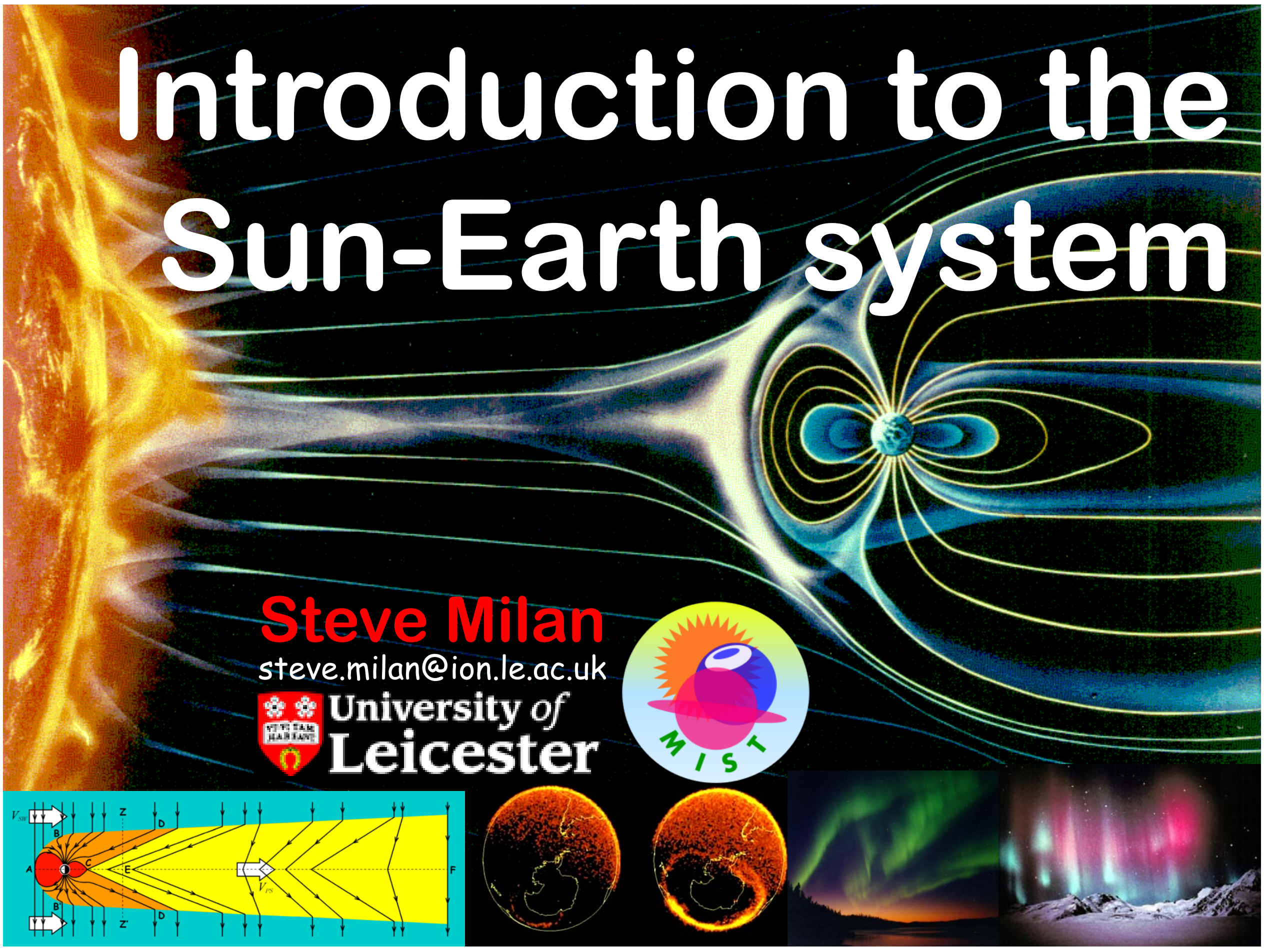
Introduction to the Sun-Earth system
Steve Milan
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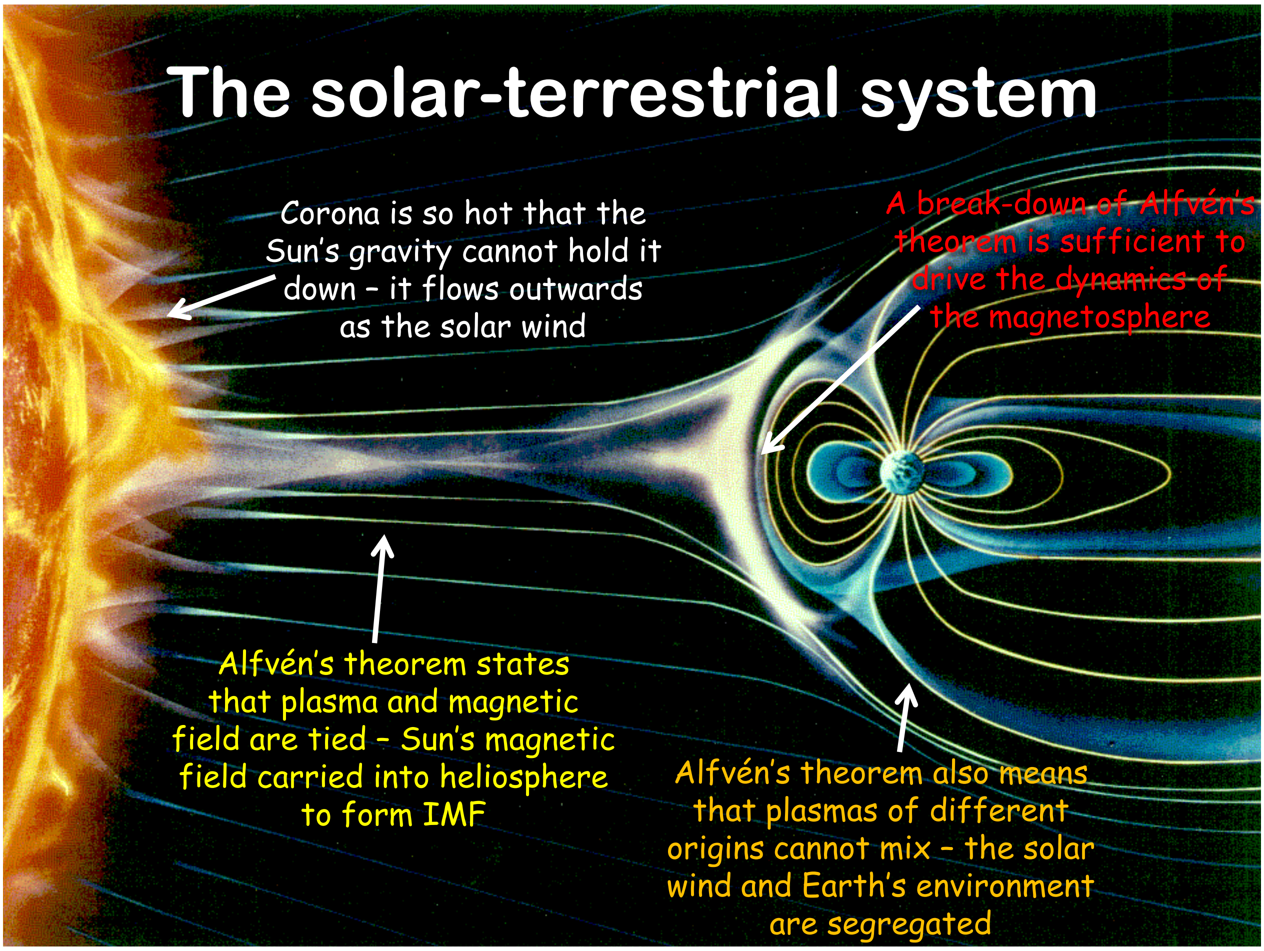
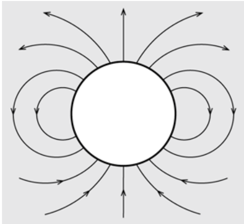
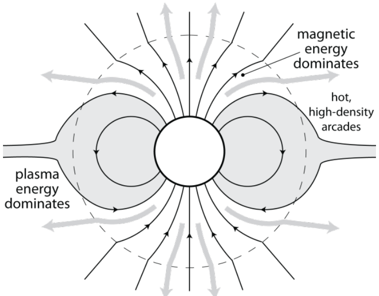
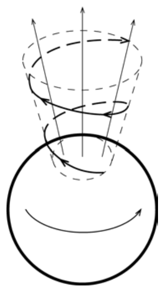
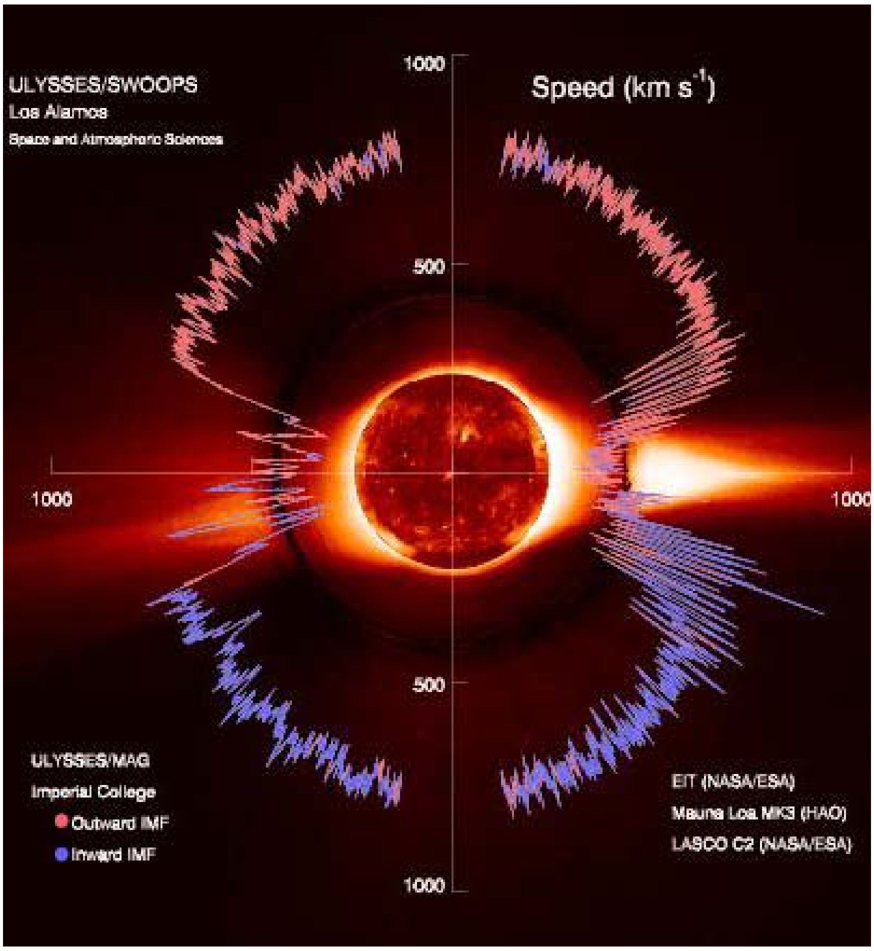
MIST

