

Διαστημικό Περιβάλλον



Space Environment

Space Environment Lecture 9



Substorms and storms
Ring current and radiation belts

Εξέλιξη μαγνητοσφαιρικής υποκαταιγίδας

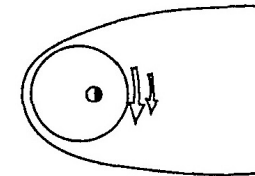
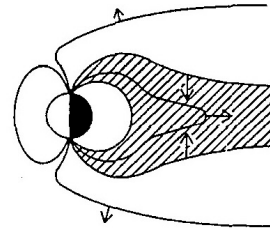
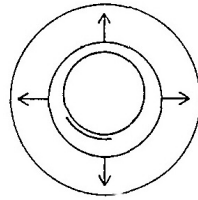
Ionosphere

Magnetosphere

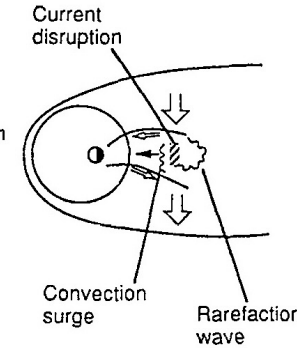
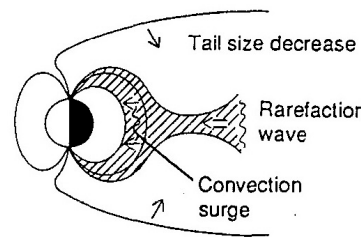
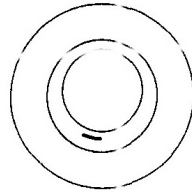
Growth
Oval boundaries
move equatorward

Noon-midnight
cross-section

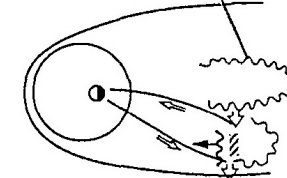
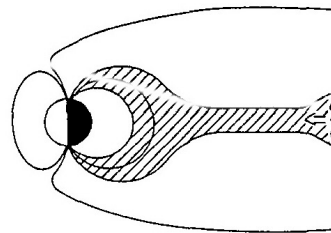
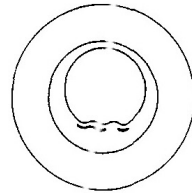
Equatorial
projection



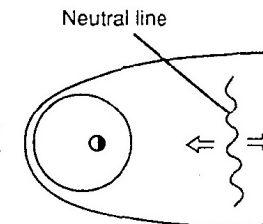
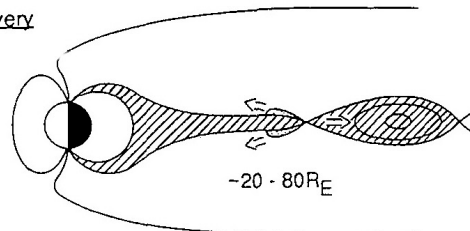
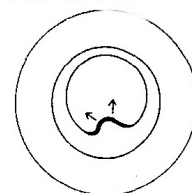
Onset
Initial arc brightening



Expansion



Late Expansion/Recovery

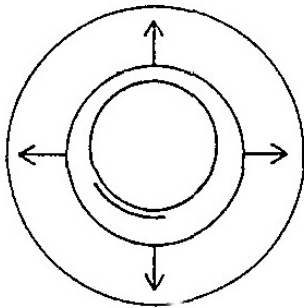


Εξέλιξη μαγνητοσφαιρικής υποκαταιγίδας

Ionosphere

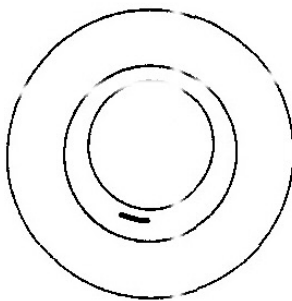
Growth

Oval boundaries move equatorward



Onset

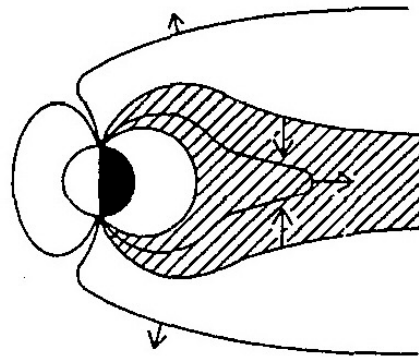
Initial arc brightening



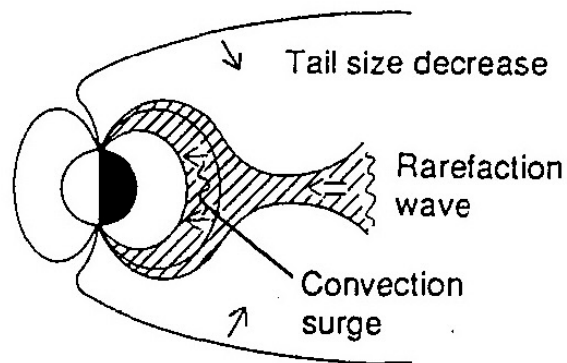
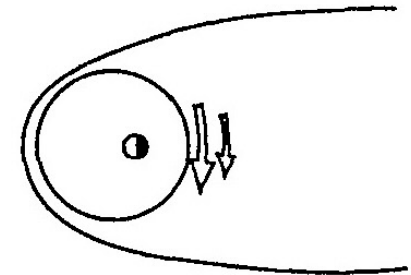
Expansion

Magnetosphere

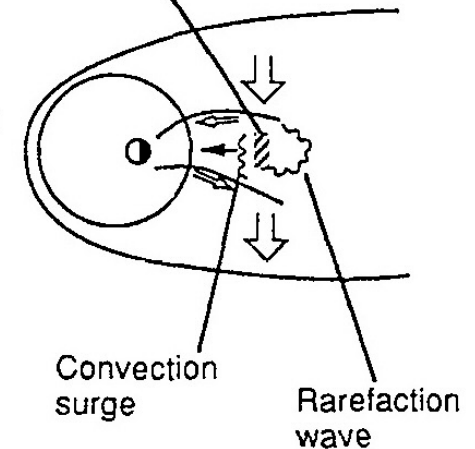
Noon-midnight cross-section



Equatorial projection

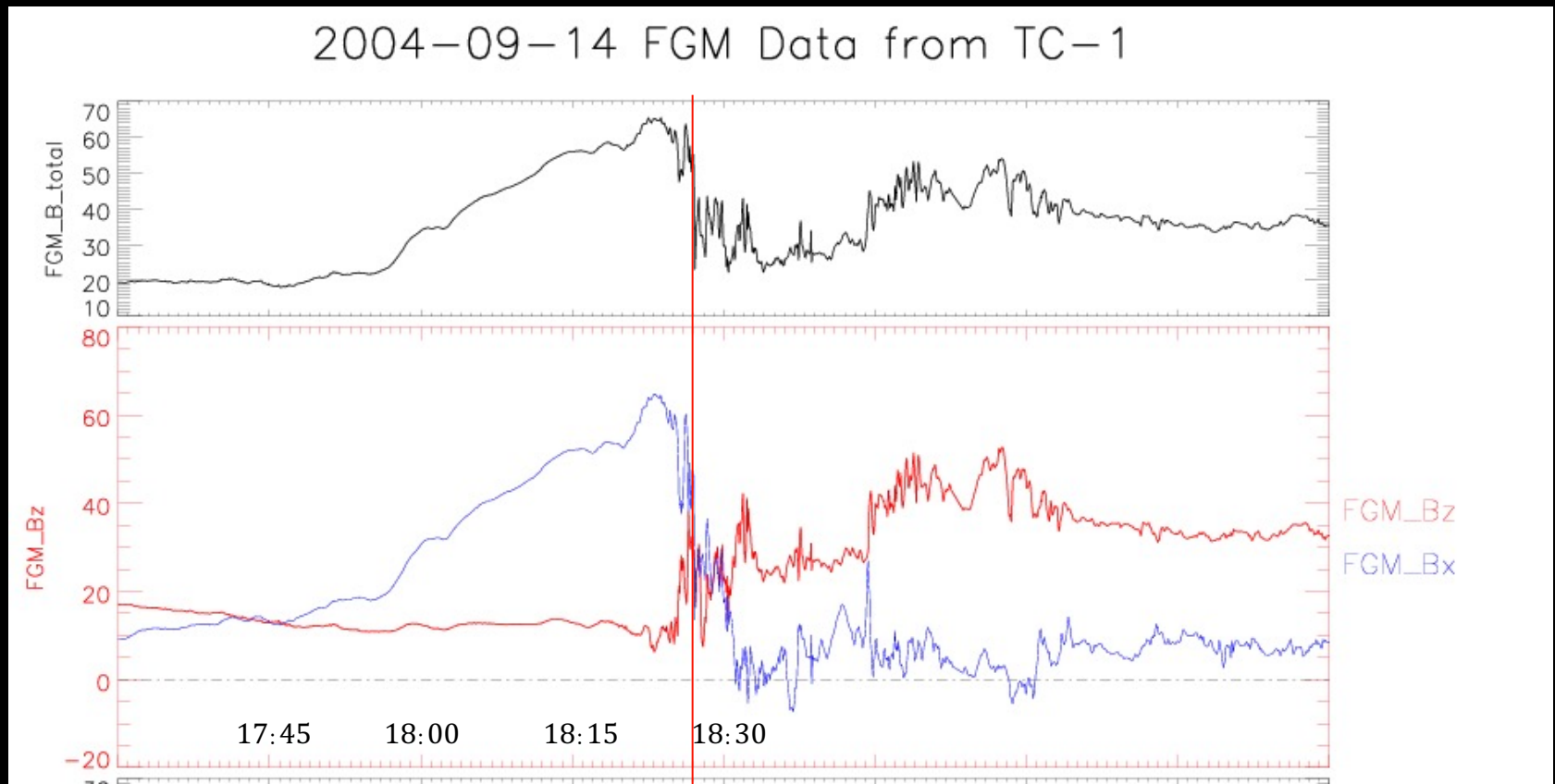


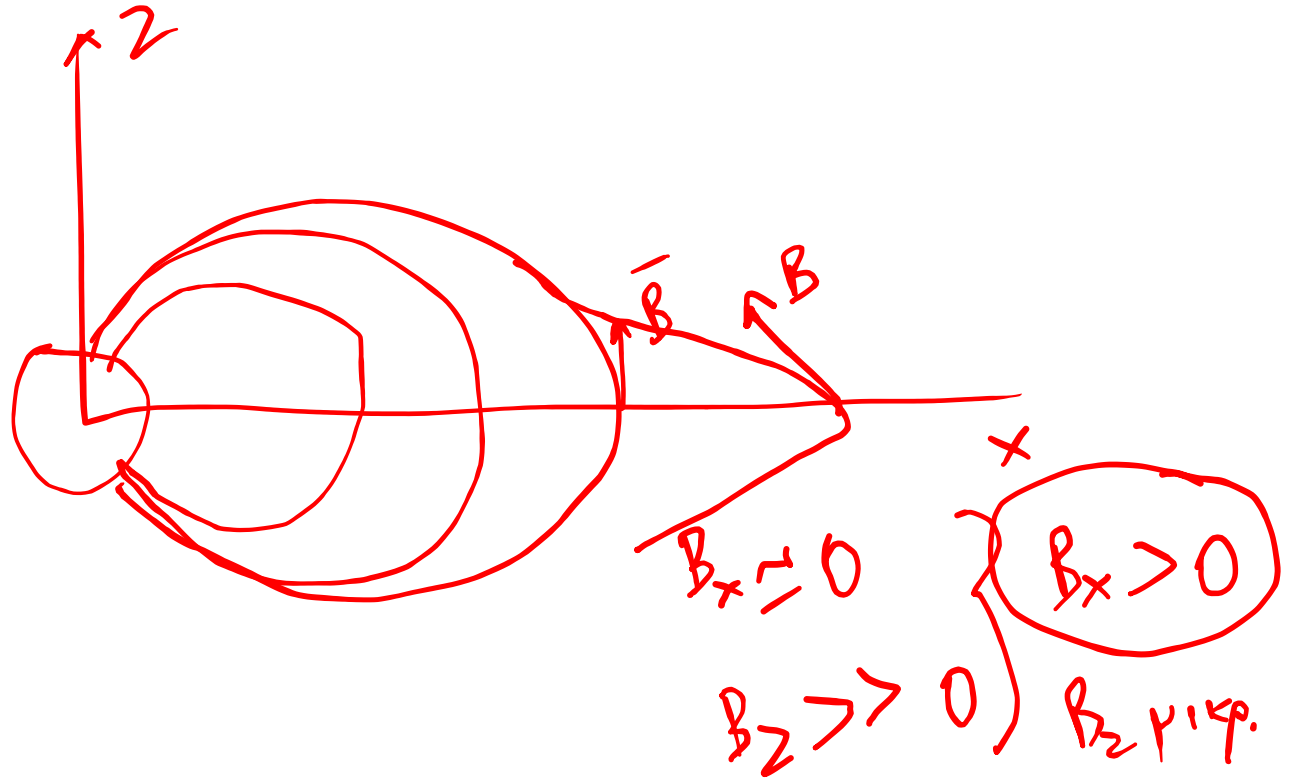
Current disruption



Τυπική μαγνητική αναδιαμόρφωση

Βαθμιαία απομάκρυνση από διάταξη διπόλου (τέντωμα / stretching) και ταχεία επιστροφή σε διάταξη διπόλου (dipolarization)

