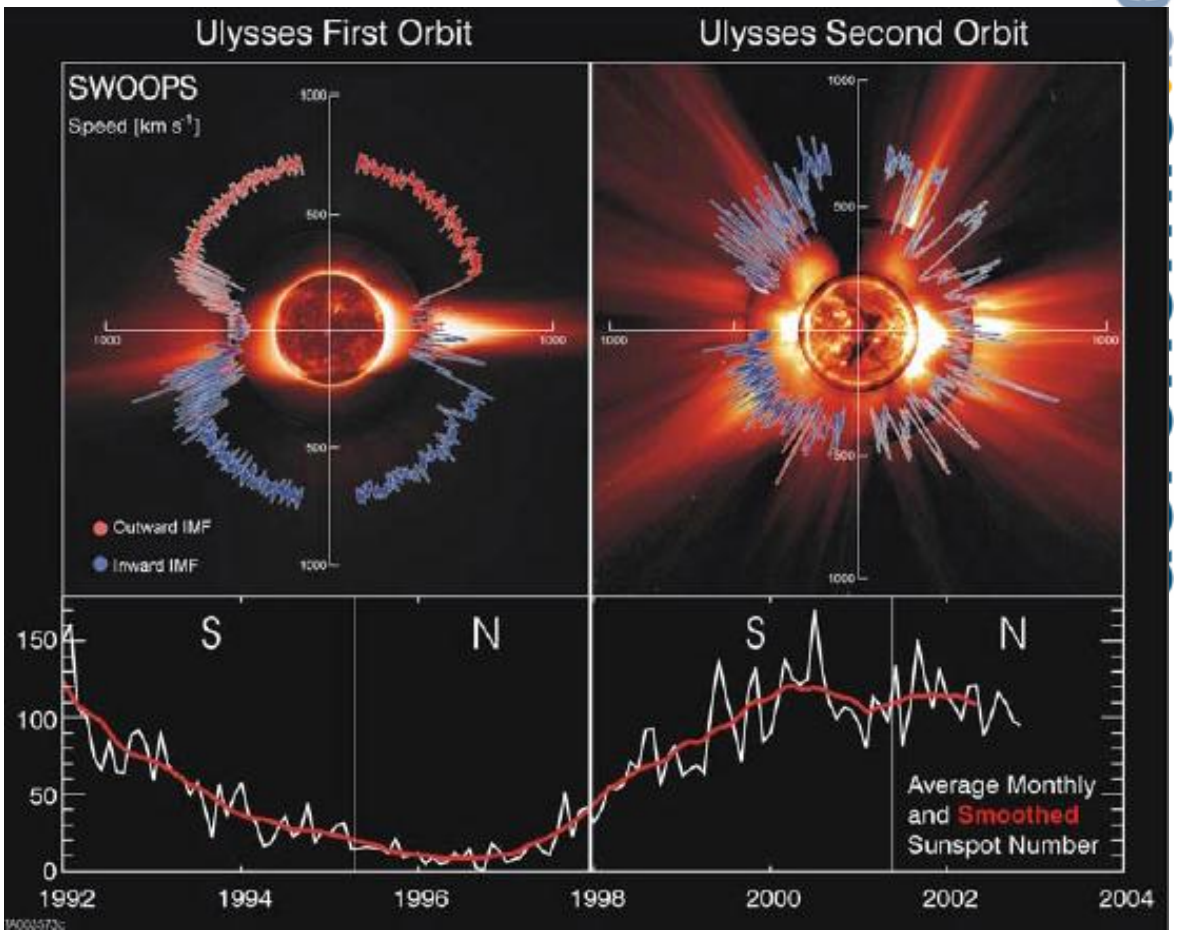
- Any successful model should be able to explain [or at least to reproduce] the results of statistical studies performed on the data.

Solar Wind: The discovery of two regimes

Ulysses spacecraft measurements of the solar wind speed and IMF polarity in the 3-D heliosphere at times near:

- solar min. (top left-hand panel)
- solar max. (top right-hand panel).

