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The Earth's magnetosphere

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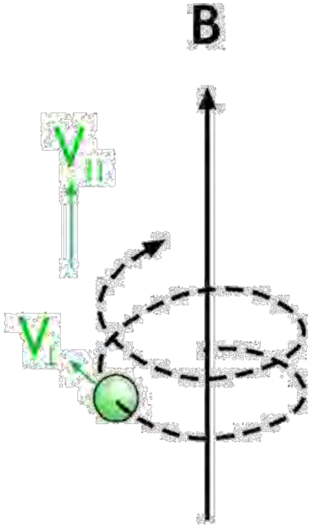
Outline

- Recap of other lectures:
  - Approaches to space plasma physics
  - Motion of charged particles
    - Particle drifts
    - Frozen-in-flow
  - Reconnection

- The closed magnetosphere
- Magnetic reconnection
- The open magnetosphere
- Magnetospheric convection
  - Convection versus corotation
- Magnetospheric current systems
- Northward IMF

Approaches to Space Plasma Physics



- Single particle motion (Monday!)
  - Treat the motion of each particle individually
  - Requires rarified plasma where collisions are infrequent
    - Typically valid for space plasmas, which are generally collisionless

- Magnetohydrodynamics (Monday!)
  - Plasma treated as a conducting fluid
  - Combination of classical fluid mechanics and Maxwell's equations

- Kinetic theory (Monday!)
  - Statistical approach to particle behaviour
  - Deduce macroscale parameters from distribution function

Single particle recap: Particle motion

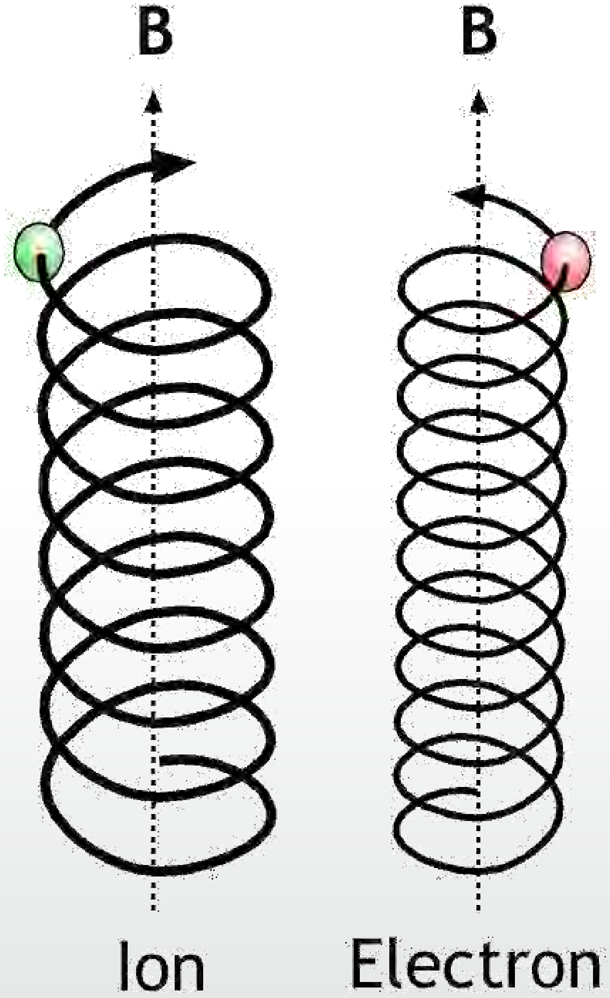
- Motion of a charged particle in presence of electric (E) and magnetic (B) fields is described by the equation of motion:

$$m\frac{d\boldsymbol{V}}{dt} = \overbrace{q(\boldsymbol{E} + \boldsymbol{V} \times \boldsymbol{B})}^{\text{Lorentz force}}$$

  where *m* is the particle mass, **V** is its velocity, *q* is its charge and *t* is time

- In a steady, uniform B field, ions and electrons follow helical orbit around field line
  - Ions and electrons orbit the field line in opposite directions
  - As $V_\perp$ increases, the radius of the circle (the gyroradius) increases
    - Gyrofrequency is $\omega_g = \frac{eB}{m}$
    - Gyroperiod is $\frac{2\pi}{\omega_g}$
    - Gyroradius is $r_g = \frac{V_\perp}{\omega_g} = \frac{mV_\perp}{eB}$

$\Rightarrow$ (1) Particles gyrate



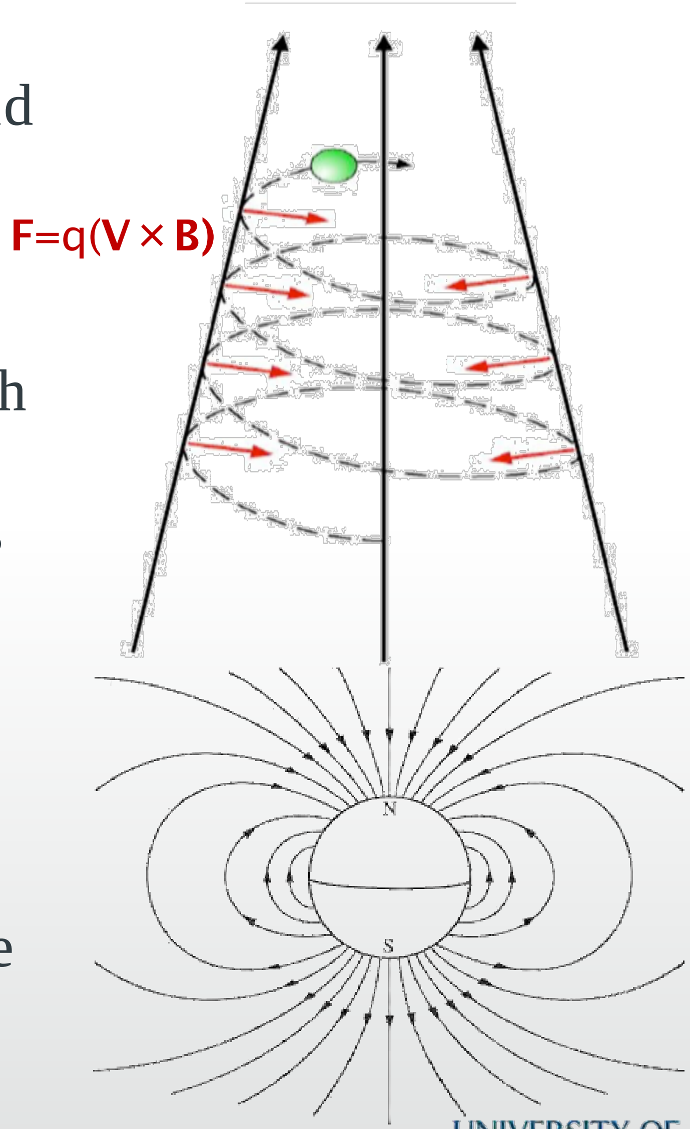
Single particle recap: Particle motion

- In a steady, uniform B field, ions and electrons follow helical orbit around field line

- In a non-uniform B field, Lorenz force has component away from region of high field
  - $V_{\|}$ decreases and eventually reverses – the particle is repelled (or mirrored) away from the region of high **B** field

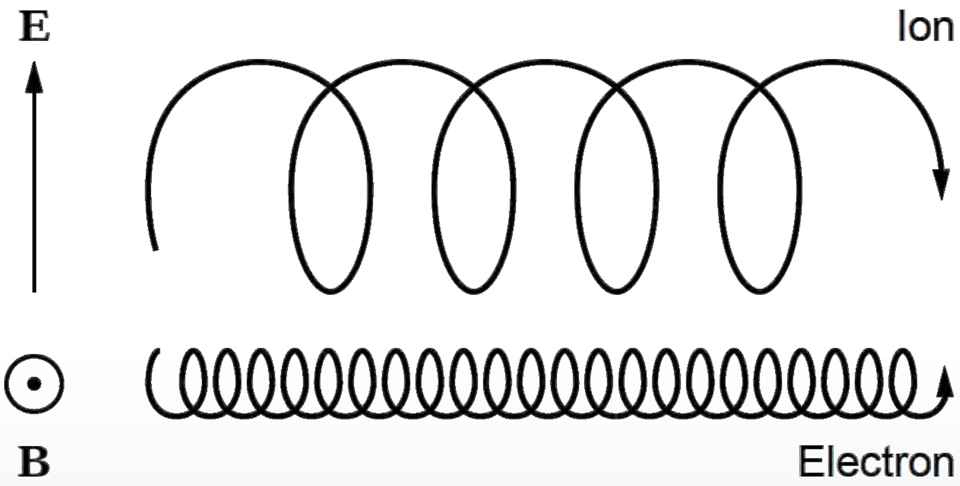
  - Since the kinetic energy remains constant, $V_{\perp}$ increases as the particle approaches the "mirror point"

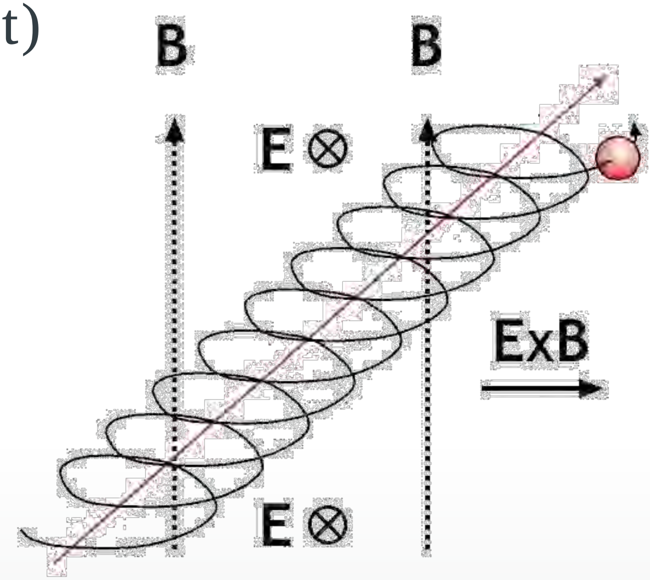
    ⇒ (2) Particles "bounce"



Single particle recap: Plasma drifts

- Add an electric field (perpendicular to **B**) and the plasma starts to drift perpendicular to **E** and **B** (**E**x**B** drift)





- Given an electric field **E**, the flow velocity of the plasma is:

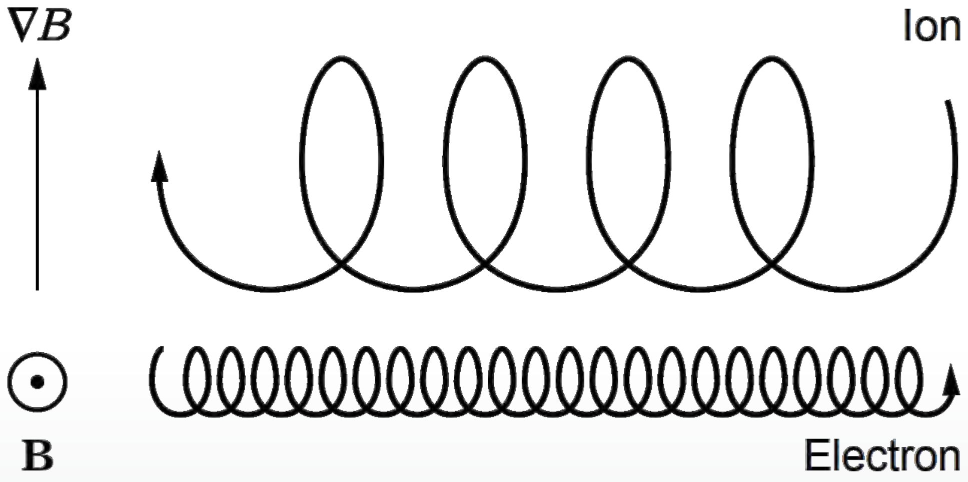
$$\boldsymbol{V} = \frac{\boldsymbol{E} \times \boldsymbol{B}}{B^2}$$

$\Rightarrow$ (3) Particles drift

- Conversely, given a plasma drift **V**, an electric field exists such that $\boldsymbol{E} = -\boldsymbol{V} \times \boldsymbol{B}$

Single particle recap: Plasma drifts

- A gradient in the magnetic field strength also causes plasma to drift (perpendicular to ∇**B**) – "Grad B" drift



- Curvature in the magnetic field leads to a similar drift (curvature drift)

- For both Grad B and Curvature drift, the direction of the drift depends on the sign of the charge
  - Electrons and ions drift in opposite direction
  - Results in currents flowing

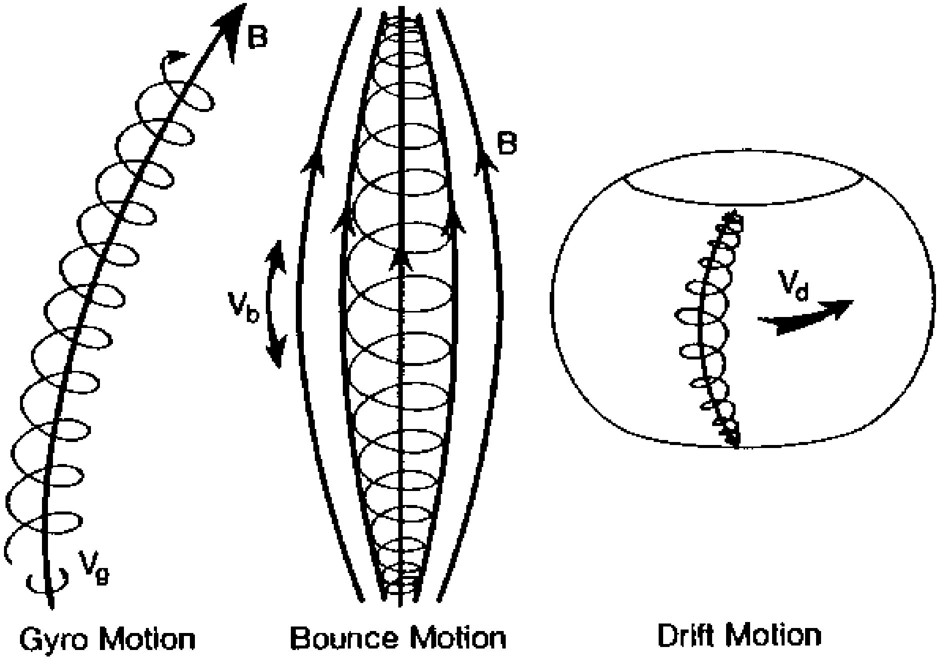
Application

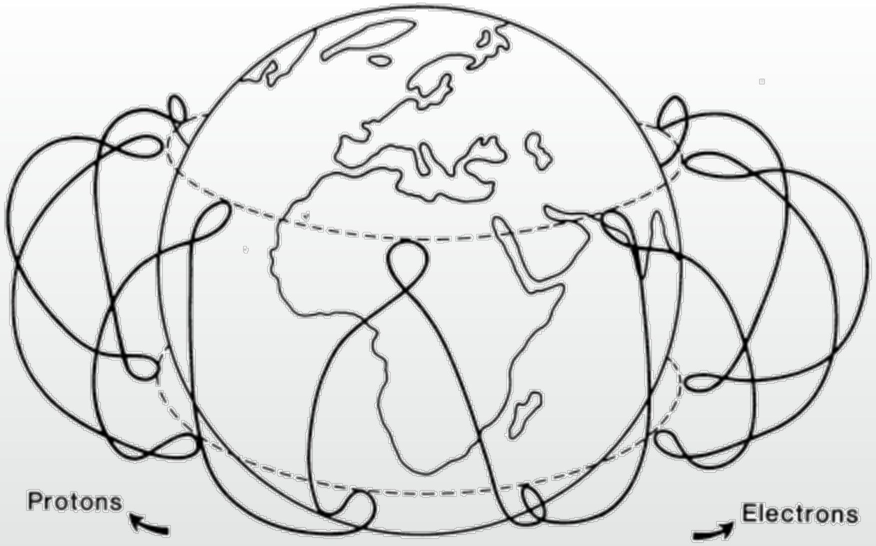
- Charged particles undergo all three types of motion in Earth's magnetosphere
  - Gyration
  - Bounce
  - Drift

- Gradient and curvature drift cause electrons and ions to drift in opposite directions

- If a field line is initially associated with a collection of particles gyrating around it, then particles will drift off over time (protons and electrons in opposite directions)
  - Low energy particles drift slowly
  - High energy particles drift quickly

- In Earth's inner magnetosphere, this leads to the presence of the ring current





MHD recap: Generalised Ohm's Law

- Combining equations of motion for electrons and ions leads to the Generalised Ohm's Law:

$$\boldsymbol{E} = -\boldsymbol{v}_i \times \boldsymbol{B} + \xcancel{\frac{\boldsymbol{j} \times \boldsymbol{B}}{en_e} - \frac{\nabla \cdot \mathbf{P}_e}{en_e} + \frac{m_e}{ne^2}\frac{\partial \boldsymbol{j}}{\partial t}} + \eta \boldsymbol{j}$$