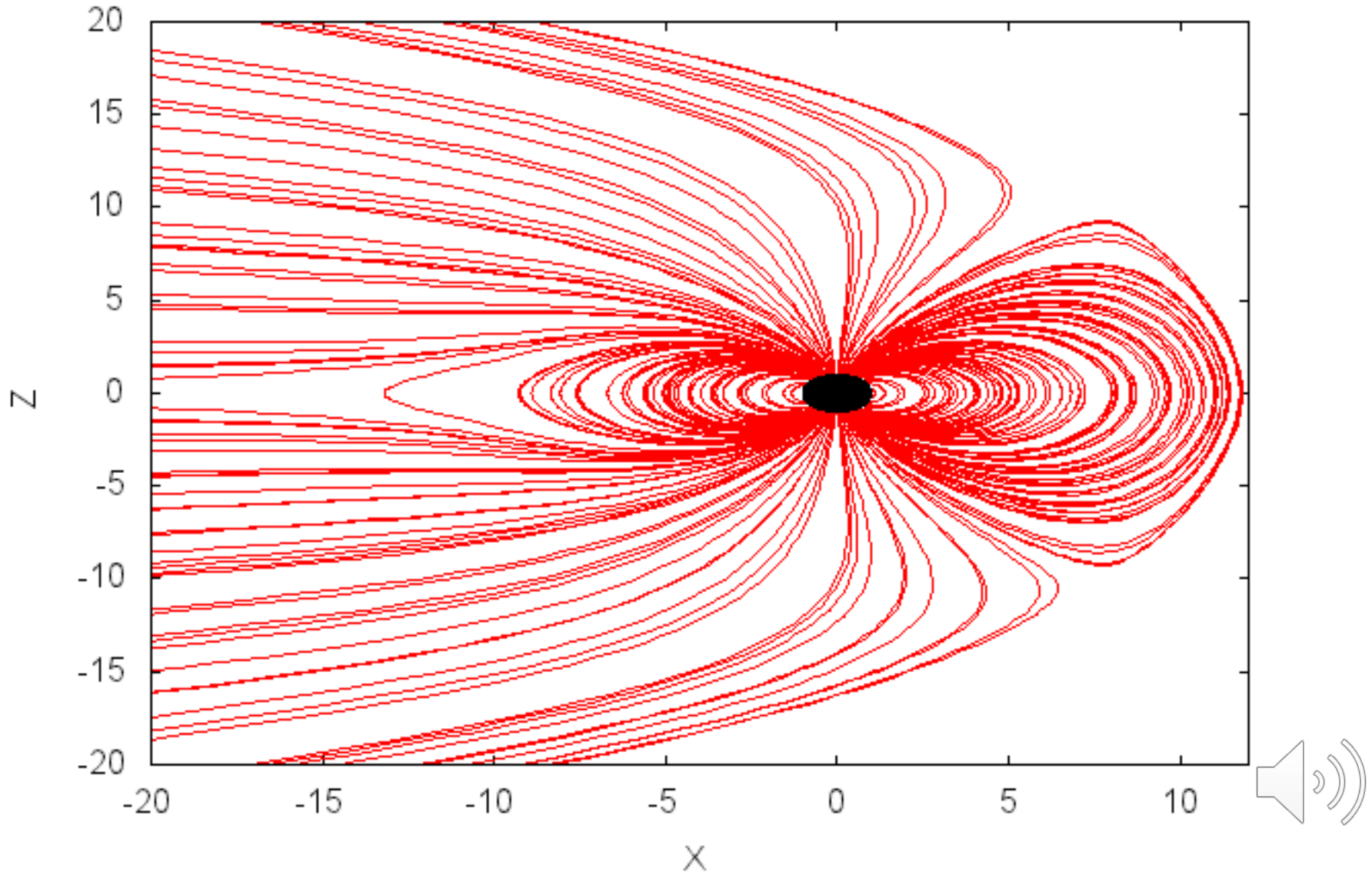


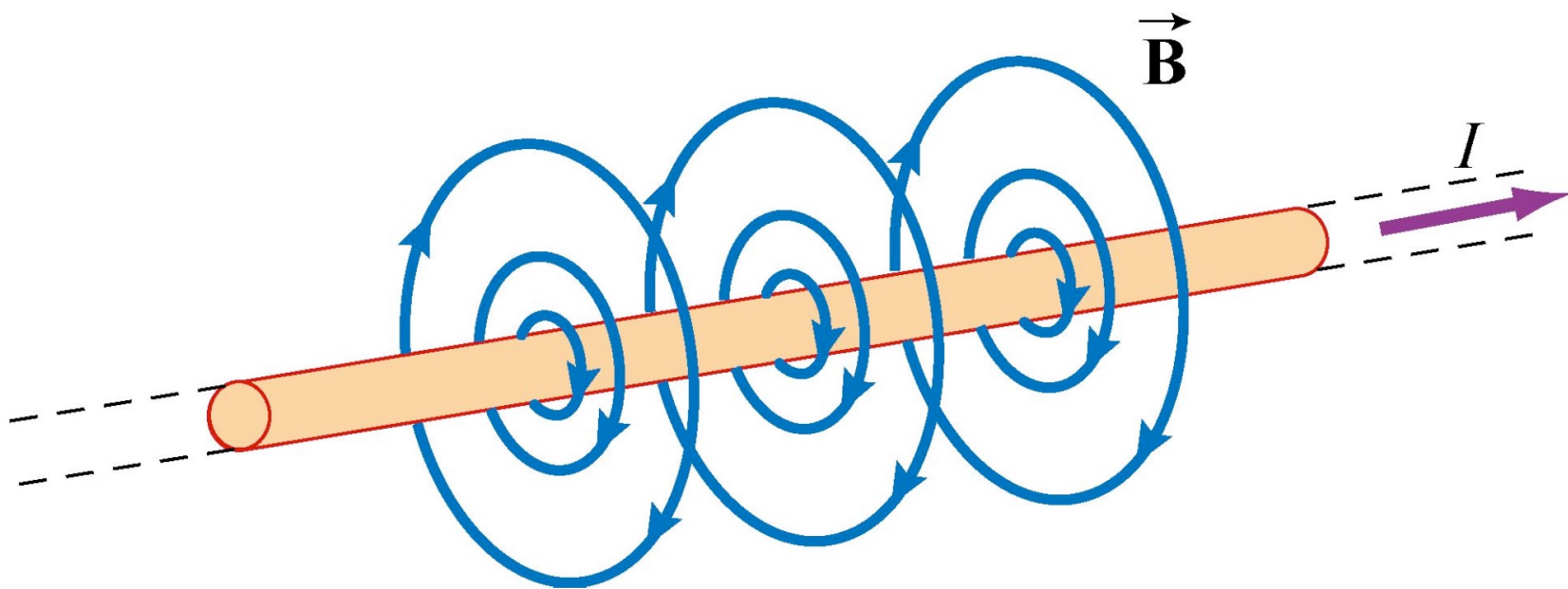


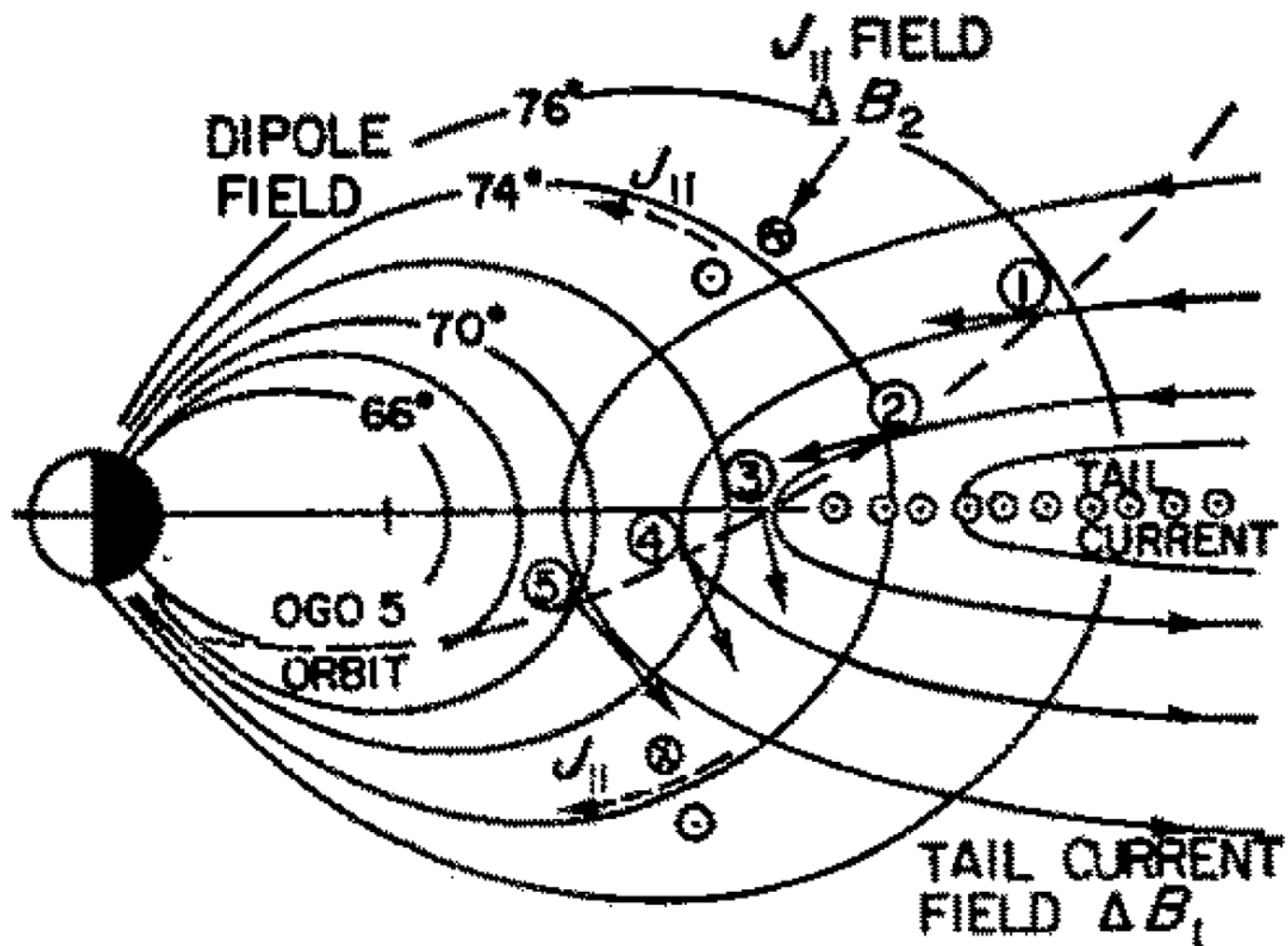
Αναδιαμορφώσεις μαγνητικού πεδίου

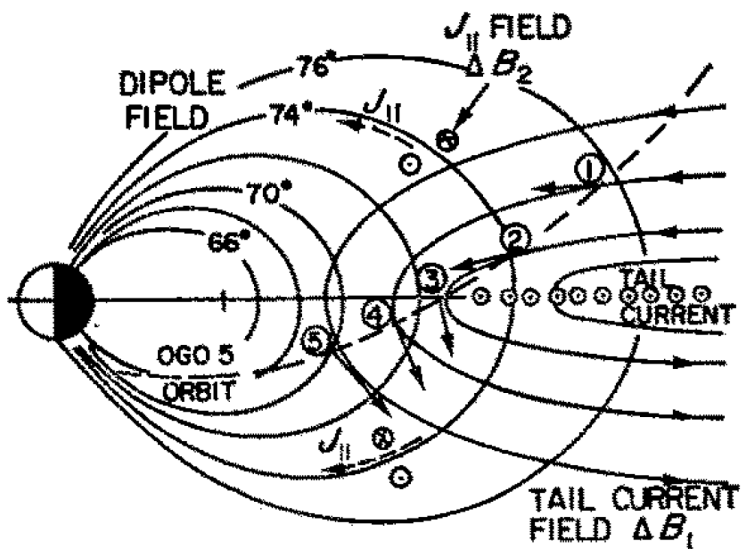
Substorm-driven Magnetosphere

t=0

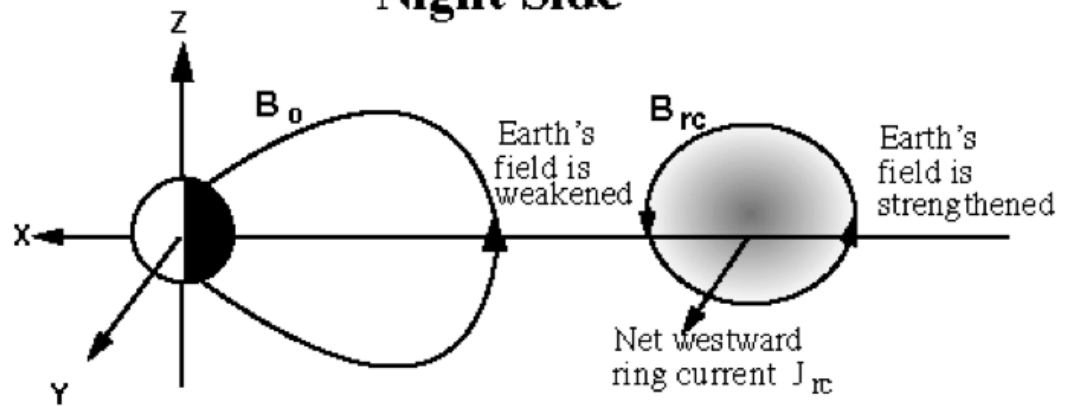








Night Side



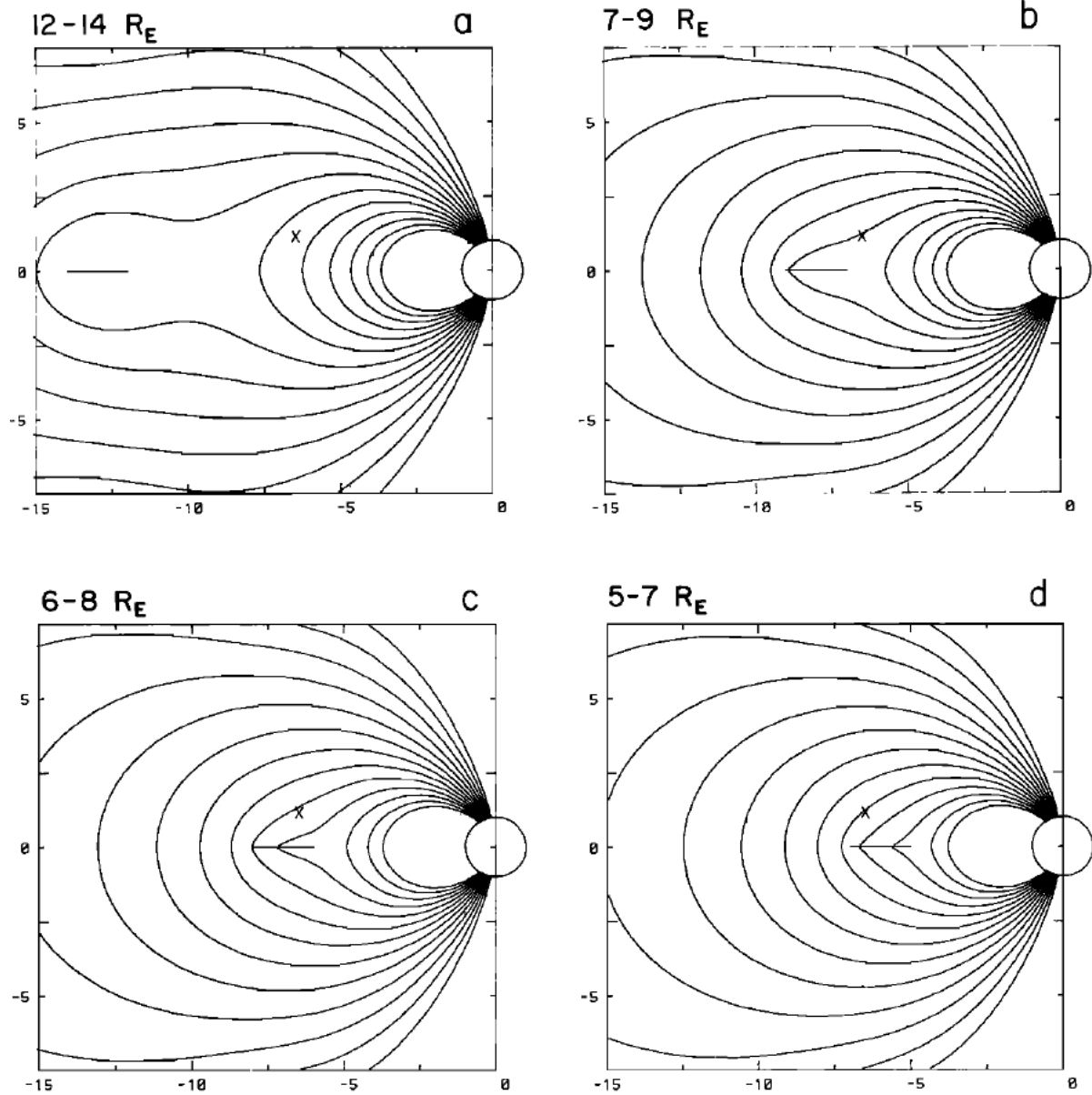


Fig. 2. Magnetic field lines in the two-dimensional model. The location of the current sheet is indicated by a straight line at the tail midplane, and by the label on each panel. The location of the ATS 6 satellite is indicated by a cross. The sheet current strength is $\kappa_y = 300$ mA/m. Field lines are traced outward starting from the earth at 2° intervals from 57° to 81° magnetic latitudes.

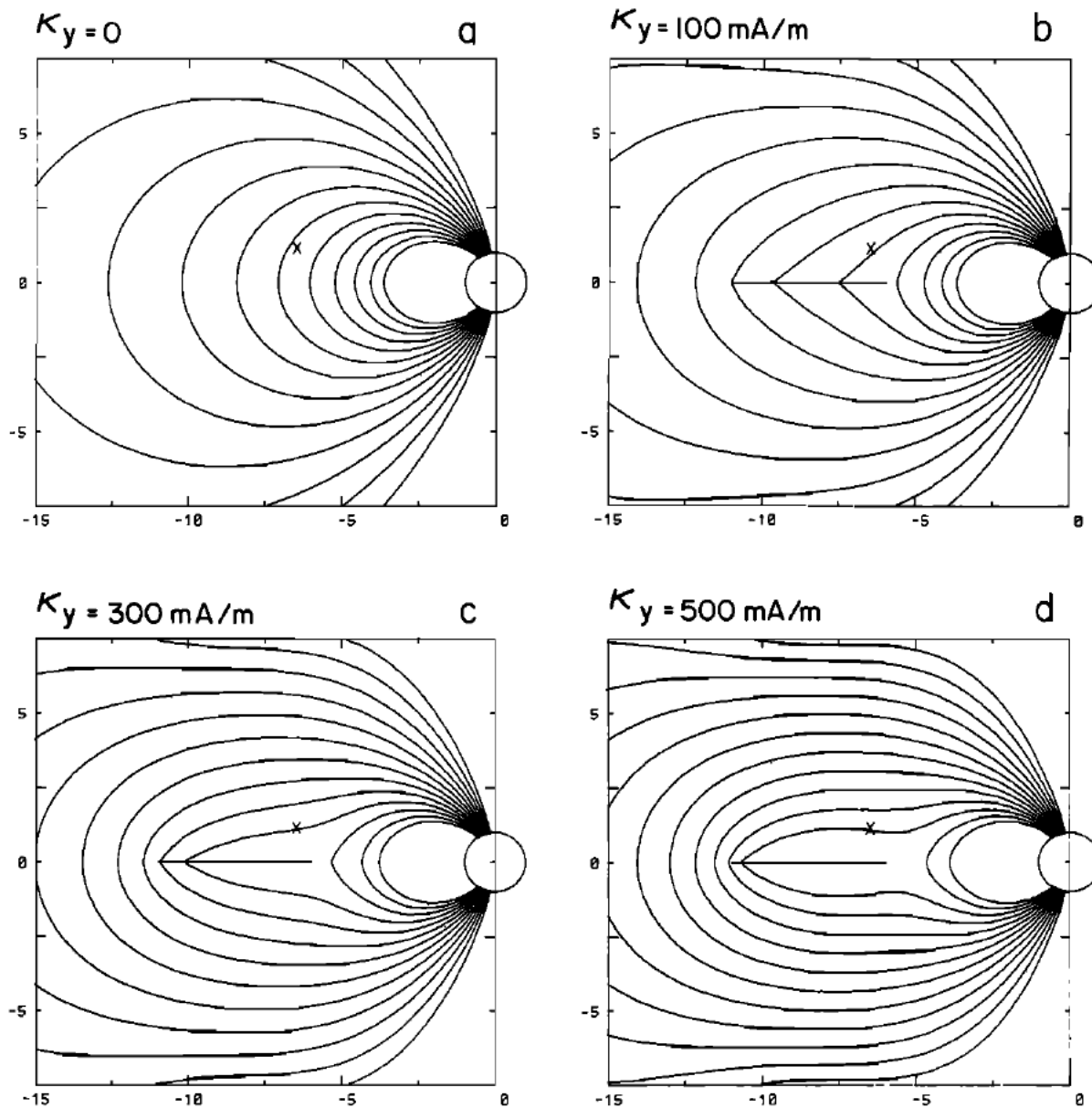
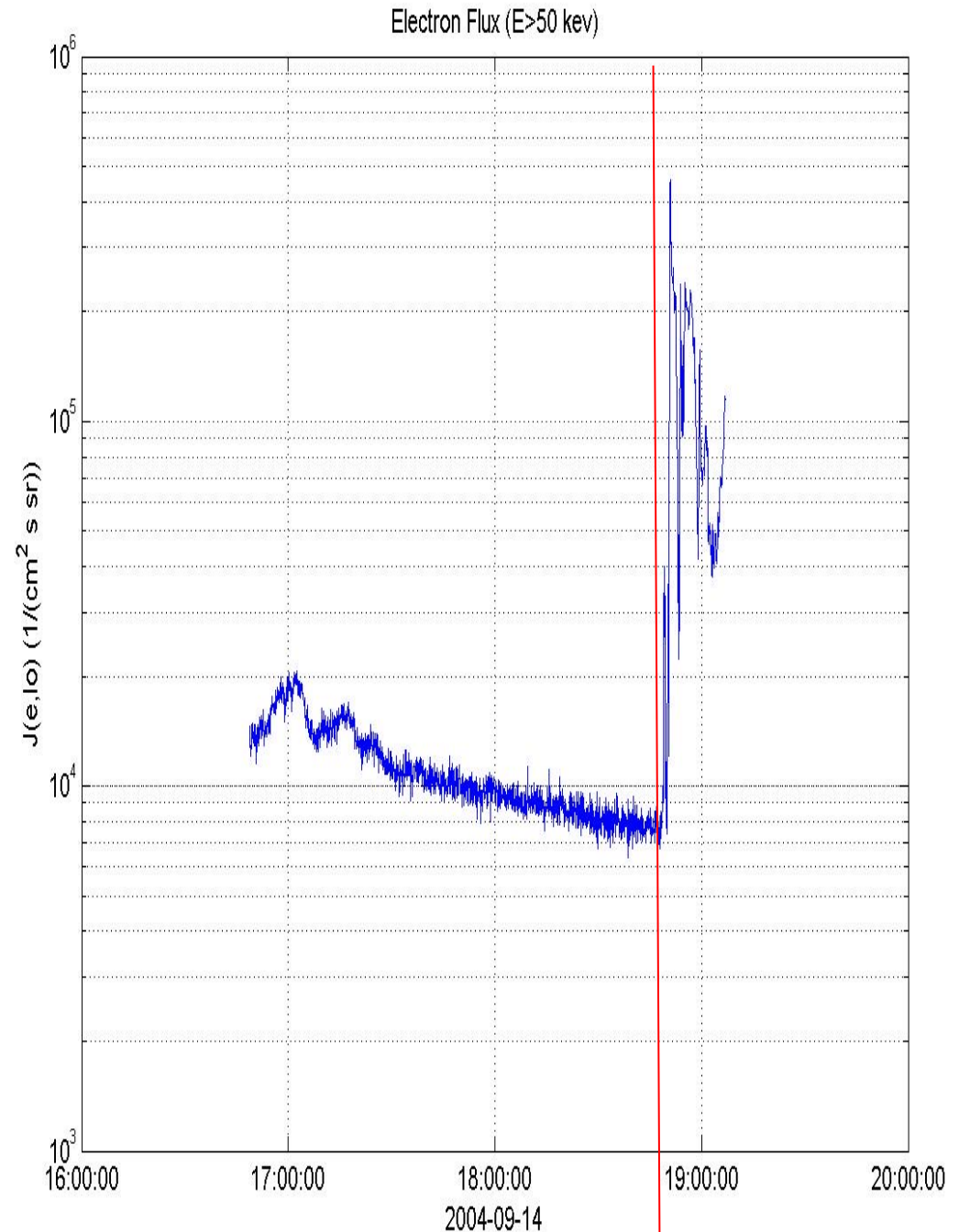


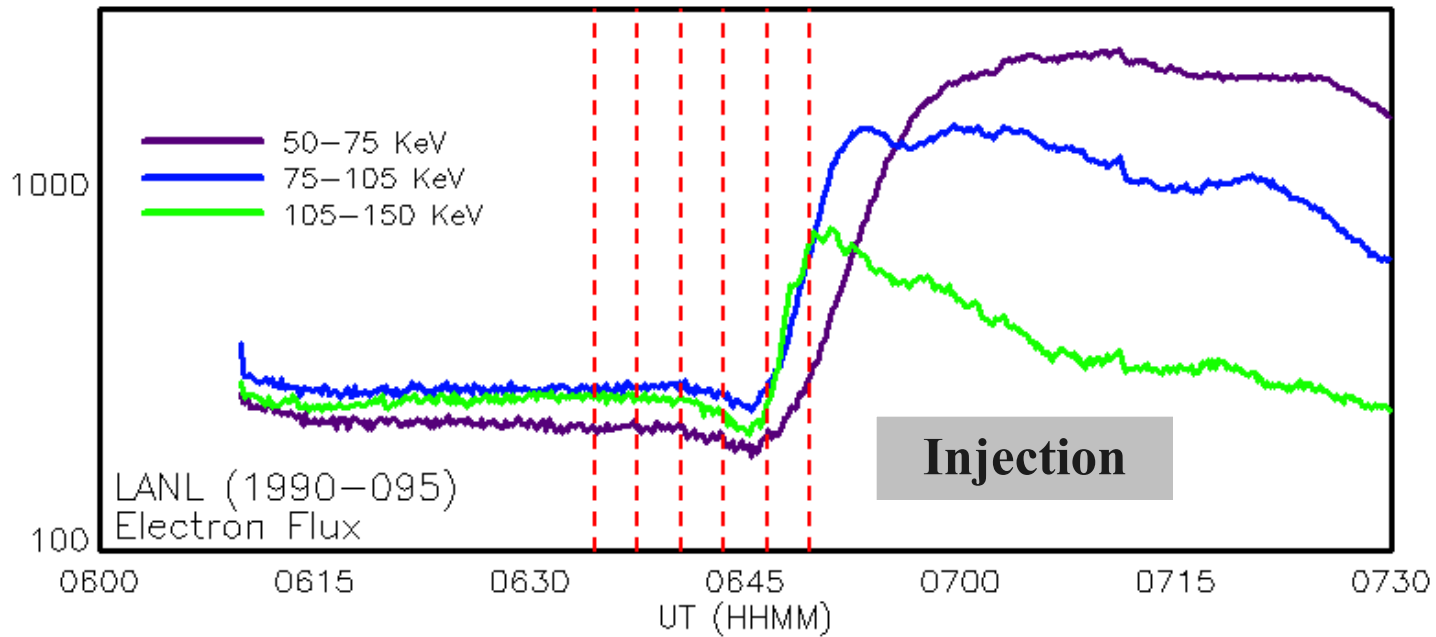
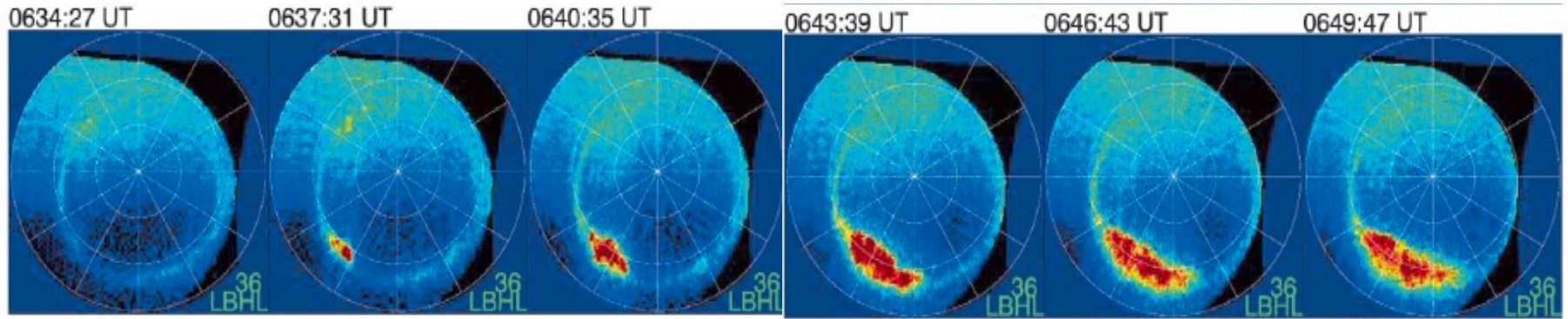
Fig. 3. Similar to Figure 2 except that the tail current sheet location is fixed and the strength varies.