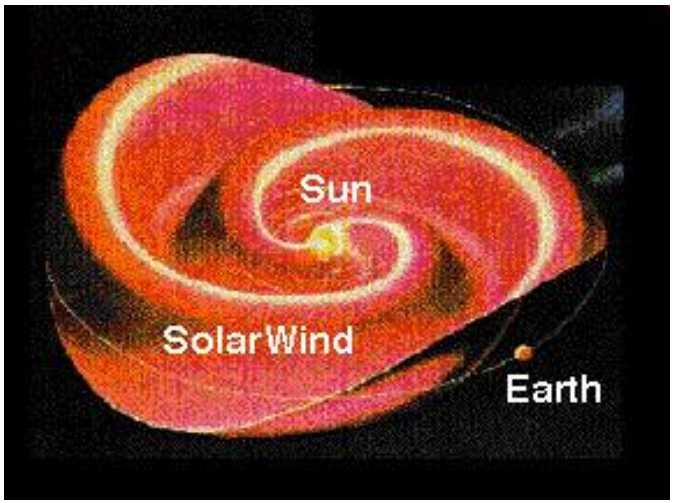
Sunspot number as a function of time.



McComas et al. (2003)

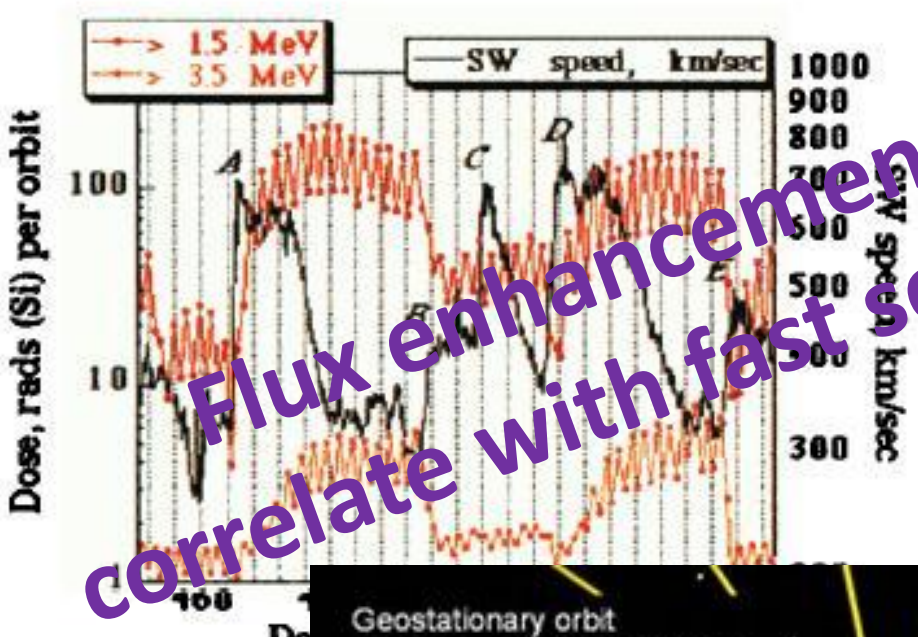
Electron enhancements in the radiation belts are for the most part correlated with:

- Fast solar wind streams [Paulikas and Blake, 1979; Baker et al., 1986].
- CME events [Li et al., 1993].
- IMF Bz < 0 [Blake et al., 1997].
- Magnetic storms [Baker et al., 1986; Reeves, 1998].