- In ideal MHD, plasma is assumed to conduct ideally, there is no electron pressure gradient and the current density is assumed to vary only slowly
  - Generalised Ohm's Law reduces to $\boxed{\boldsymbol{E} = -\boldsymbol{v} \times \boldsymbol{B}}$ for ideally conducting plasma

MHD recap: Frozen-in-flow (Alfvén's theorem)

- From Generalised Ohm's Law and Maxwell's equations, can derive the MHD Induction Equation:

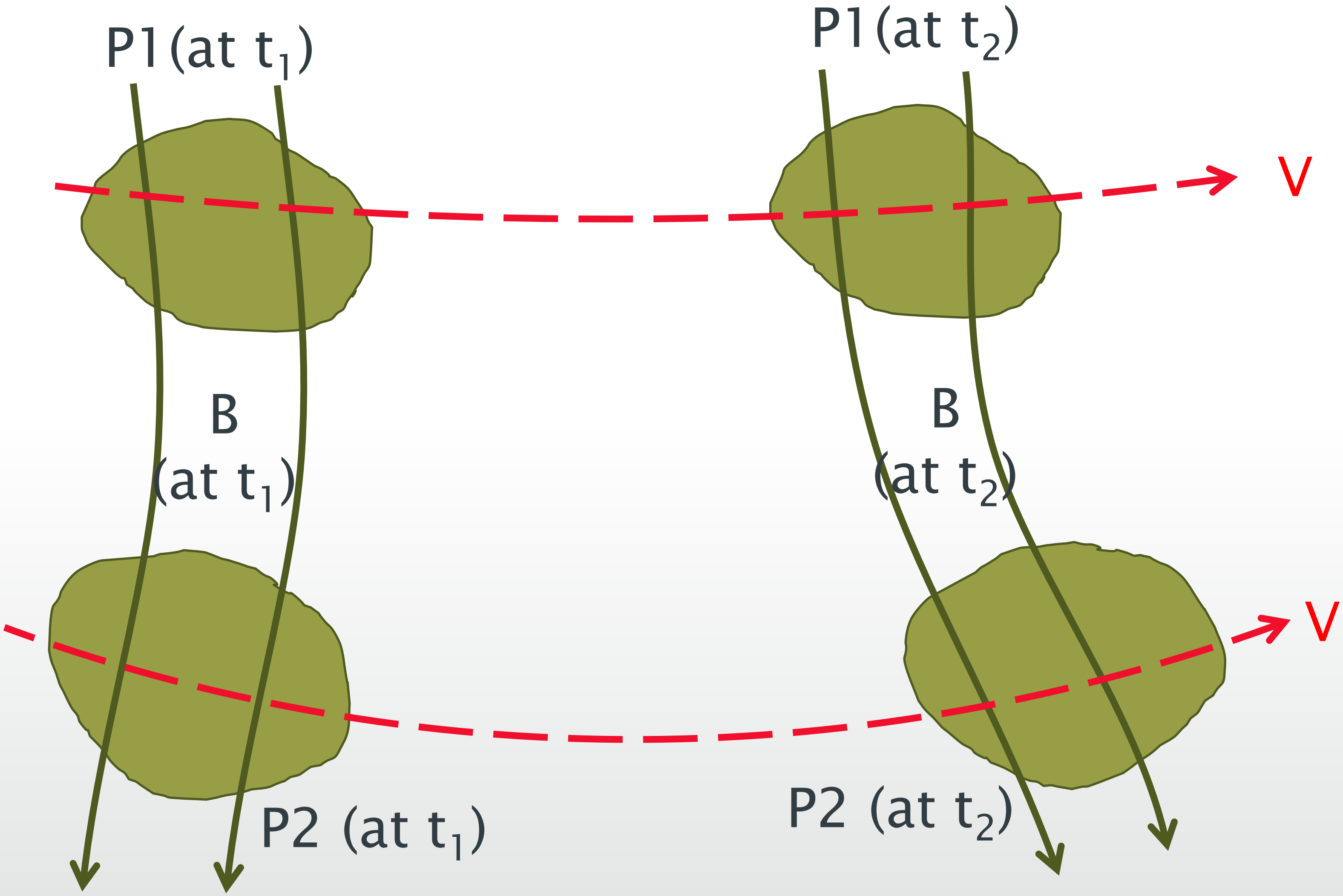
$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) + \xcancel{\frac{1}{\mu_0 \sigma} \nabla^2 \boldsymbol{B}}$$

- In ideal MHD, plasma is assumed to conduct ideally, so σ is very large and the last term cancels. This is called the convective limit.

- It can then be shown that the magnetic flux passing through a surface in the plasma (which moves with the plasma) remains constant

- "In a perfectly conducting fluid, magnetic field lines move with the fluid: the field lines are 'frozen' into the plasma" (Alfvén, 1943)

MHD recap: Frozen-in-flow (Alfvén's theorem)



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Implications of frozen-in-flow

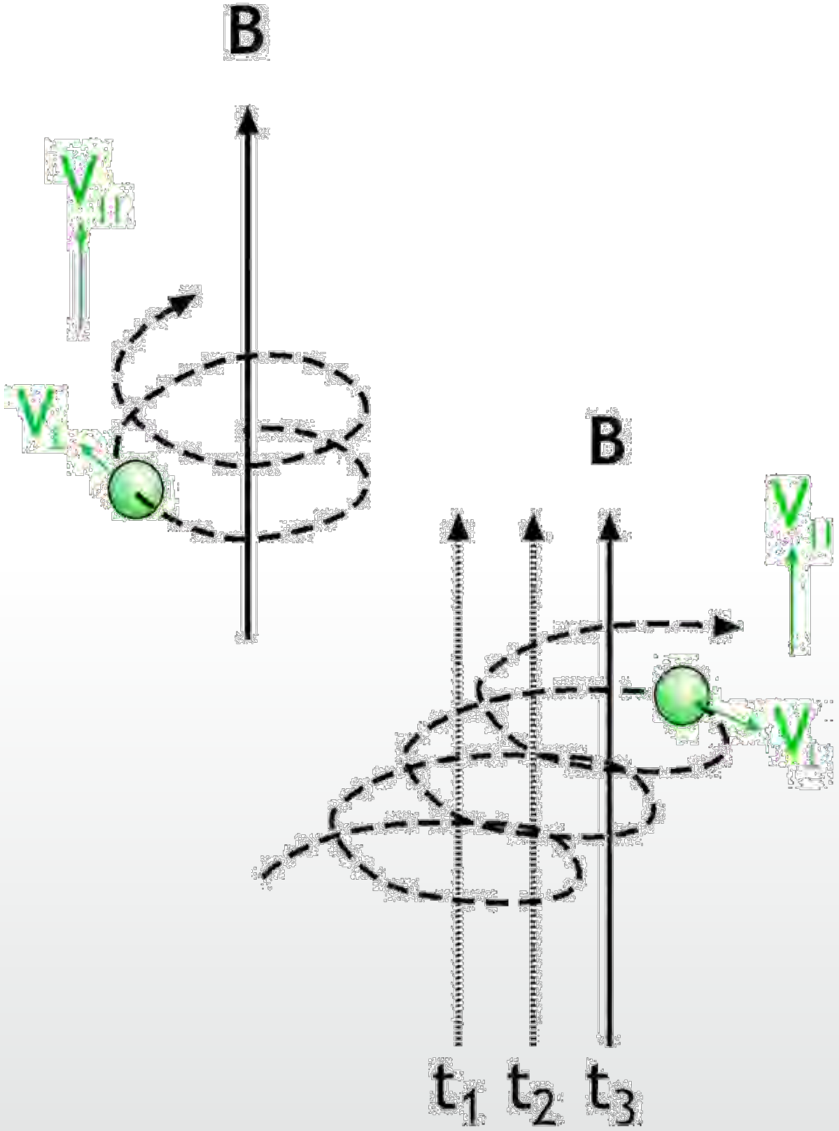
- As particles move (gyrate, move parallel to B, undergo **E × B** drift), their guiding centres remain on the same field line

- i.e. Magnetic field lines move with the particles (and vice versa)

- Flow of plasma (and magnetic field) gives rise to an electric field in the observer's frame

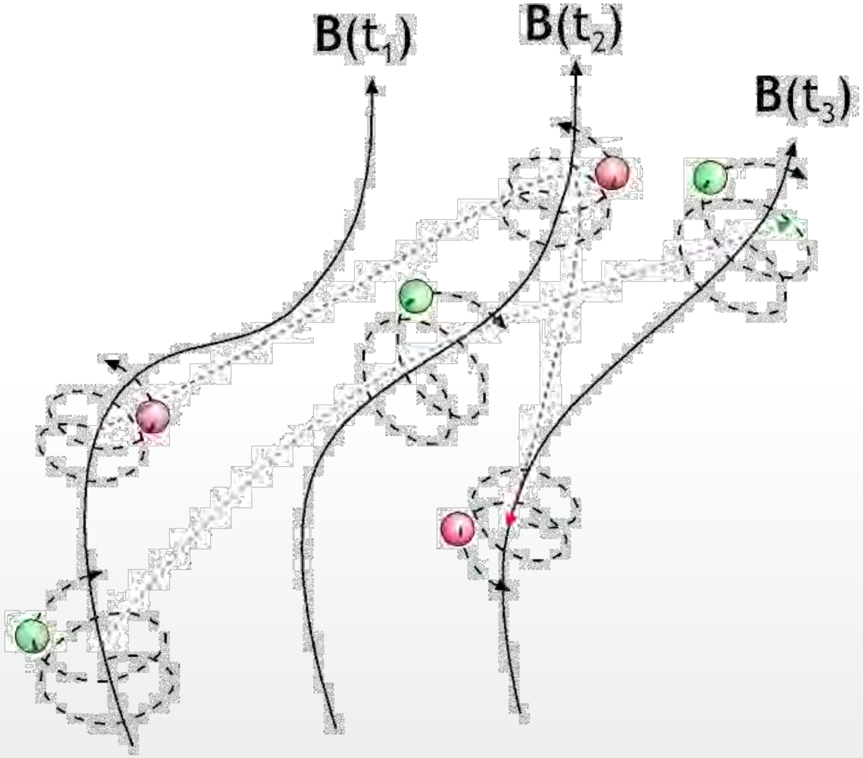
$$\boldsymbol{E} = -\boldsymbol{v} \times \boldsymbol{B}$$

(from Generalised Ohm's Law)

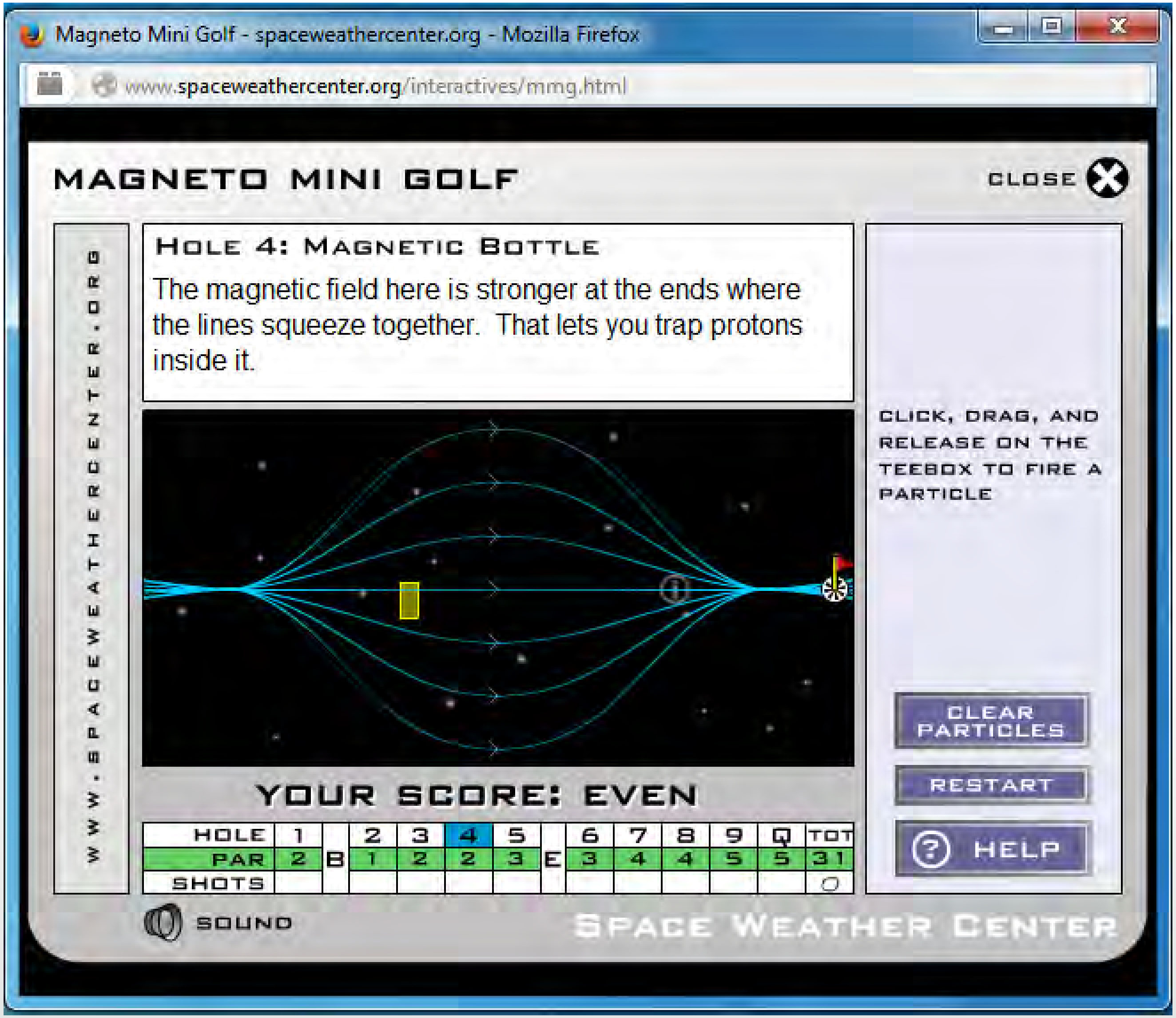


Implications of frozen-in-flow

- Particles remain associated with the same field line for all time
- Particles on different magnetic field lines do not mix
- Caveat
  - This is only an approximation to the actual flow (but usually a good one in space plasmas)
  - Only applies when the magnetic field seen by a particle varies slowly in space and time
  - e.g. **E**x**B** drift consistent with frozen-in theorem, but gradient and curvature drifts violate it (e^- and ions drift in opposite directions)
  - Reconnection also violates



Test your skills!



HOLE 4: MAGNETIC BOTTLE

The magnetic field here is stronger at the ends where the lines squeeze together. That lets you trap protons inside it.