Τυπική μεταβολή υποκαταιγίδας

Επιτάχυνση
σωματιδίων
και έγχυση
στην ενδότερη
μαγνητόσφαιρα

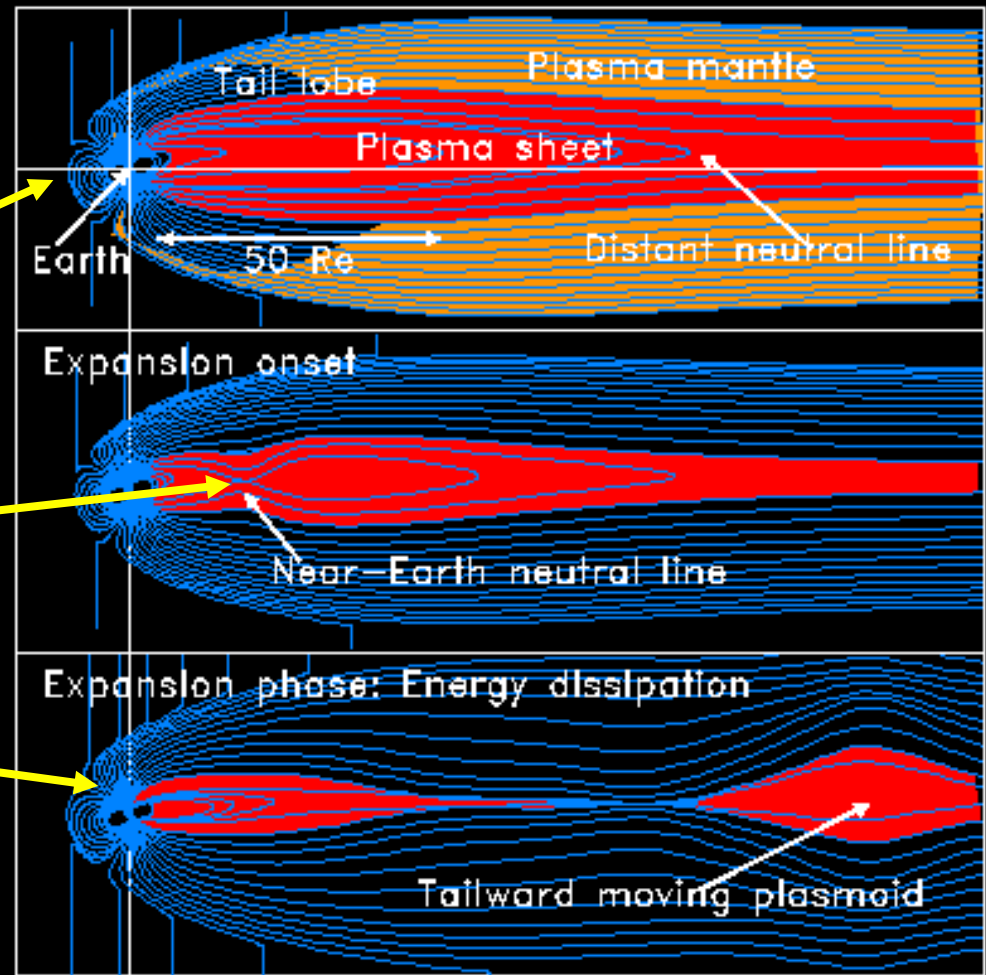


Electron injections and aurora during substorms



Magnetospheric substorms

- Duration: 2-3 hours
- Energy: 10^{15} - 10^{16} J
- dayside reconnection = energy loading
- nightside reconnection = msp. reconfigurations, energy dissipation, particle acceleration, plasmoid ejection
- auroral brightening, field-aligned currents, Joule heating
- Rate: several / day



10^{15} : Yearly electricity consumption in Greenland in 2008. 10^{16} : Impact energy released in forming Meteor Crater

10 MAGNETIC STORMS CAUSED BY COROTATING SOLAR WIND STREAMS

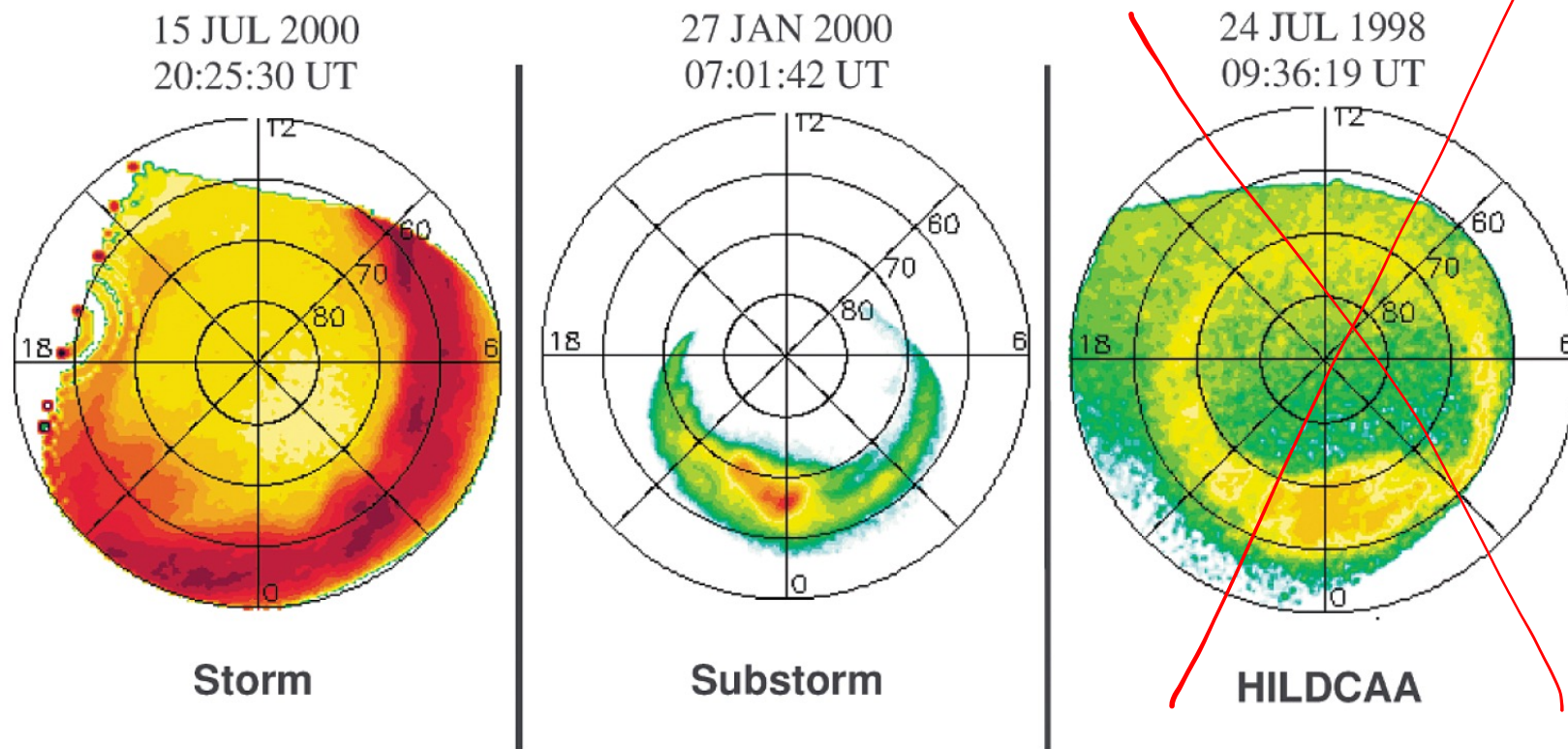
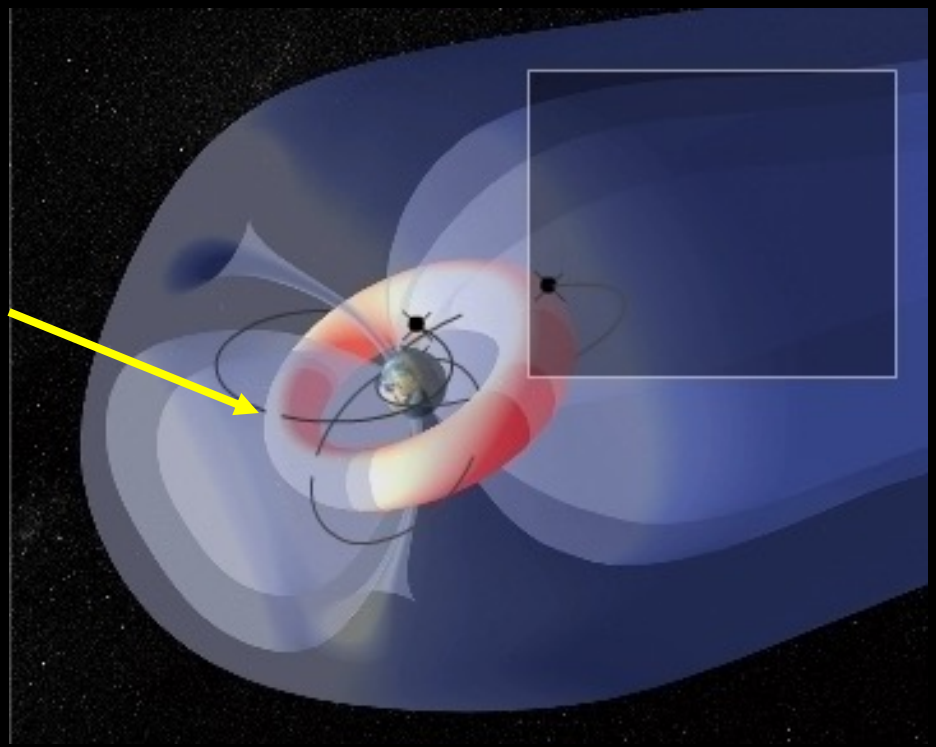



Plate 1. A comparison of typical auroral intensities during a magnetic storm, a substorm and a HILDCAA event. The HILDCAA event has the lowest of the three auroral luminosities. The figure is taken from *Guarnieri (2005)*.

Geospace magnetic storms

- Duration: 1-3 days
- Energy: 10^{16} - 10^{18} J
- Magnetosphere:
 - ◆ global B disturbances
 - ◆ **intense currents (RC)**
 - ◆ particle acceleration
- Auroral regions
 - ◆ bright auroral displays
 - ◆ intense ionospheric currents (electrojets)
 - ◆ rapid surface B variations
- Rate: 1/month





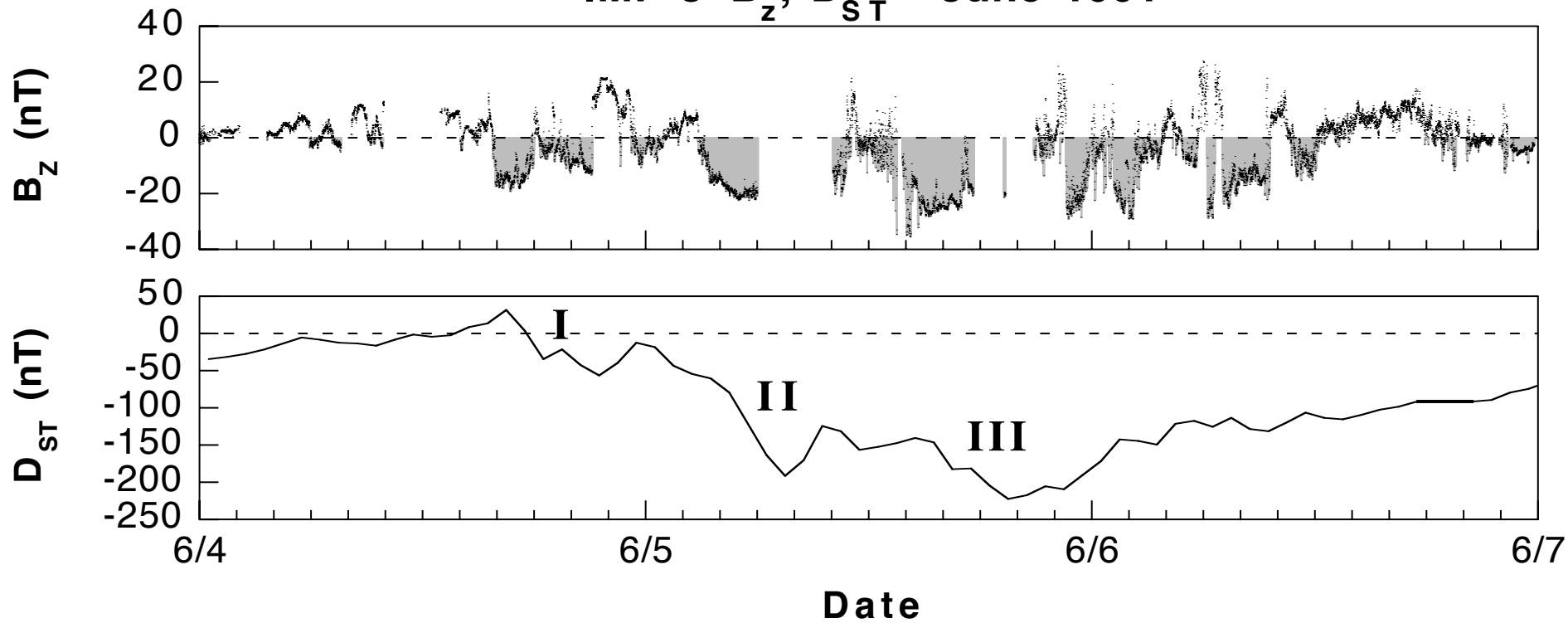
Καθοριστικό χαρακτηριστικό
της μαγνητικής καταιγίδας:

Παγκόσμια Μείωση
(σε μεσαία και χαμηλά πλάτη και
σε όλα τα γεωγραφικά μήκη)
της οριζόντιας συνιστώσας
του γεωμαγνητικού πεδίου

«Προαπαιτούμενο» καταιγίδων

Ισχυρό νότιο διαπλανητικό μαγνητικό πεδίο
μεγάλης διάρκειας (= πολλές ώρες)

IMP-8 B_z , D_{ST} - June 1991



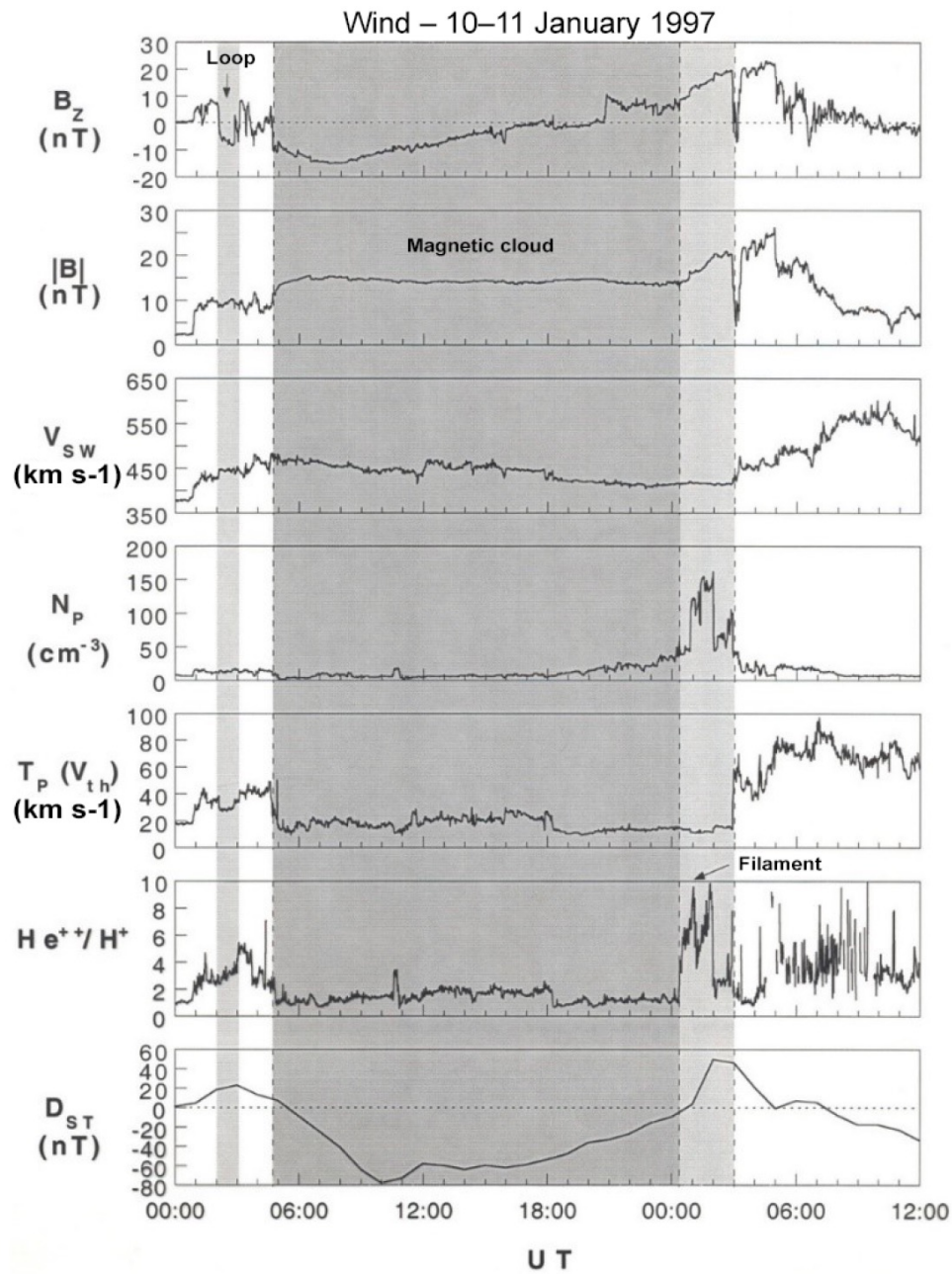


Figure 3. An ICME detected at 1 AU just upstream of the Earth.

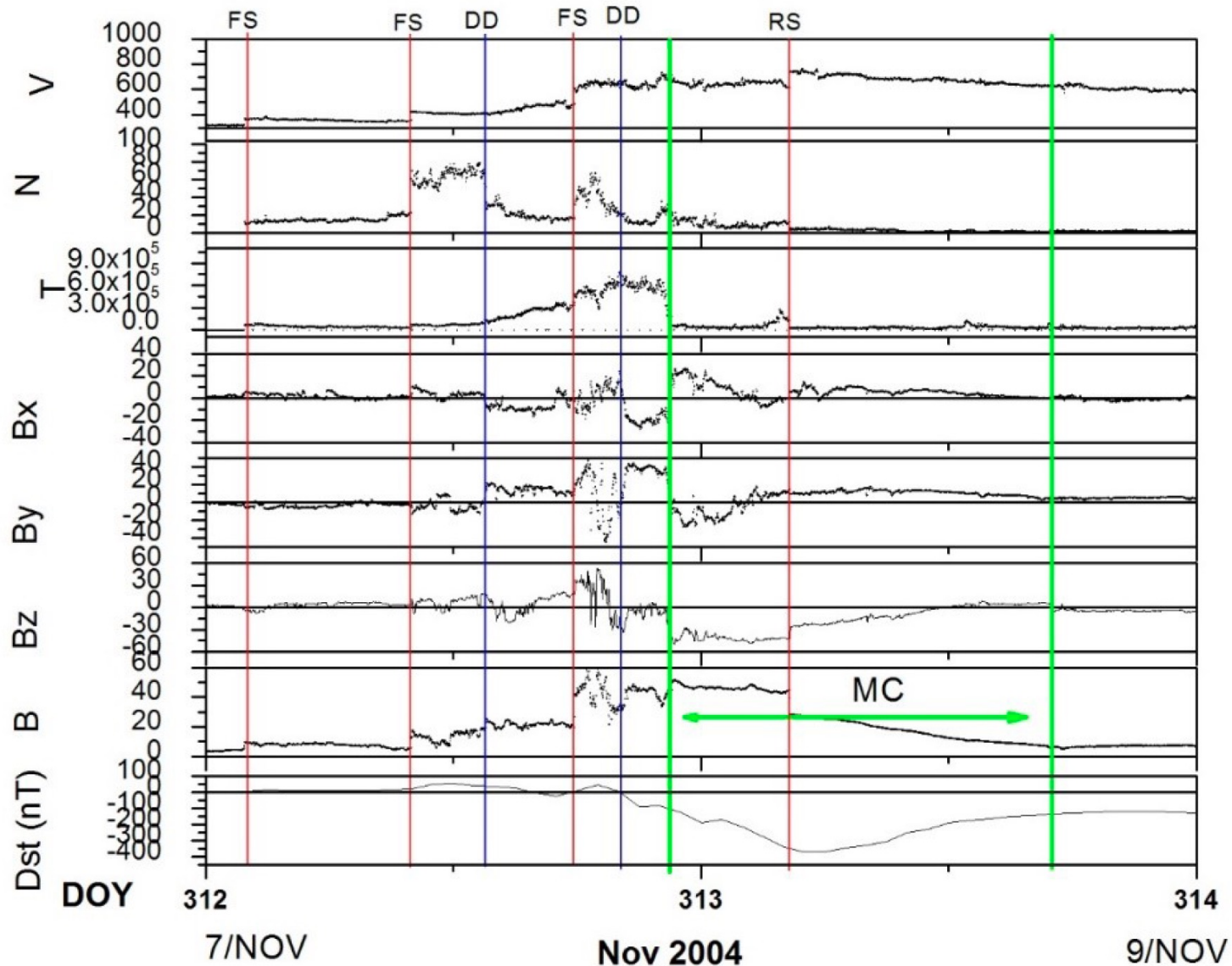
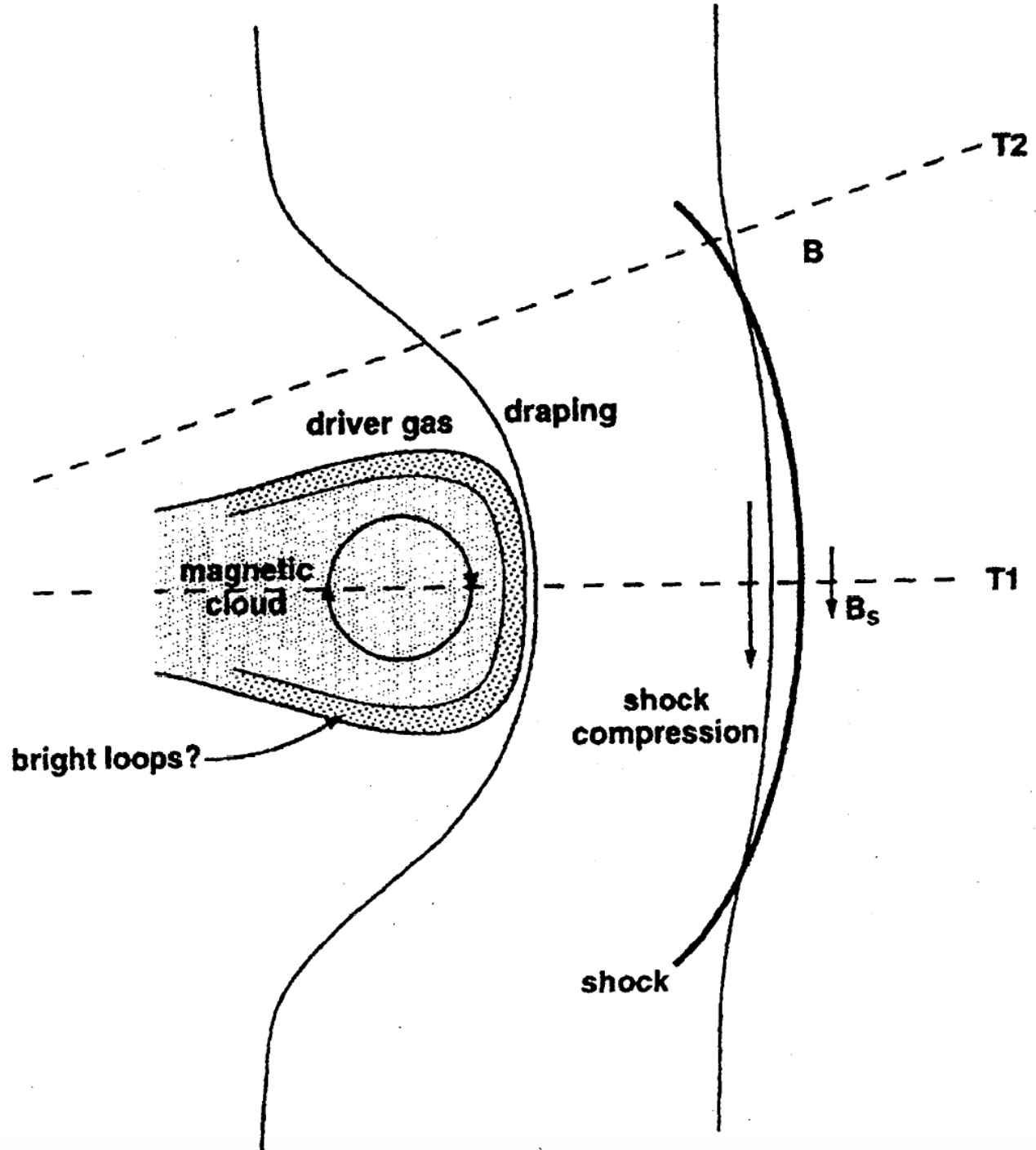
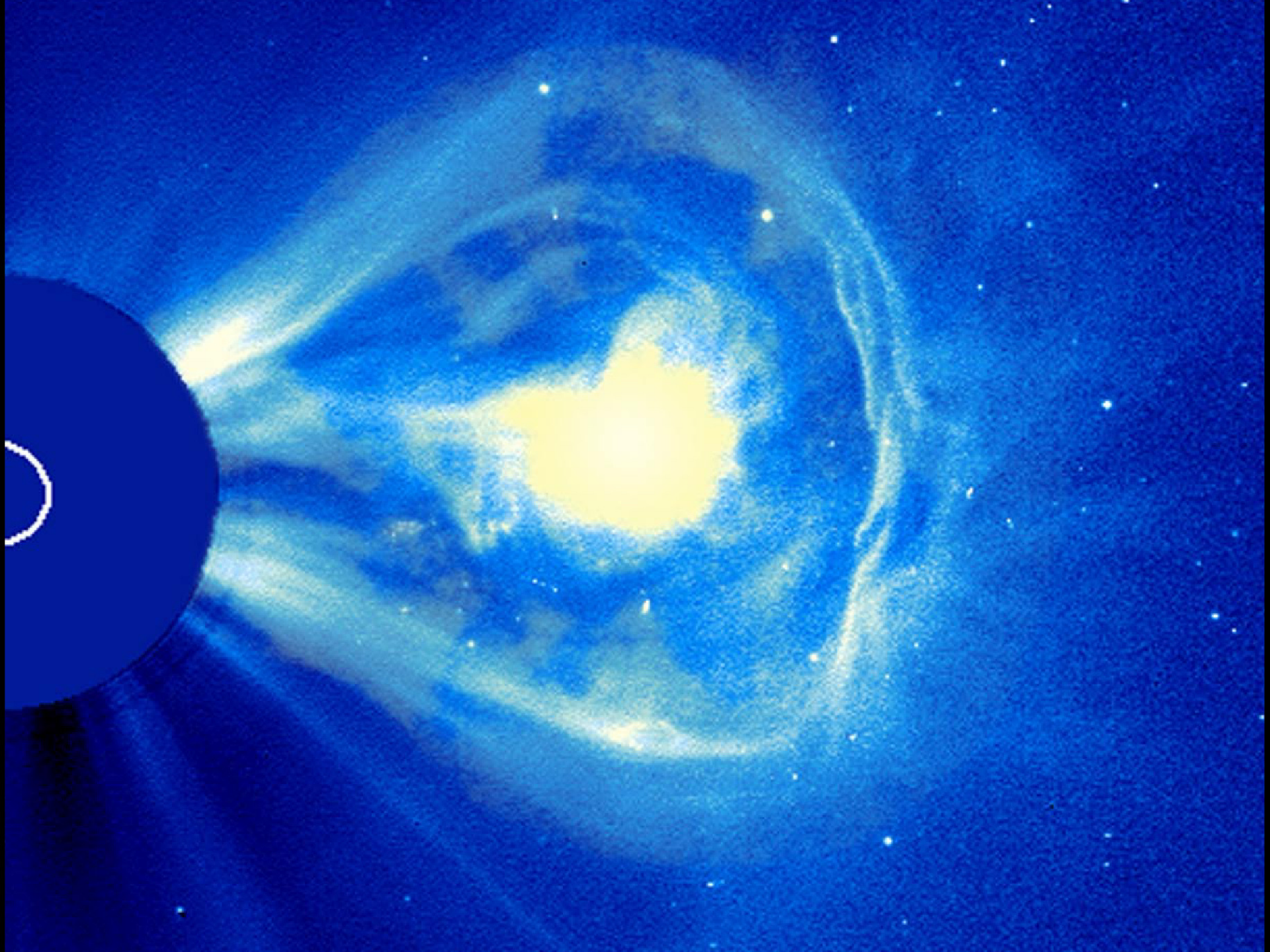
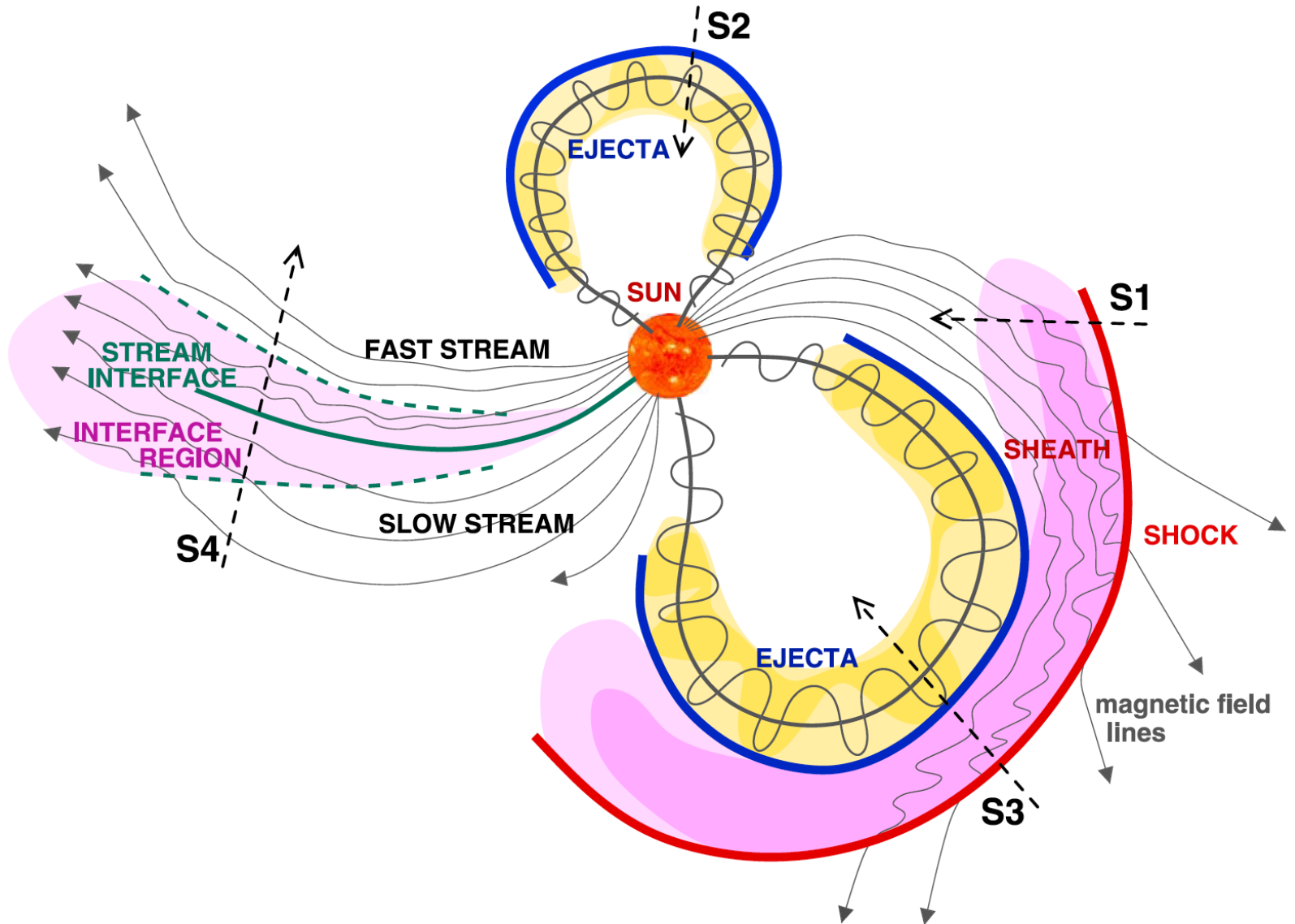