Vsw > 500 km/s
Bz < 0 nT

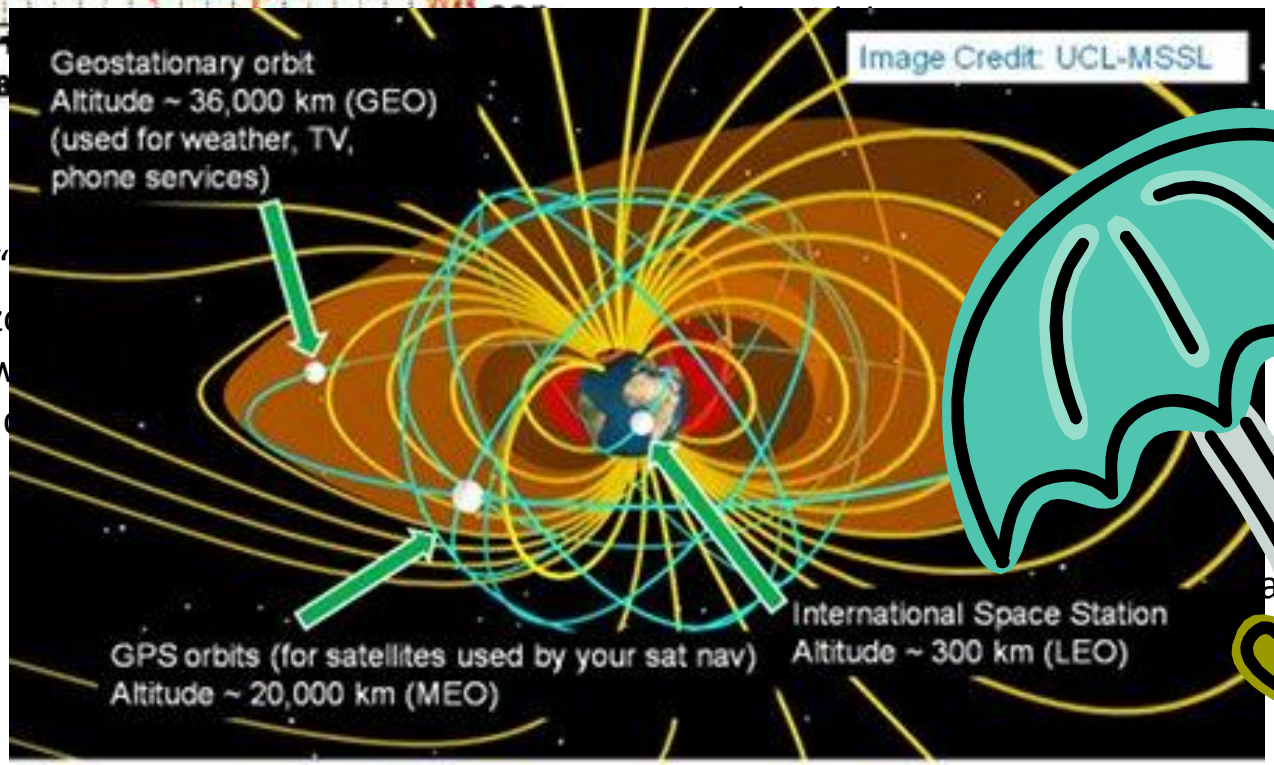
L1 monitoring of the solar wind is vital for space weather forecasting!



Flux enhancements sometimes correlate with fast solar wind streams.

Case A: There was a large increase in the solar wind velocity, a large pressure pulse, and a southward turning of the inter-planetary field. The relativistic electrons first strongly decreased over a few hours, and then increased over the next several days to a level much higher than prior to the arrival of the high-speed solar wind.

Case B: Similar to Case A except that the solar-wind speed increase was much smaller. It appears to have been inadequate to cause a large increase in the relativistic electron intensity, although an



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SOLAR WIND

OMNIWeb data

Crosby N., Meredith N., Coates A., Iles R., NPG, 12, 993, 2005

V_{sw} (km/s) [daily averaged]