CLICK, DRAG, AND RELEASE ON THE TEEBOX TO FIRE A PARTICLE

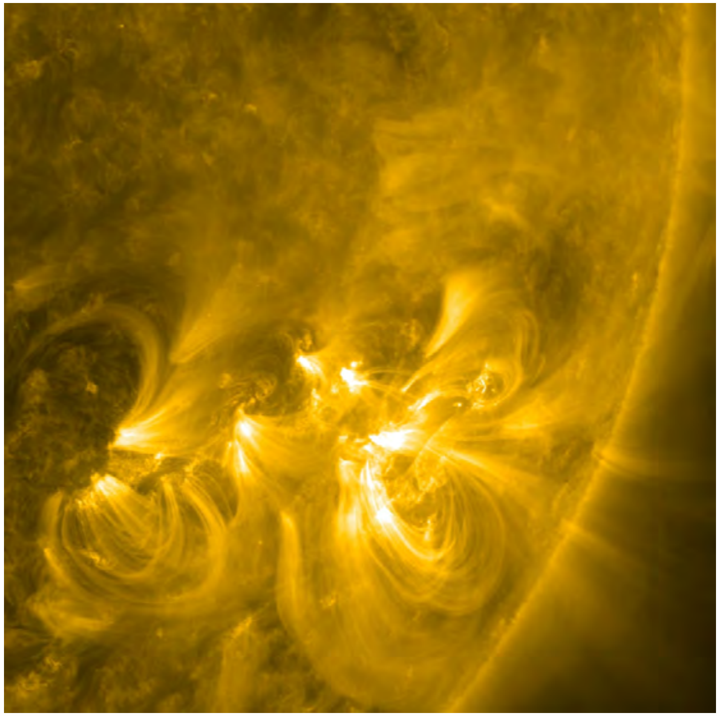
YOUR SCORE: EVEN

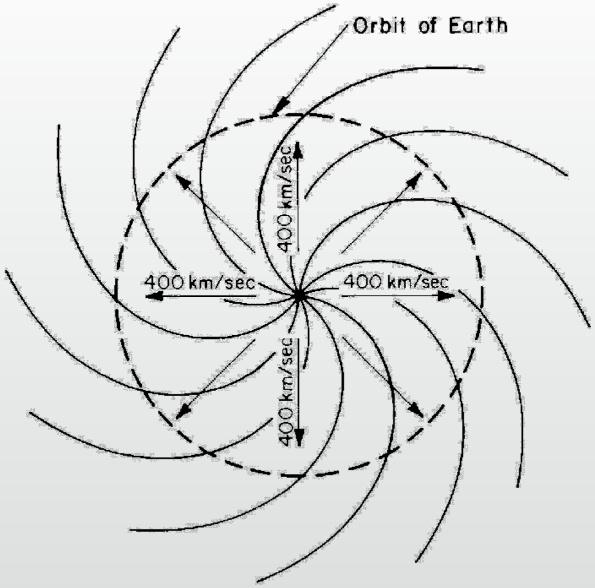
HOLE	1		2	3	4	5		6	7	8	9	Q	TOT
PAR	2	B	1	2	2	3	E	3	4	4	5	5	31
SHOTS													0

http://www.spaceweathercenter.org/our_protective_shield/01/minigolf.html

The solar wind

- Solar wind is extension of solar corona into interplanetary space
- Solar wind flows outward through the solar system
- Carries solar magnetic field with it (Interplanetary Magnetic Field – IMF)





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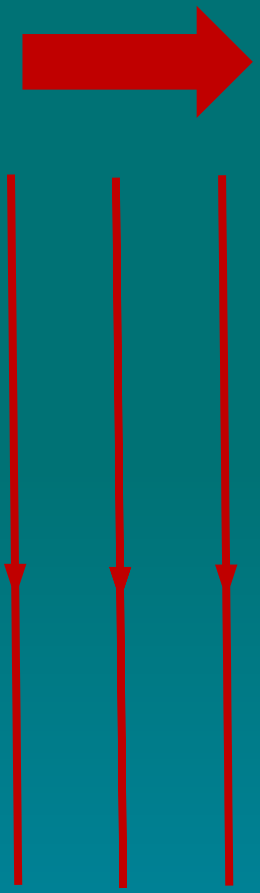
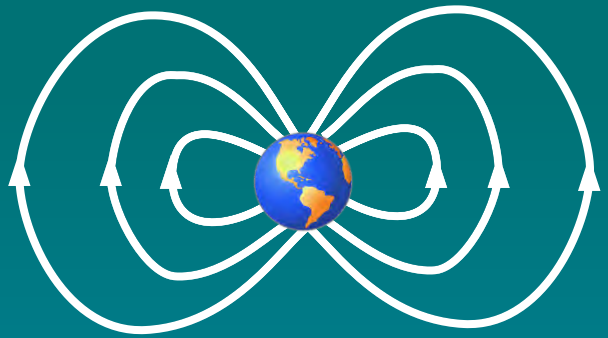
What happens when the solar wind encounters Earth?

Solar wind flow

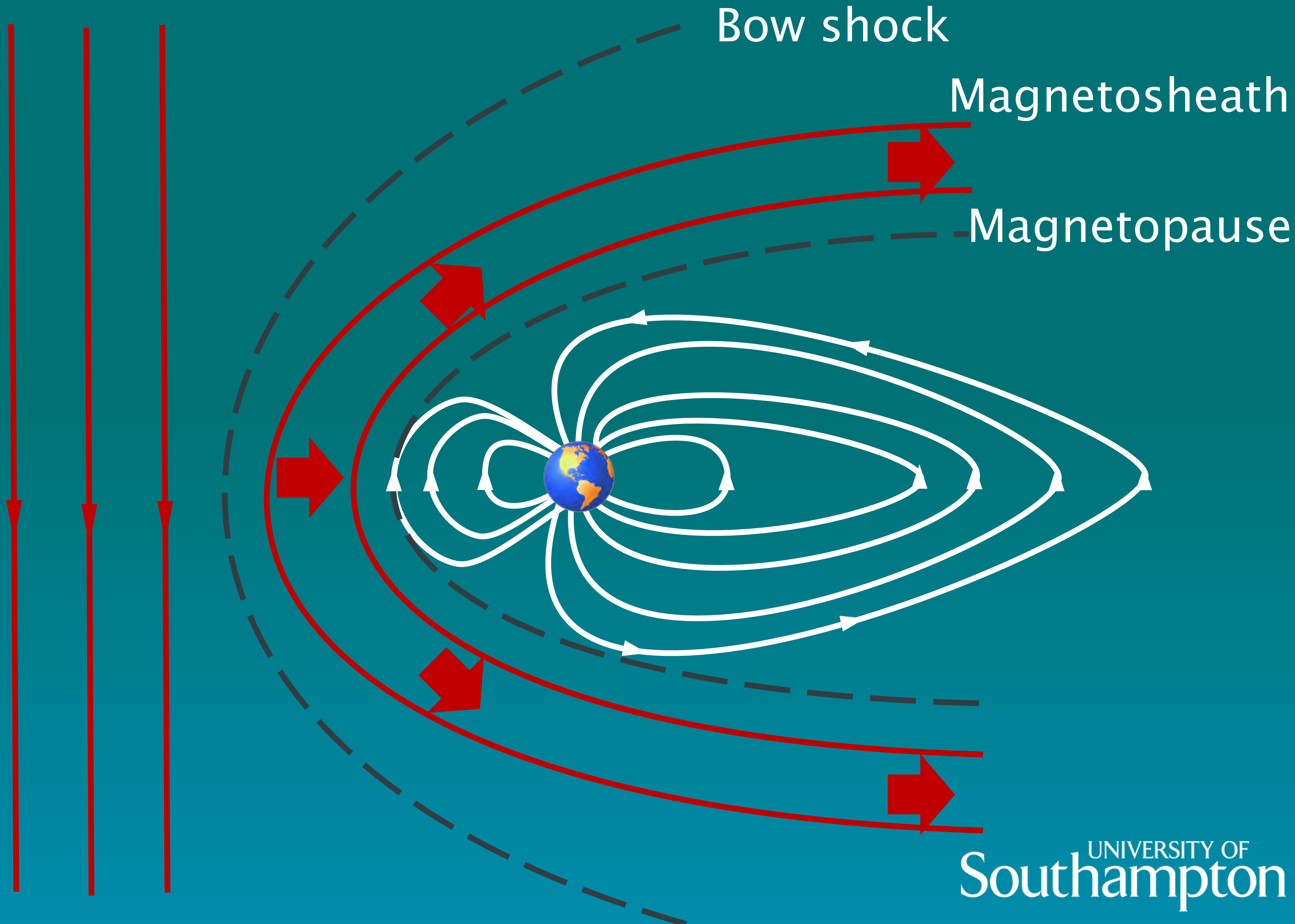


Solar wind plasma
(Interplanetary
Magnetic field)

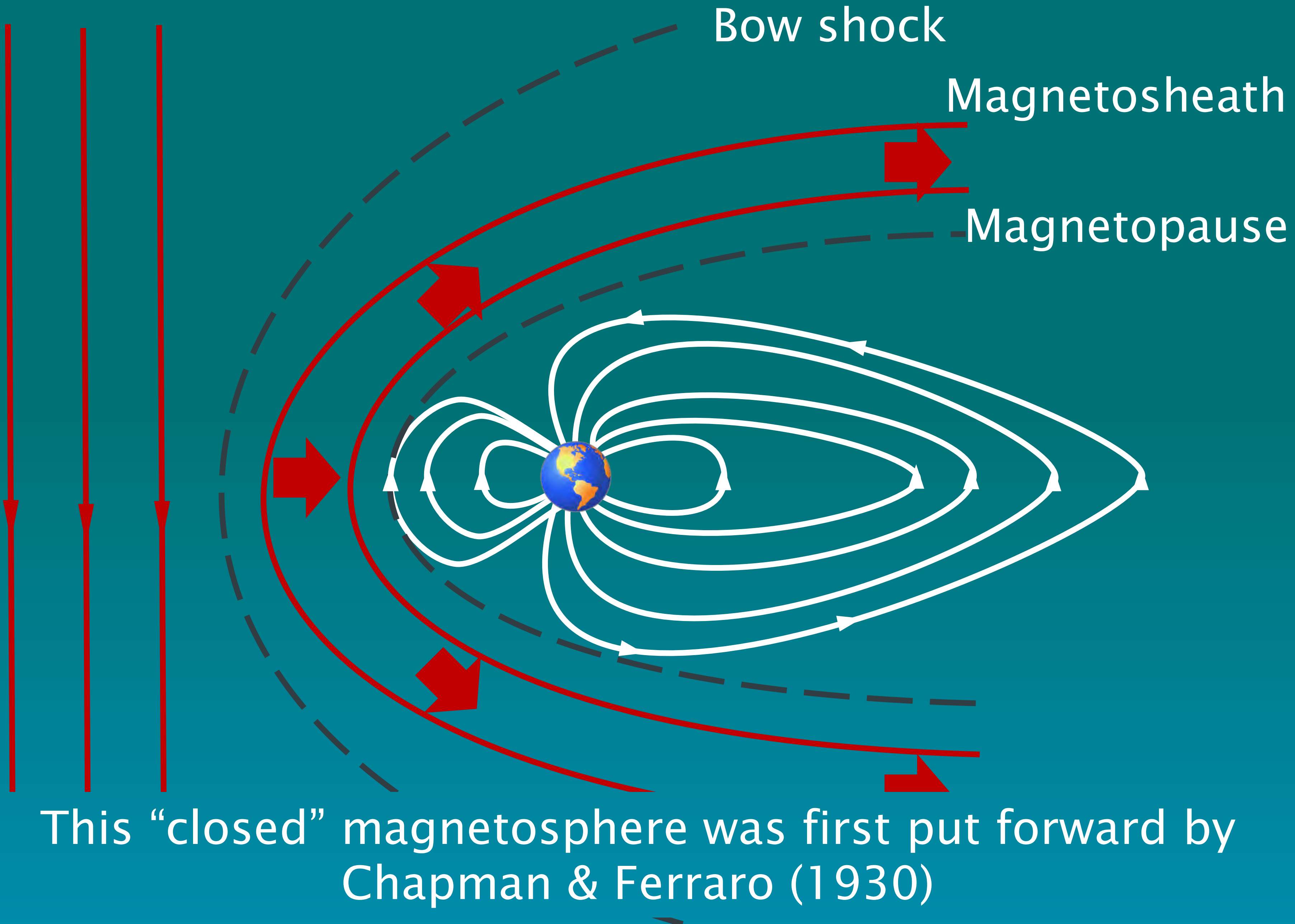


Terrestrial plasma
(Geomagnetic field)

What happens when the solar wind encounters Earth?

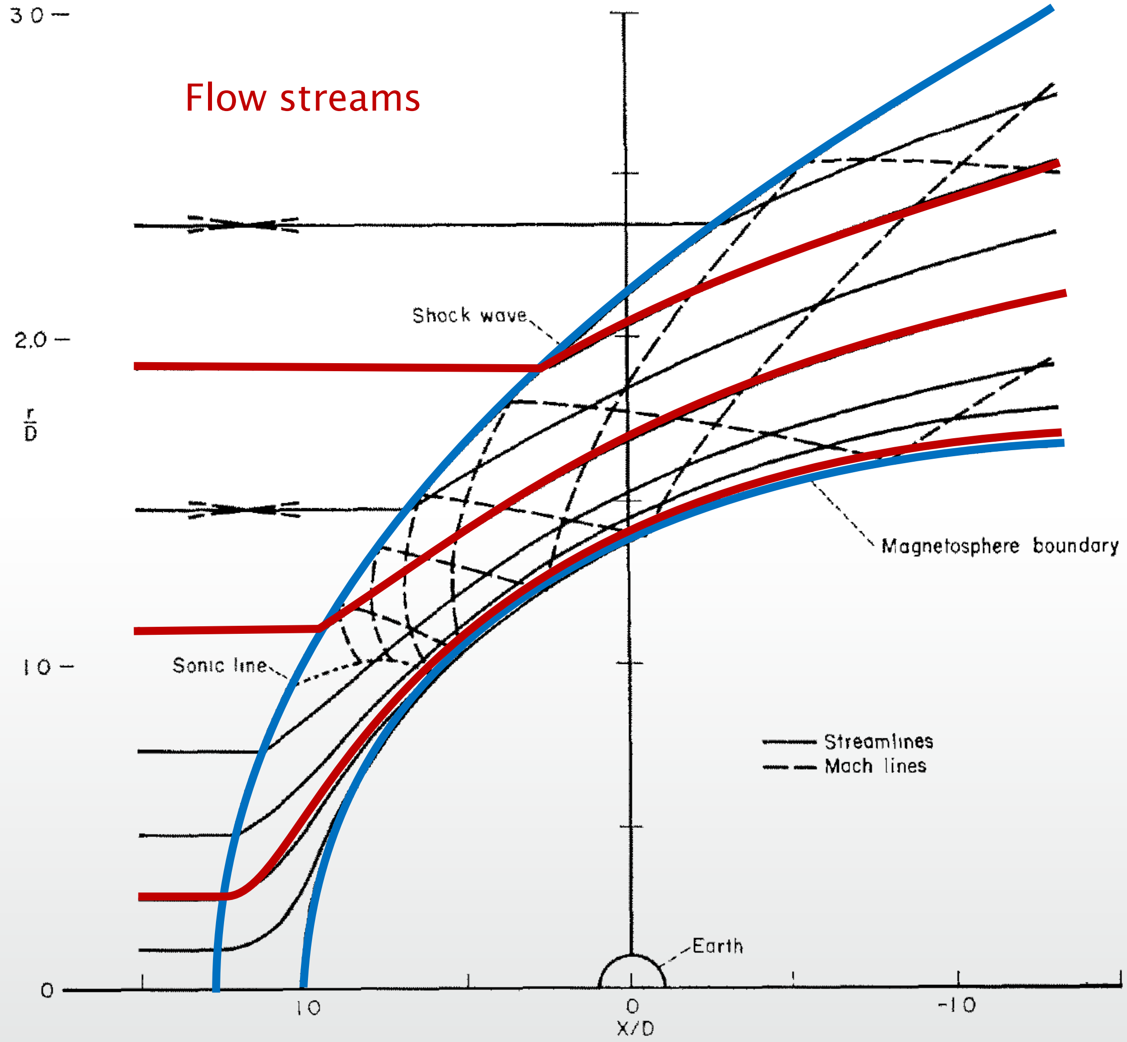


What happens when the solar wind encounters Earth?