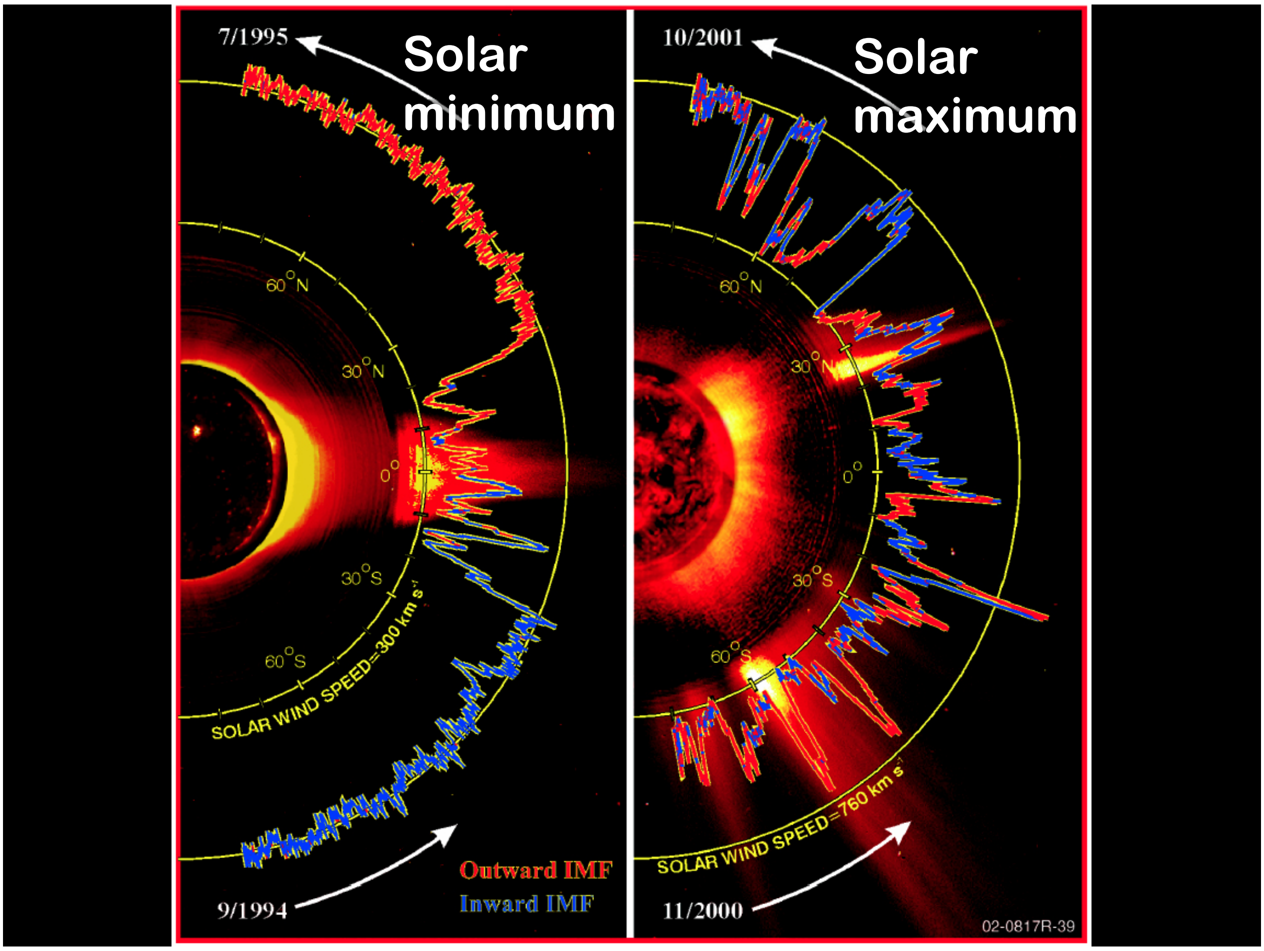

The solar-terrestrial system
Corona is so hot that the Sun's gravity cannot hold it down – it flows outwards as the solar wind
A break-down of Alfvén's theorem is sufficient to drive the dynamics of the magnetosphere
Alfvén's theorem states that plasma and magnetic field are tied – Sun's magnetic field carried into heliosphere to form IMF
Alfvén's theorem also means that plasmas of different origins cannot mix – the solar wind and Earth's environment are segregated



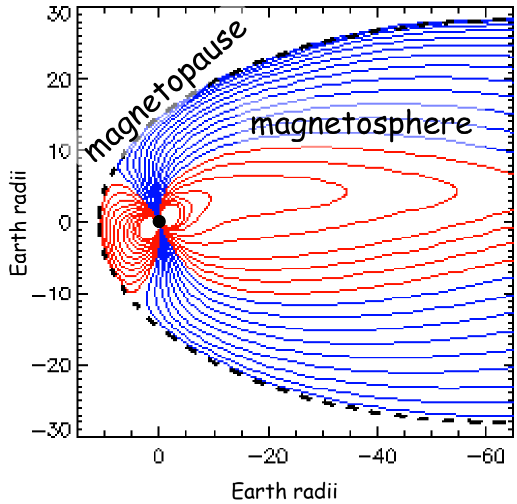

magnetic
energy
dominates
hot,
high-density
arcades
plasma
energy
dominates




ULYSSES/SWOOPS
Los Alamos
Space and Atmospheric Sciences
Speed (km s^{-1})
1000
500
1000
1000
500
1000
ULYSSES/MAG
Imperial College
Outward IMF
Inward IMF
EIT (NASA/ESA)
Mauna Loa MK3 (HAO)
LASCO C2 (NASA/ESA)

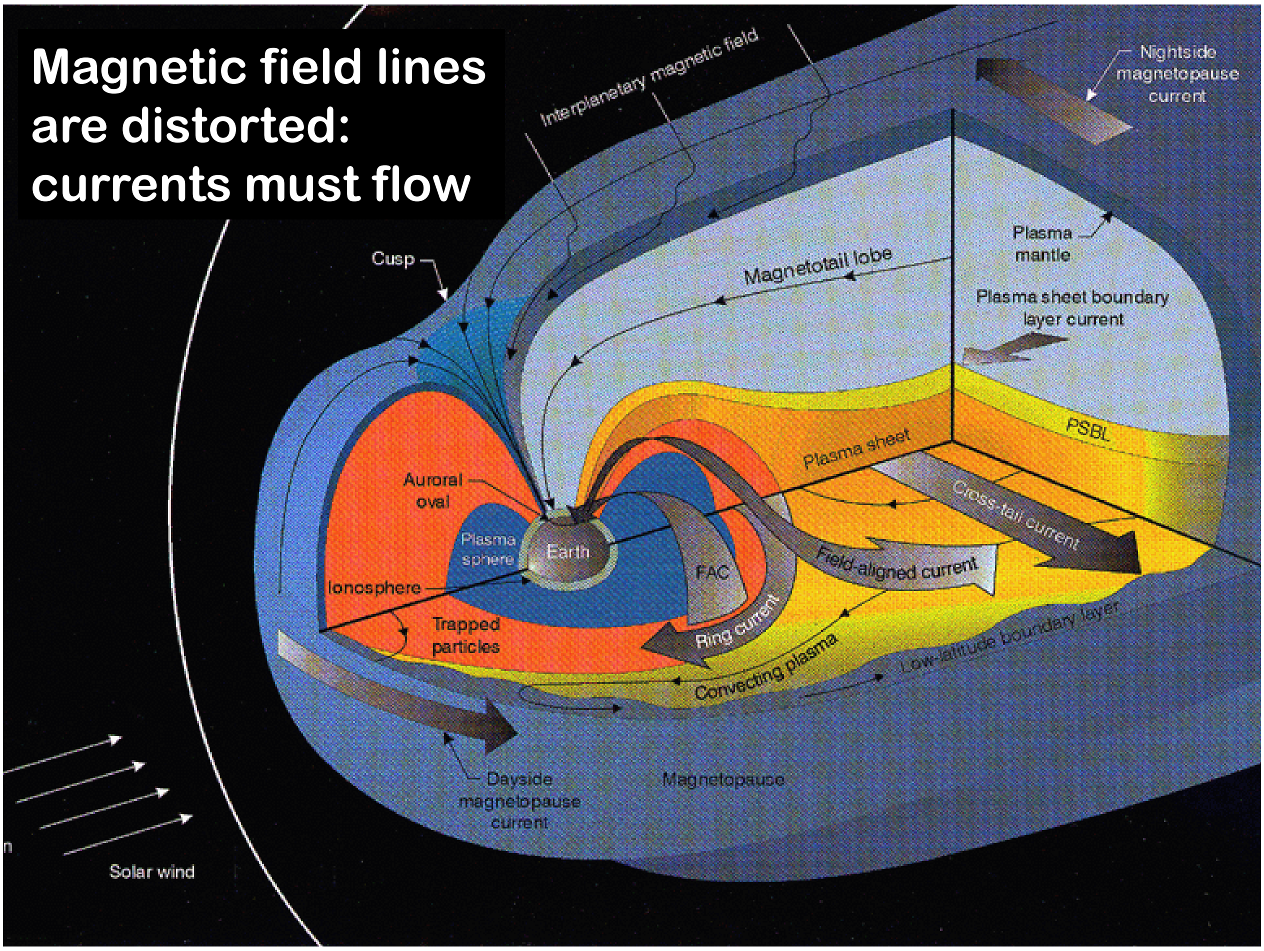

7/1995
Solar
minimum
60° N
30° N
0°
30° S
60° S
SOLAR WIND SPEED=300 km s^{-1}
9/1994
Outward IMF
Inward IMF
10/2001
Solar
maximum
60° N
30° N
0°
30° S
60° S
SOLAR WIND SPEED=760 km s^{-1}
11/2000
02-0817R-39

The magnetospheric cavity



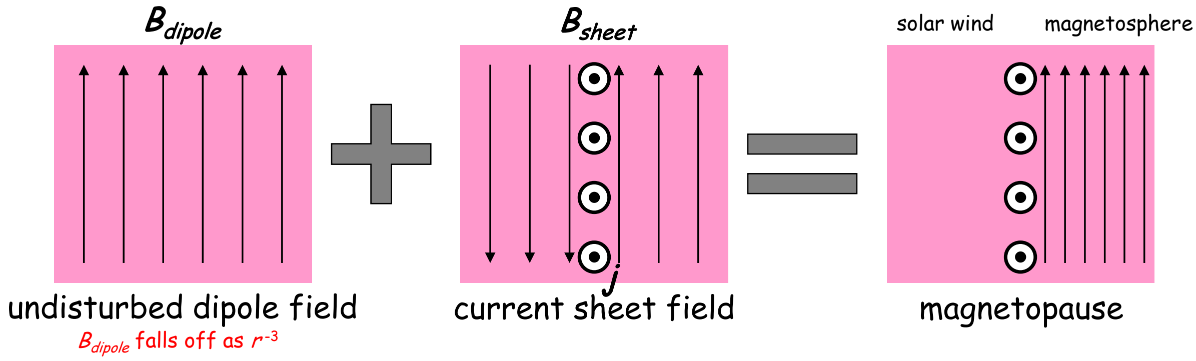
- The Earth's magnetic field and plasma environment provide an impenetrable obstacle to the outward flow of the solar wind
- The dipolar magnetic field of the Earth is distorted by the impinging solar wind
- Inside the magnetic field strength is greater than in the solar wind, but the plasma density is much lower: the magnetosphere is a *cavity*

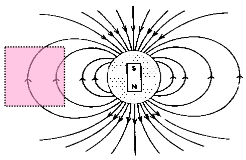
	Solar wind	Outer magnetosphere
Magnetic field strength	7 nT	20-60 nT
Particle density	7 cm^{-3}	0.01-1 cm^{-3}



Chapman-Ferraro currents

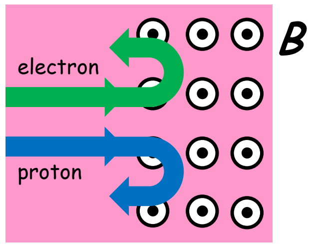
As the solar wind compresses the magnetosphere a current layer must form