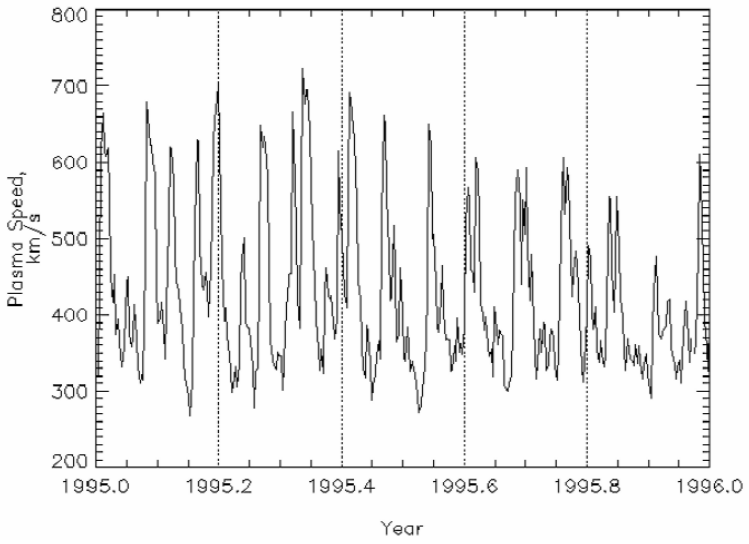
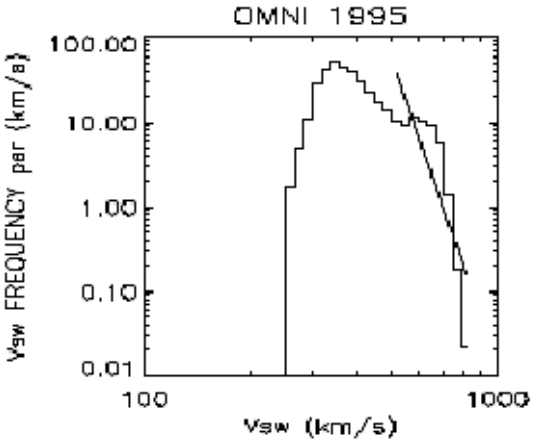


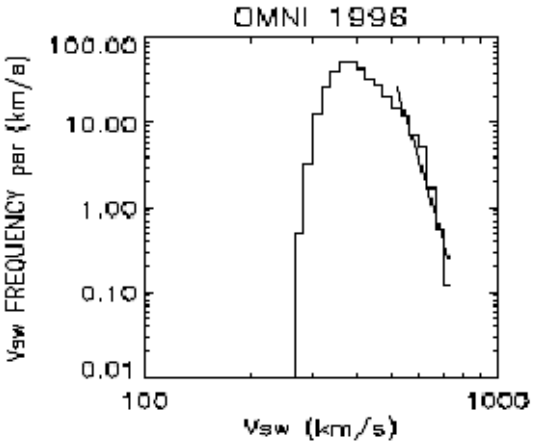
Table 5. Characteristics for the solar wind velocity (V_{sw}) frequency distributions for different years and interplanetary magnetic field intervals.

YEAR	V_{sw} $(-Bz+Bz)$	V_{sw} $(-Bz)$	V_{sw} $(+Bz)$
1995	−5.54±0.15	−5.66±0.19	−5.40±0.26
1996	−10.45±0.27	−10.59±0.35	−10.27±0.43
1997	−13.76±0.59	−13.44±0.74	−14.32±0.99