Figure 5. An example of three fast forward shocks pumping up the interplanetary magnetic field intensity. Taken from Tsurutani et al. (2008a). ²²





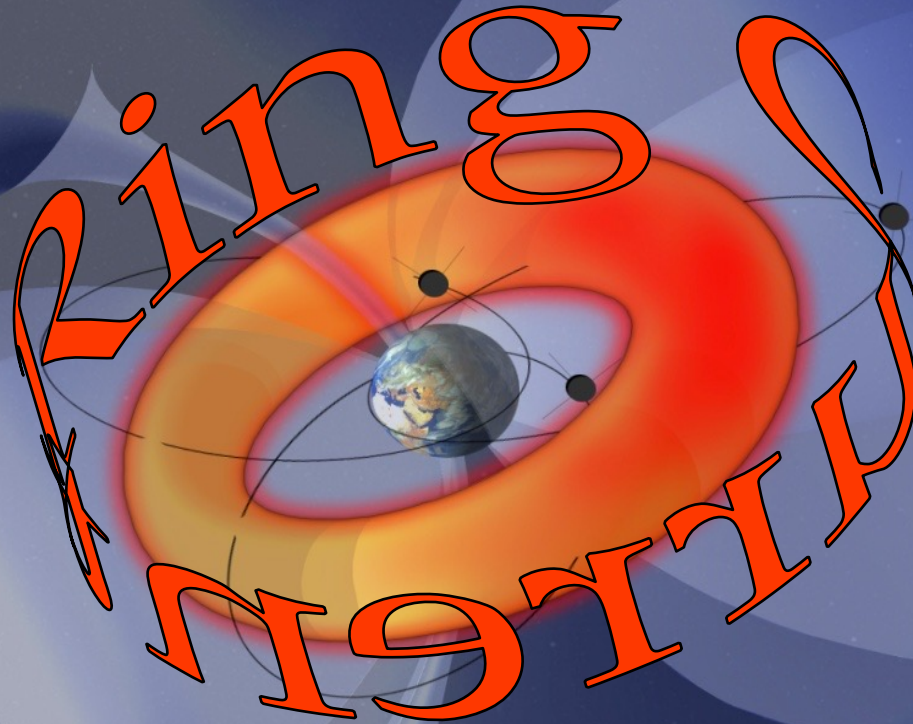




Καθοριστικό χαρακτηριστικό
της μαγνητικής καταιγίδας:

Παγκόσμια Μείωση του Γεωμαγνητικού Πεδίου
που μπορεί να ερμηνευθεί με το
διαμαγνητικό αποτέλεσμα
ενός γιγάντιου
κυκλικού/δακτυλιοειδούς ρεύματος
που ρέει στο διάστημα γύρω από τη Γη

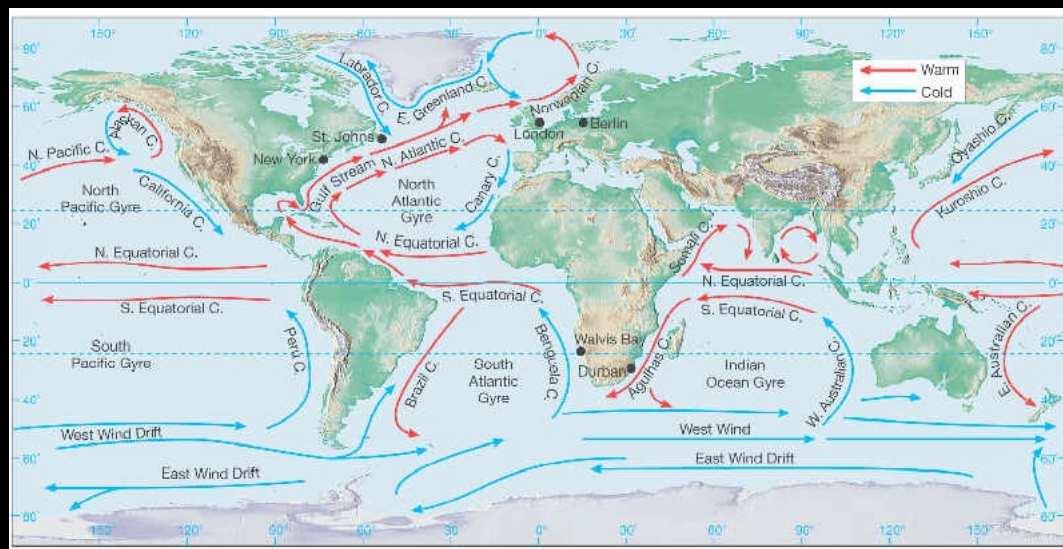
The Ring Current



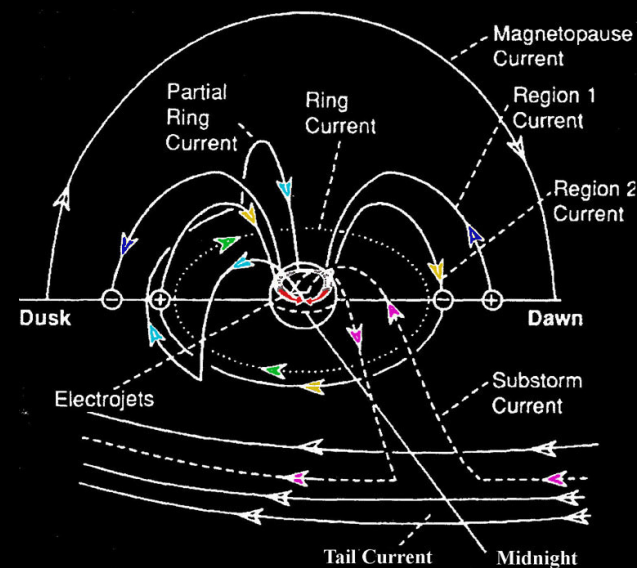
essential element of the magnetospheric electrodynamics

- The ring current is an essential part of a global system of electric currents that surround the Earth's coupled Magnetosphere - Ionosphere space environment.
- Similar processes take place in other planets' magnetospheres.

Earth



Geospace

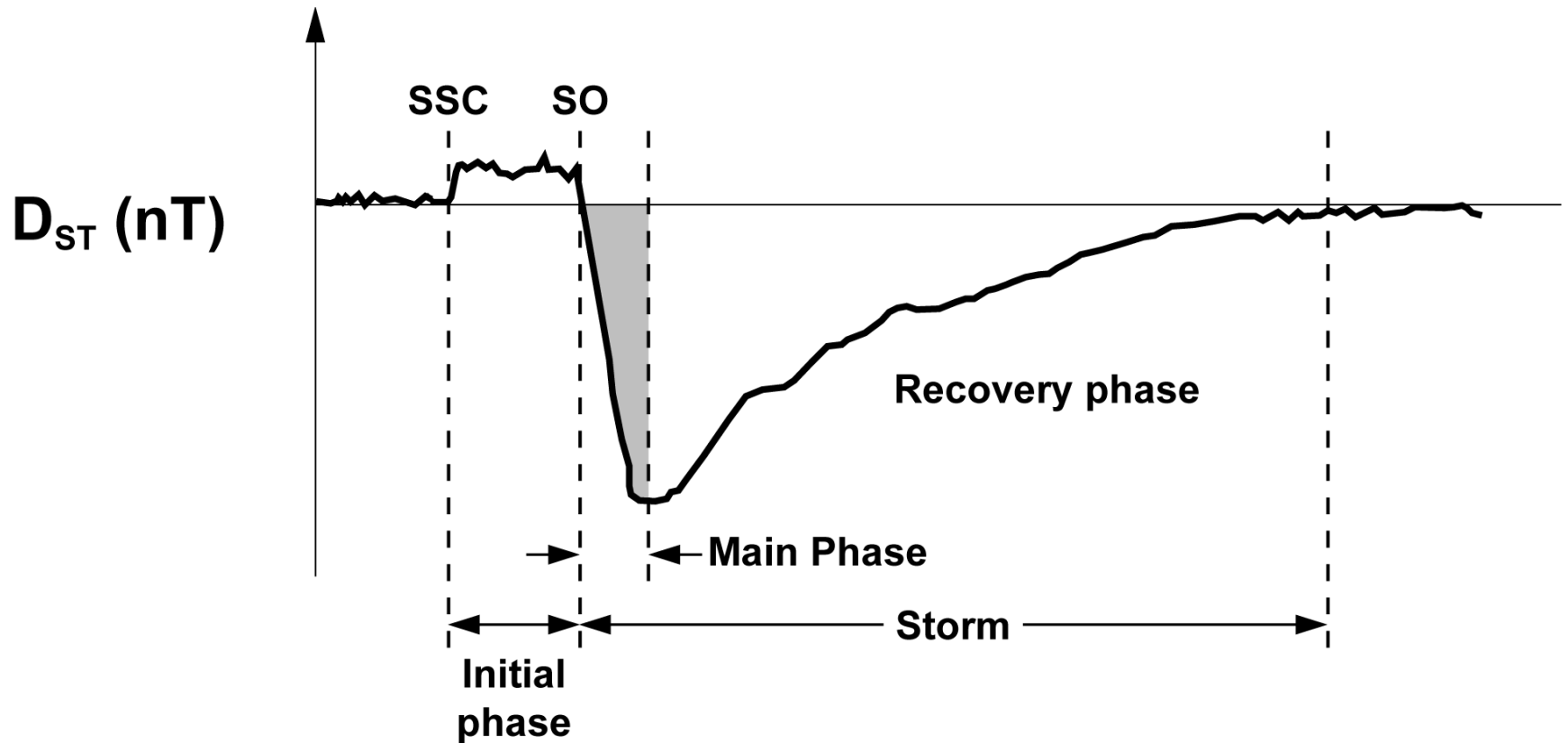


Κυριότερα χαρακτηριστικά του:

- Current carried by electrons and **mainly by ions** (H^+ , O^+ , He^{++} , He^+) in the energy range ~ 1 keV to 500 keV
- Maximum pressure within 50-100 keV
- Broad spatial extent: 3-8 R_E (geocentric)
- Maximum intensity at 3-5 R_E (geocentric)

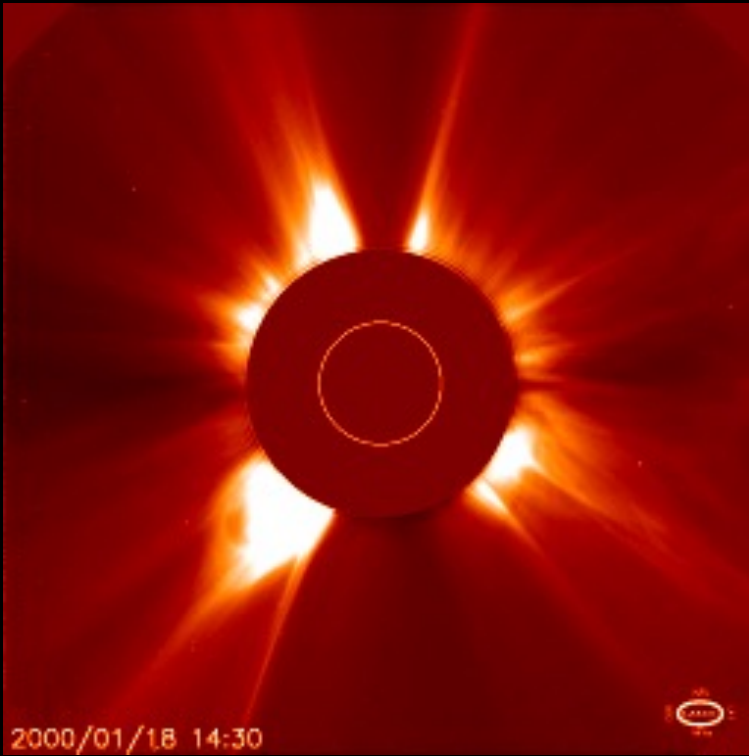
Ισχυρό νότιο διαπλανητικό μαγνητικό πεδίο μεγάλης διάρκειας έχει ως αποτέλεσμα την παρατεταμένη μεταφορά μαγνητικής ροής στη μαγνητοουρά και την αυξημένη συσσώρευση διαθέσιμης μαγνητικής ενέργειας. Πέρα από το ιδιαίτερα λαμπρό και χωρικά πολύ εκτεταμένο σέλας, που το συνοδεύουν συνεχείς γεωμαγνητικές διαταραχές σε υψηλά γεωγραφικά πλάτη λόγω ισχυρών ηλεκτρικών ρευμάτων («ηλεκτροχειμάρρων») που ρέουν στην ιονόσφαιρα, καταγράφονται και γεωμαγνητικές διαταραχές σε μεσαία και χαμηλά πλάτη και **σε όλα τα γεωγραφικά μήκη (δηλ. παγκοσμίως)**, καθώς επίσης και παρατεταμένη επιτάχυνση και έγχυση ενεργητικών ιόντων και ηλεκτρονίων, με αποτέλεσμα τη δημιουργία ενός δακτυλιοειδούς ηλεκτρικού ρεύματος γύρω από τη Γη.³¹

<https://wdc.kugi.kyoto-u.ac.jp/dstdir/>
Dst-index Home Page



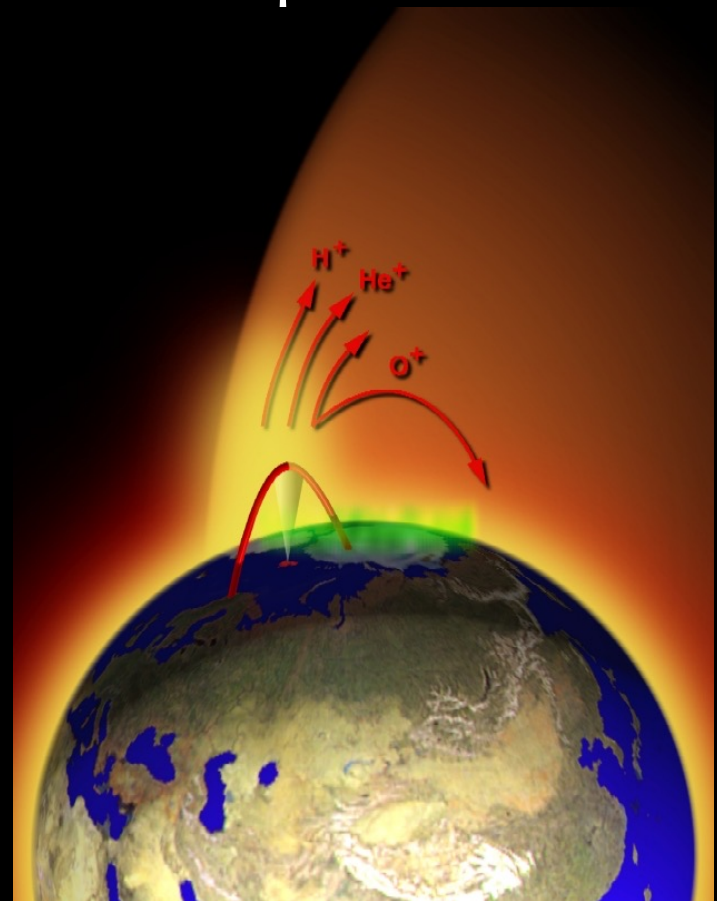
https://wdc.kugi.kyoto-u.ac.jp/dst_realtime/202304/index.html
April 2023