This "closed" magnetosphere was first put forward by Chapman & Ferraro (1930)

The magnetosheath: plasma flow



Spreiter et al. (1966)

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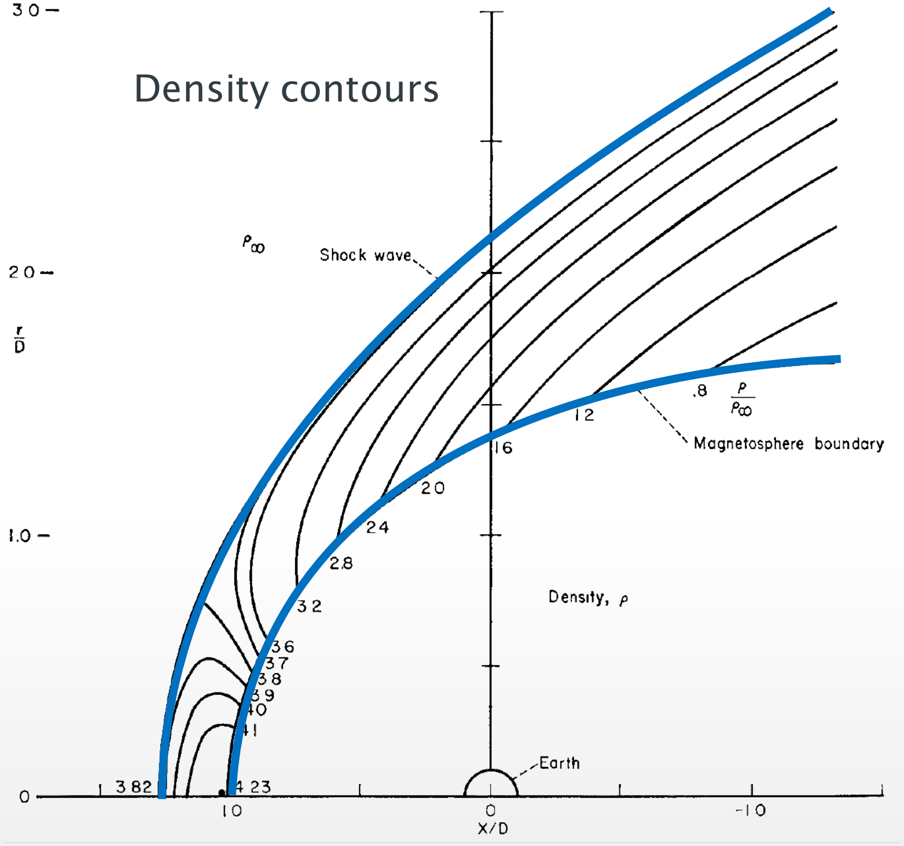
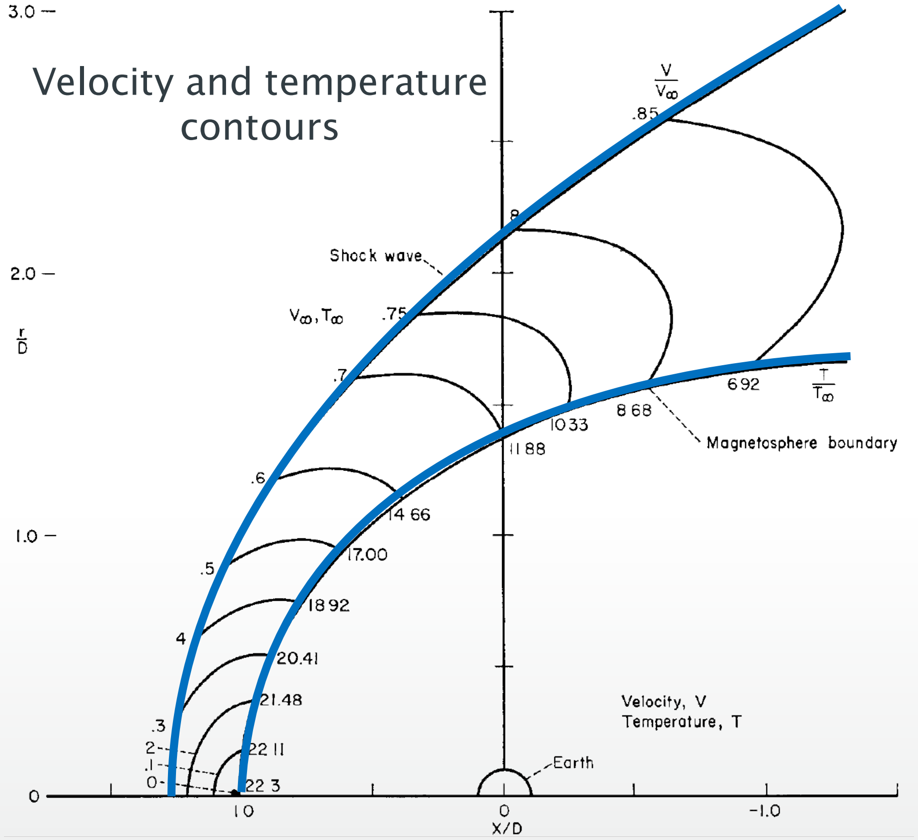
The magnetosheath: density, velocity, temperature



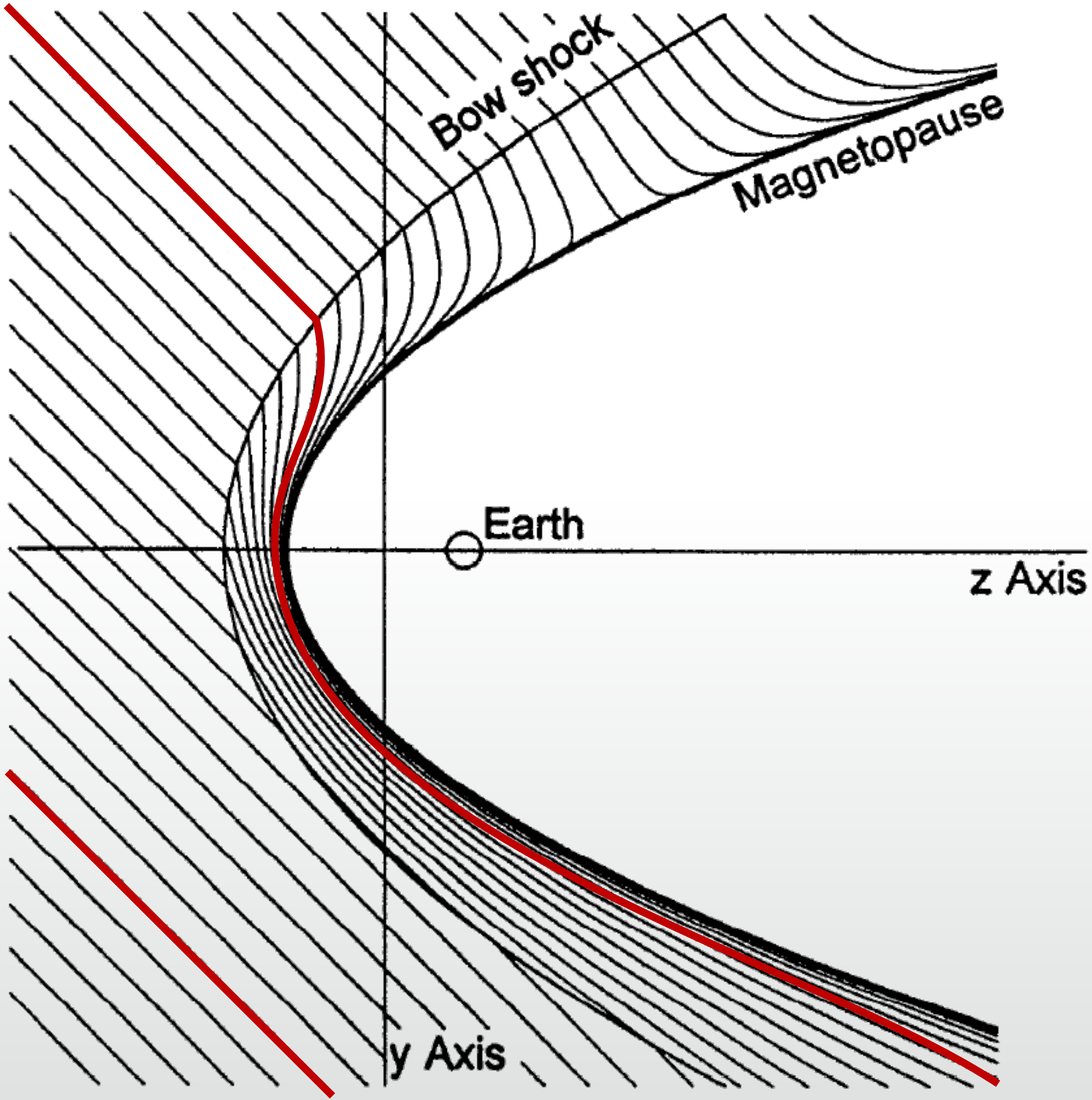
Density contours



Velocity and temperature contours

Spreiter et al. (1966)

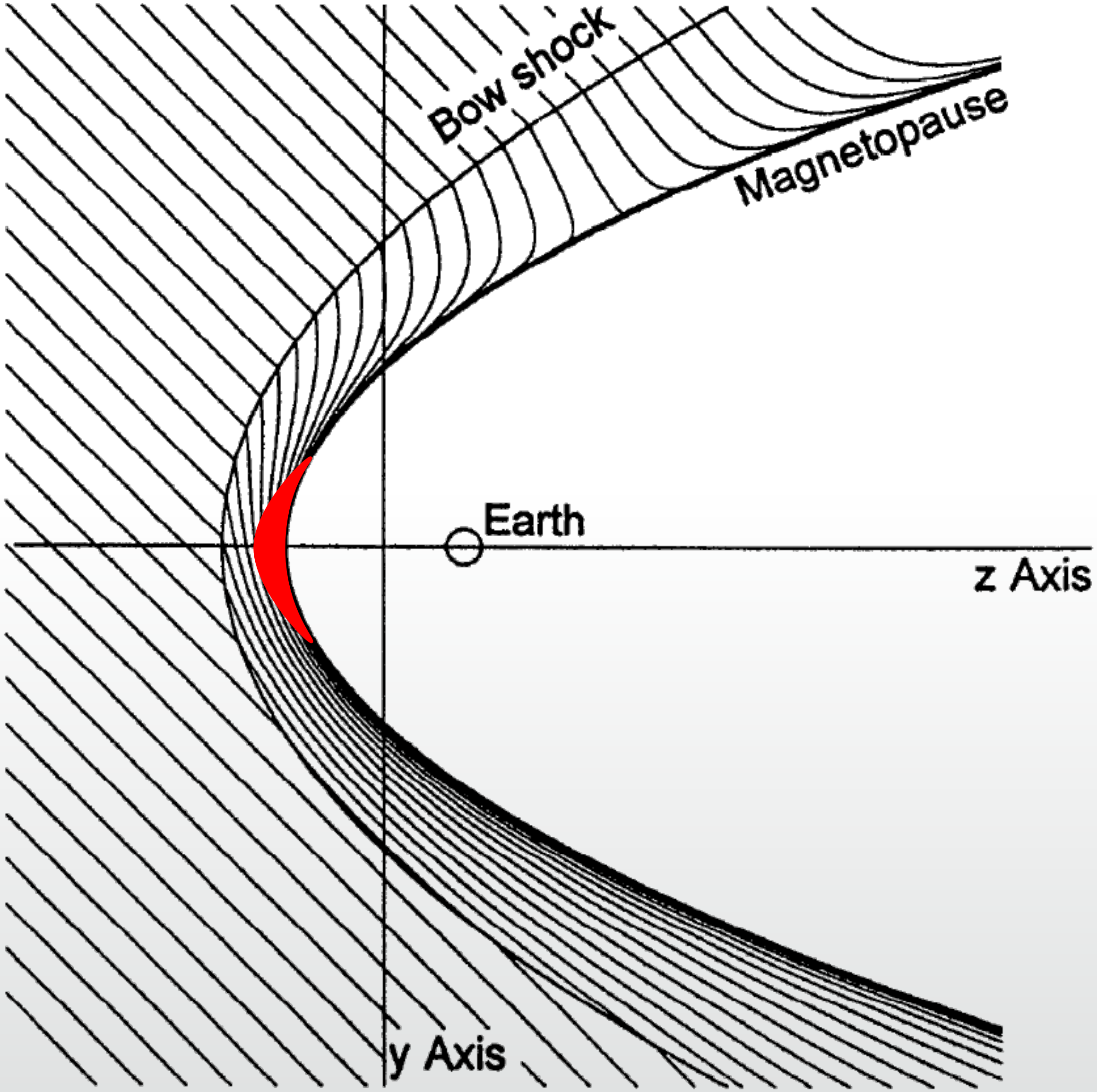
The magnetosheath: Draped magnetic field



Kobel & Flückinger (1994)

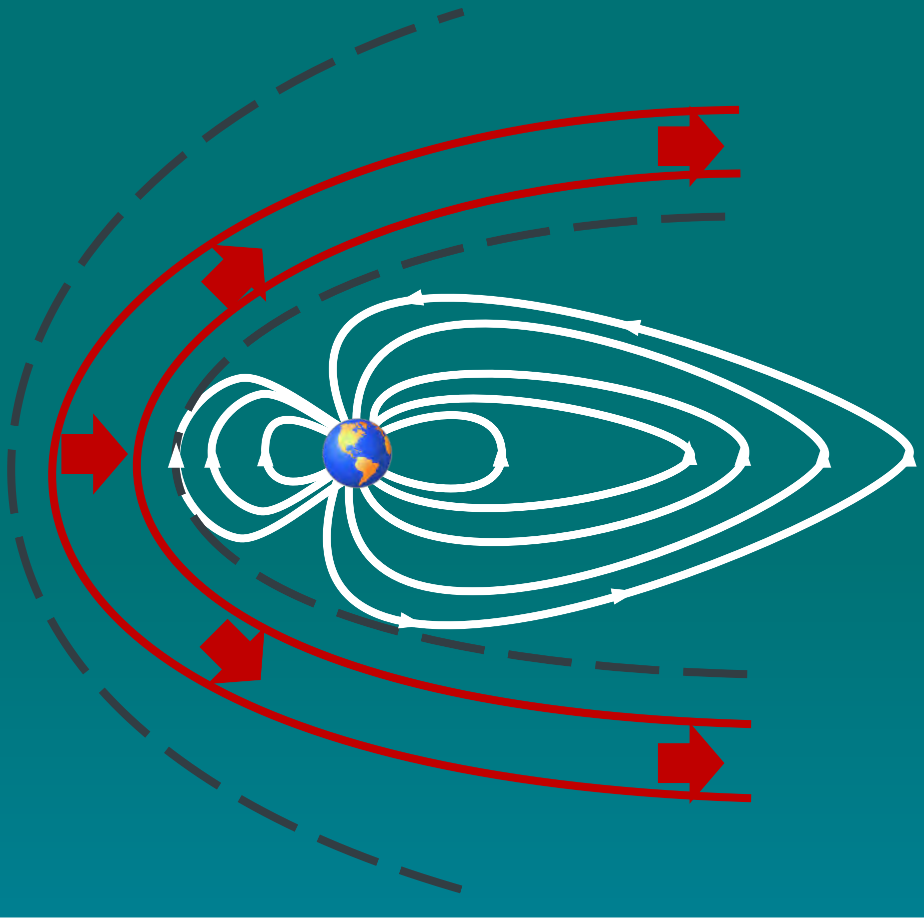
- Magnetosheath plasma flows away from the subsolar point in all directions around the magnetosphere
- The "frozen-in" approximation implies that the magnetic field remains frozen to the plasma
- Therefore the magnetic field drapes around the magnetosphere

The magnetosheath: Plasma depletion layer



- Draping of B over the magnetosphere leads to a maximum in |B| just upstream of the subsolar magnetopause
- Plasma is ‘squeezed’ out of this region, along magnetic field lines, as a result of particle mirroring
- This can result in a relative reduction in the magnetosheath density – the plasma depletion layer – particularly when the IMF is northward

What happens when the solar wind encounters Earth?



- Earth's magnetic field is an impenetrable obstacle to 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}