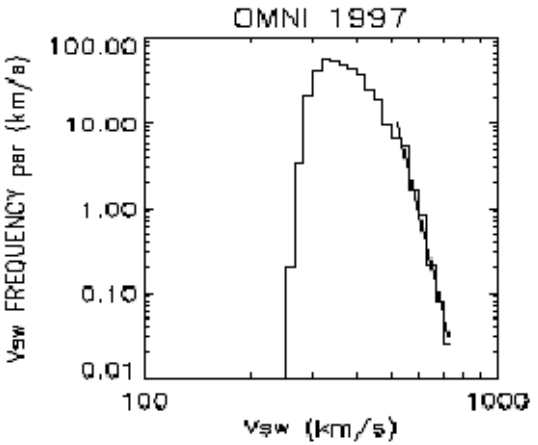
1995



1996



1997

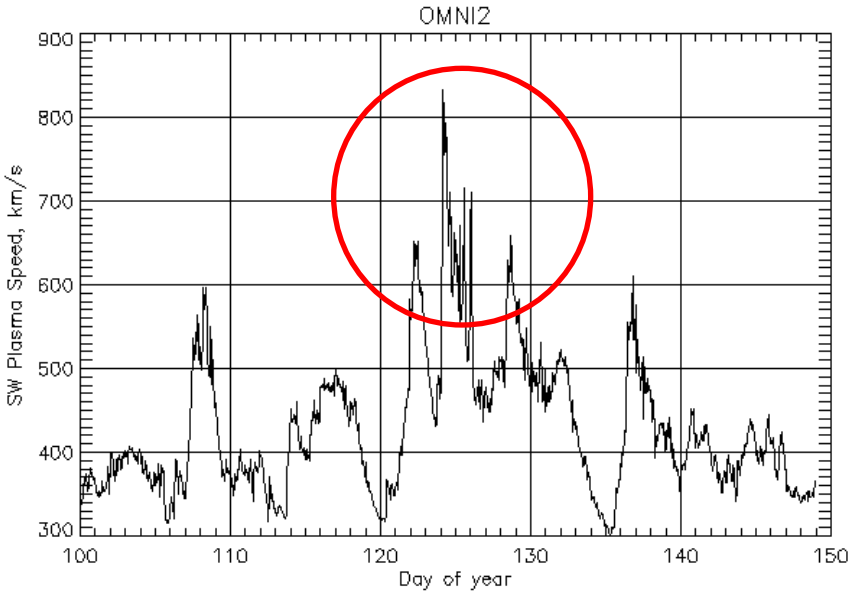


OUTER ELECTRON RADIATION BELT – SOLAR WIND

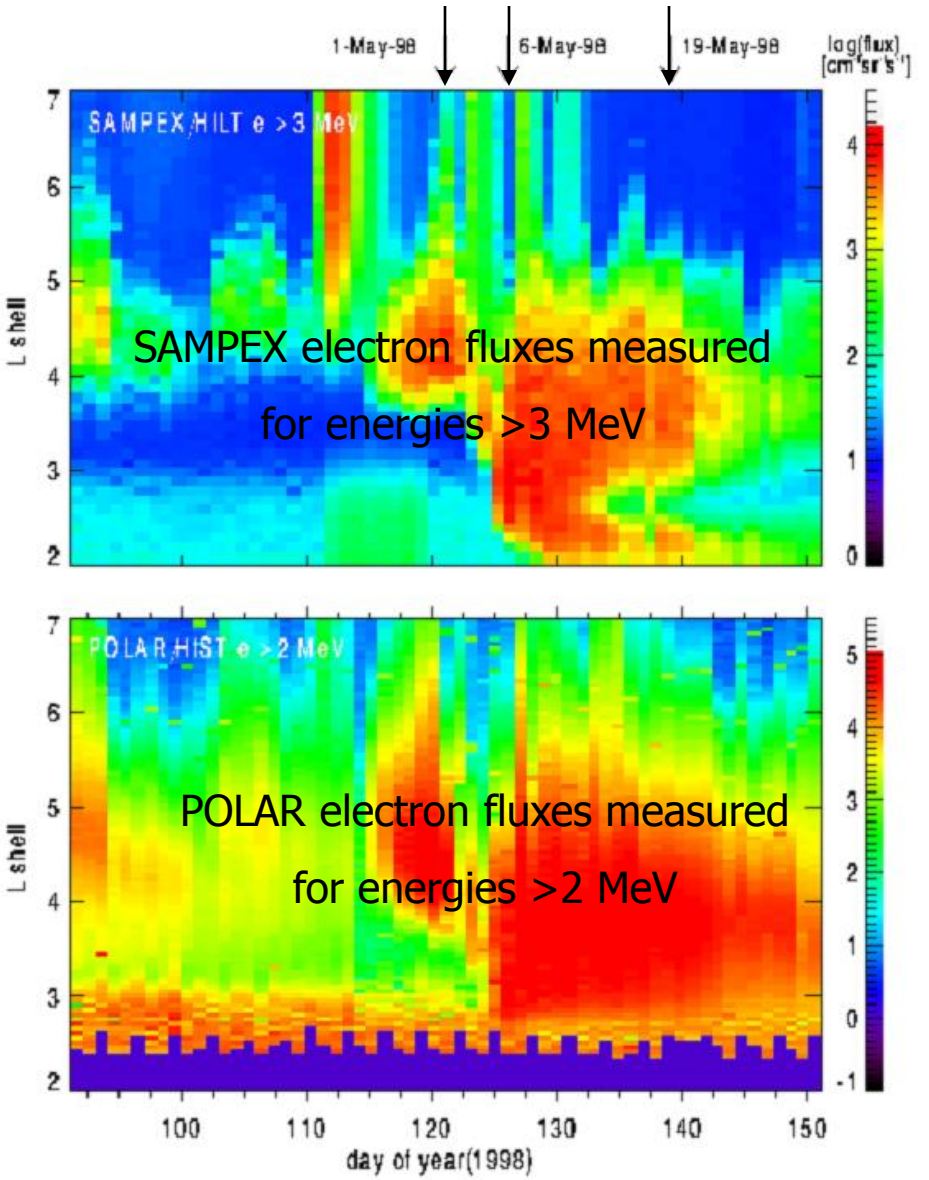
	CID/STRV-1a Outer Electron Radiation Belt Data			OMNI Solar Wind Data	
Year	T_{REC} (ΣL) 4.1 < L< 7.7 slope	TREC (ΣL) 4.1 < L< 5.5 Slope	TREC (ΣL) 5.5 < L < 7.7 slope	Vsw (-Bz & +Bz) slope	Vsw (-Bz) slope
1995	-1.195+/-0.060	-1.254+/-0.069	-1.548+/-0.122	-5.54+/-0.15	-5.66+/-0.19
1996	-1.535+/-0.082	-1.430+/-0.104	-2.074+/-0.193	-10.45+/-0.27	-10.59+/-0.35
1997	-1.739+/-0.092	-1.950+/-0.119	-2.675+/-0.234	-13.76+/-0.59	-13.44+/-0.74