Ring current sources



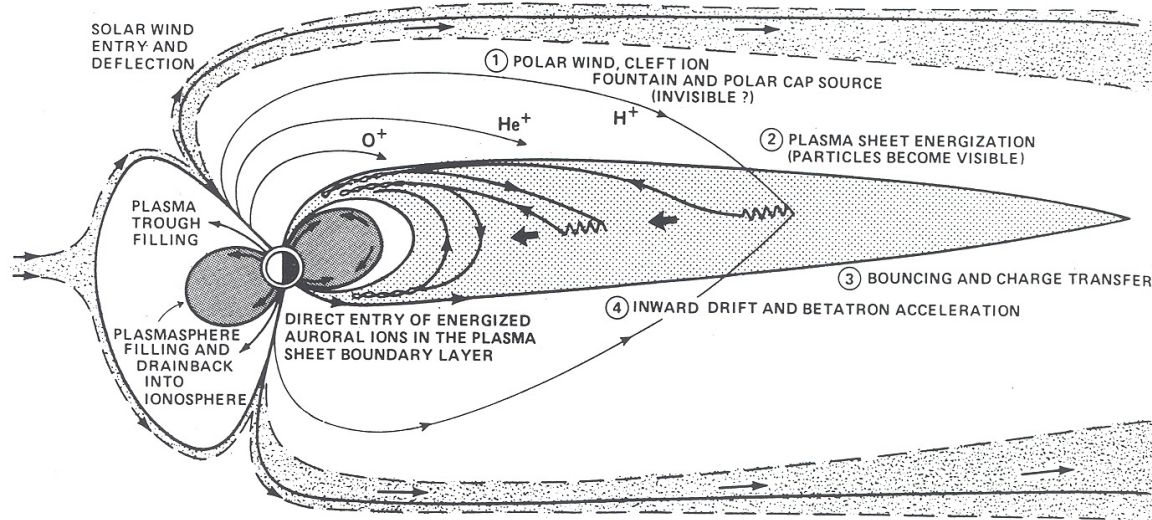
The solar atmosphere

The terrestrial atmosphere



Sources of Ring Current Ions

- Solar wind
- Ionosphere



[Chappell et al., 1987]

	Solar Maximum			Solar Minimum		
	H ⁺	He ⁺	O ⁺	H ⁺	He ⁺	O ⁺
<i>Quiet plasma sheet</i>						
Polar wind	4.7×10^{25}	3.3×10^{24}		1.4×10^{26}	1.8×10^{24}	
Cleft ion fountain	3.3×10^{24}		1.6×10^{25}	6.3×10^{24}		7.3×10^{24}
Auroral zone	2.1×10^{25}		1.6×10^{25}	1.7×10^{25}		1.0×10^{25}
Polar cap	2.4×10^{24}		2.4×10^{24}	4.3×10^{24}		3.9×10^{24}
Total	7.4×10^{25}	3.3×10^{24}	3.4×10^{25}	1.7×10^{26}	1.8×10^{24}	2.1×10^{25}
Total Ions		1.1×10^{26}			1.9×10^{26}	
<i>Active plasma sheet</i>						
Polar wind	3.2×10^{25}	1.2×10^{24}		9.4×10^{25}	8.6×10^{23}	
Cleft ion fountain	4.3×10^{24}		4.8×10^{25}	4.3×10^{24}		1.9×10^{25}
Auroral zone	2.6×10^{25}		7.7×10^{25}	3.3×10^{25}		3.2×10^{25}
Polar cap	6.1×10^{24}		2.5×10^{25}	1.0×10^{25}		1.5×10^{25}
Total	6.7×10^{25}	1.2×10^{24}	1.5×10^{26}	1.4×10^{26}	8.6×10^{23}	6.6×10^{25}
Total Ions		2.2×10^{26}			2.1×10^{26}	

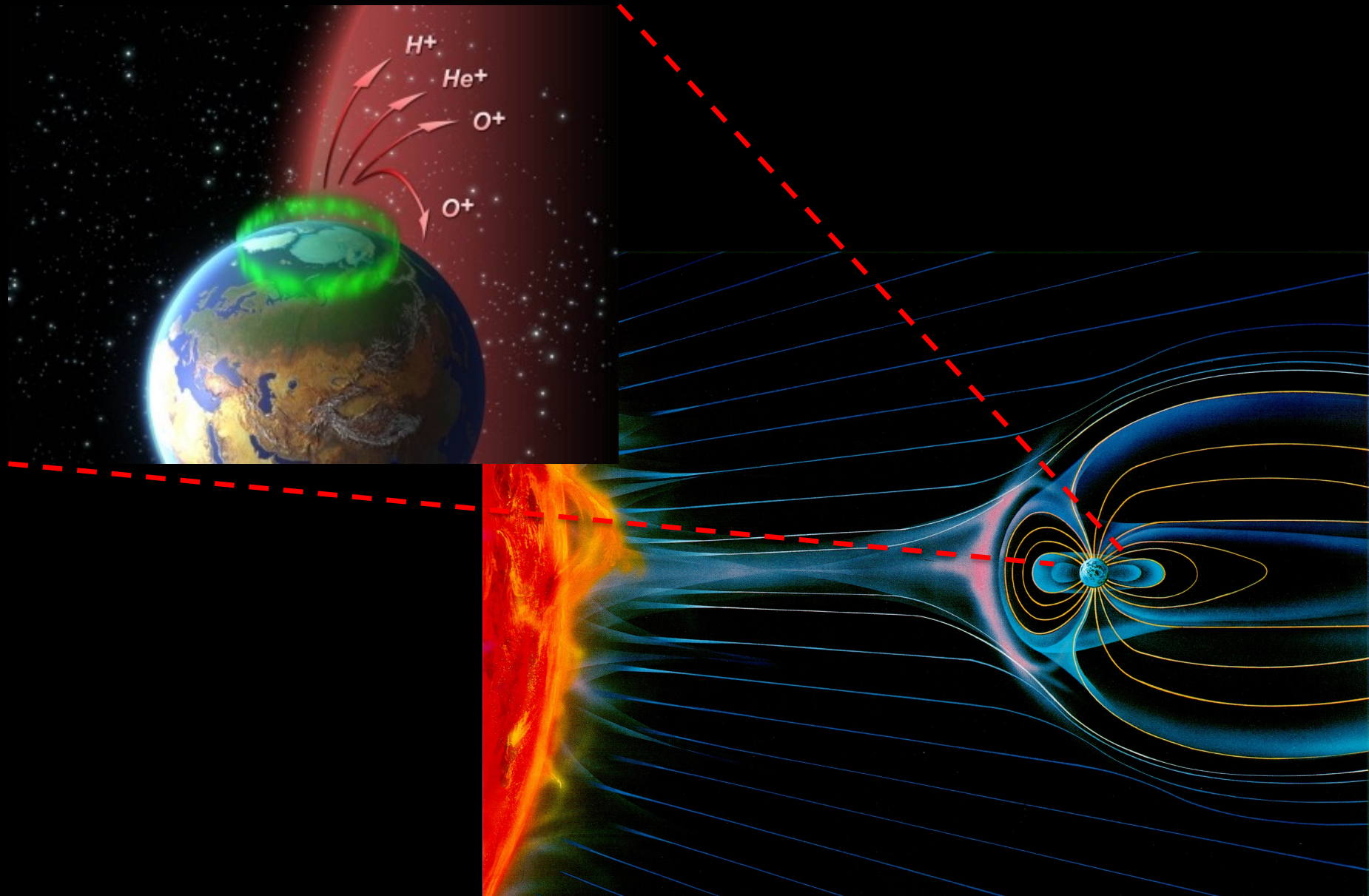
max H⁺: solar min & quiet conditions

max O⁺: solar max & active conditions

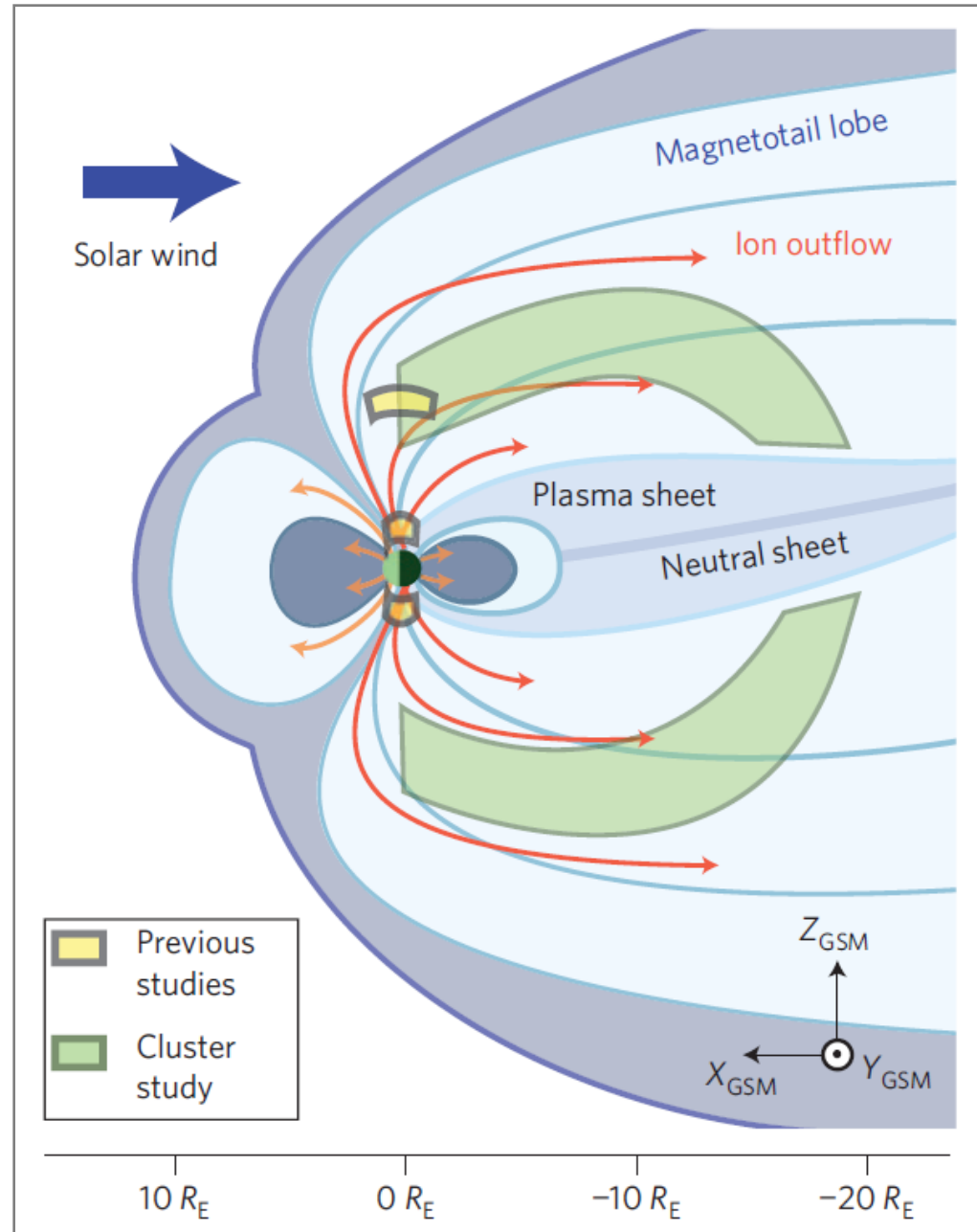
Total ionospheric flux ~ 10^{26} ions/s
=> comparable to solar wind source

Fluxes given in ions s⁻¹.

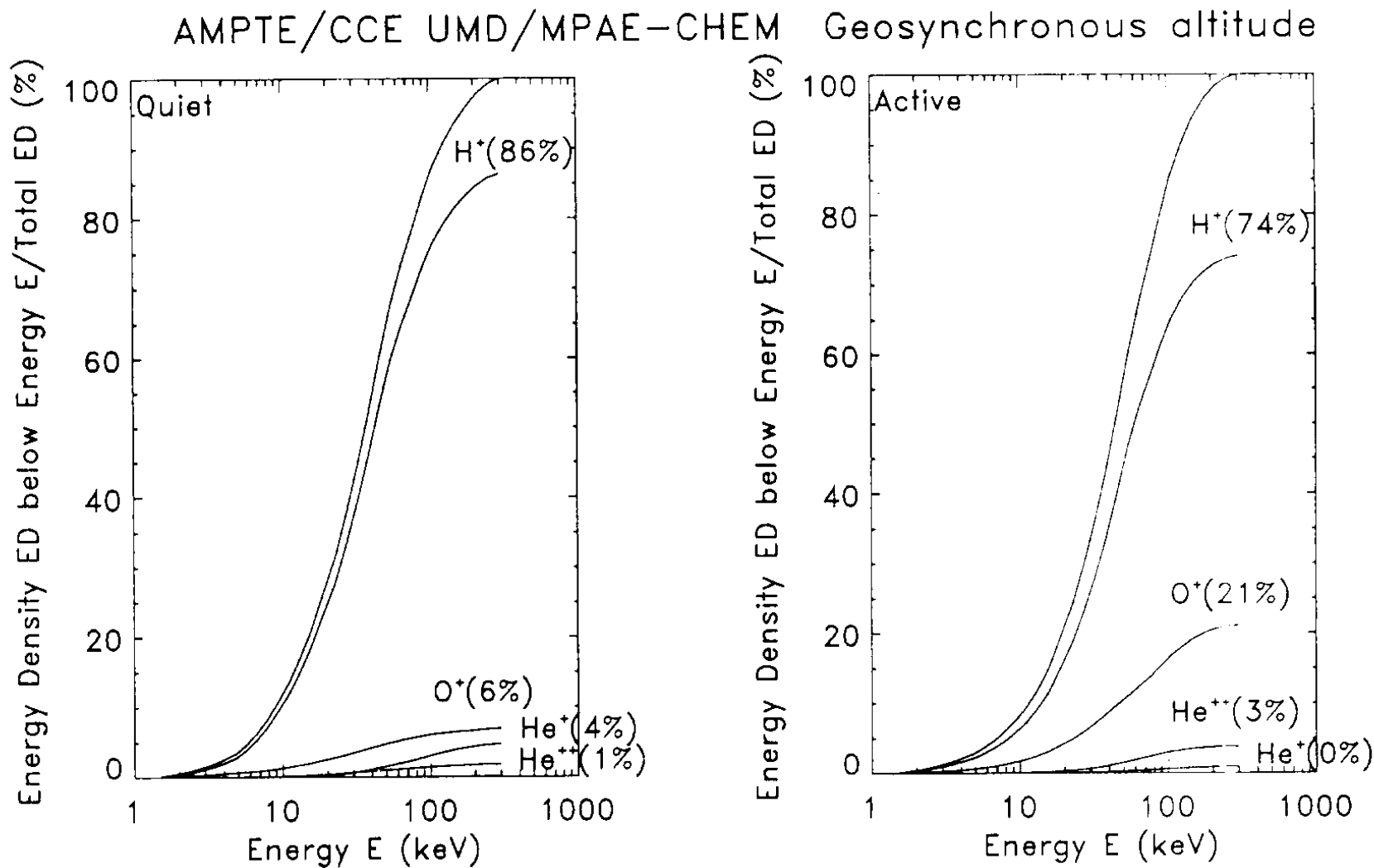
Διαφυγή ιονοσφαιρικού πλάσματος



Ο ρυθμός διαφυγής
($\sim 10^{26}$ ιόντα / sec)
μεταβάλλεται ($\sim 3x$) ως
συνάρτηση της ηλιακής
και της γεωμαγνητικής
δραστηριότητας



Ring Current Composition (mainly H⁺ and O⁺)



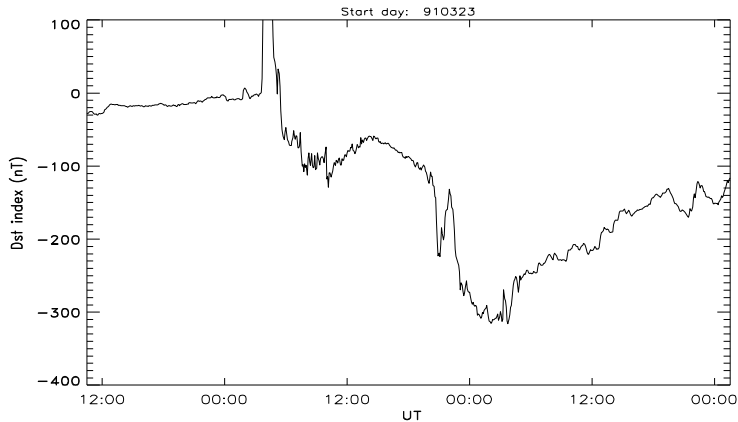
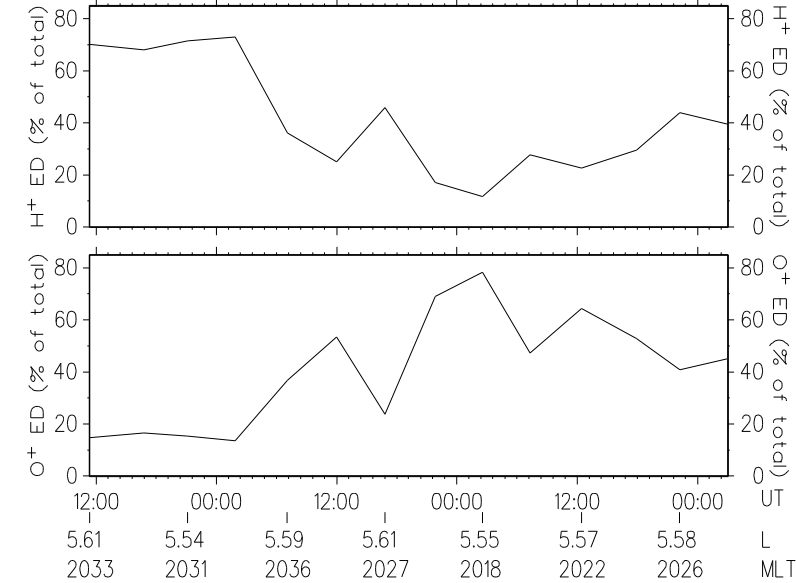
1984 - 1989

Daglis et al. 1993

Ring current during intense storms - Dominant role of O⁺

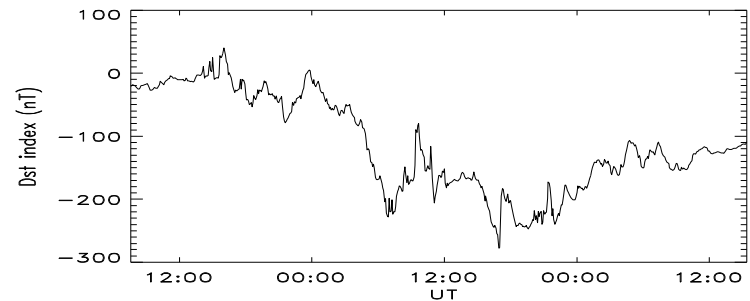
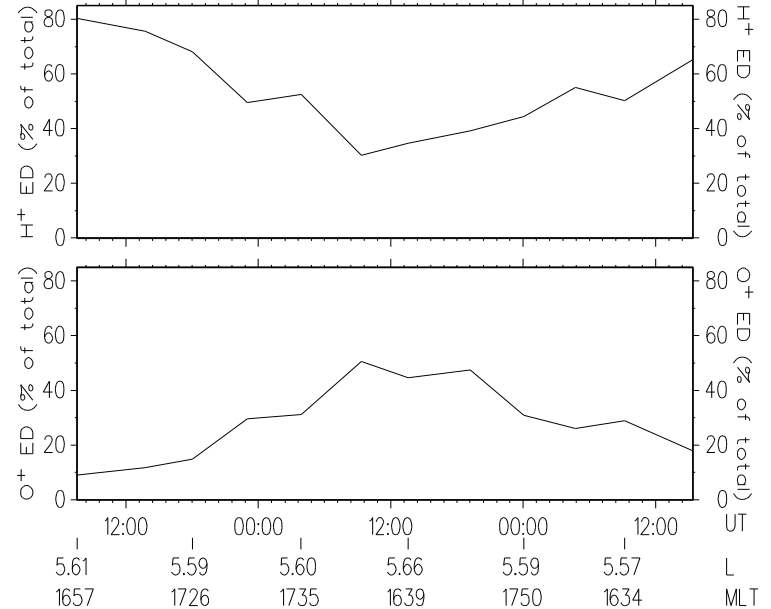
CRRES orbits 0586-0592 MICS
Date: 23.03.91 DOY: 082

Energy range: 50.0-426.0 keV



CRRES orbits 0764-0769 MICS
Date: 04.06.91 DOY: 155

Energy range: 50.0-426.0 keV



Lots of oxygen – not so much nitrogen. Why?