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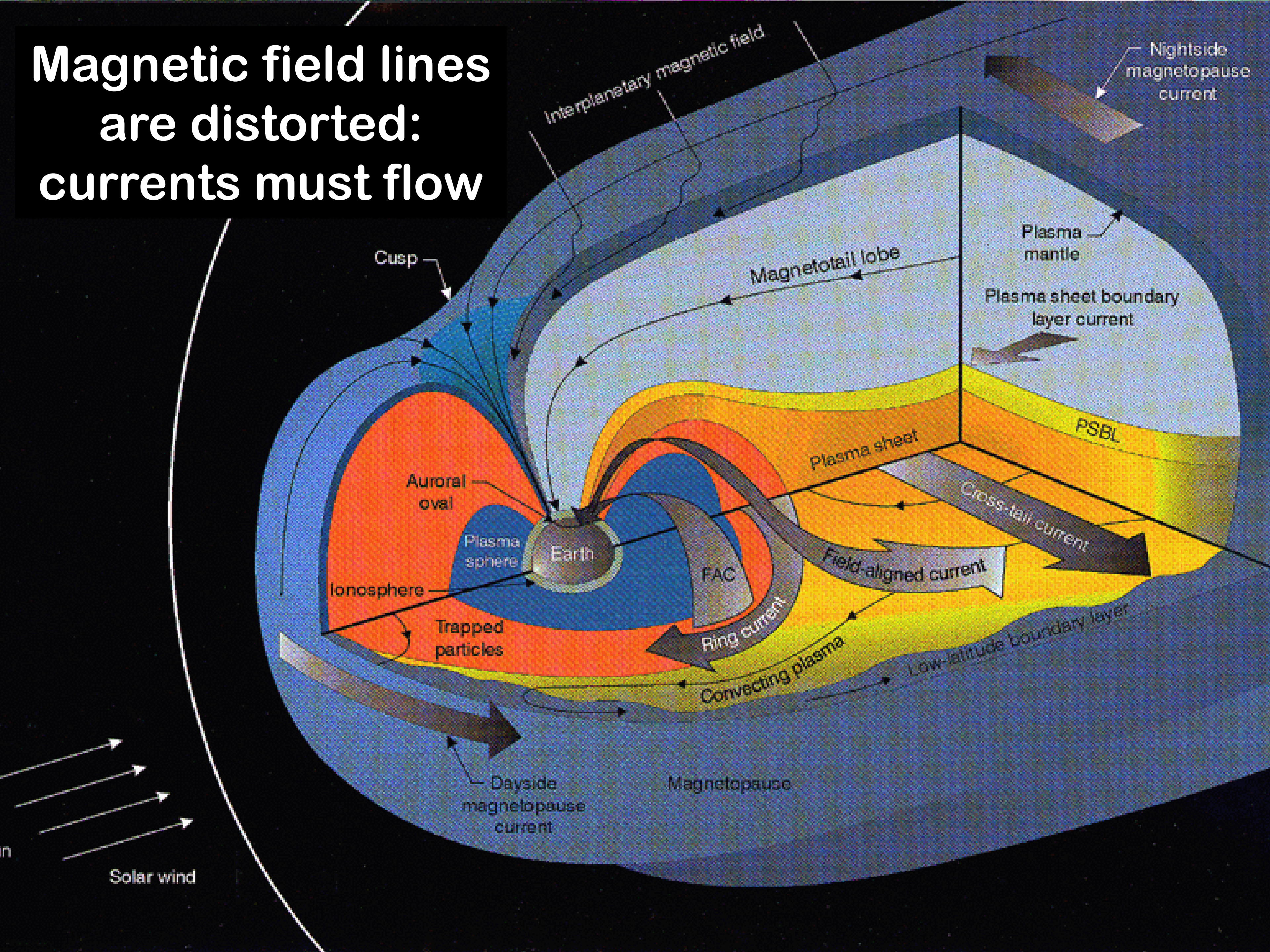
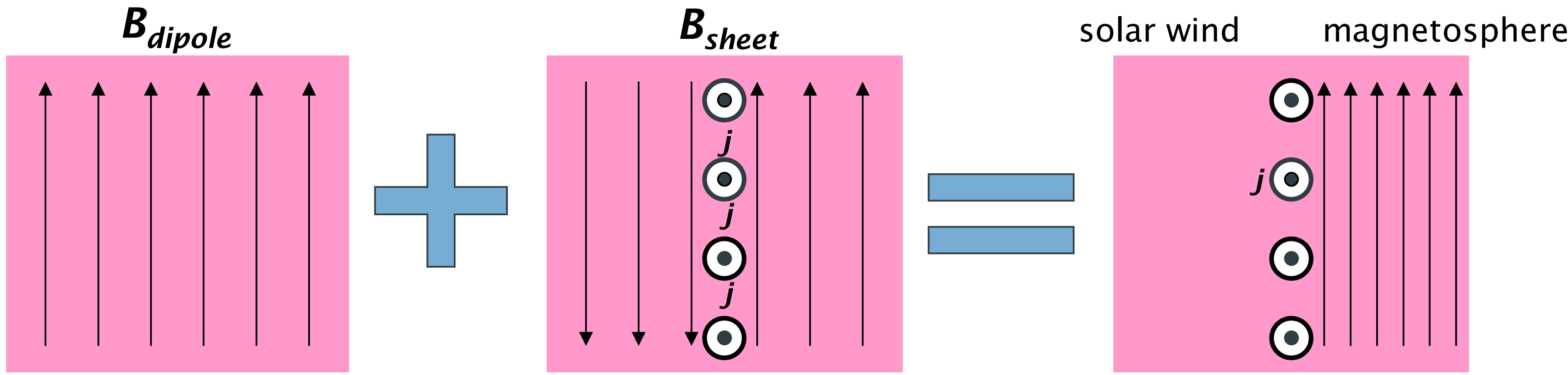
Magnetic field lines are distorted: currents must flow



Chapman-Ferraro currents

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

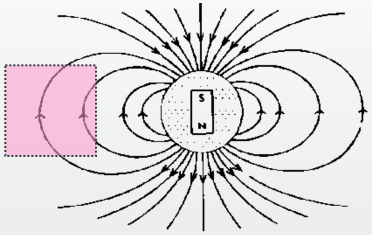


undisturbed dipole field

current sheet field

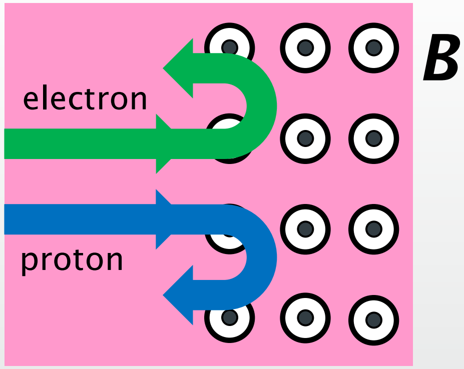
magnetopause

B_{dipole} falls off as r^{-3}



Ampére's Law:

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

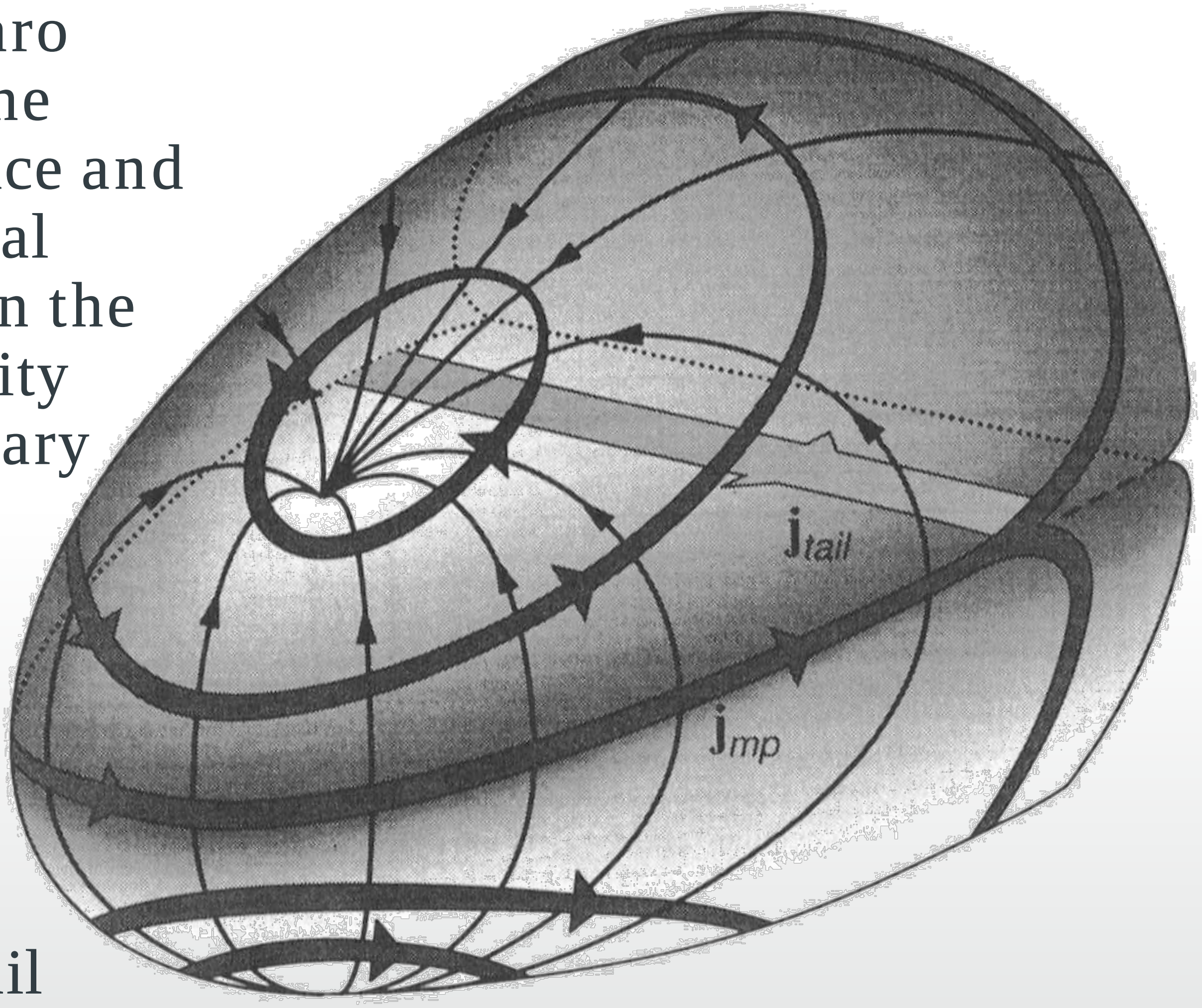


For field strength to (almost) cancel out in solar wind $\boldsymbol{B}_{sheet} \approx \boldsymbol{B}_{dipole}$

Thus, just inside magnetopause the field strength is “compressed” to $2\boldsymbol{B}_{dipole}$

Chapman-Ferraro currents

- The Chapman-Ferraro currents flow over the magnetopause surface and contain the terrestrial magnetic field within the magnetospheric cavity (and the interplanetary magnetic field outside)



- Tail magnetopause currents close through the cross-tail current

Scale size of the magnetosphere

- Location of magnetopause is determined by balance of pressure:
  - Dynamic (ram) pressure exerted by solar wind
  - Magnetic pressure exerted by compression of magnetosphere

- Dynamic pressure given by momentum crossing unit area in unit time:

$$P_{dyn} = nm_pV^2$$

- For typical solar wind values ($n = 7\ \mathrm{cm}^{-3}$, $V = 450\ \mathrm{km\ s}^{-1}$), then $P_{dyn} = 2.5$ nPa

- Magnetic field exerts a pressure equal to:

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

- Magnetosphere compresses until magnetic pressure just inside magnetopause balances solar wind pressure
  - At nose of magnetosphere, the dipole field must be compressed to ~60 nT to give $P_{mag} = 2.5$ nPa – this occurs at a stand-off distance of 10 R_E

Breakdown of the frozen-in approximation

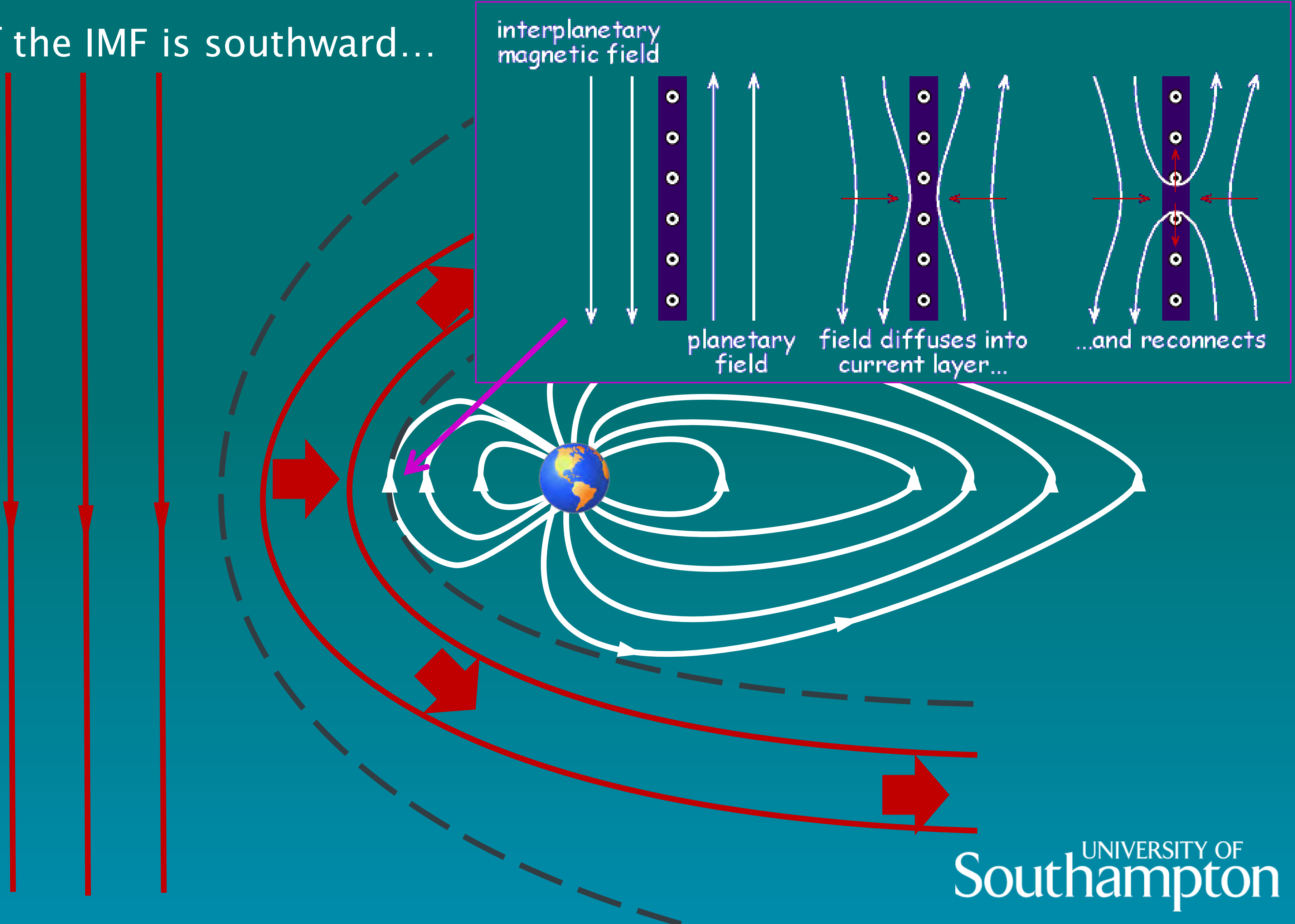
- But observations show a more complex situation…
- Also, recall caveat that “frozen in” assumption relies on low gradients in magnetic field
- Recall the Induction Equation:

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) + \boxed{\frac{1}{\mu_0 \sigma} \nabla^2 \boldsymbol{B}}$$

- With strong spatial gradients, second term (diffusion) becomes significant
- Leads to reconnection (see Tuesday’s lecture)

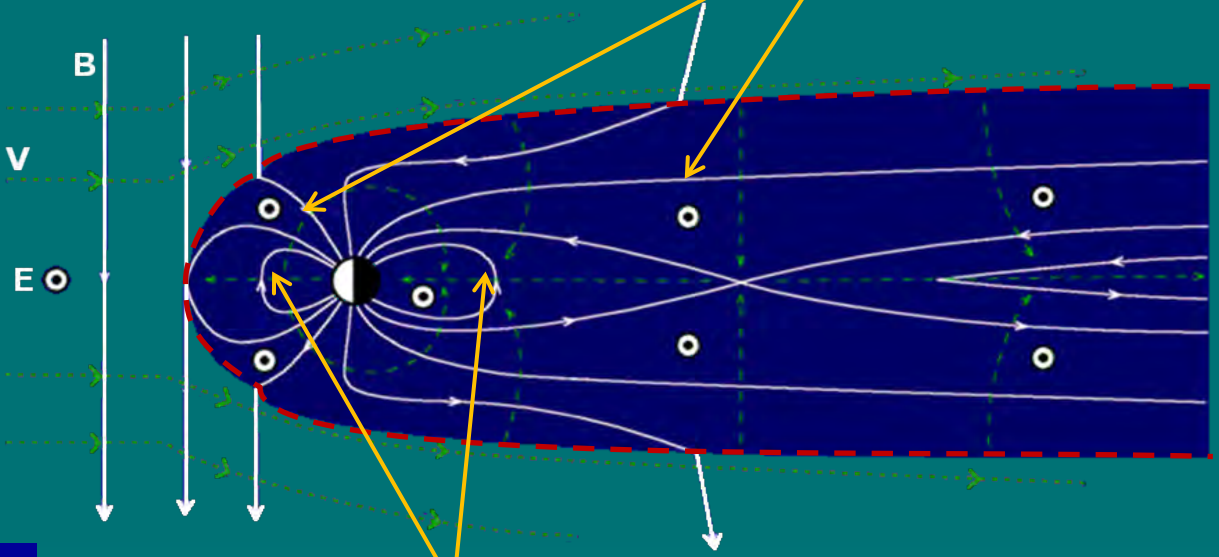
What happens when the solar wind encounters Earth?