Crosby N., Meredith N., Coates A., Iles R., NPG, 12, 993, 2005

Satellite Anomalies



A very intense flux of electrons evident in the magnetosphere during May 1998 may have caused the Galaxy 4 satellite failure.



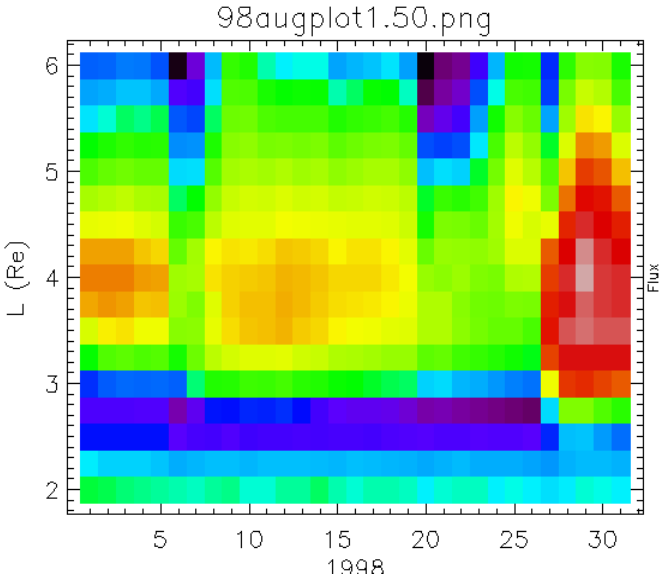
Baker, D.N., J.H. Allen, S.G. Kanekal, and G.D. Reeves; EOS, 79, p. 477, 1998