Ampére's Law:

$$\mathrm{curl}\,\boldsymbol{B} = \mu_0 \boldsymbol{j}$$



For field strength to (almost) cancel out in solar wind $B_{sheet} \approx B_{dipole}$

Thus, just inside magnetopause the field strength is "compressed" to $2B_{dipole}$

The location of the boundary (the magnetopause) is determined by **magnetic pressure** on the inside and particle **ram pressure** on the outside

ram (dynamic) pressure = momentum crossing unit area in unit time

$$P_{dyn} = m_p V \times nV = nm_p V^2$$

If solar wind $n = 7$ cm^{-3}, and $V = 450$ km s^{-1}, then $P_{dyn} = 2.5$ nPa

(cf. you blow with a dynamic pressure of ~1 Pa)

The mass striking the dayside magnetopause (assuming radius of ~10 R_E) is ~60 kg s^{-1}

The kinetic energy carried by these protons is ~6x10^{12} W

(cf. sunlight falling on Earth's surface ~10^{17} W)

A magnetic field exerts a pressure equal to

$$P_{mag} = \frac{B^2}{2\mu_0}$$

B_{dipole} falls off as r^{-3}, so P_{mag} falls off as r^{-6}

The magnetosphere compresses until the magnetic pressure just inside the magnetopause balances the solar wind ram pressure

At the nose of the magnetosphere the dipole field must be compressed to a field strength of ~60 nT to give P_{mag} = 2.5 nT

This occurs where the magnetopause is pushed in to a stand-off distance of ~10 R_E

Away from the nose, the solar wind strikes the magnetopause obliquely, so the normal component of the ram pressure decreases

Hence the magnetosphere flares outwards

Not all magnetospheres are created equal

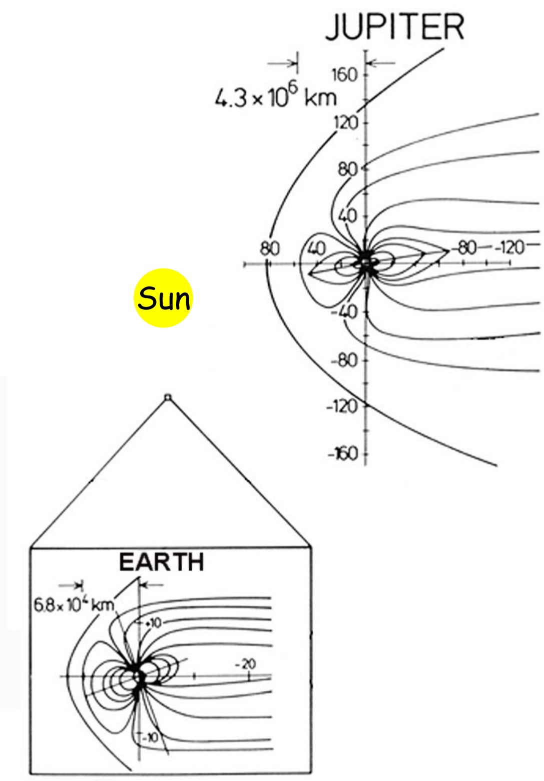
The size of a magnetosphere depends on:

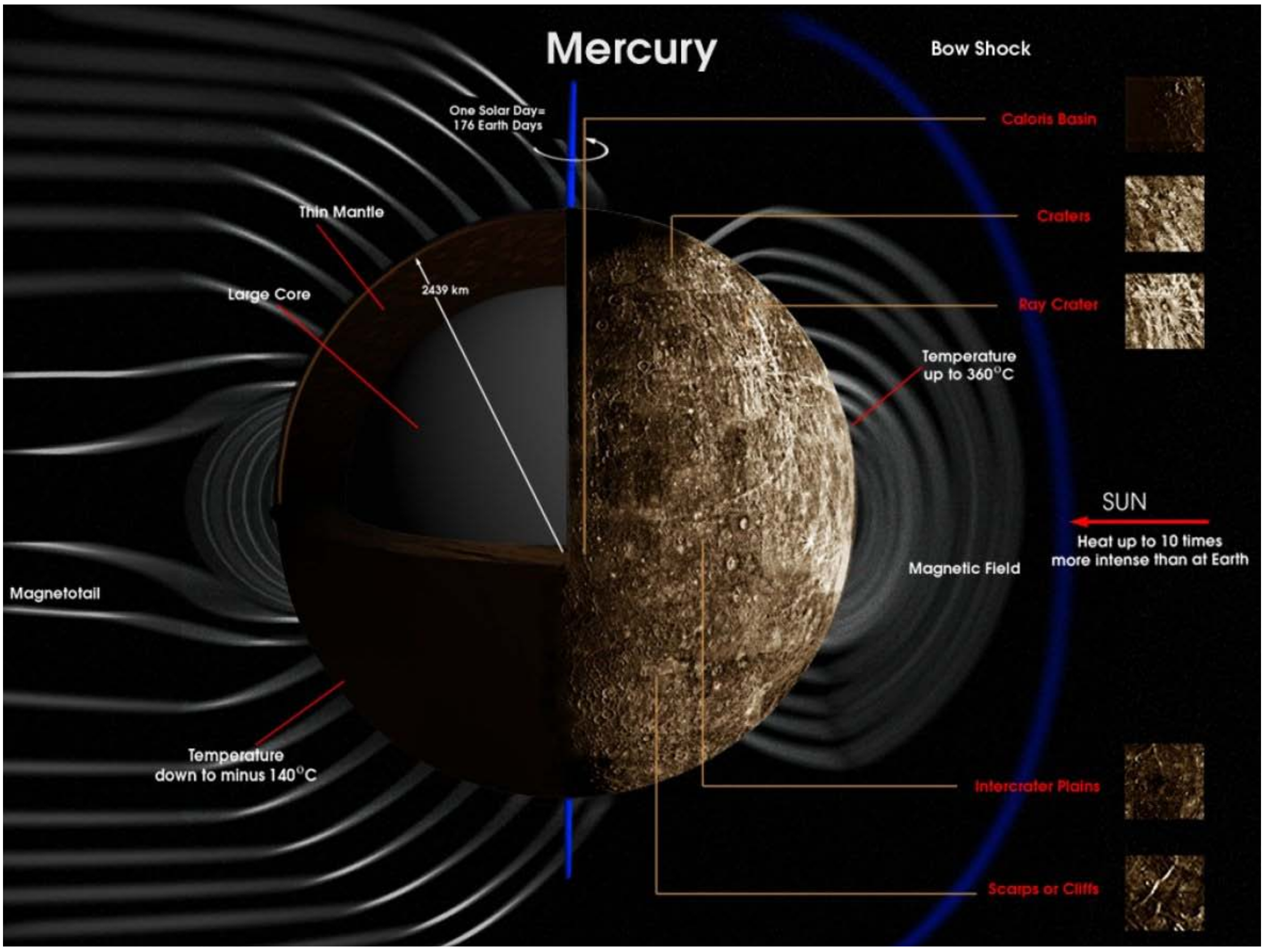
- the strength of the magnetic field of the planet
- the ram pressure of the solar wind

Jupiter is 5 times further from the Sun than the Earth, so the solar wind pressure is reduced by a factor of 1/25

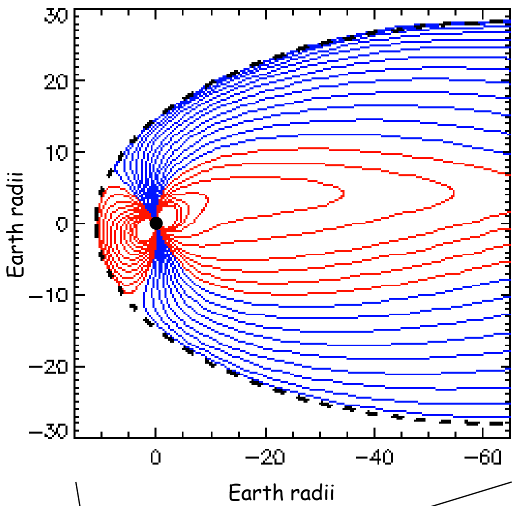
The magnetic field of Jupiter is over 10 times stronger than the Earth's

Jupiter's magnetosphere is 5 times larger than the Sun





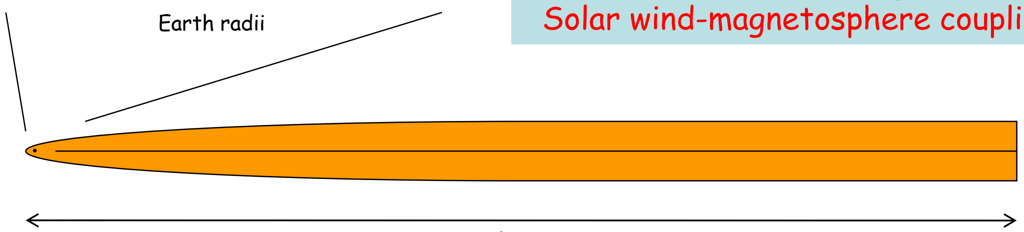
The magnetotail



These calculations explain the shape of the near-Earth magnetosphere

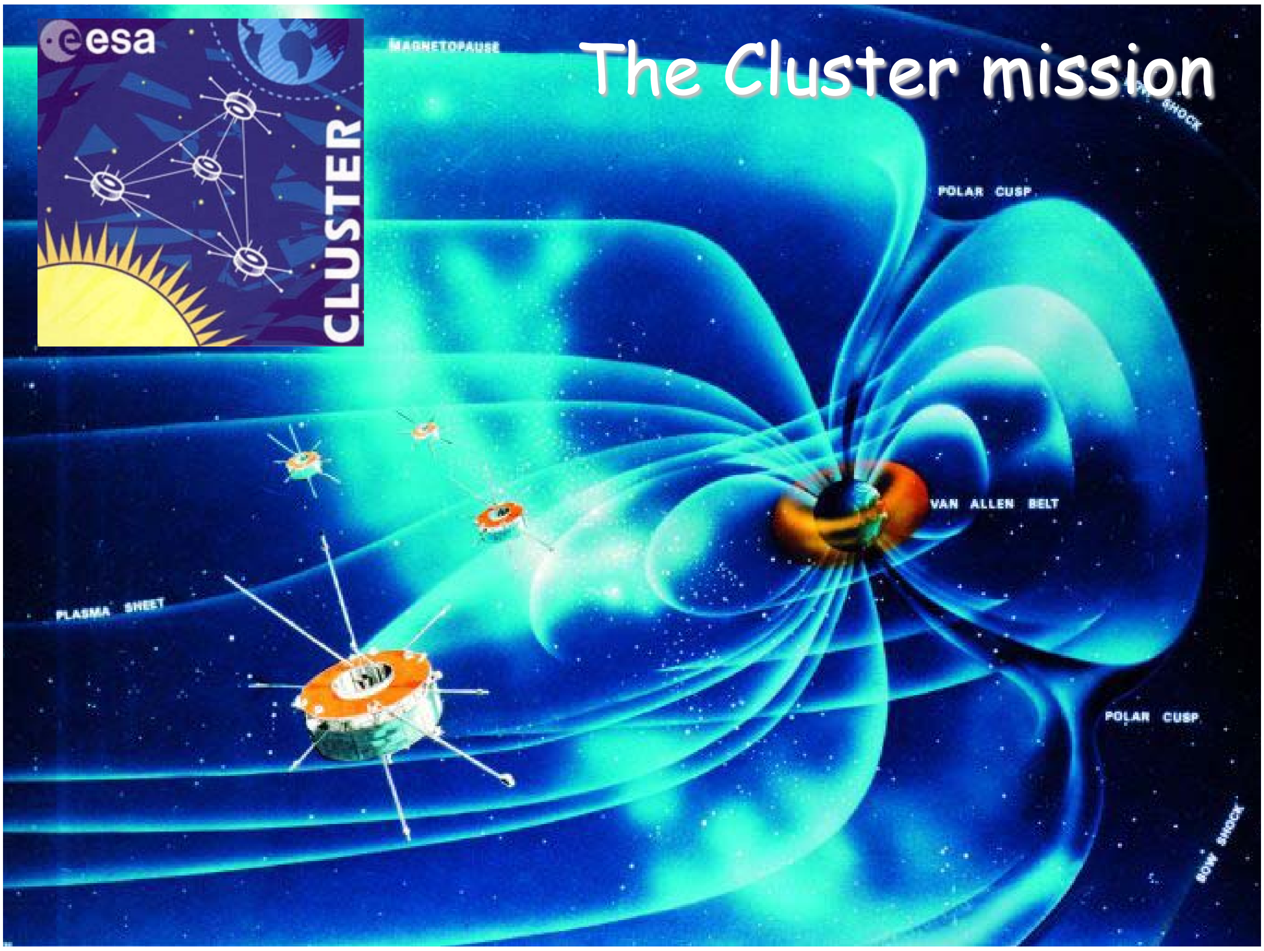
Overall the magnetosphere should be rain-drop shaped, but is observed to have a long "tail", perhaps **1000** R_E or more in length