If the IMF is southward…



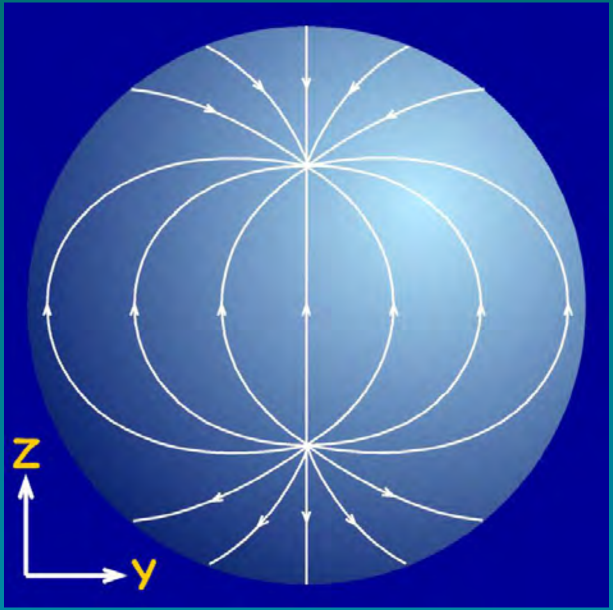
The open magnetosphere

- Magnetic reconnection results in an “open” magnetosphere



Open flux

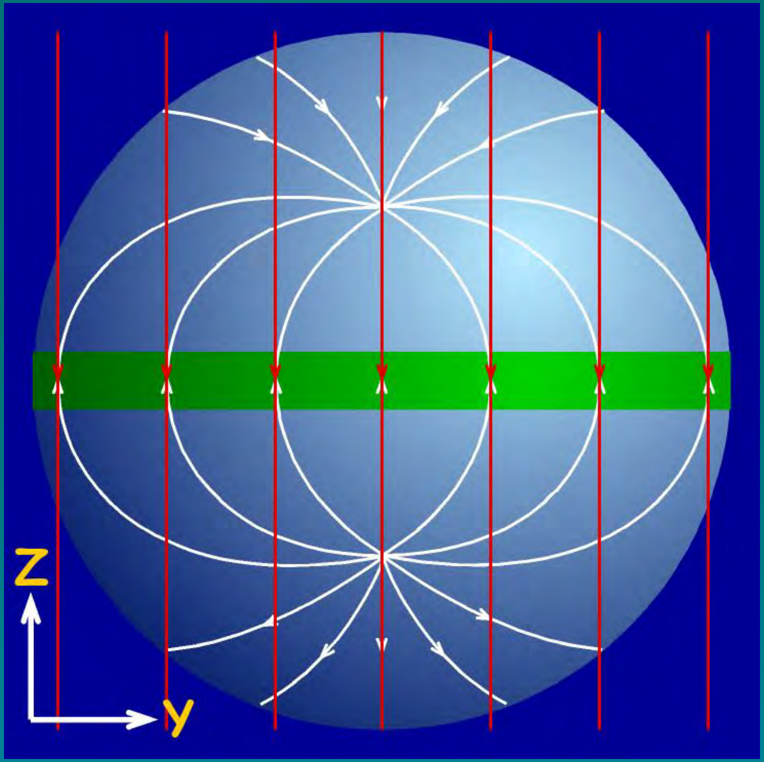
Closed flux



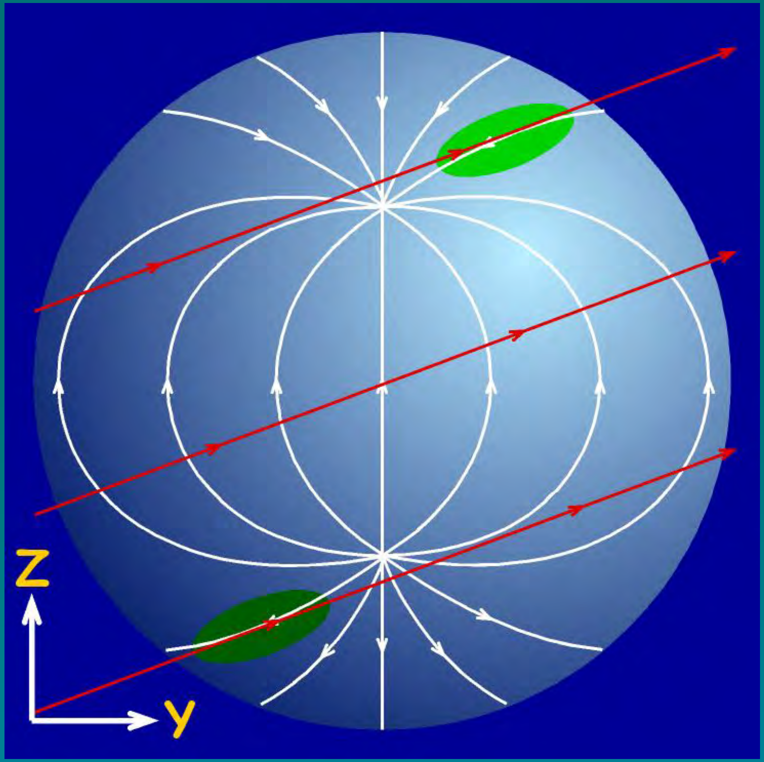
- Where reconnection occurs on the magnetopause depends on the relative orientation between the incoming interplanetary magnetic field (IMF) and field lines at the magnetopause

Location of reconnection

IMF $B_z < 0$, $B_y = 0$



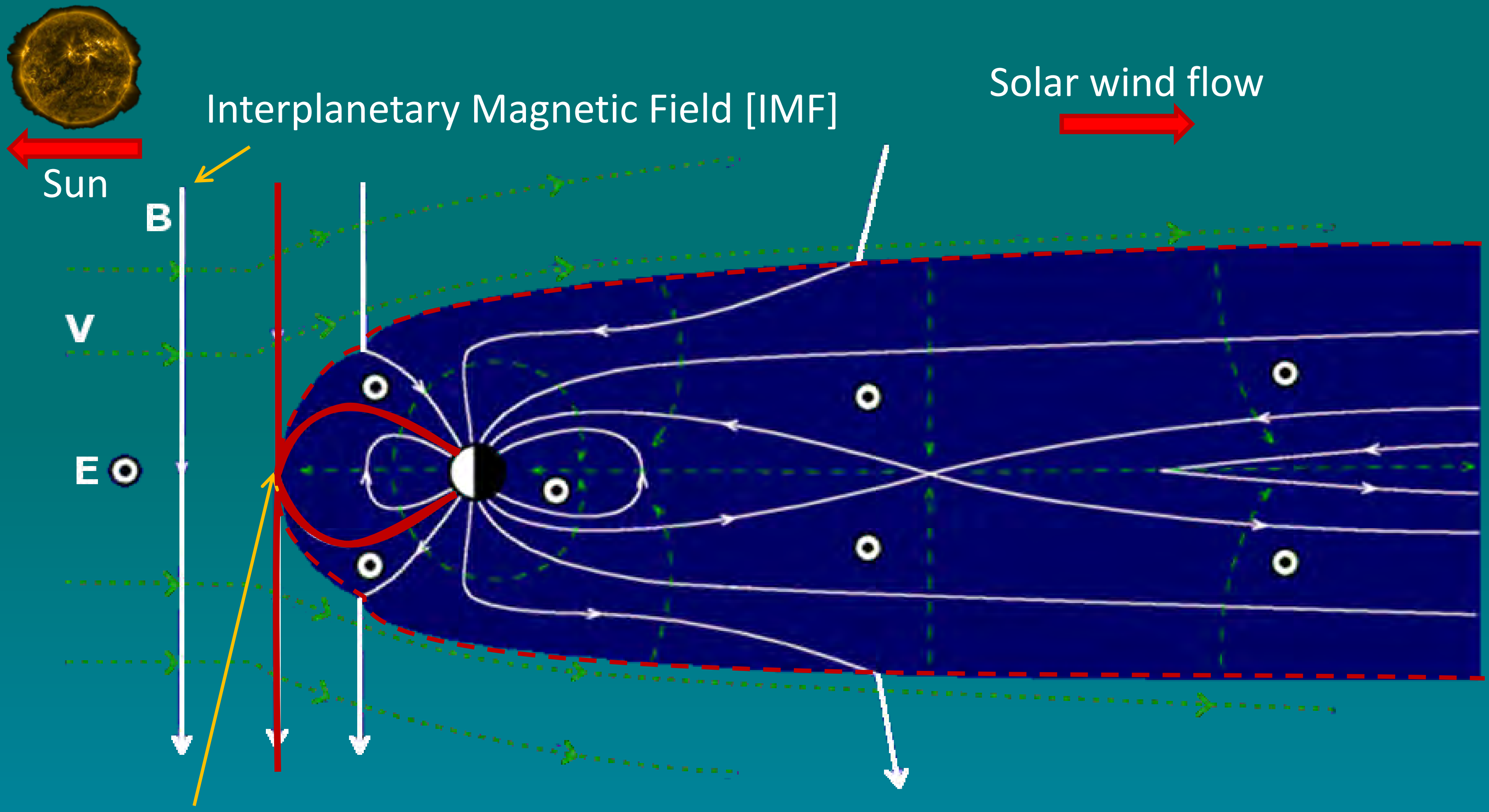
IMF $B_z > 0$, $B_y > 0$



Reconnection with closed field lines

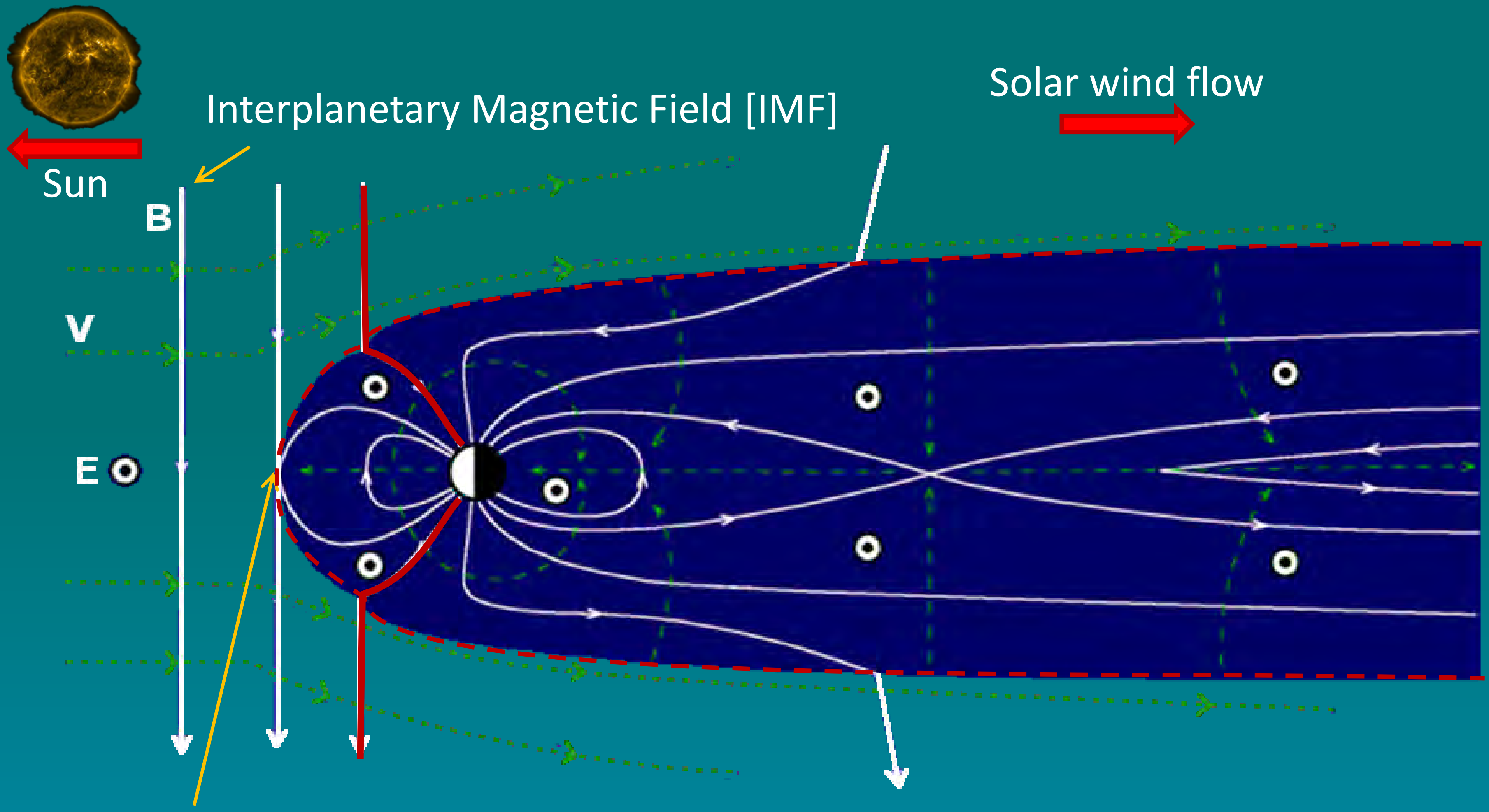
Reconnection with open field lines

The Dungey cycle: The open magnetosphere



Magnetic flux is "opened"

The Dungey cycle: The open magnetosphere



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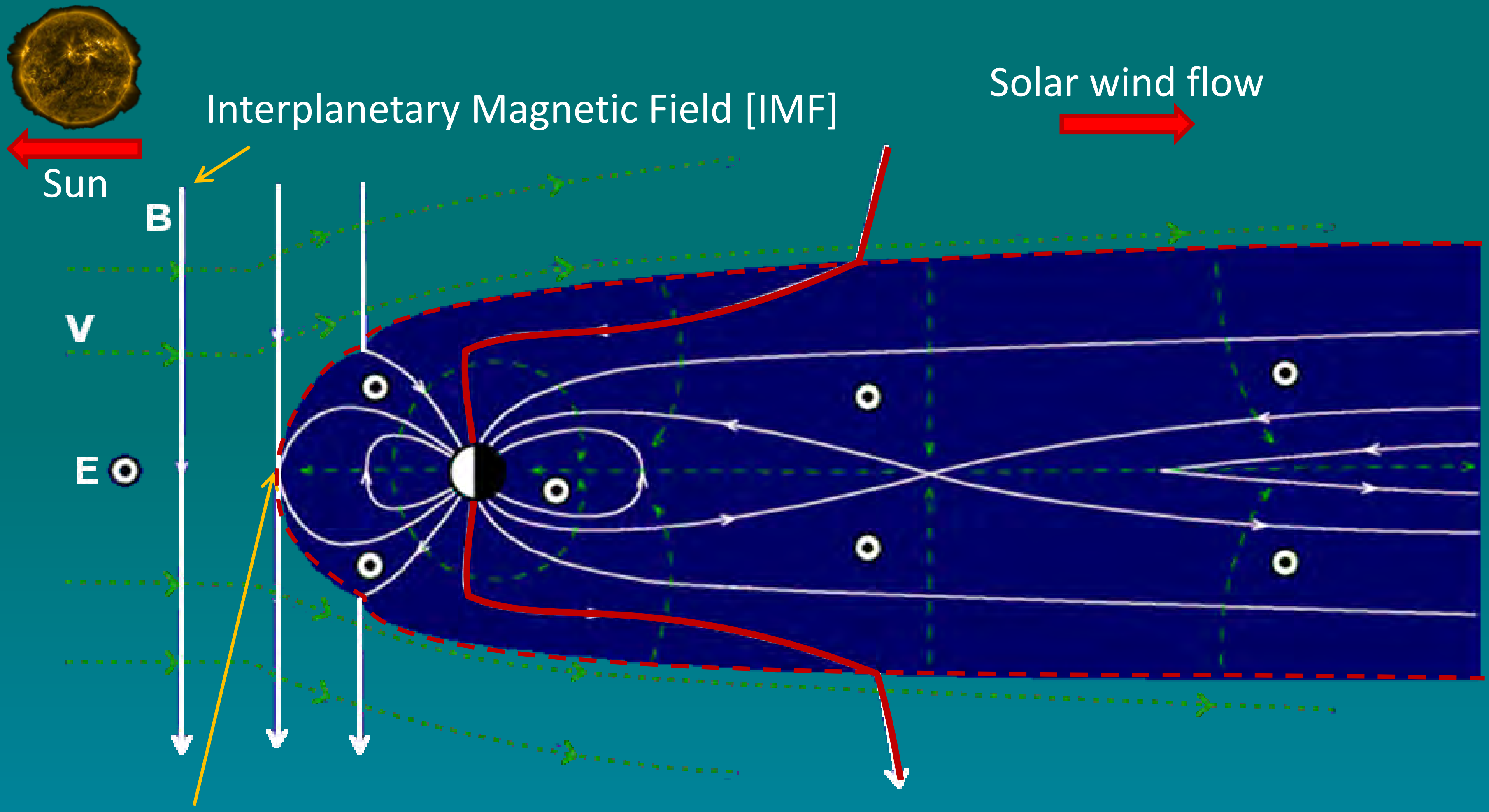

Magnetic flux is “opened”