Διαφυγή αζώτου

Ενέργεια διάσπασης μοριακού δεσμού:

N_2 (τριπλός): 945 kJ/mol (9.79 eV) ←

O_2 (διπλός): 497 kJ/mole (5.15 eV) ←

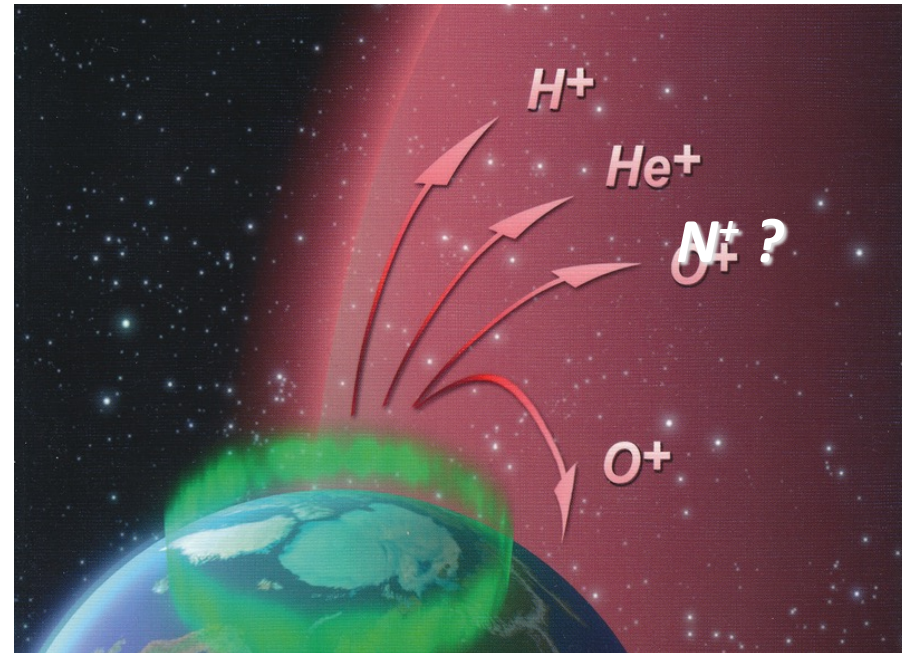
H_2 : 436 kJ/mole (4.52 eV)

Ενέργεια ιονισμού:

N: 1402 kJ/mole (14.53 eV) ←

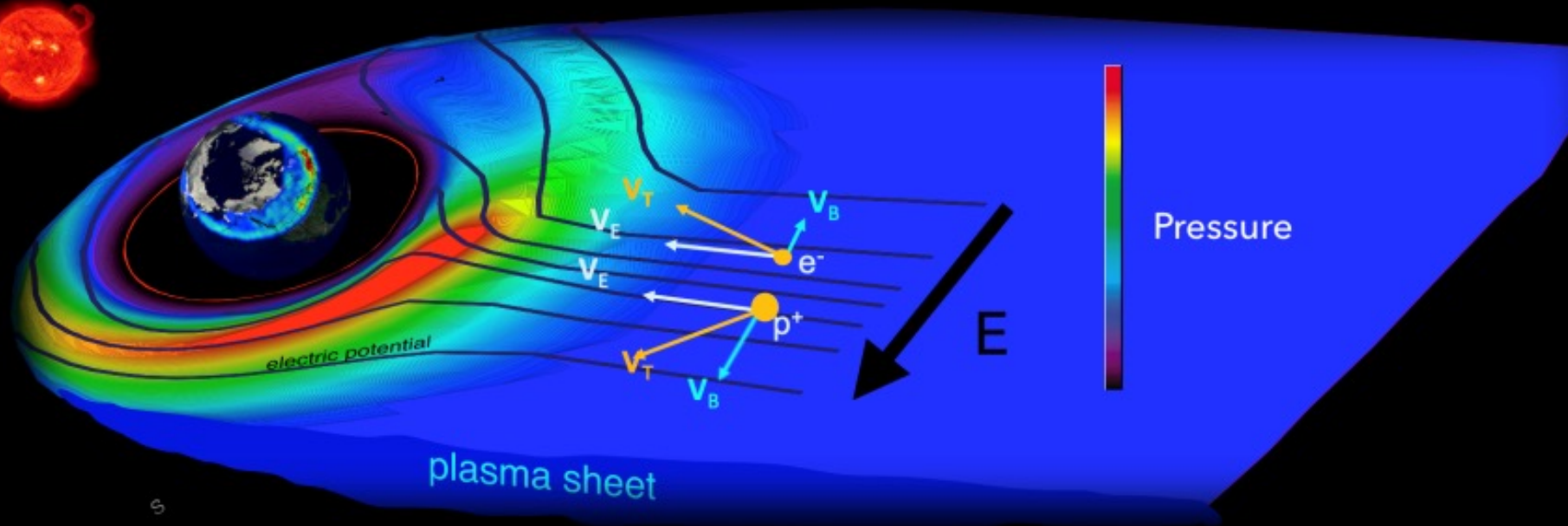
O: 1314 kJ/mole (13.62 eV) ←

H: 1312 kJ/mole (13.60 eV)



- ☐ Το **άζωτο** είναι **πολύ** **δυσκολότερο** να **διασπαστεί** και να **ιονιστεί**
 - **Δυσκολότερη** **διαφυγή**

$$\mathbf{j}_{\perp} = \frac{\hat{\mathbf{b}}}{B} \times \left(\frac{\nabla p_{\perp}}{B} + (p_{\parallel} - p_{\perp}) \frac{\hat{\mathbf{b}} \cdot \nabla \mathbf{B}}{B} \right)$$

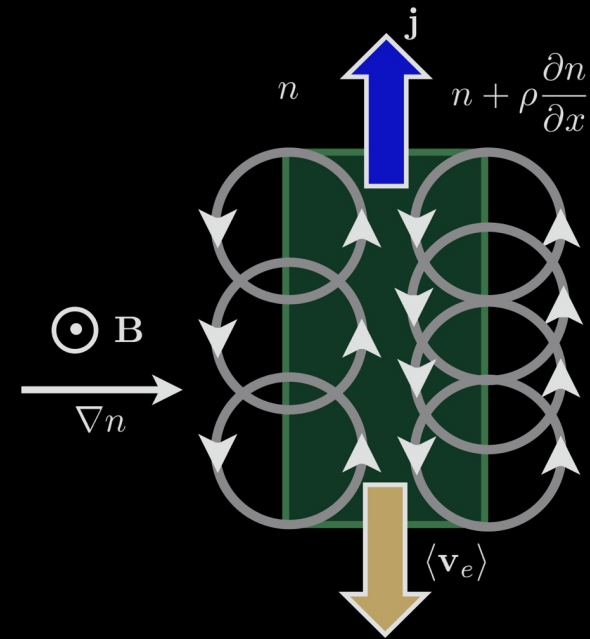


What Drives the Current?

Electric current density:

$$\mathbf{j} = \sum_s e_s n_s \langle \mathbf{v} \rangle$$

plasma "collective behaviour"

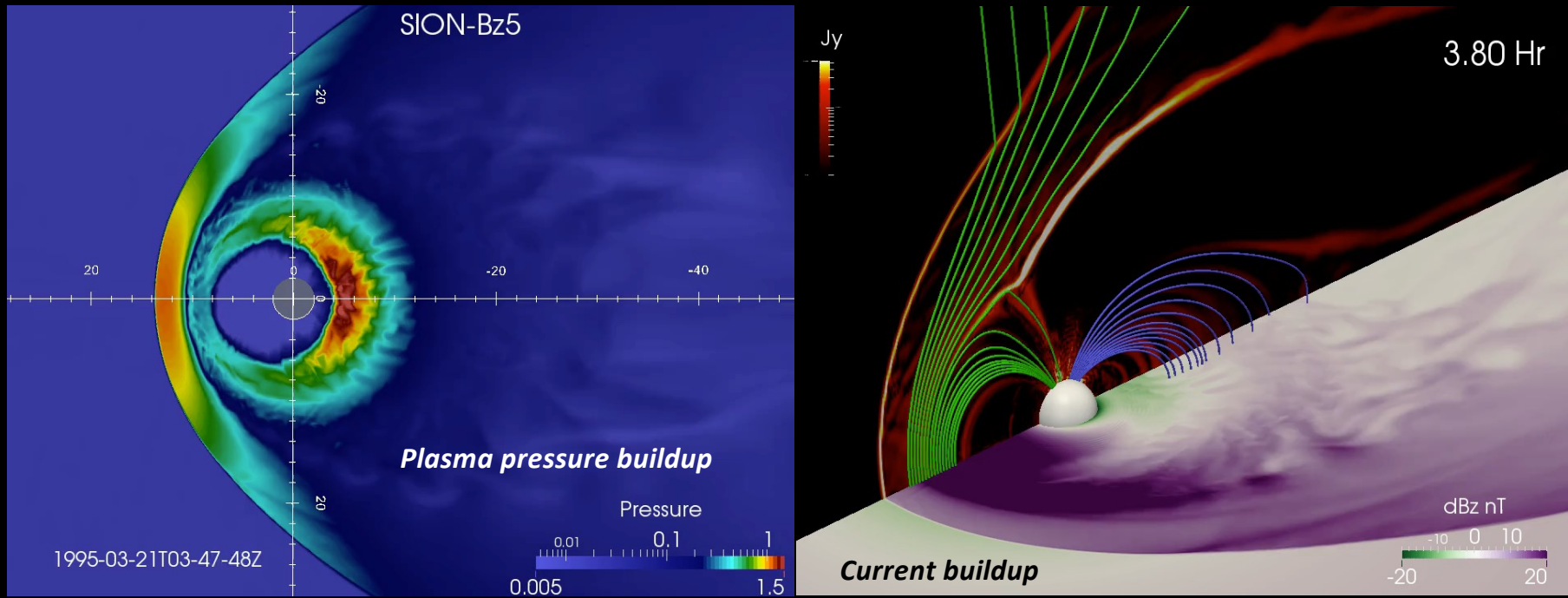


$$\mathbf{j}_\perp = \frac{\hat{\mathbf{b}}}{B} \times \left(\frac{\nabla p_\perp}{B} + (p_\parallel - p_\perp) \frac{\hat{\mathbf{b}} \cdot \nabla B}{B} \right)$$

pressure
gradient

pressure
anisotropy

Global magnetohydrodynamic models



Courtesy of Dr. Slava Merkin

$$\mathbf{j}_{\perp} = \frac{\hat{\mathbf{b}}}{B} \times \left(\frac{\nabla p_{\perp}}{B} + (p_{\parallel} - p_{\perp}) \frac{\hat{\mathbf{b}} \cdot \nabla B}{B} \right)$$

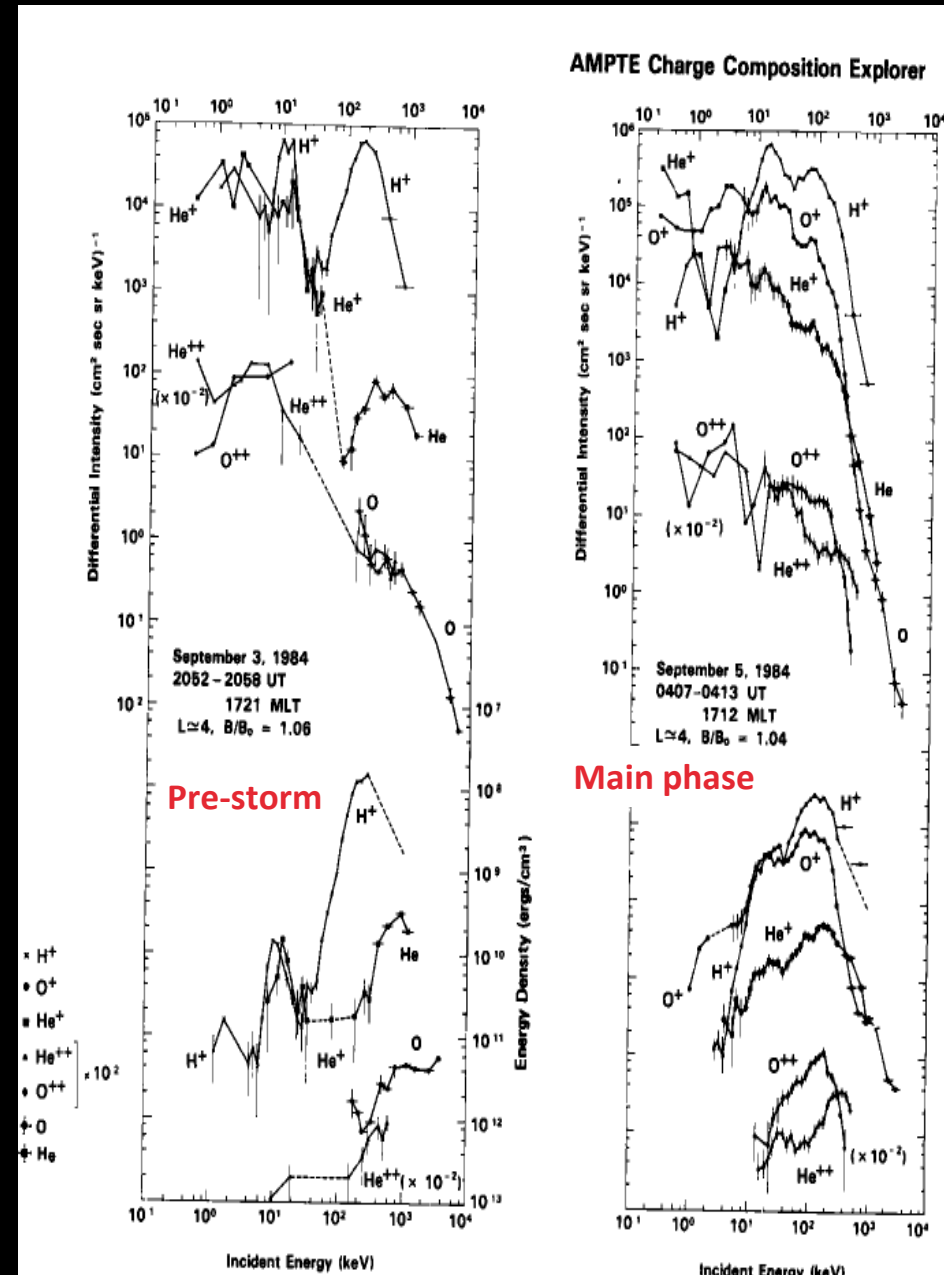
Plasma injected into the inner magnetosphere

Pressure buildup

Current buildup

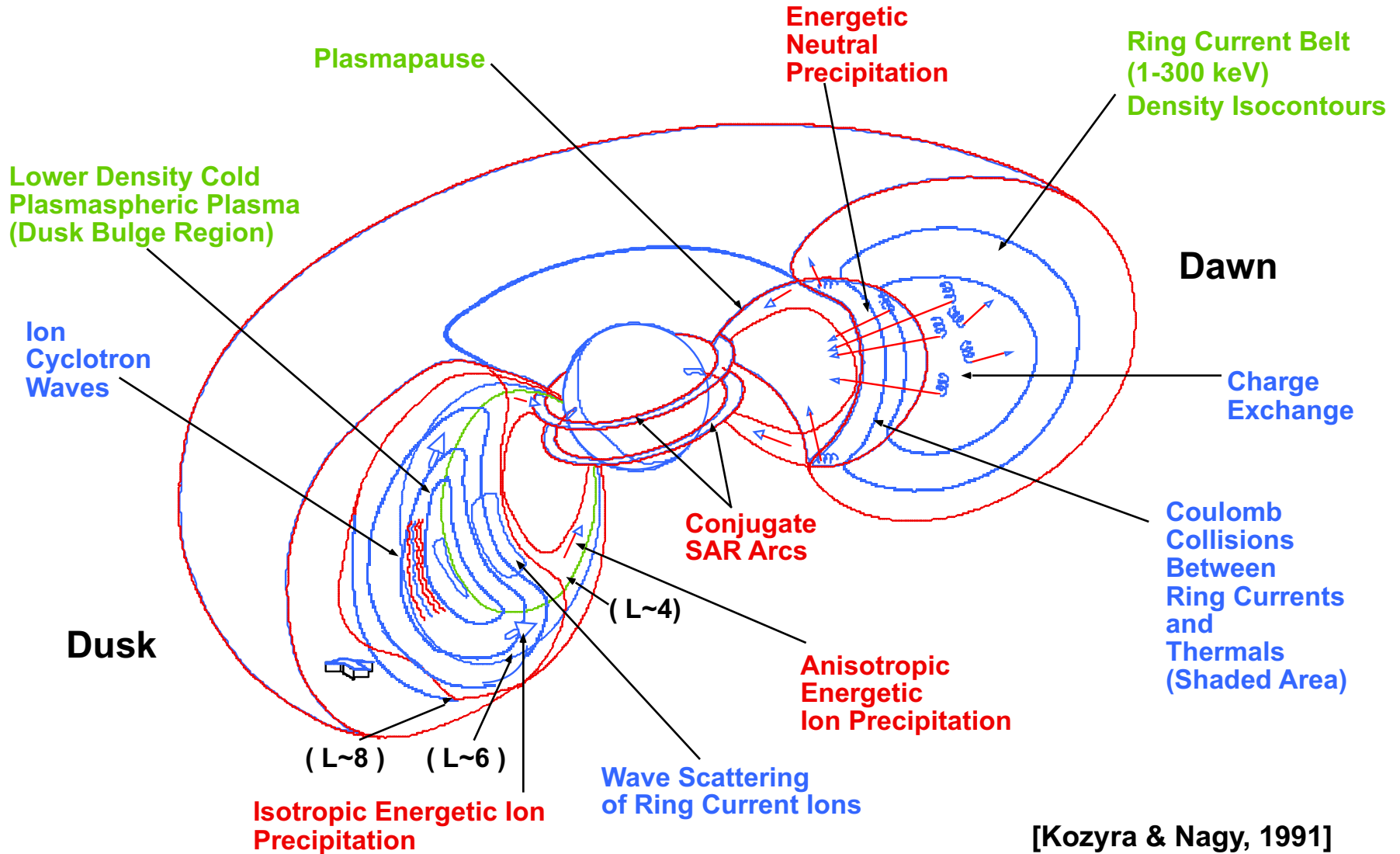
In-situ observations of the ring current

- ▶ Protons > 100 keV are dominant during quiet time conditions
- ▶ Main phase pressure enhancement is mainly due to few keV to tens of keV protons and O^+



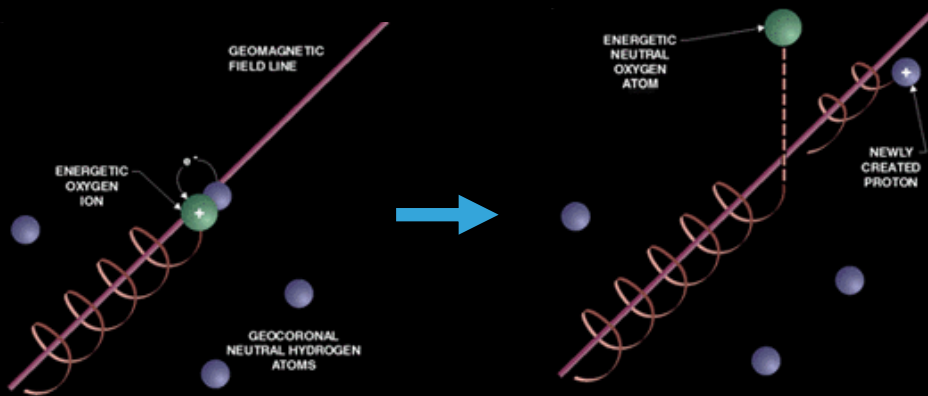
Krimigis et al., [1985]

Ring Current Loss Processes



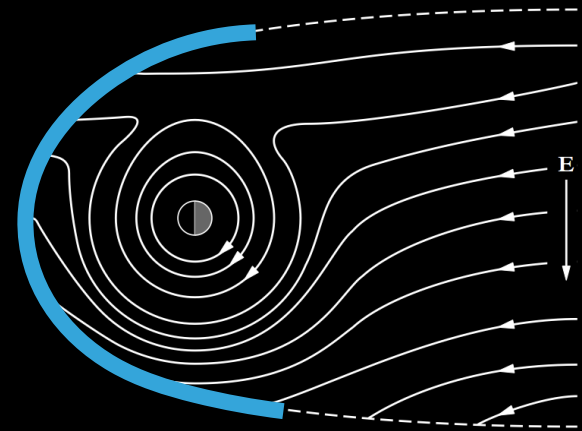
[Kozyra & Nagy, 1991]

Losses



Charge exchange with geocoronal neutral hydrogen atoms:

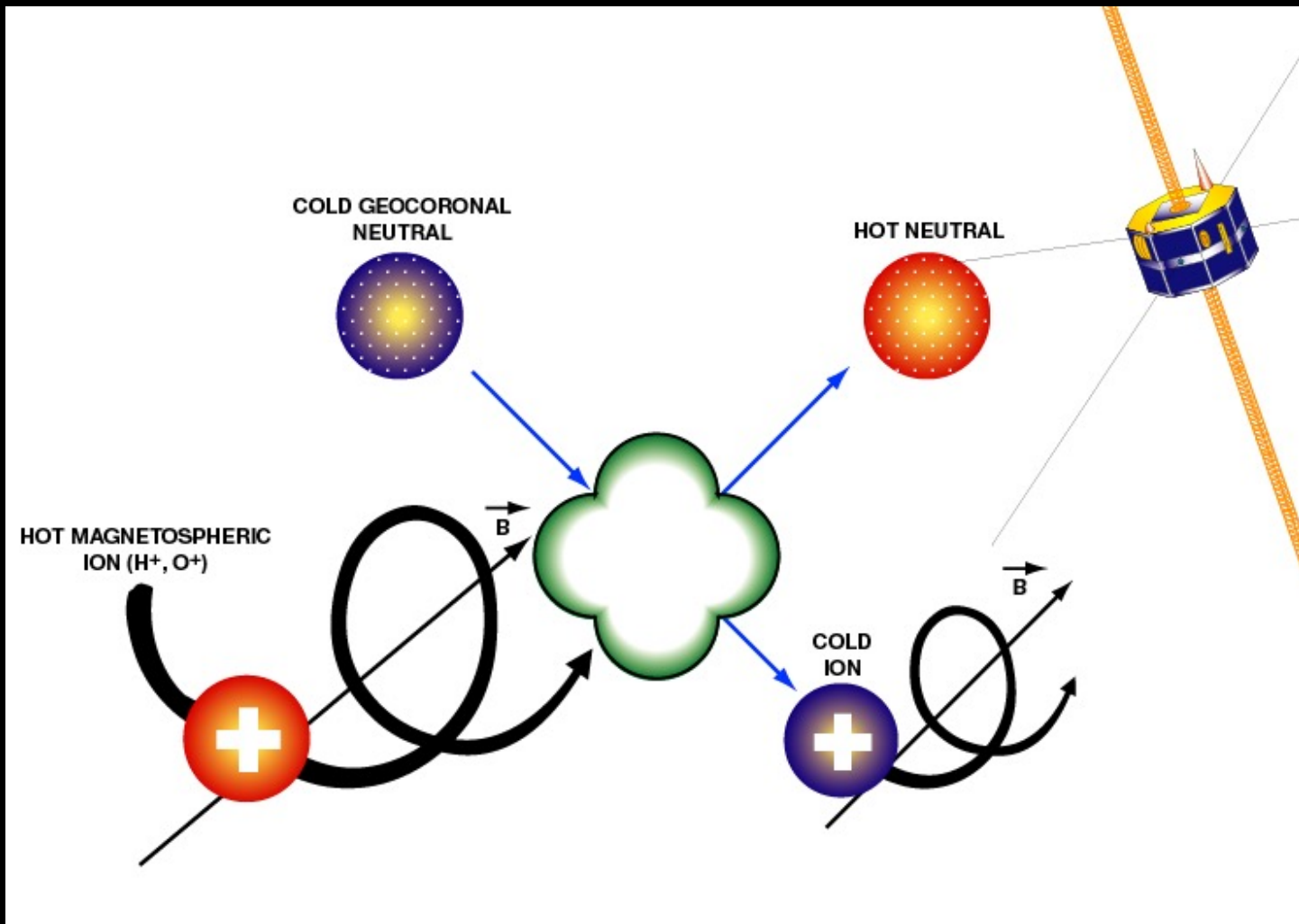
A singly charged ion collides with a neutral atom or molecule and captures one of its electrons, thereby becoming a neutral atom, no longer affected by electric and magnetic fields.



Magnetopause losses:

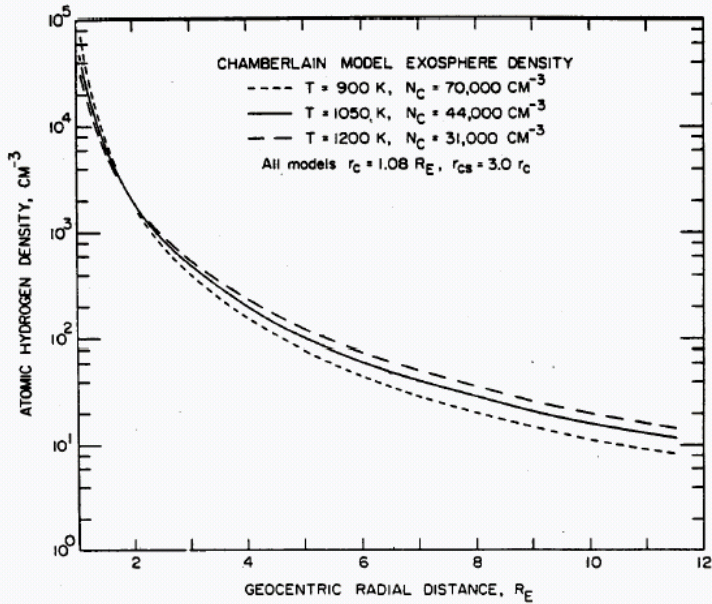
Ions in open drift paths cross the magnetopause boundary and are lost from the system.