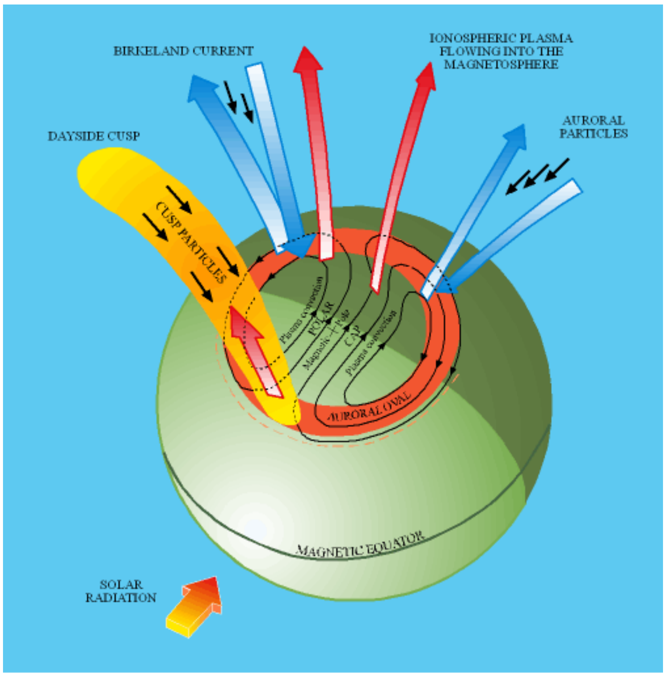
This indicates that a "viscous-like" interaction must take place between the solar wind and the magnetopause to stretch it into a "magnetotail": Solar wind-magnetosphere coupling



~1/20 AU

The Cluster mission





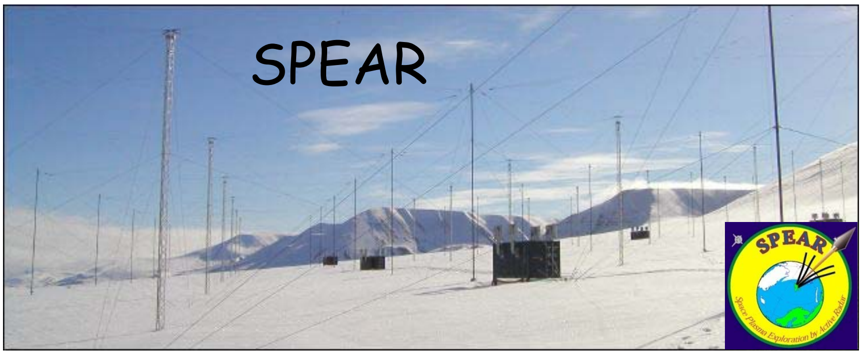
The ionosphere acts as a screen on which the magnetosphere is projected

In most situations in the solar system, plasmas are “frozen” to their internal magnetic fields

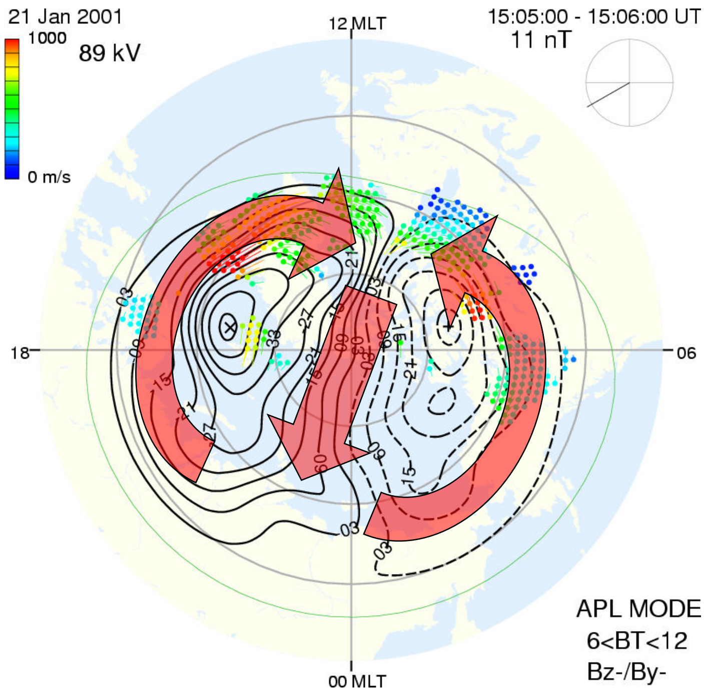
If the field moves then the plasma moves with it, and *vice versa*

Particles can much more freely move *along* field lines however, and the magnetosphere and ionosphere communicate through field-guided currents, waves, and precipitation

Ionospheric radars



Ionospheric convection

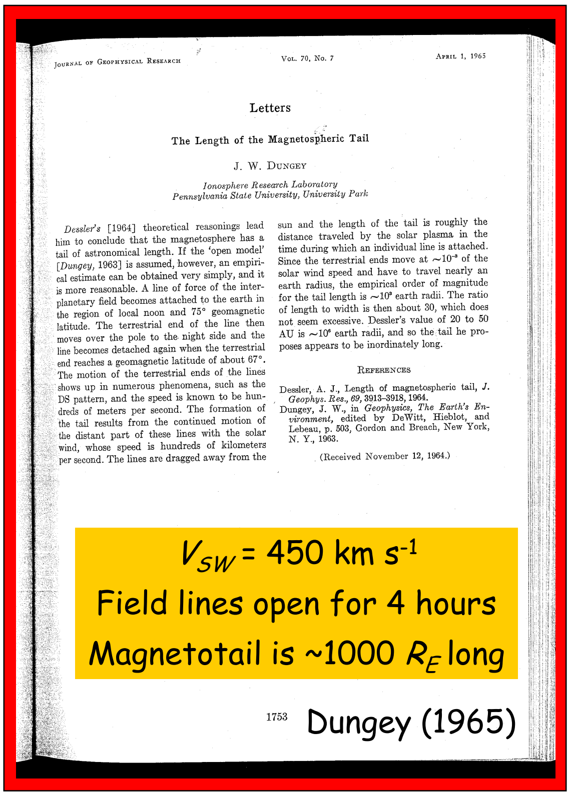


Measurements of the ionospheric plasma convection show that field lines remain open for 4 hours and closed for 8 hours

A solar wind speed of 450 km s^{-1} implies that the magnetotail is ~1000 R_E in length

The size of the "polar cap" determines the amount of magnetic flux in the "lobes"

This in turn allows the radial dimension of the magnetotail to be estimated at ~25 R_E


Journal of Geophysical Research Vol. 70, No. 7 April 1, 1965

Letters

The Length of the Magnetospheric Tail

J. W. Dungey

Ionosphere Research Laboratory
Pennsylvania State University, University Park

Dessler's [1964] theoretical reasonings lead him to conclude that the magnetosphere has a tail of astronomical length. If the 'open model' [*Dungey*, 1963] is assumed, however, an empirical estimate can be obtained very simply, and it is more reasonable. A line of force of the interplanetary field becomes attached to the earth in the region of local noon and 75° geomagnetic latitude. The terrestrial end of the line then moves over the pole to the night side and the line becomes detached again when the terrestrial end reaches a geomagnetic latitude of about 67°. The motion of the terrestrial ends of the lines shows up in numerous phenomena, such as the DS pattern, and the speed is known to be hundreds of meters per second. The formation of the tail results from the continued motion of the distant part of these lines with the solar wind, whose speed is hundreds of kilometers per second. The lines are dragged away from the sun and the length of the tail is roughly the distance traveled by the solar plasma in the time during which an individual line is attached. Since the terrestrial ends move at $\sim 10^{-3}$ of the solar wind speed and have to travel nearly an earth radius, the empirical order of magnitude for the tail length is $\sim 10^3$ earth radii. The ratio of length to width is then about 30, which does not seem excessive. Dessler's value of 20 to 50 AU is $\sim 10^6$ earth radii, and so the tail he proposes appears to be inordinately long.

References

Dessler, A. J., Length of magnetospheric tail, *J. Geophys. Res.*, *69*, 3913–3918, 1964.
Dungey, J. W., in *Geophysics, The Earth's Environment*, edited by DeWitt, Hieblot, and Lebeau, p. 503, Gordon and Breach, New York, N. Y., 1963.

(Received November 12, 1964.)

V_{SW} = 450 km s^{-1}

Field lines open for 4 hours

Magnetotail is ~1000 R_E long

Dungey (1965)

S. W. H. Cowley

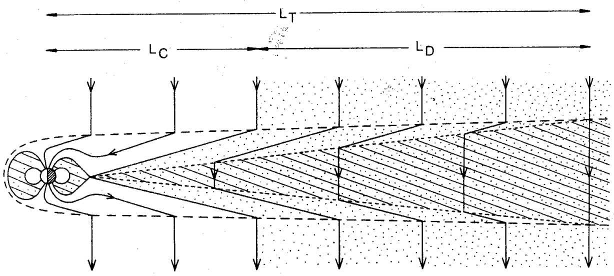


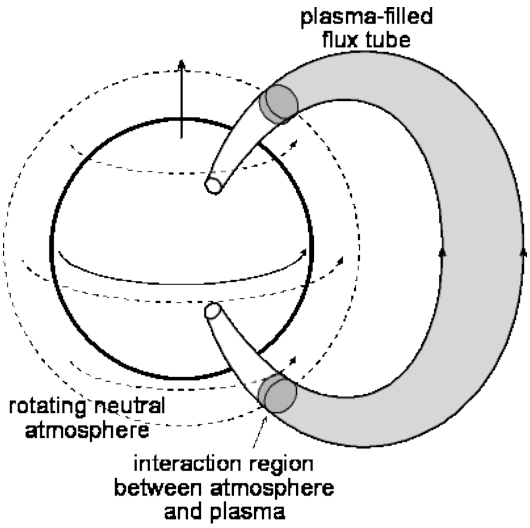
Fig. 1. Noon–midnight meridian sketch through the Earth's magnetosphere and tail, showing magnetic field lines (solid lines), the magnetopause (dashed line), the plasma sheet (hatched area), and energetic particle regions (dotted). The lengths of the "connected" and "disconnected" tails, L_C and L_D respectively, are also indicated.