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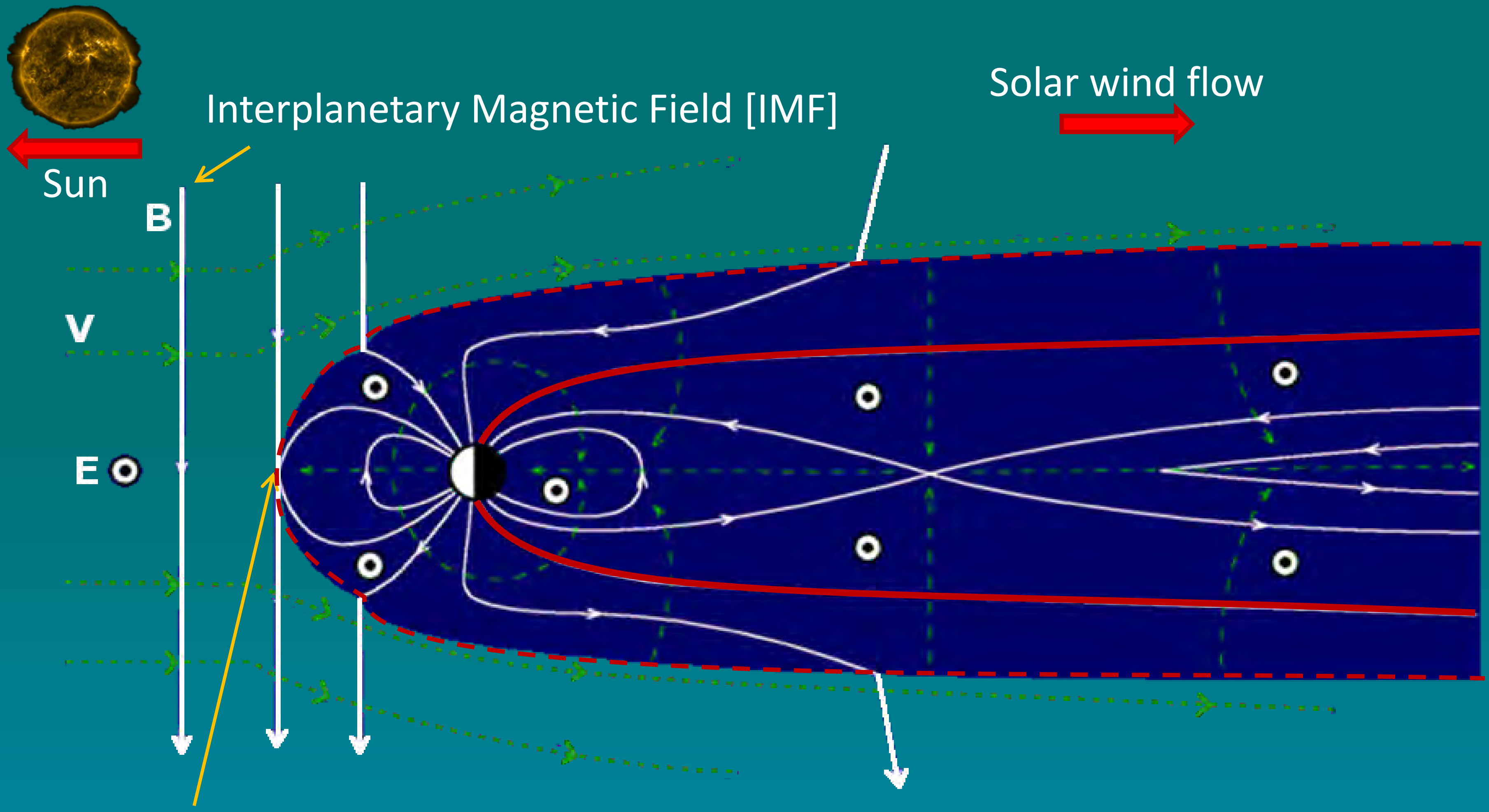
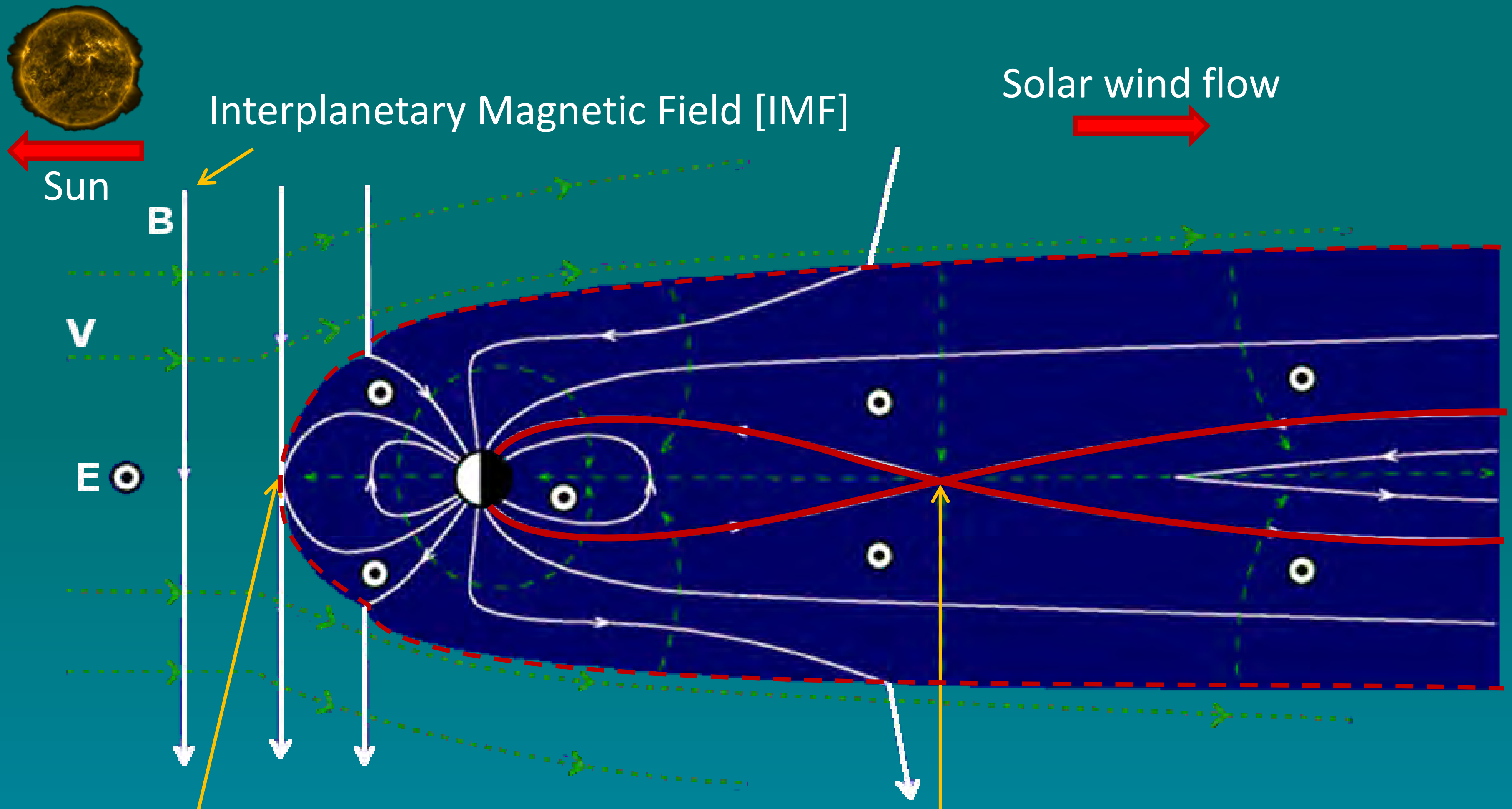
The Dungey cycle: The open magnetosphere



Magnetic flux is “opened”

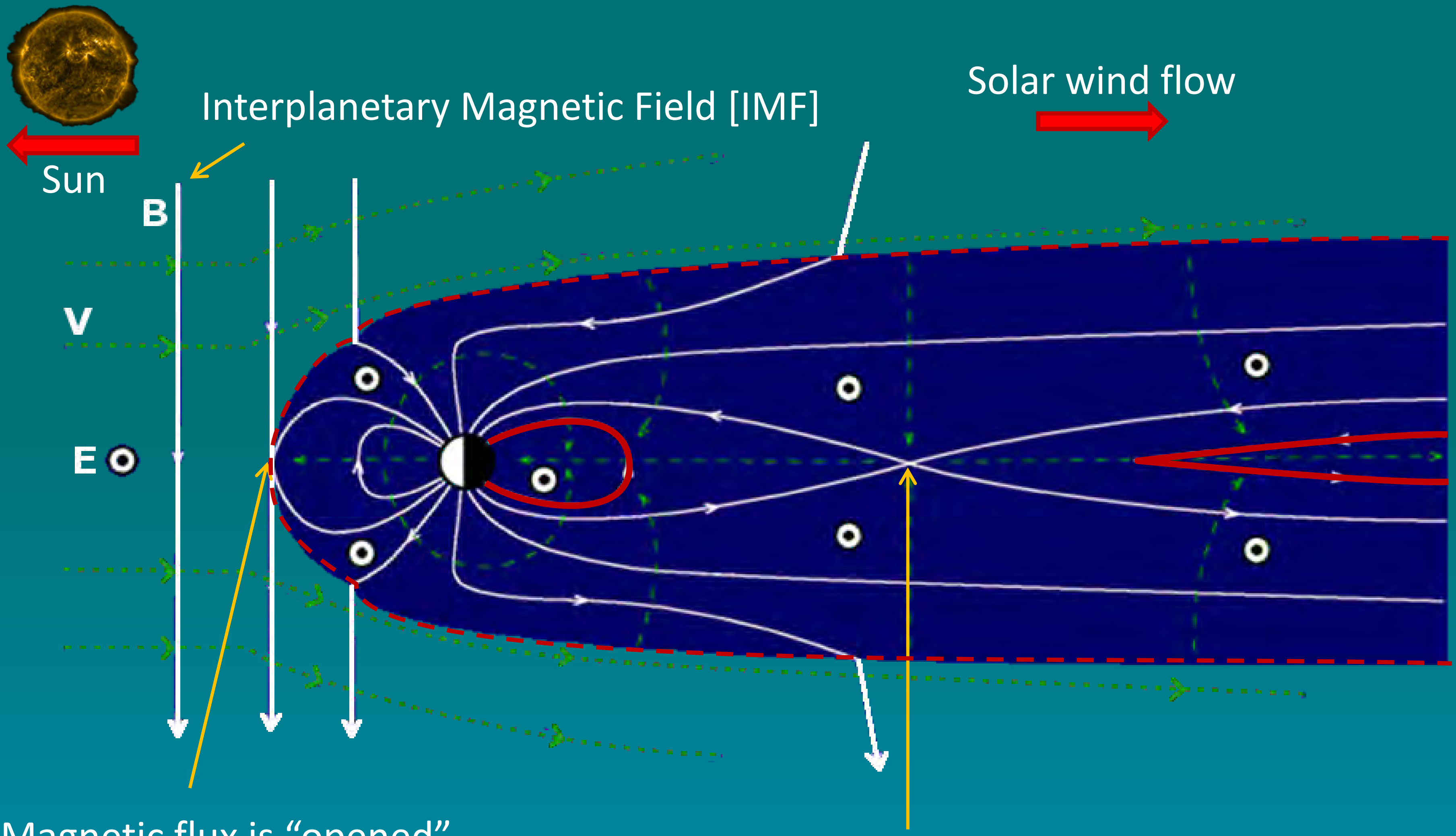
The Dungey cycle: The open magnetosphere



Magnetic flux is "opened"

"Open" flux is "closed"

The Dungey cycle: The open magnetosphere



Interplanetary Magnetic Field [IMF]

Solar wind flow

Magnetic flux is "opened"

"Open" flux is "closed"

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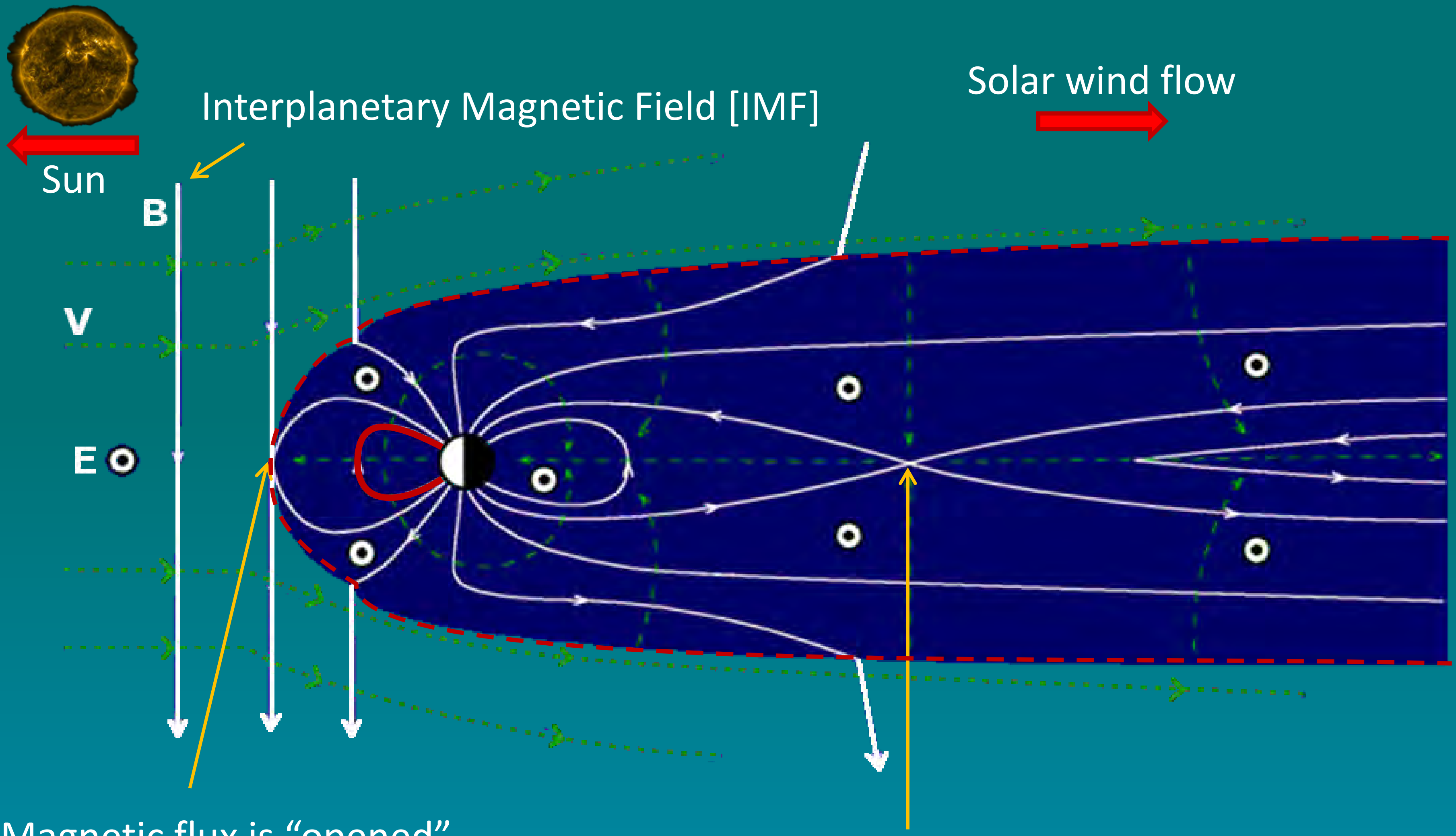
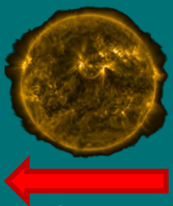
The Dungey cycle: The open magnetosphere



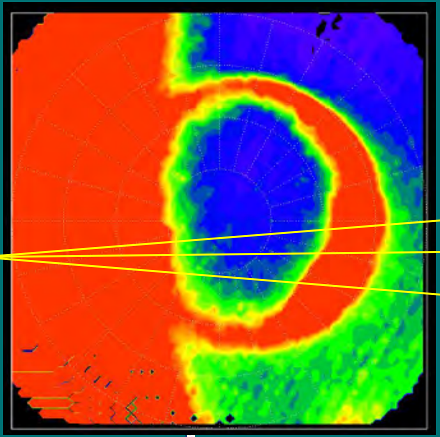
Magnetic flux is “opened”

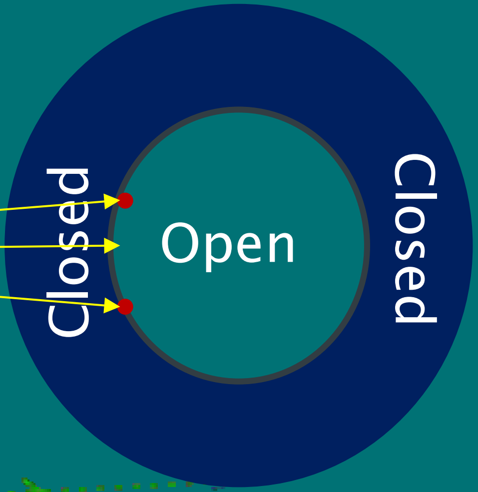
“Open” flux is “closed”