Charge Exchange Process

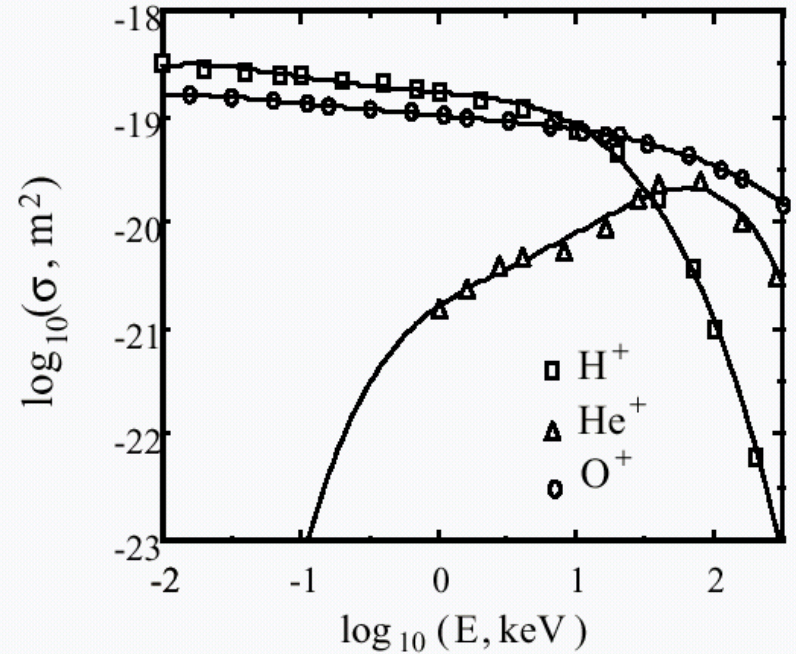




Charge Exchange Model

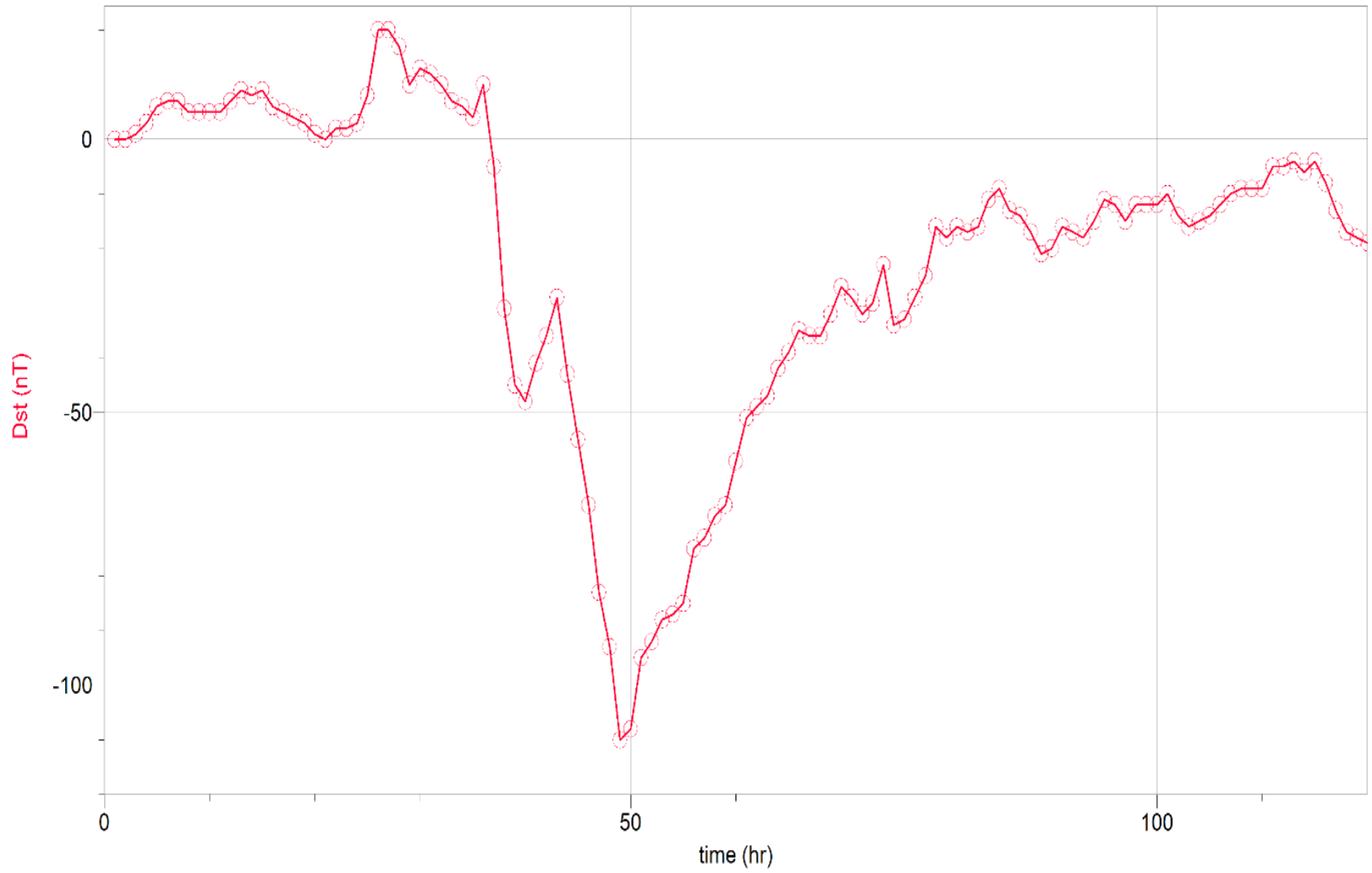


Equatorial exospheric Hydrogen densities
[Rairden et al., 1986]

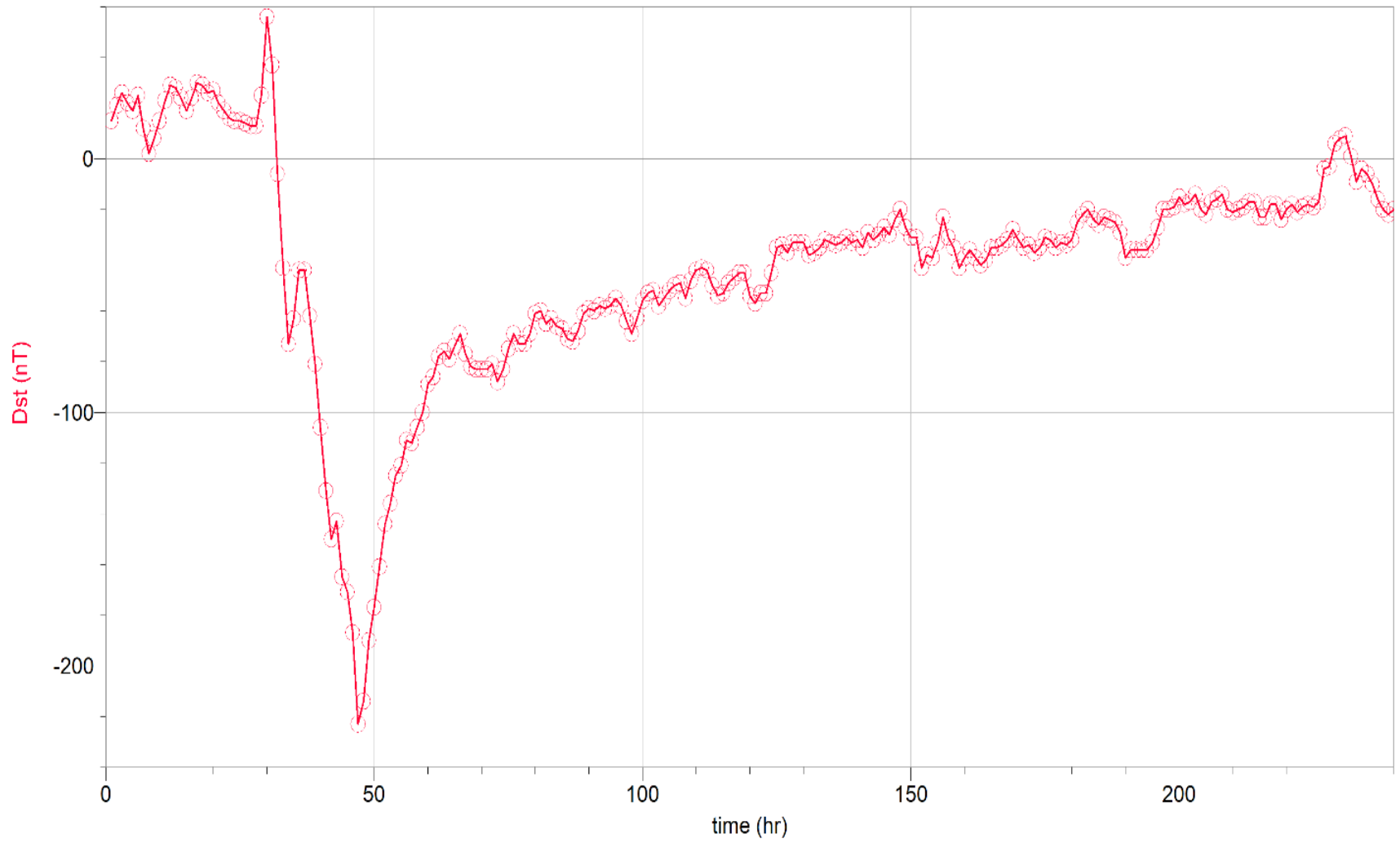


Charge exchange cross sections
[Phaneuf et al., 1987; Barnett, 1990]

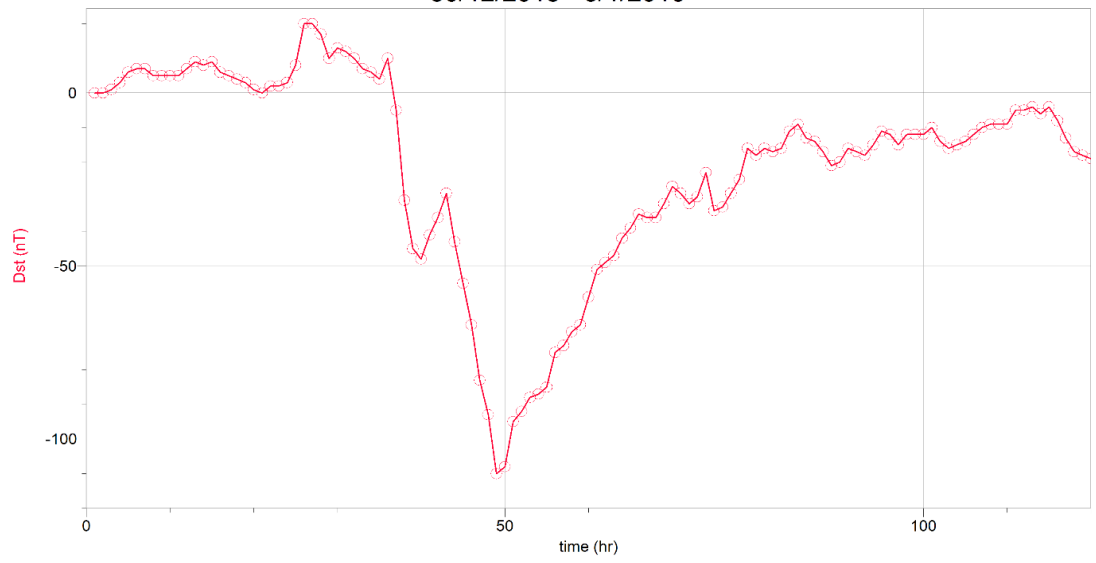
30/12/2015 - 3/1/2016



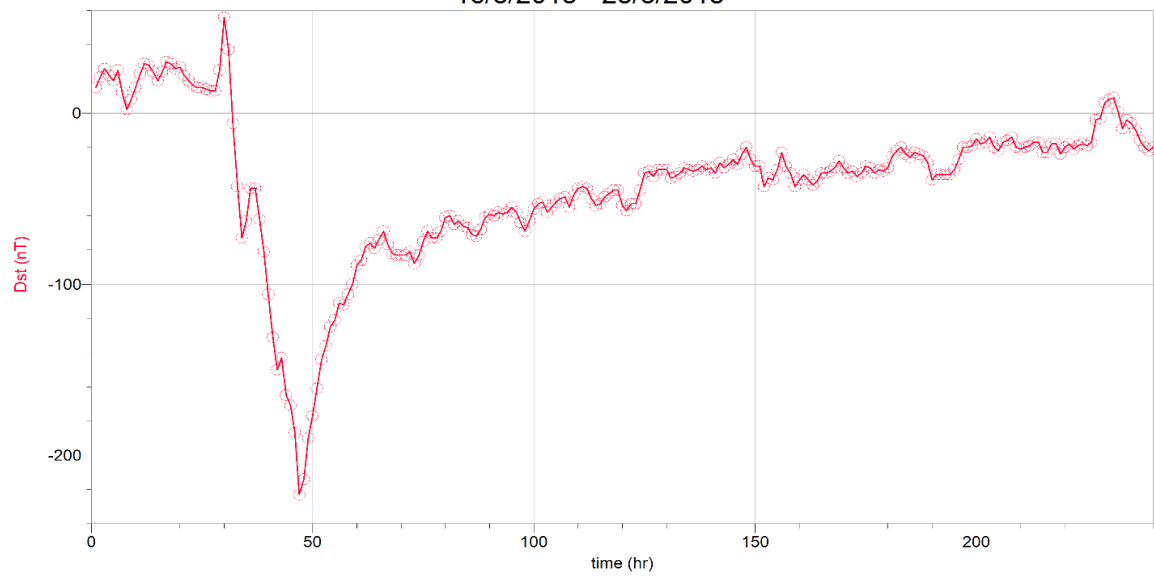
16/3/2015 - 25/3/2015



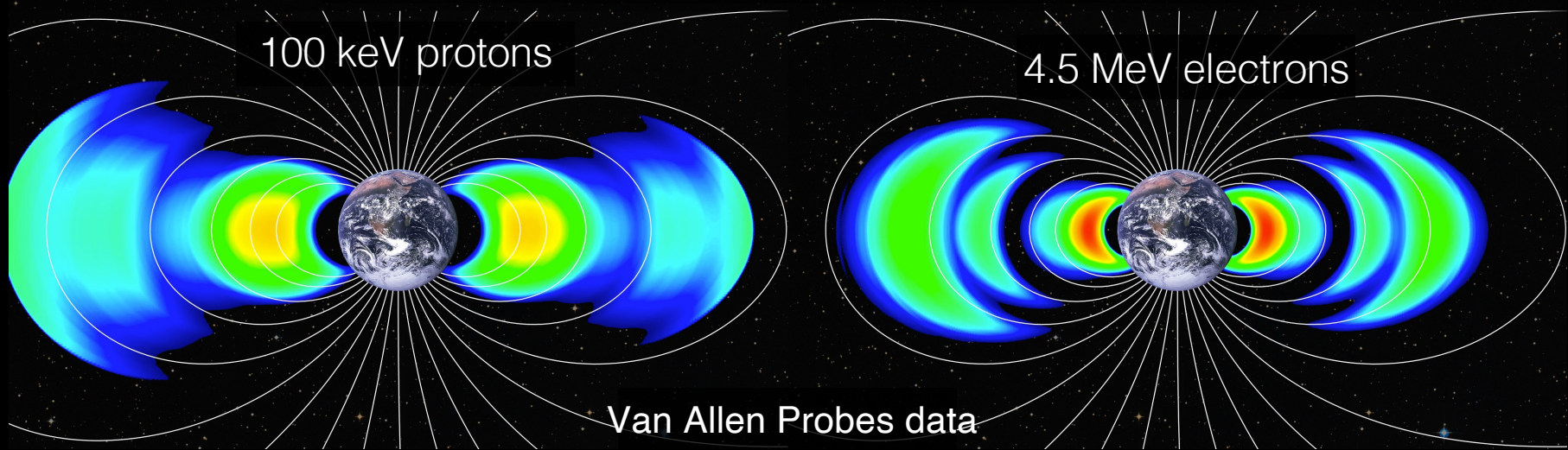
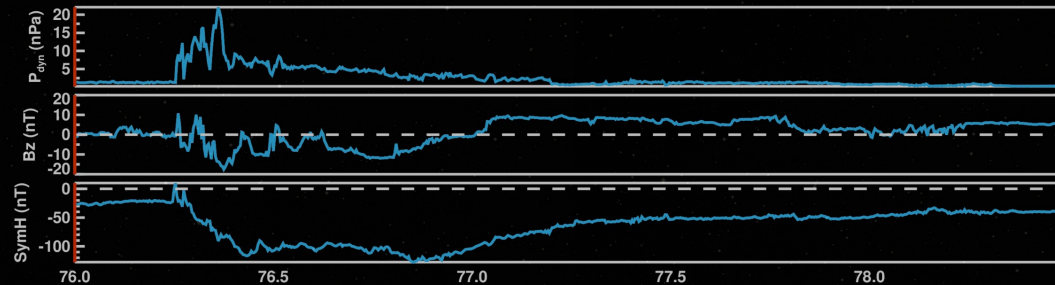
30/12/2015 - 3/1/2016



16/3/2015 - 25/3/2015



Key Space Weather element: Radiation Belt Losses

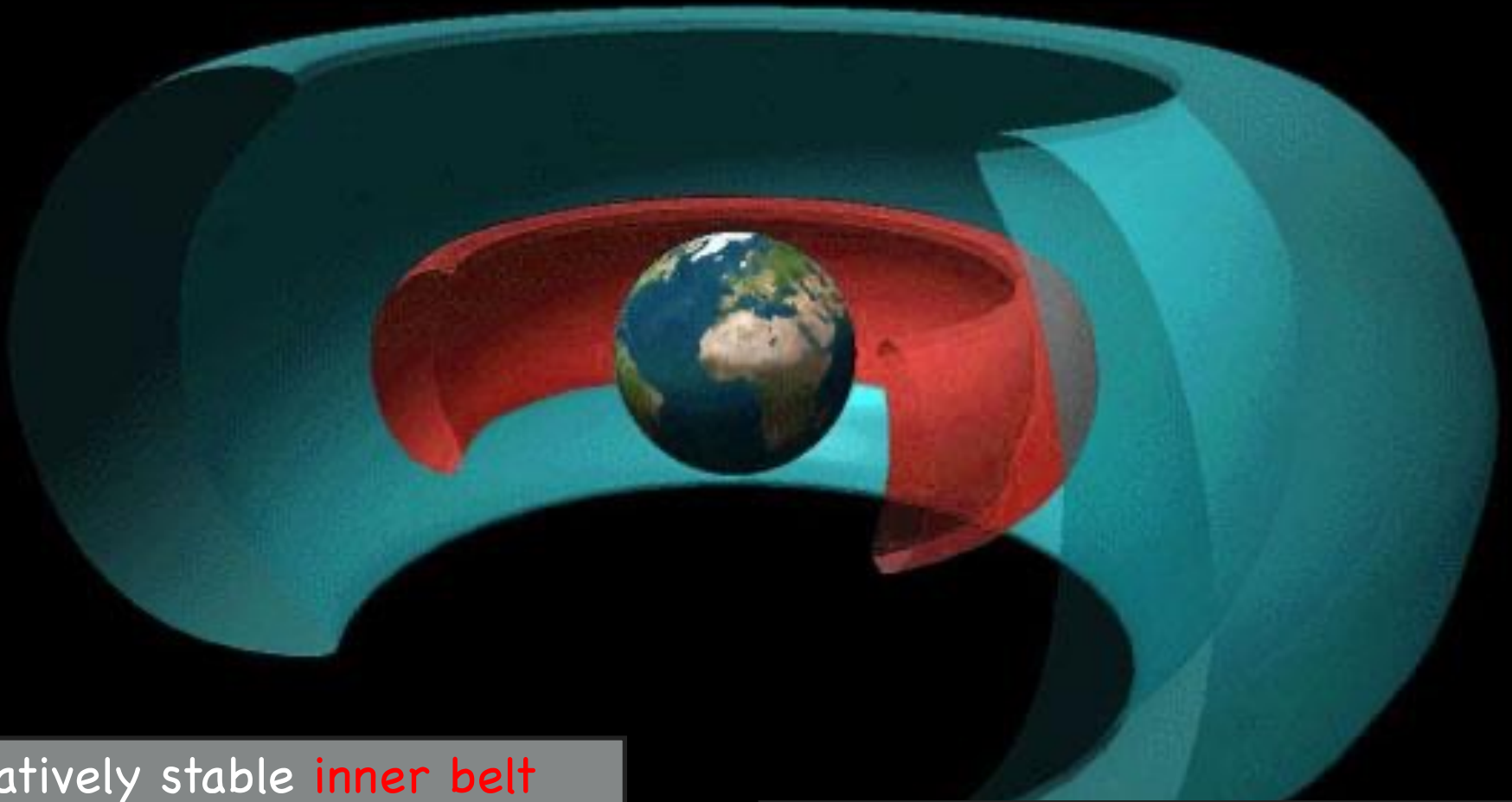


Van Allen Probes data

Courtesy of Grant Stephens

The distortion of the Earth's magnetic field in the inner magnetosphere due to the ring current formation, affects the transport and loss of radiation belt particles.