Cowley (1992)

Disconnected field lines un-kink at a speed of ~1.2 V_{SW}

Disconnected tail is ~5 times longer than connected tail

Corotation

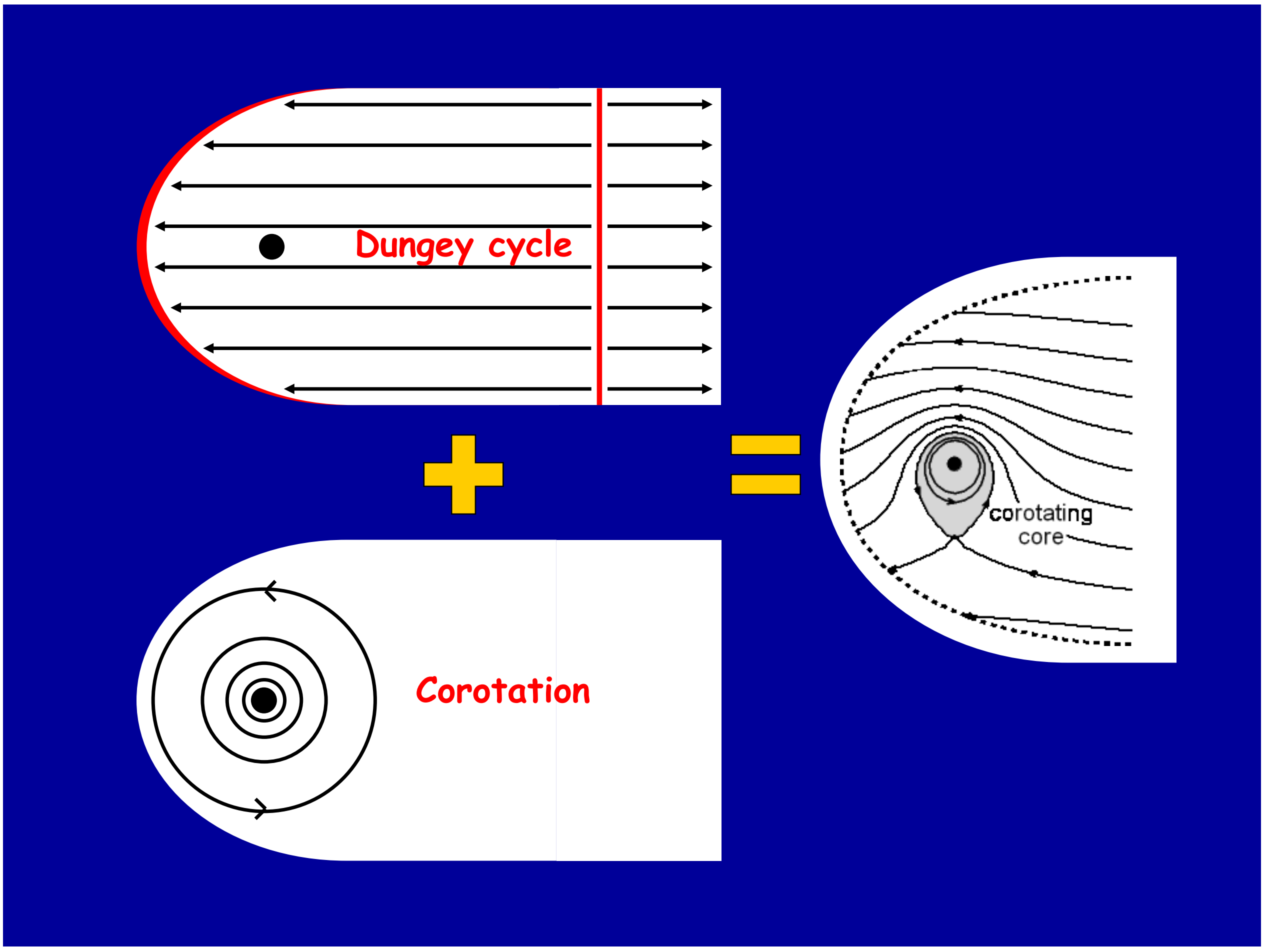


The rotation of the planet also imparts momentum to the magnetospheric plasma

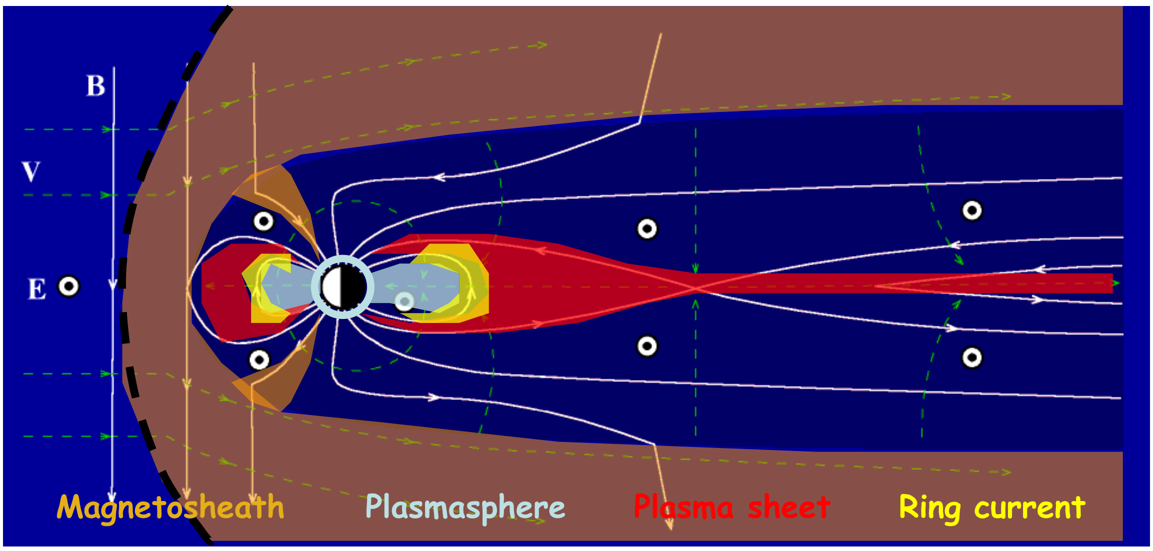
Ionospheric plasma is frictionally coupled to the neutral atmosphere

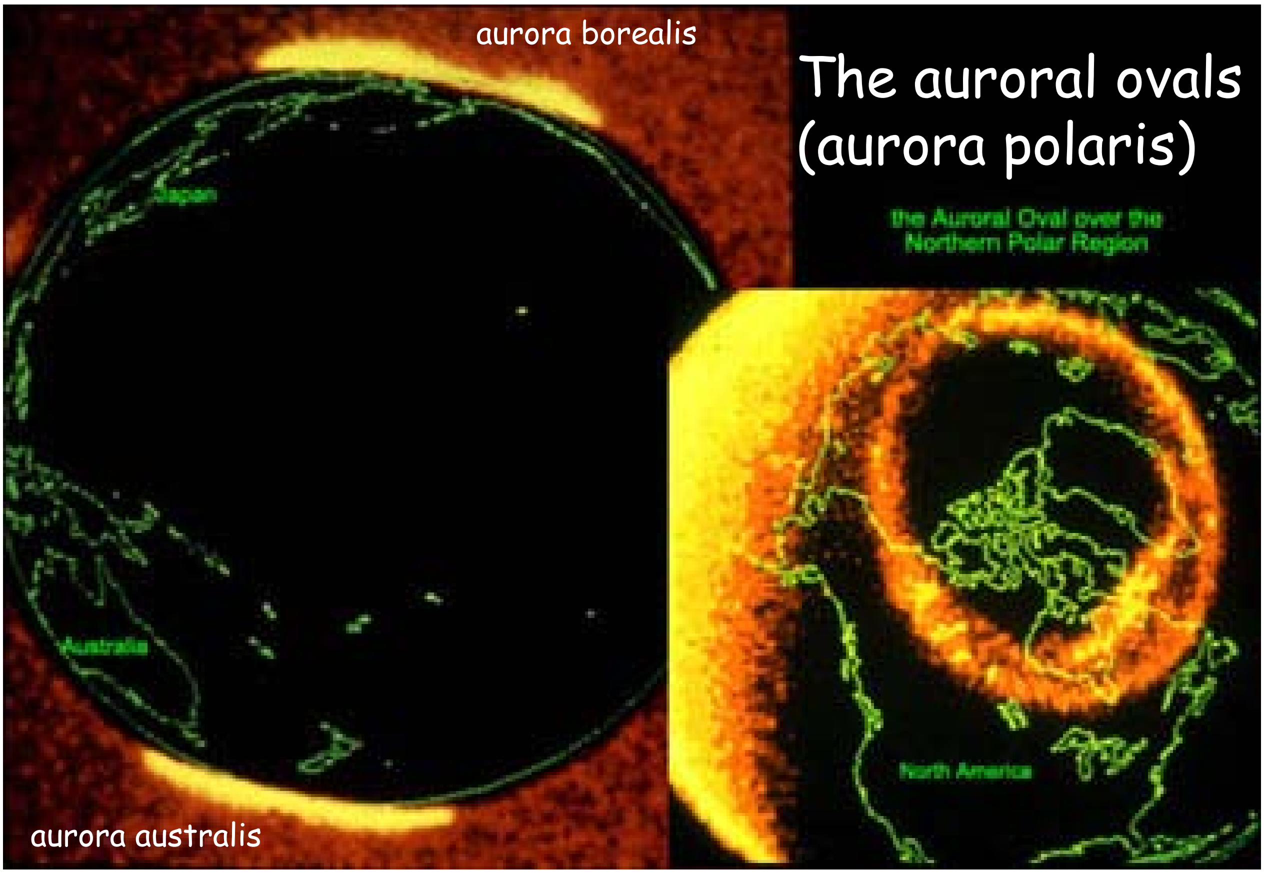
The magnetic field lines, frozen to this plasma, attempt to rotate with the planet

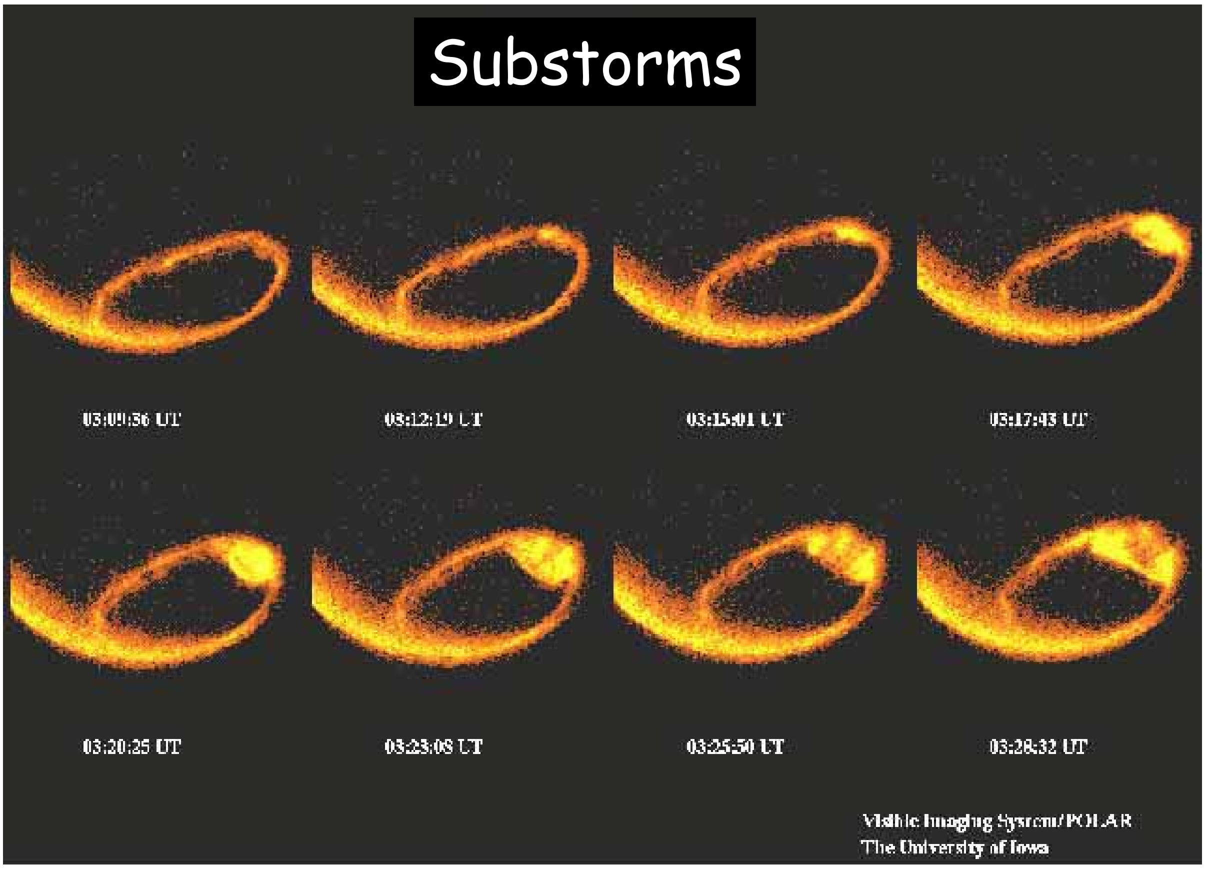
In turn, the magnetospheric plasma is frozen to the corotating magnetic field