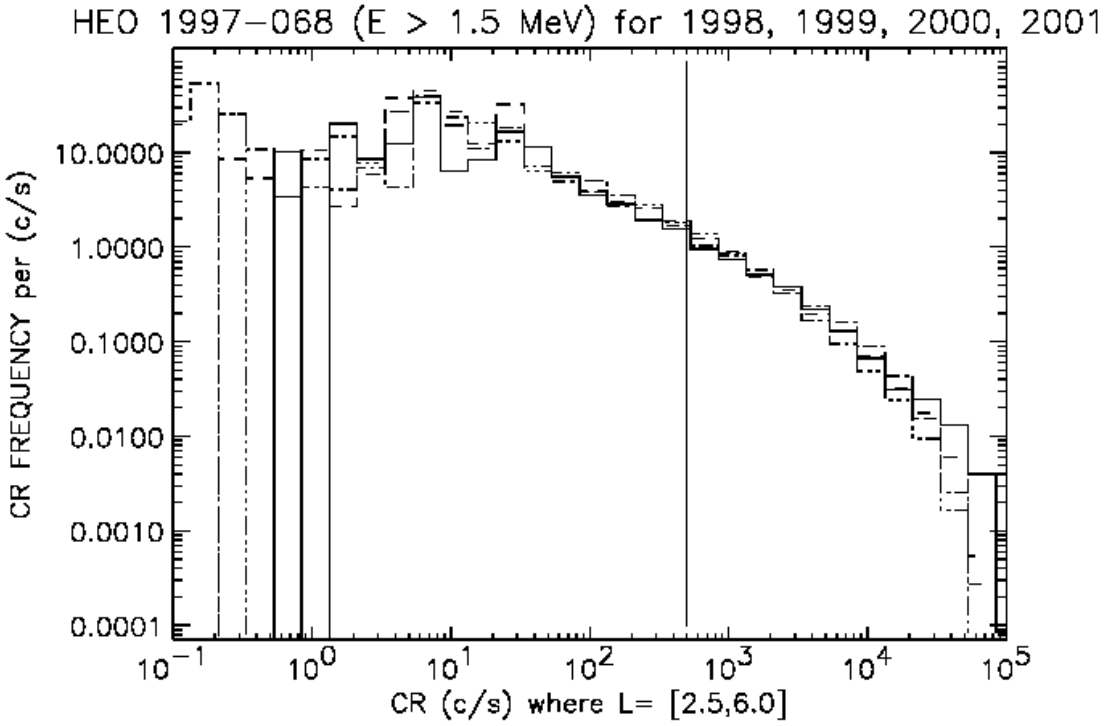
Daily Averaged Electron Outer Radiation Belt Count Rate Data

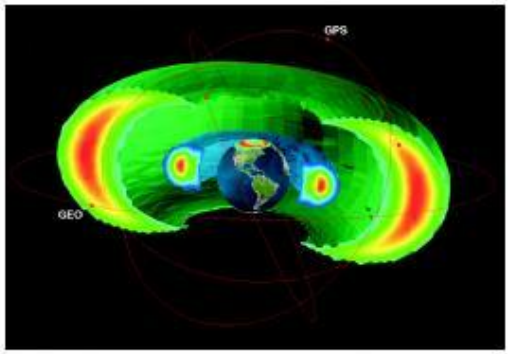
HEO data courtesy of The Aerospace Corporation

L=6.0

L=2.5







Credit: NASA/RBSP

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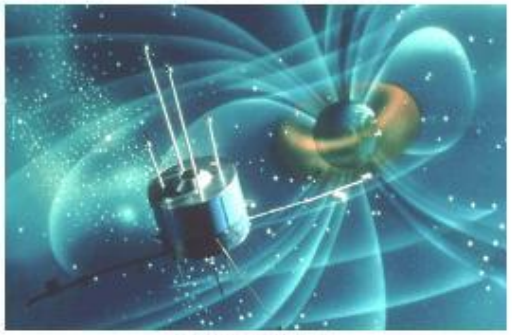

Credit: ESA/BAS

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