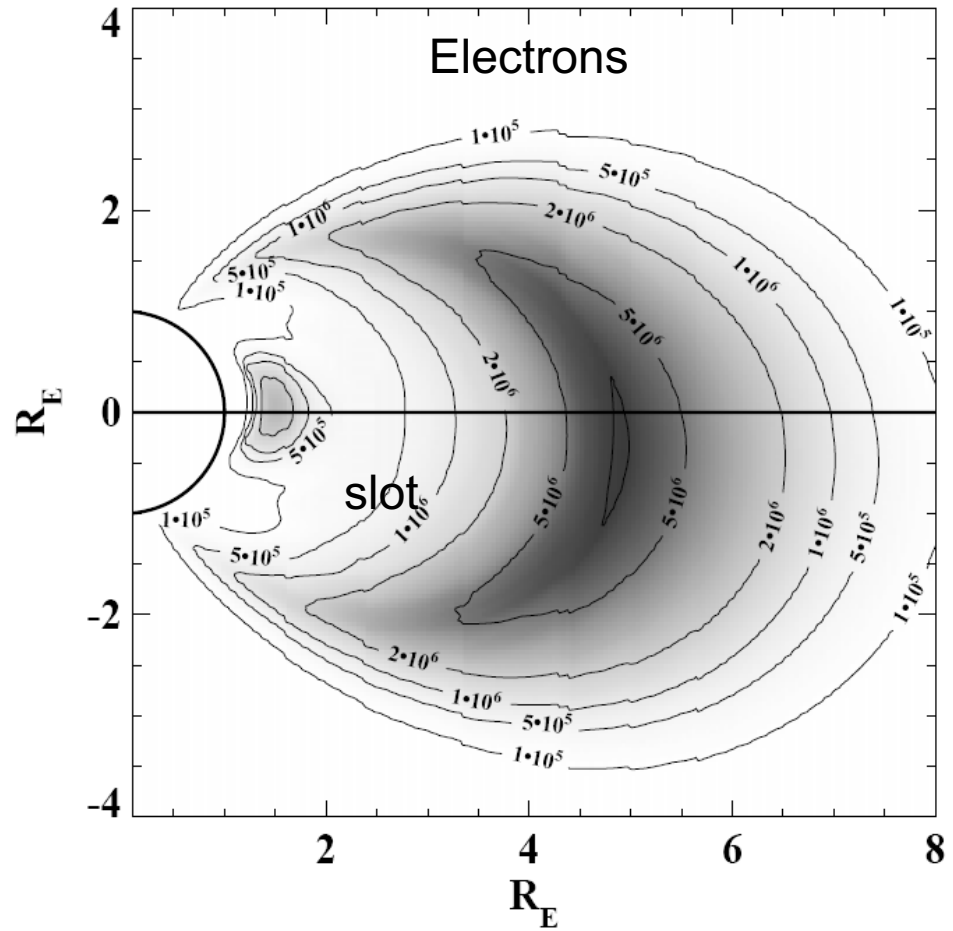
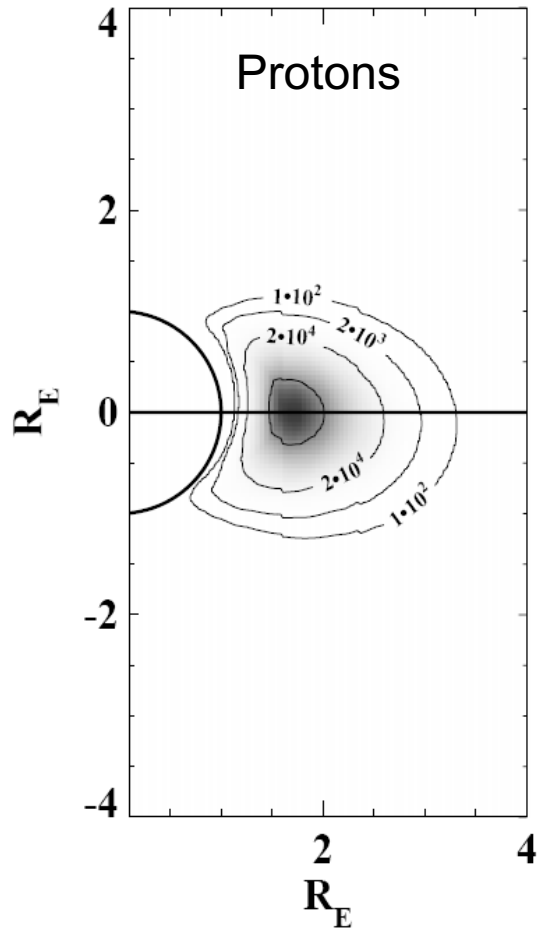
Van Allen radiation belts



Relatively stable **inner belt**
mostly high-energy protons
Sources : CRAND protons
SEP events

Dynamic **outer belt**
mostly high-energy electrons
Sources : Magnetotail electrons

Radiation Belts: Inner, Outer



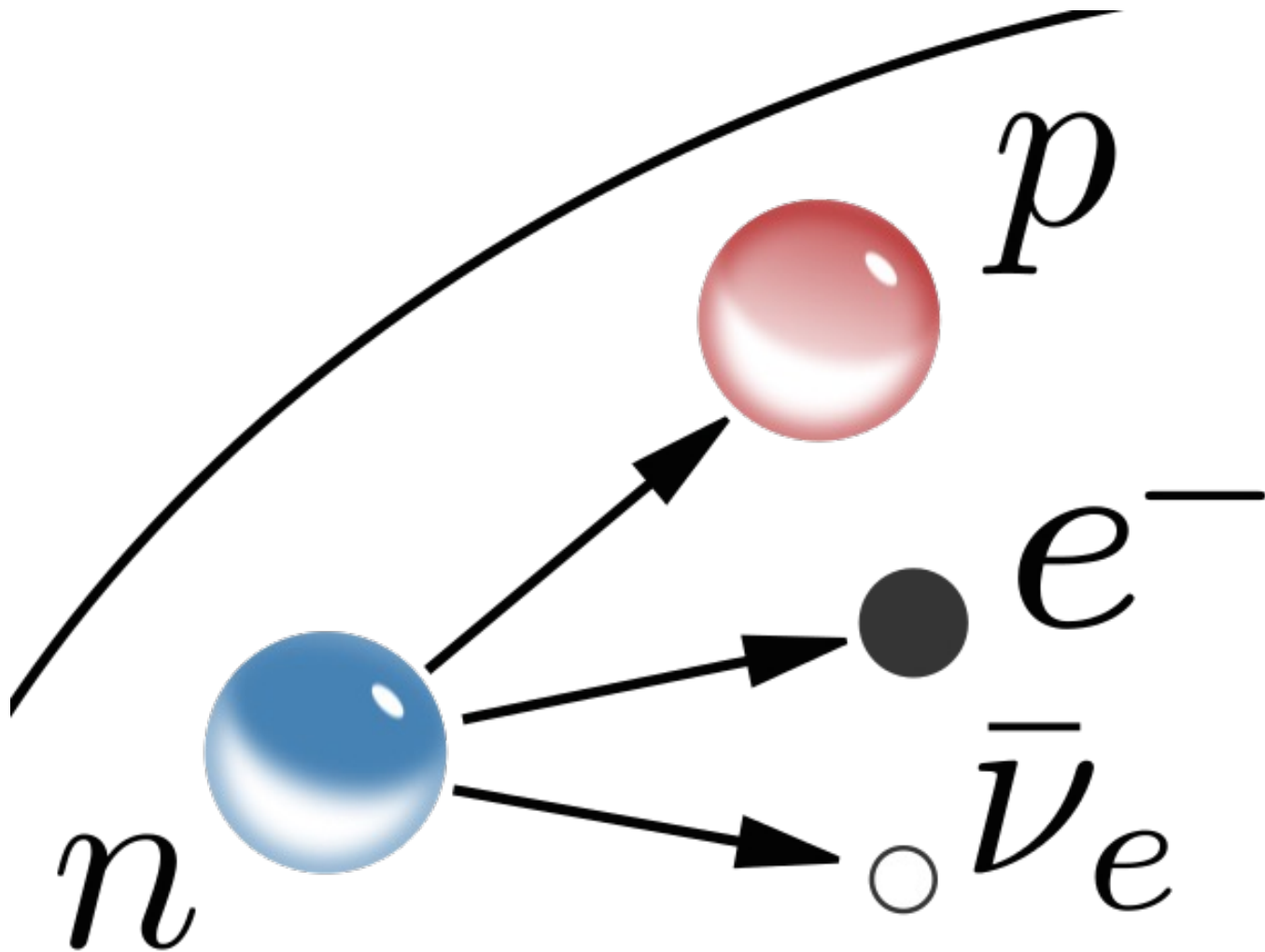
Inner belt: CRAND
(**Cosmic Ray Albedo Neutron Decay**)

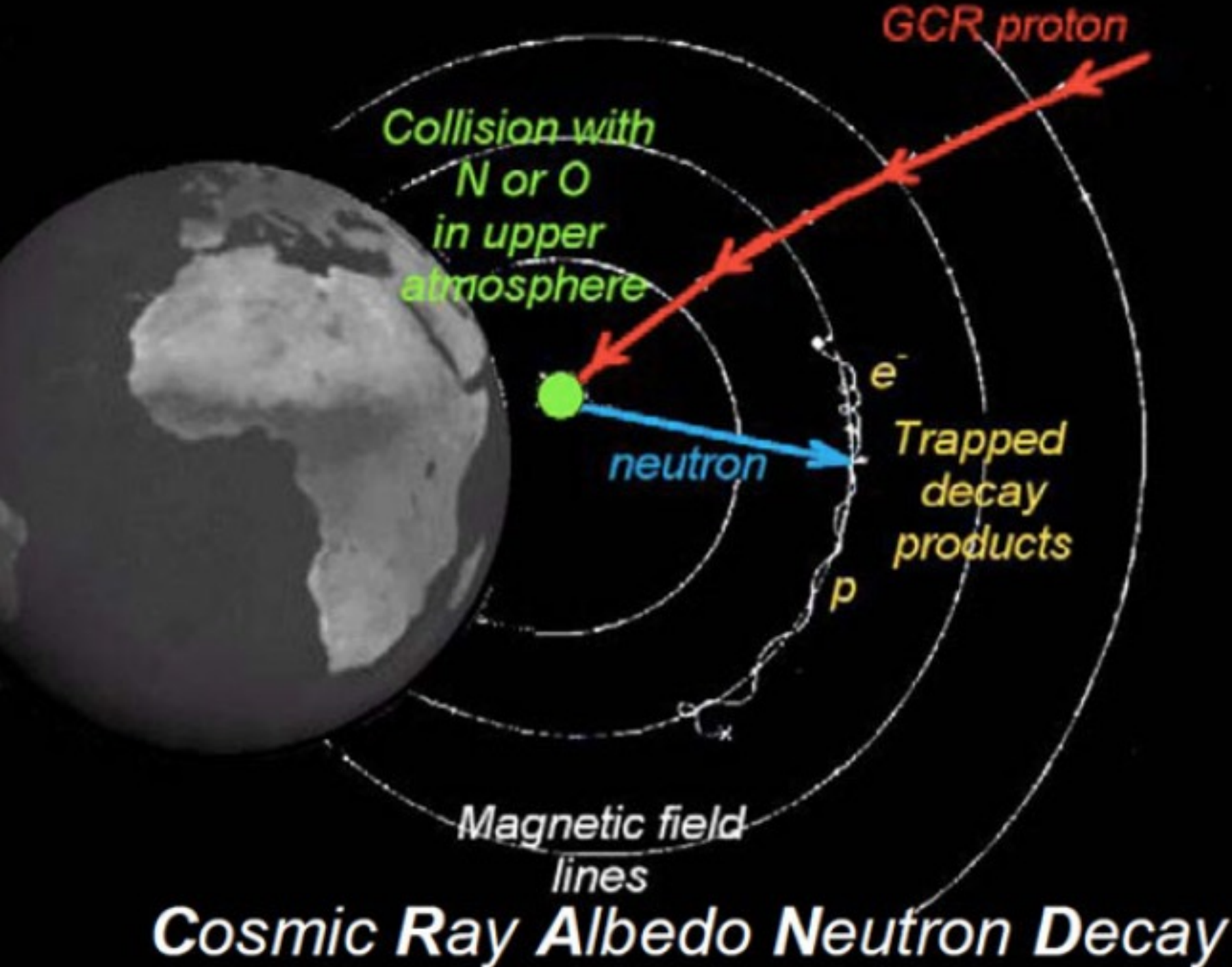
Λευκάγεια κοσμικών ακτίνων:

Secondary particles
which have appeared
as the result of the interaction of cosmic rays
in the underlying layers of the atmosphere.
Neutrons decay with a 10 min half-life.

Inner belt: CRAND (Cosmic Ray Albedo Neutron Decay)

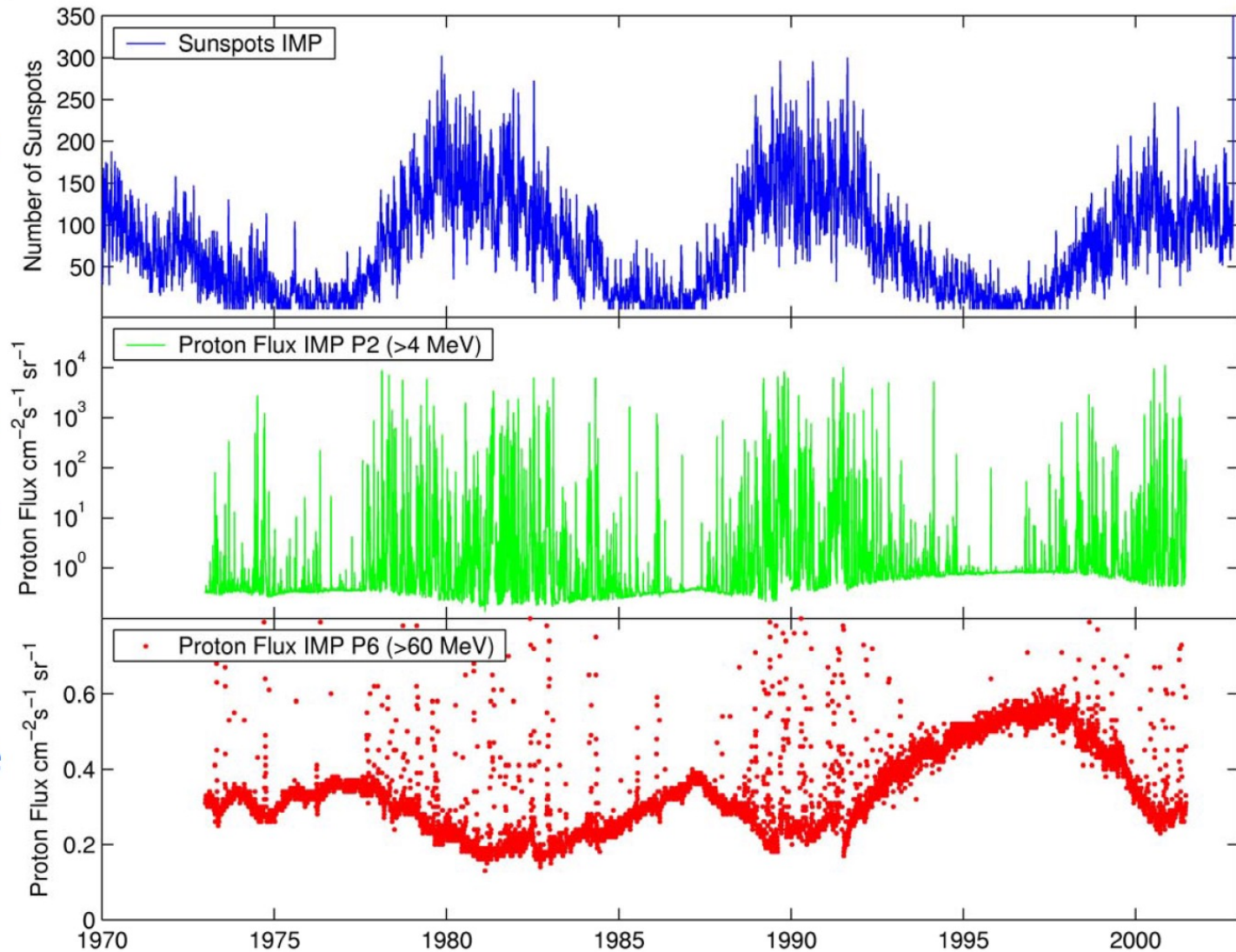
Διάσπαση β^- : διάσπαση ενός νετρονίου σε ένα πρωτόνιο, ένα ηλεκτρόνιο και ένα αντινετρίνο του ηλεκτρονίου



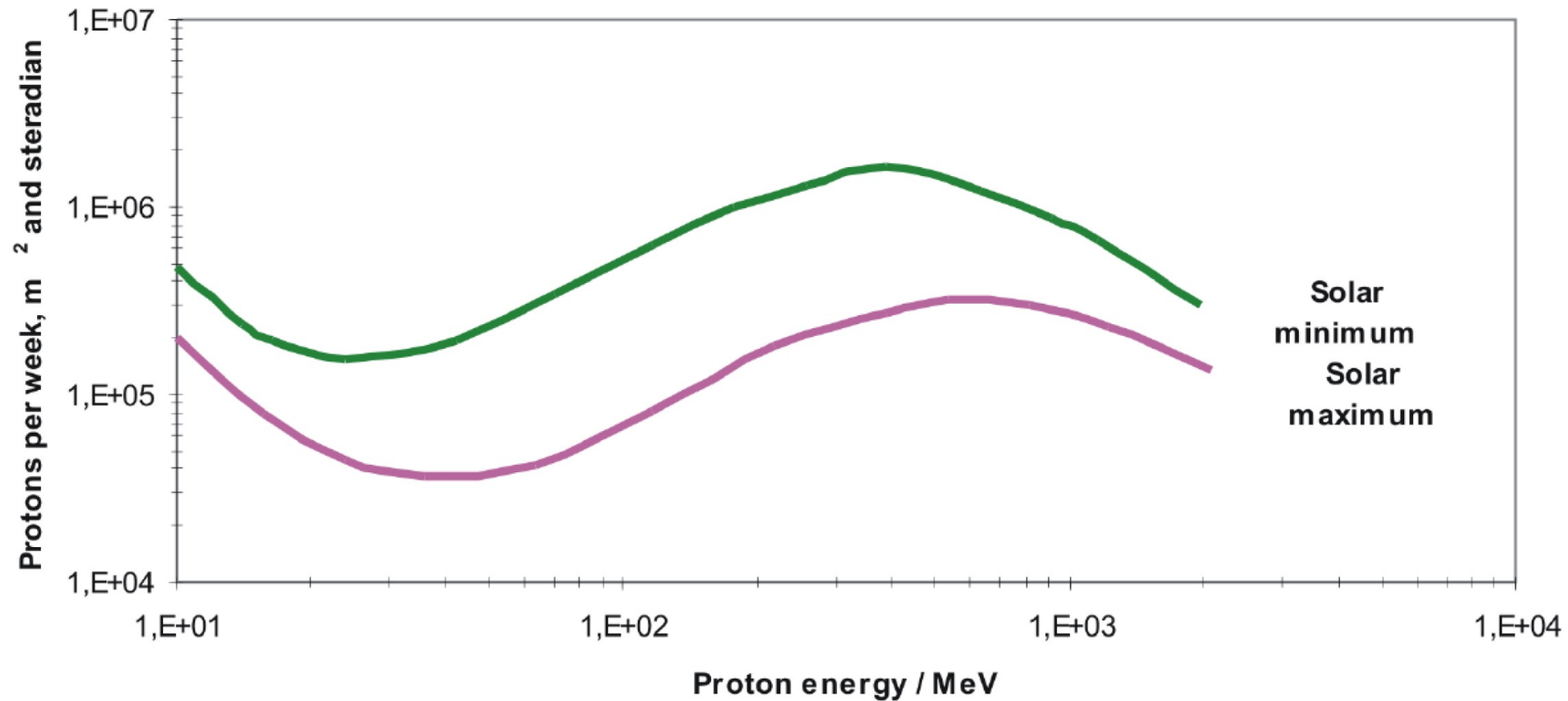


Particles during the solar cycle

- Spikes are solar energetic particles (SEPs): individual events of solar origin (flares, CMEs)
- SEPs are observed during solar minimum although with smaller likelihood
- Background anti-correlated with the solar cycle.



Cosmic ray modulation, important for inner zone



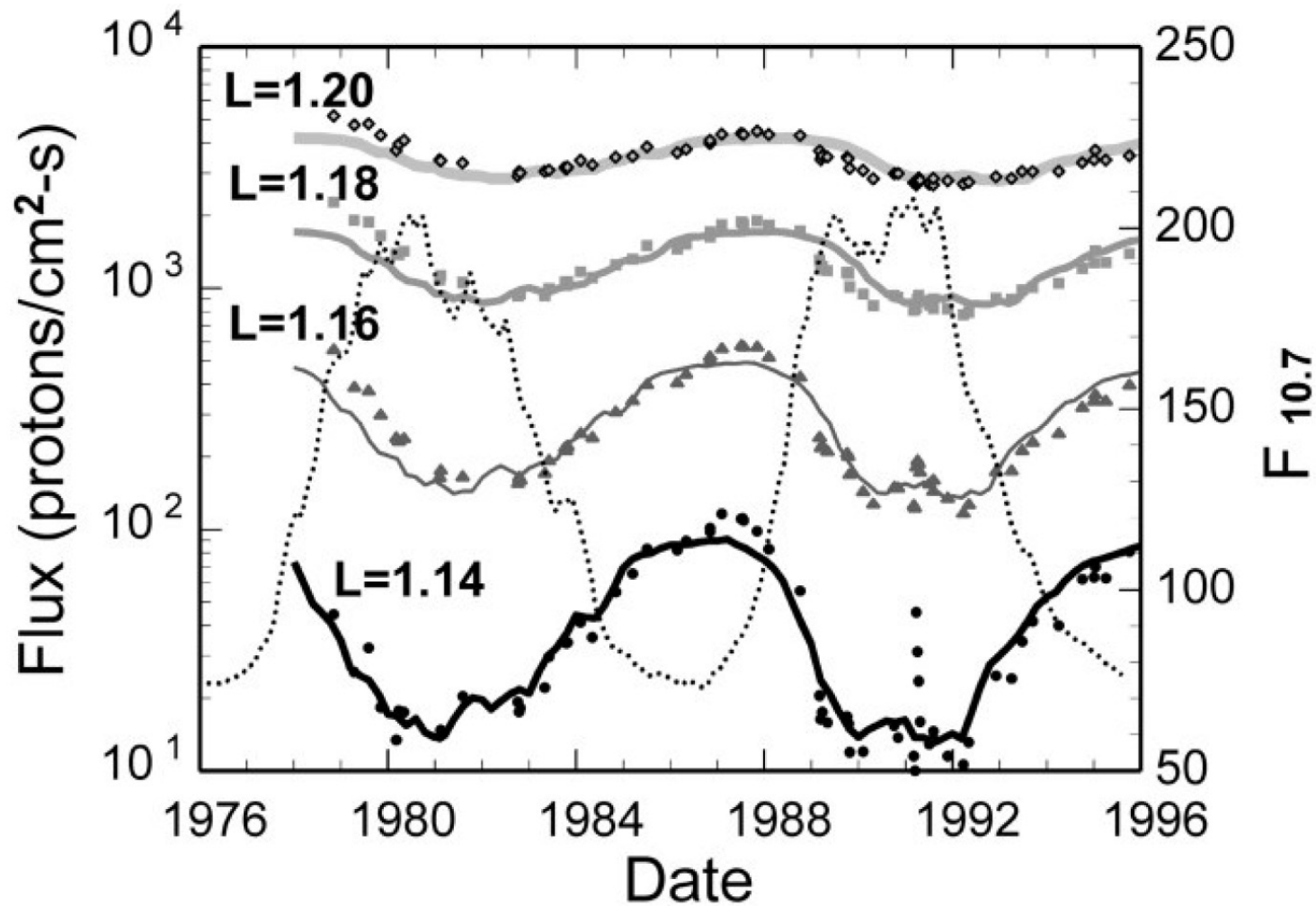


Fig. 15. Proton distributions on the magnetic equator for protons in the inner zone at $E > 80$ MeV which were used as the basis for the first trapped proton