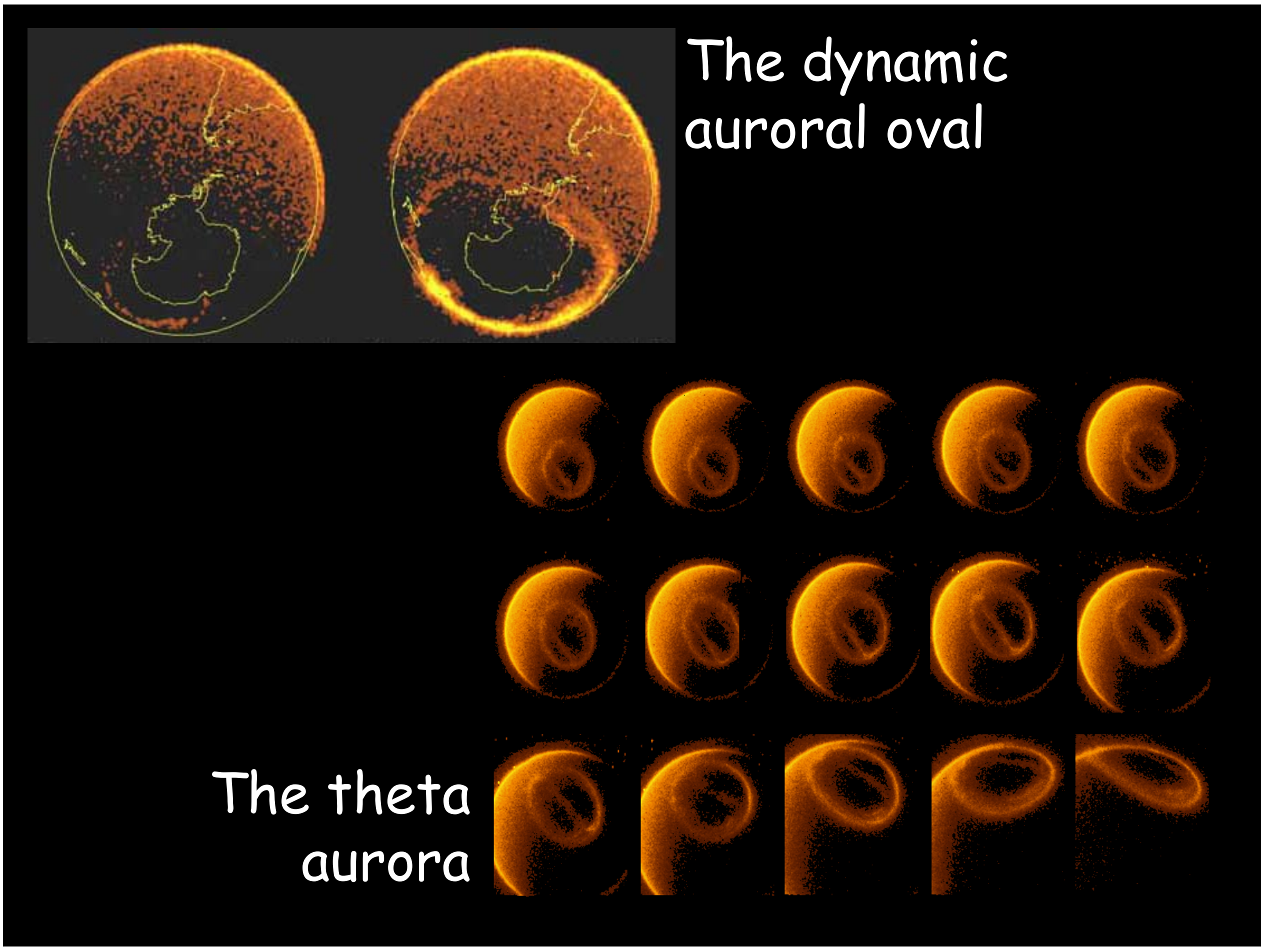


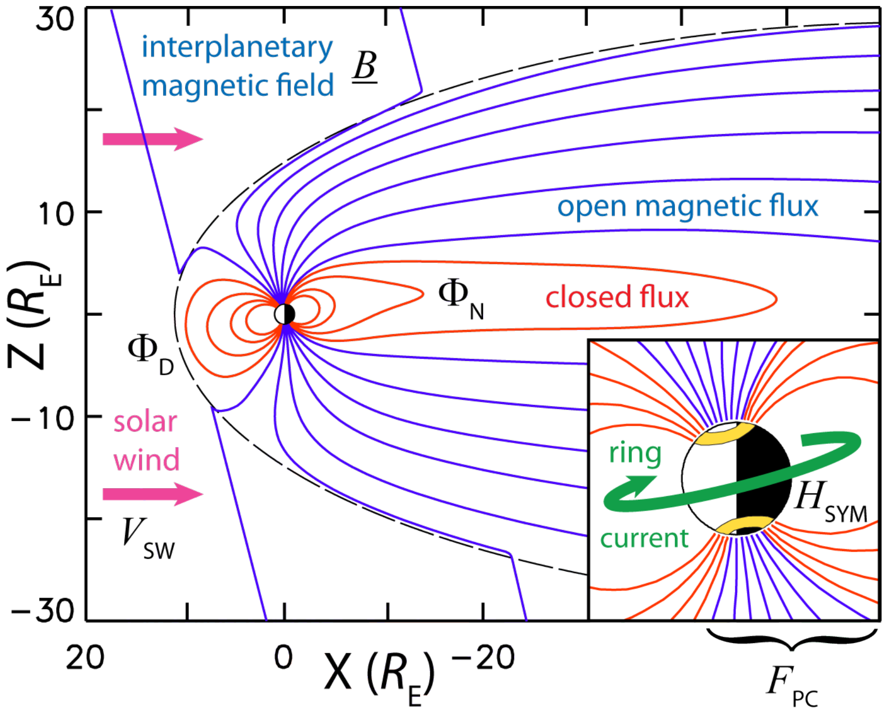
Plasma populations in the magnetosphere




aurora borealis
The auroral ovals
(aurora polaris)
the Auroral Oval over the
Northern Polar Region
Japan
Australia
North America
aurora australis


Substorms
03:09:36 UT
03:12:19 UT
03:15:01 UT
03:17:43 UT
03:20:25 UT
03:23:08 UT
03:25:50 UT
03:28:32 UT
Visible Imaging System/POLAR
The University of Iowa





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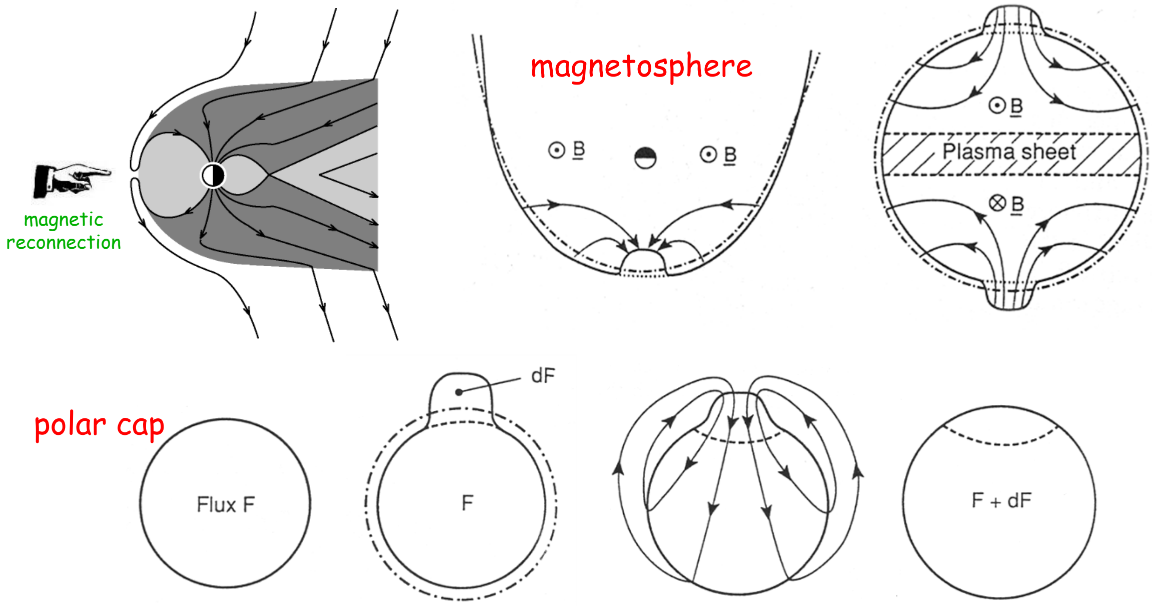
The response of the magnetosphere to a burst of low latitude magnetopause reconnection



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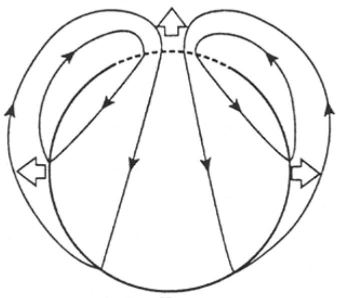
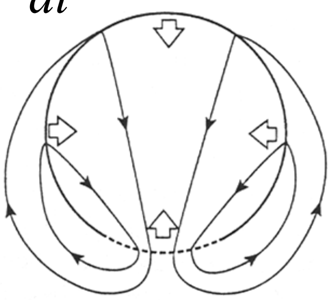
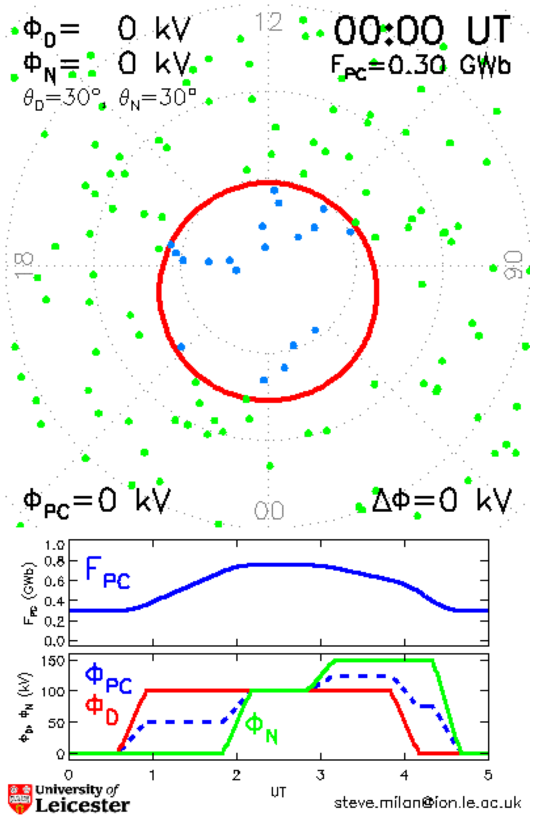
Dungey (1961, 1963), Cowley and Lockwood (1992)

The expanding/contracting polar cap



$$\frac{dF_{PC}}{dt} = \Phi_D - \Phi_N$$





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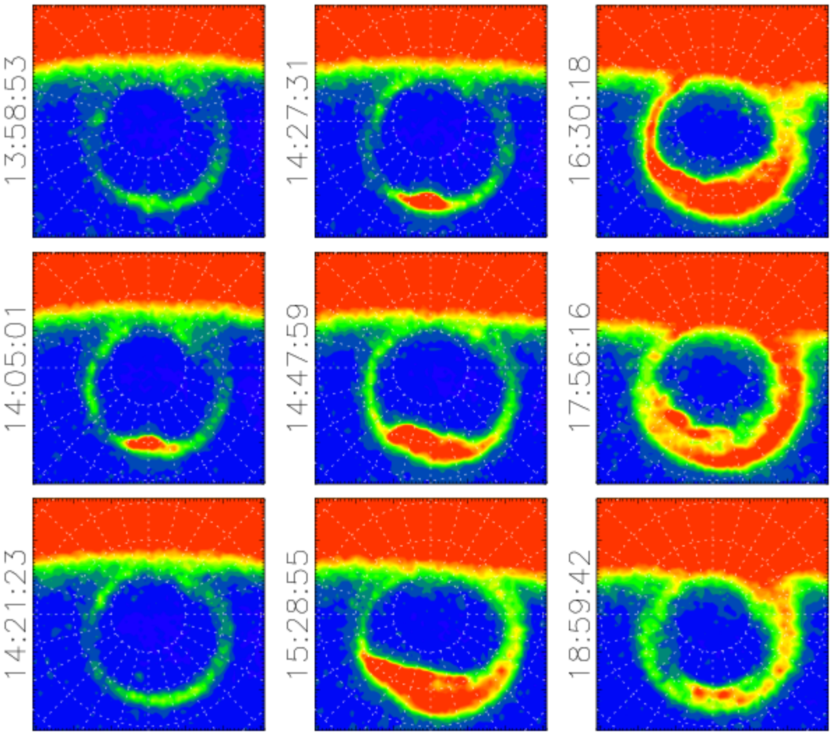
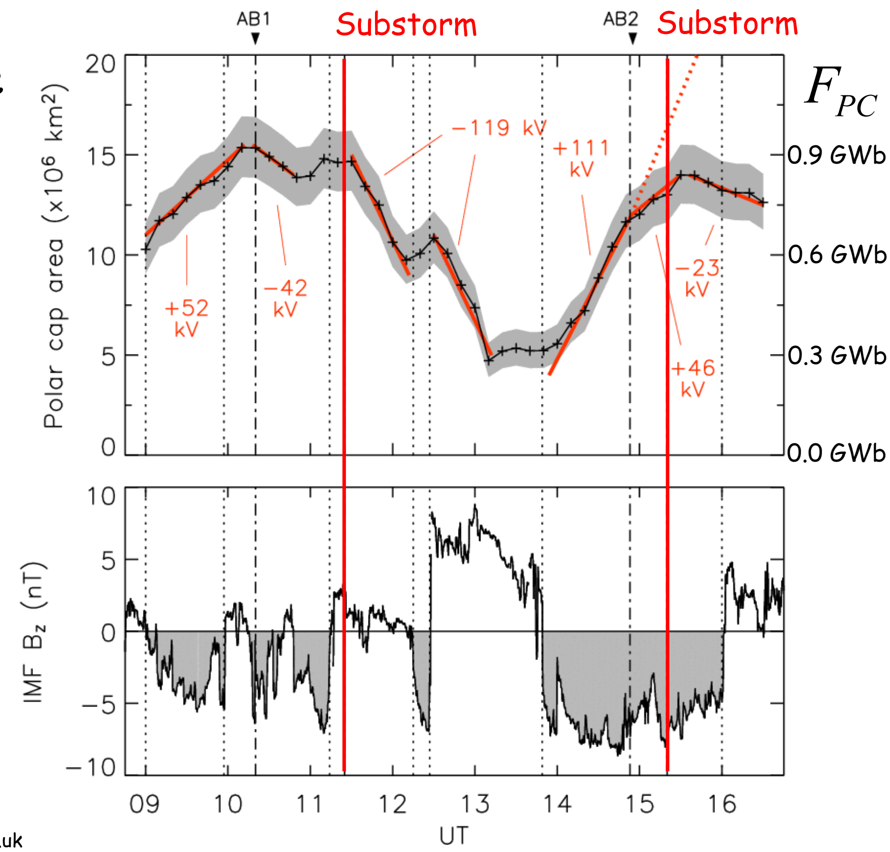
Faraday (1831)
Siscoe and Huang (1985)
Cowley and Lockwood (1992)

The auroral substorm



5 June 1998



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Questions

Solar wind-magnetosphere coupling leads to the occurrence of substorms, but...

- What triggers substorm onset?
- How does the dayside reconnection rate influence the rate and size of substorms?
- Why does the auroral oval move to very low latitudes during disturbed conditions?

20 August – 6 September, 2005

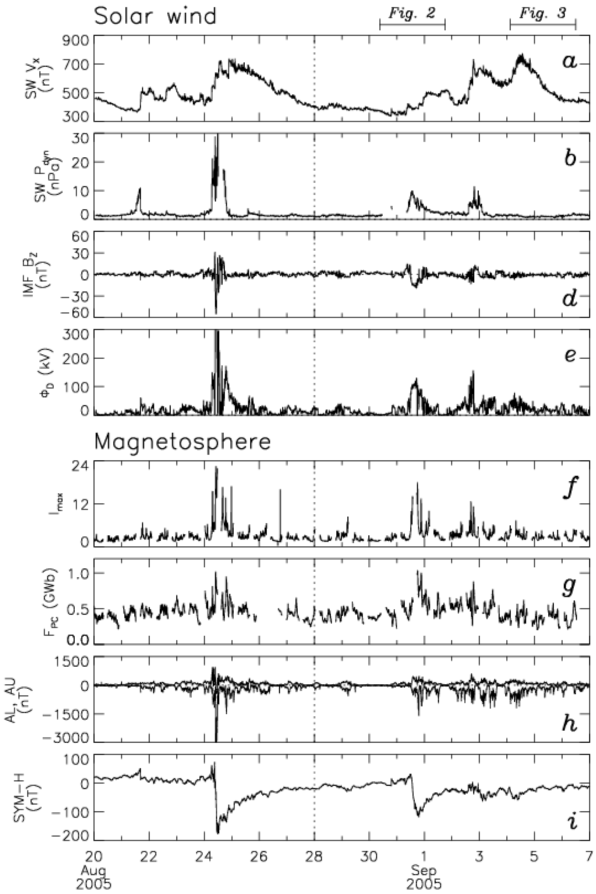

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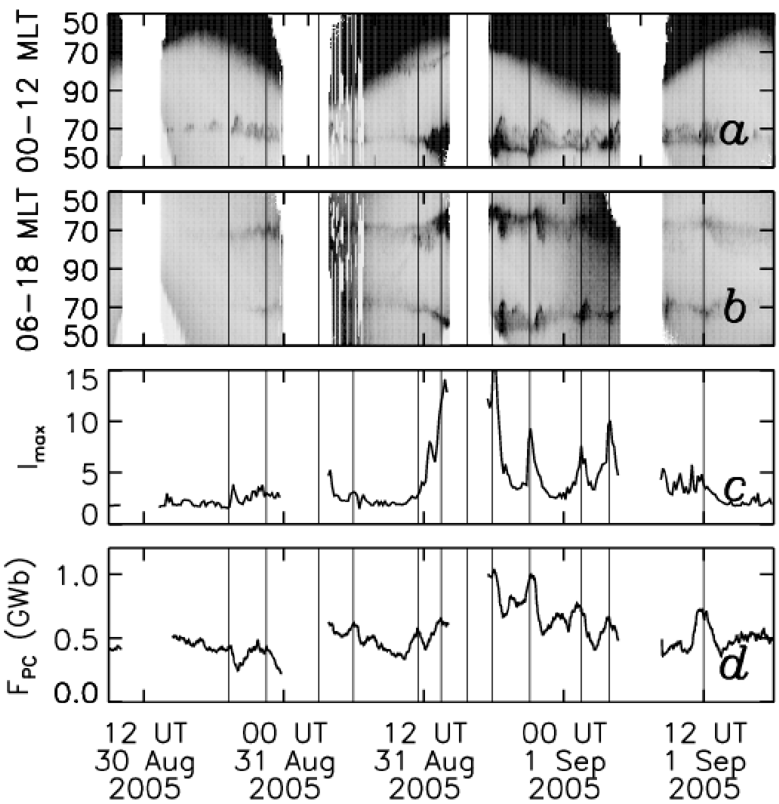
IMAGE FUV

IMAGE FUV/WIC observations allow identification of substorms and quantification of changes in polar cap flux F_{PC}

F_{PC} increases during substorm growth phase and decreases after expansion phase onset



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Magnetotail signatures

Good comparison with ground signatures of substorms in AU and AL

Cluster shows magneto-tail inflation during growth phase, and deflation and dipolar-ization after expansion phase onset

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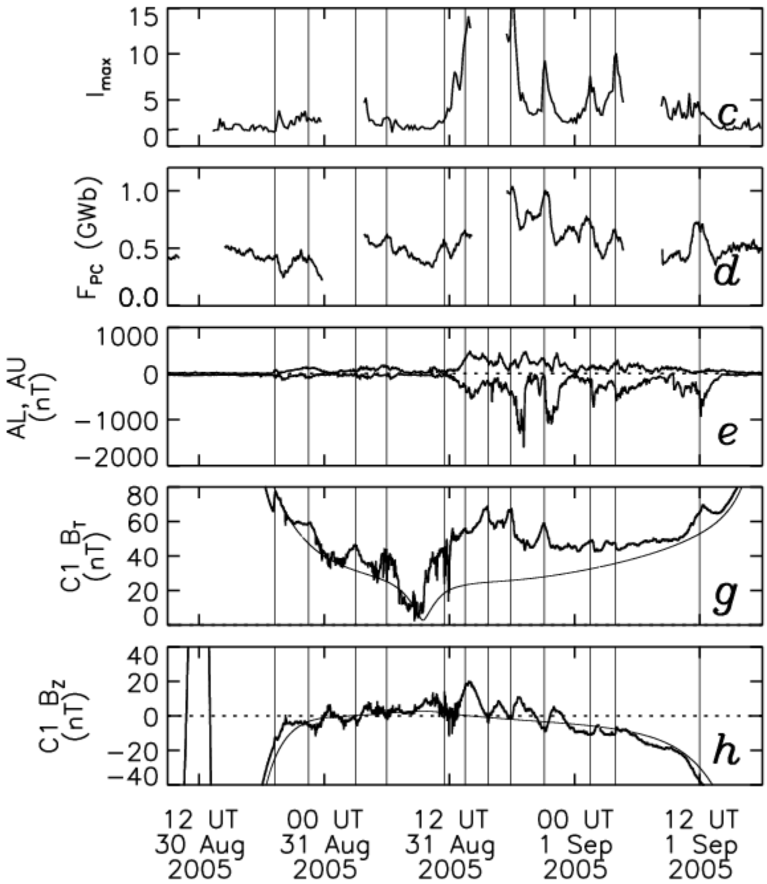

Another way of looking at substorms

Superposed epoch analyses of auroral intensity, open flux, AU and AL, Sym-H, and SW-coupling during 40 substorms

Substorms binned by open flux at onset

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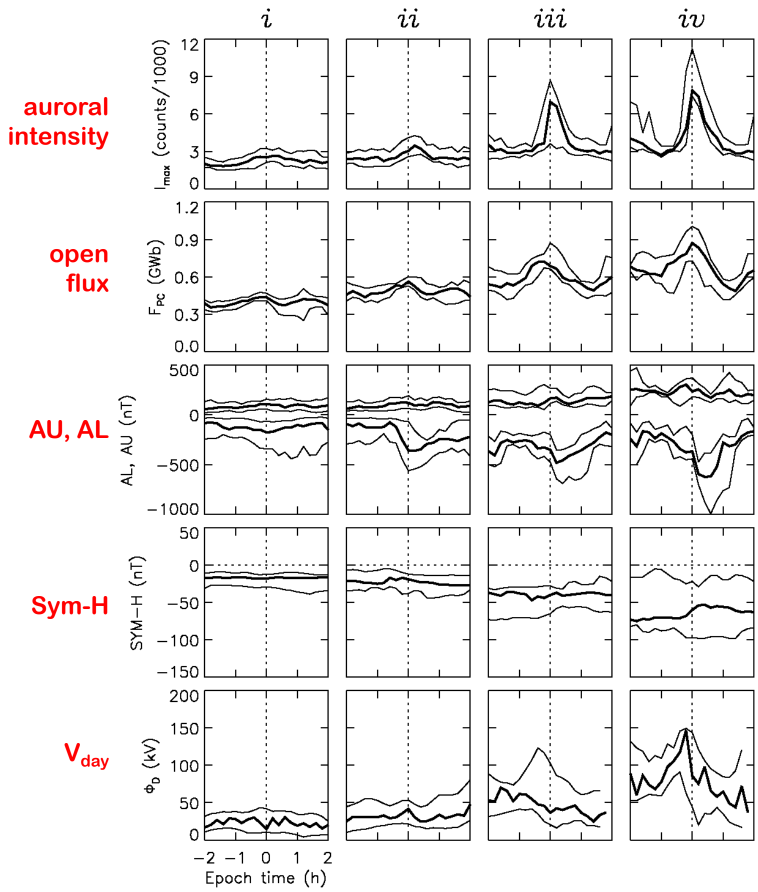

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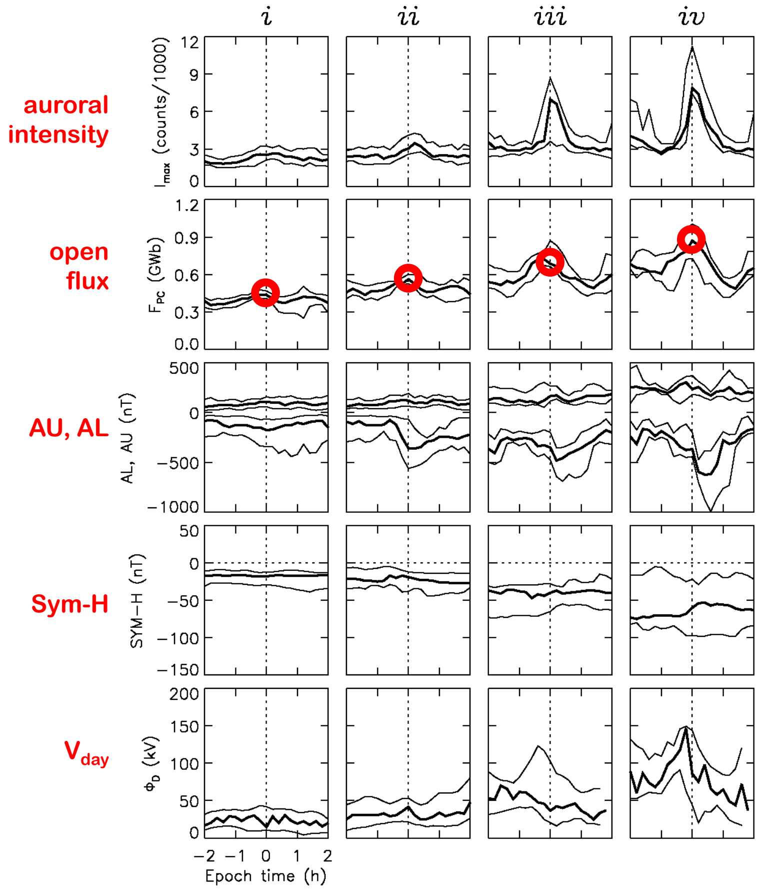

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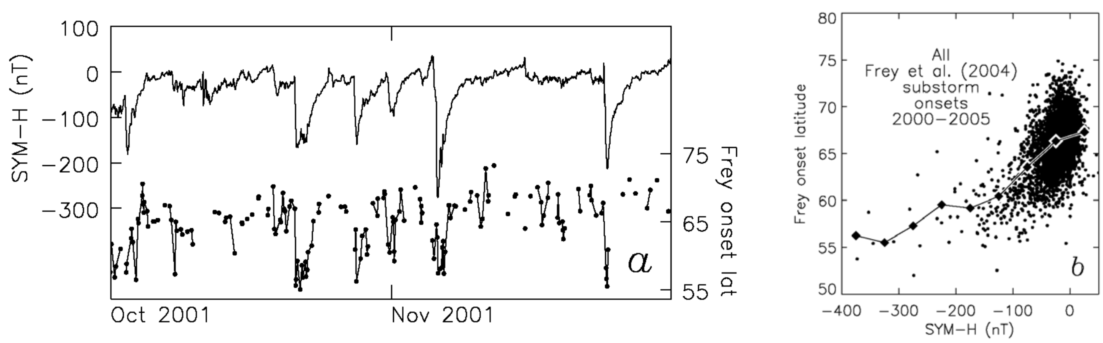
Low latitude onset substorms are more intense than high latitude onset substorms, but...

What controls the onset latitude?

Why does the magnetosphere allow itself to accumulate more open flux prior to some substorms than others?



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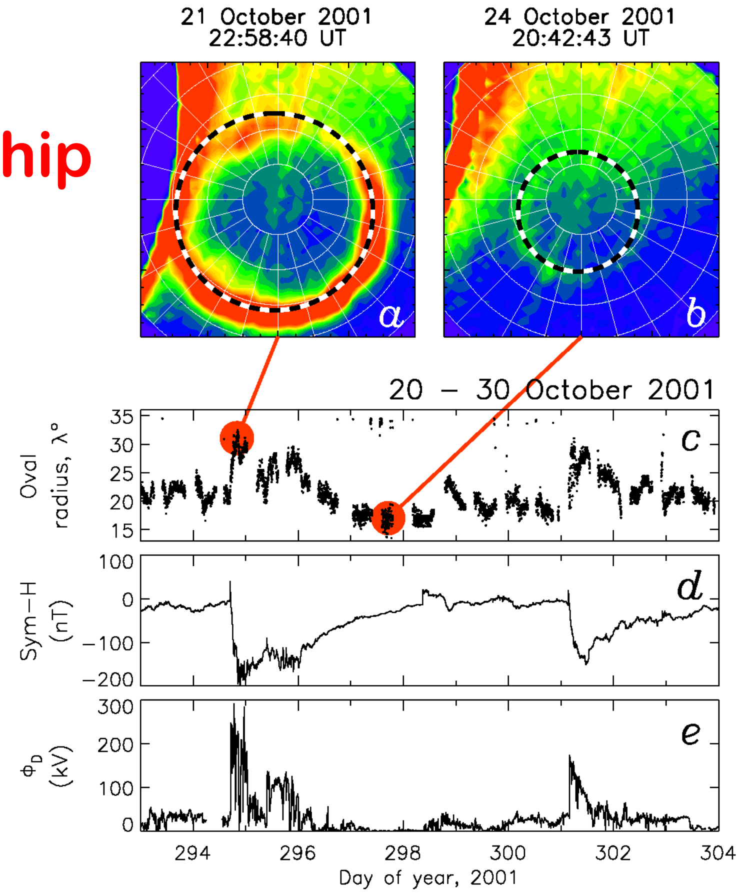
Close relationship between oval radius and ring current intensity



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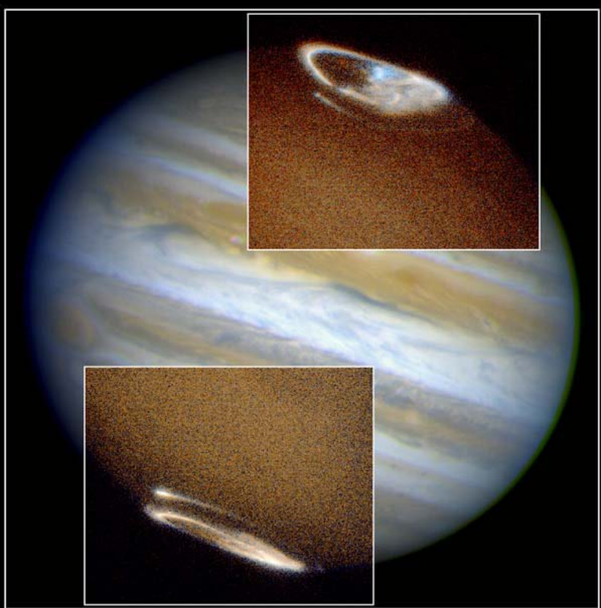
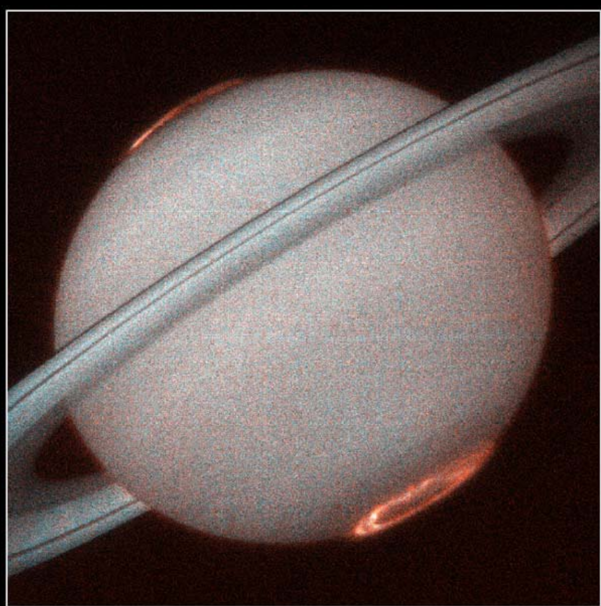
Other planets have aurora, too



Jupiter Aurora HST • STIS • WFPC2
PRC98-04 • ST ScI OPO • January 7, 1998
J. Clarke (University of Michigan) and NASA



Saturn Aurora HST • STIS
PRC98-05 • ST ScI OPO • January 7, 1998 • J. Trauger (JPL) and NASA