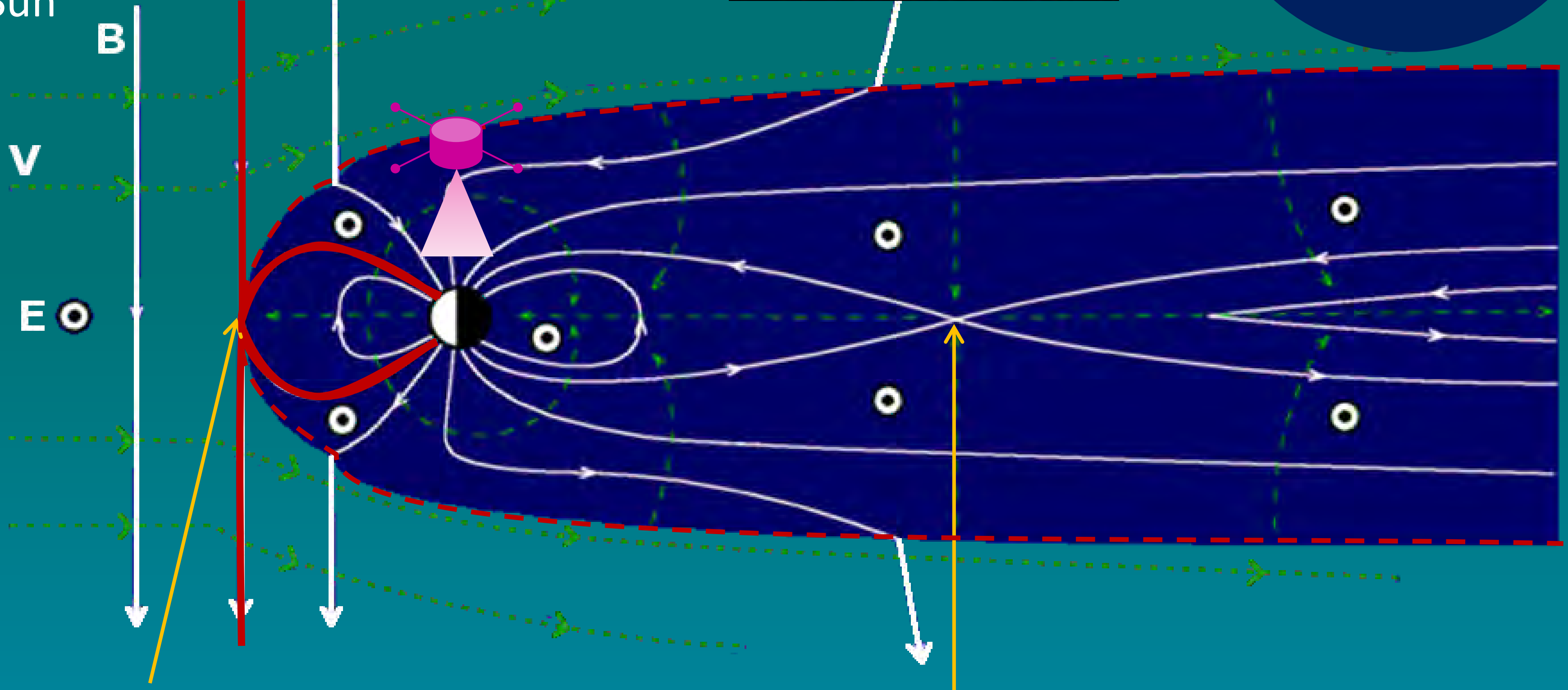
The Dungey cycle



Aurora at the footprint of these field lines are the signature of plasma entry due to reconnection



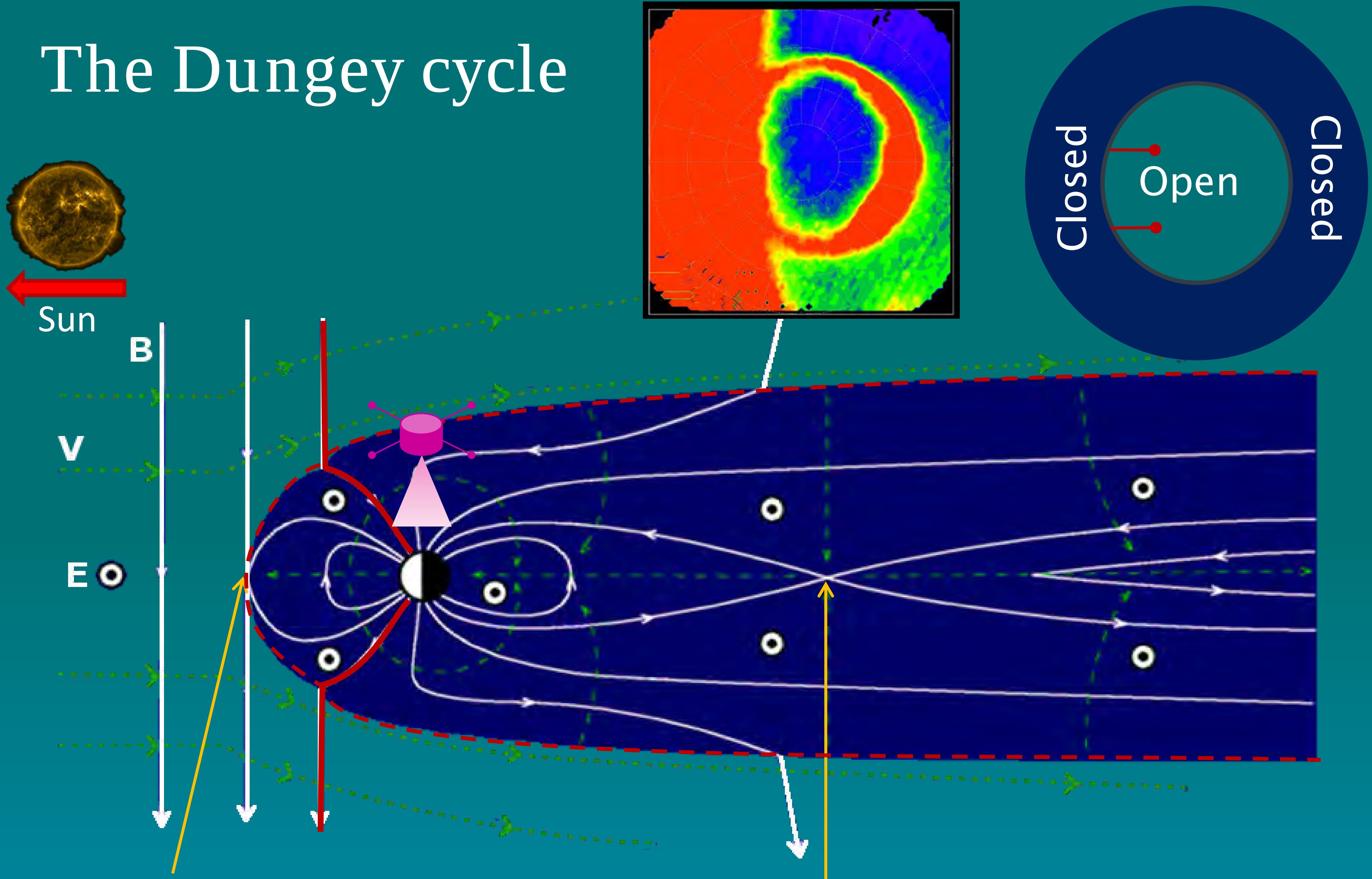




Magnetic flux is “opened”

“Open” flux is “closed”

The Dungey cycle



Magnetic flux is "opened"

"Open" flux is "closed"

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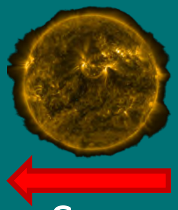
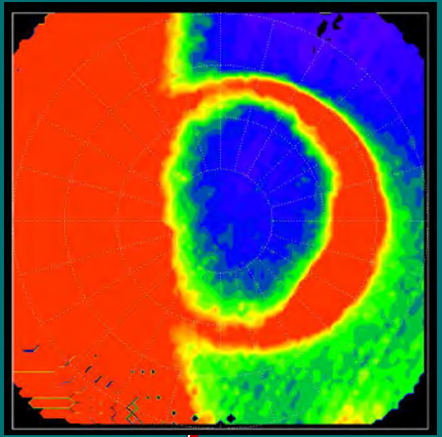
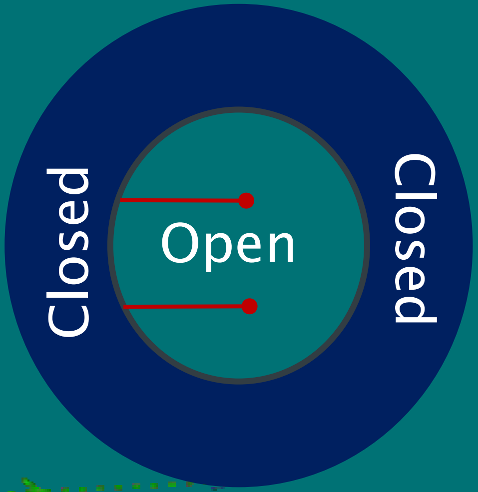
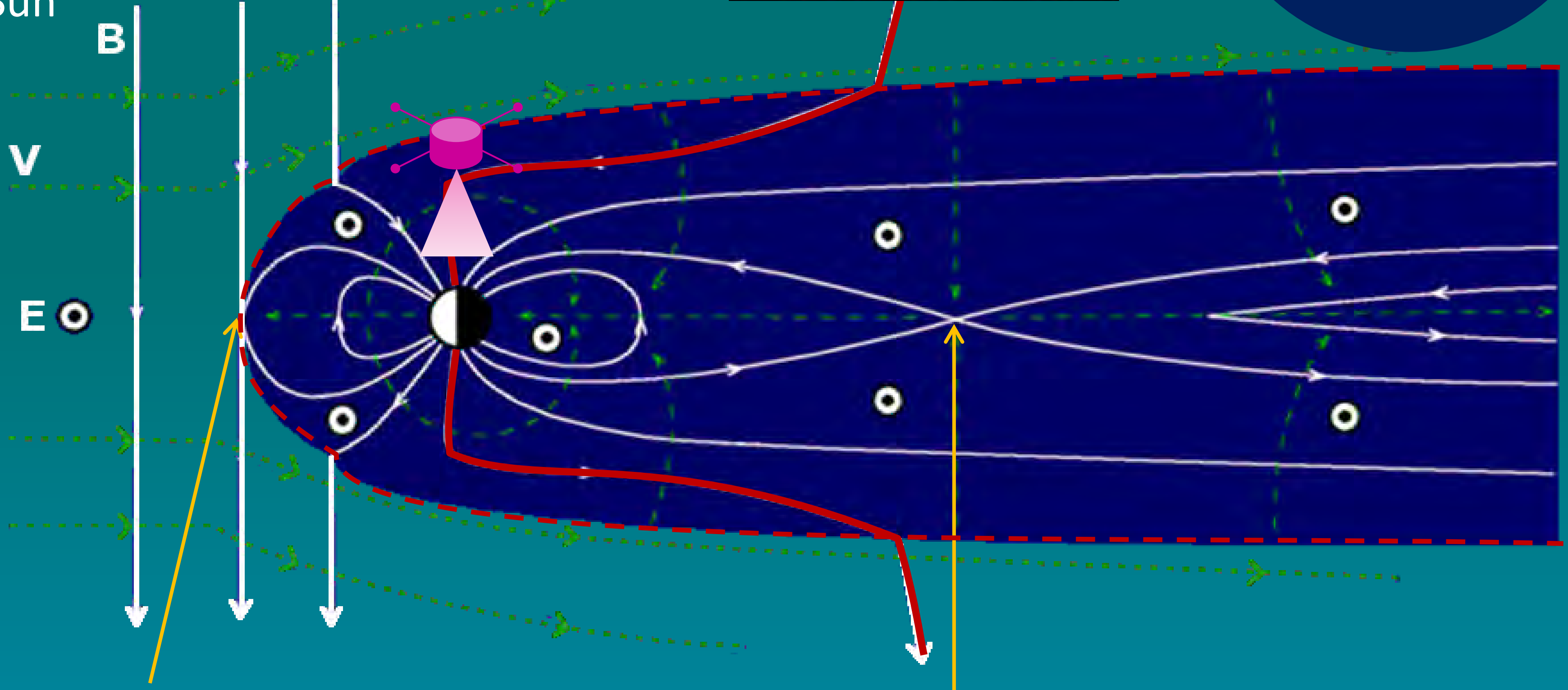
The Dungey cycle









Magnetic flux is “opened”

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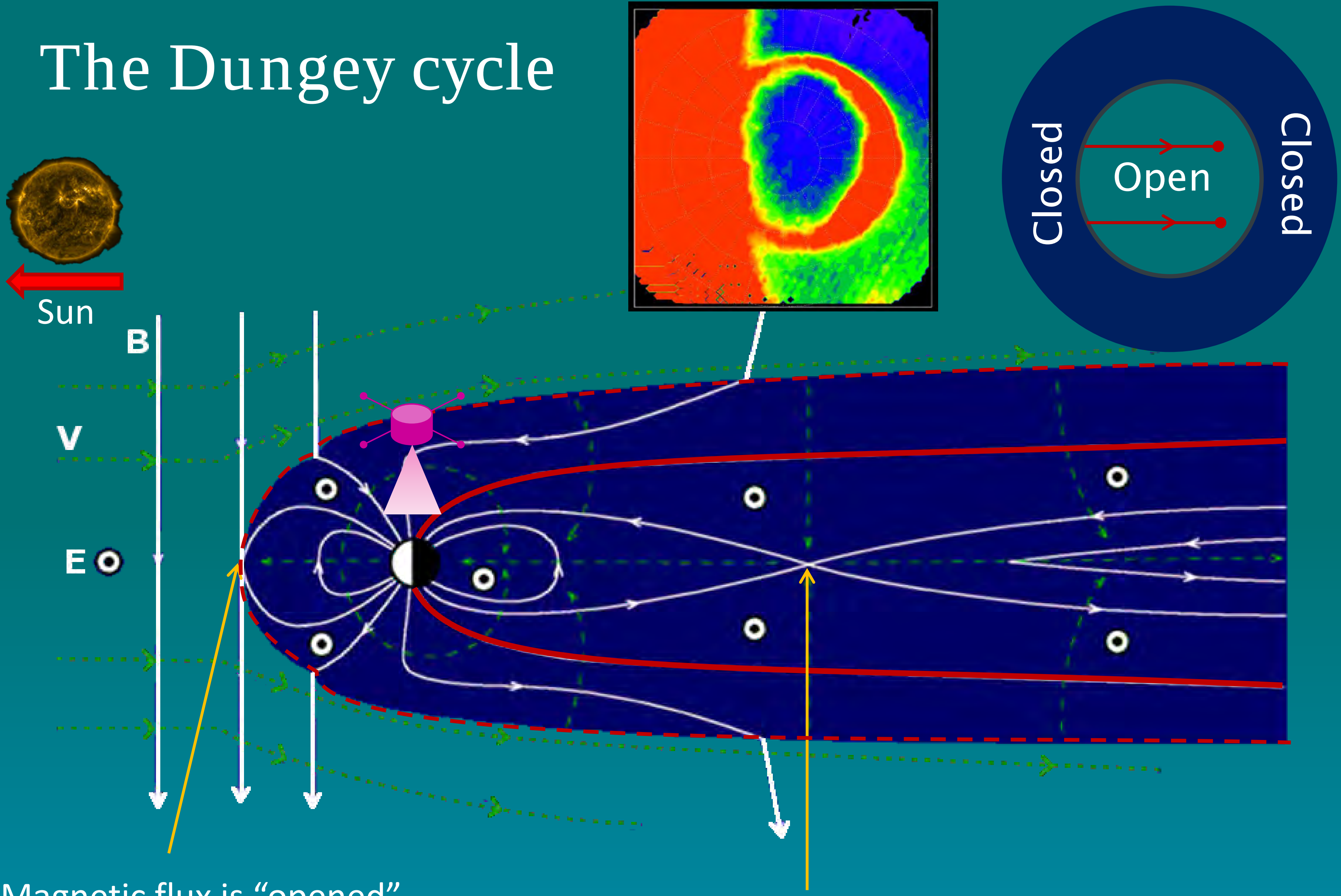
The Dungey cycle

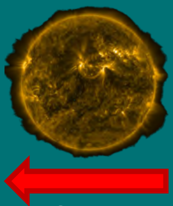


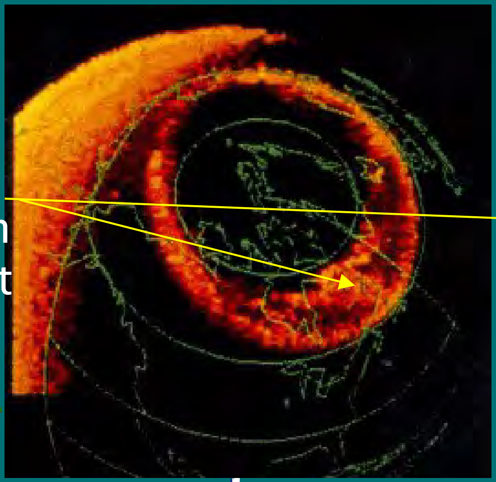
Magnetic flux is “opened”

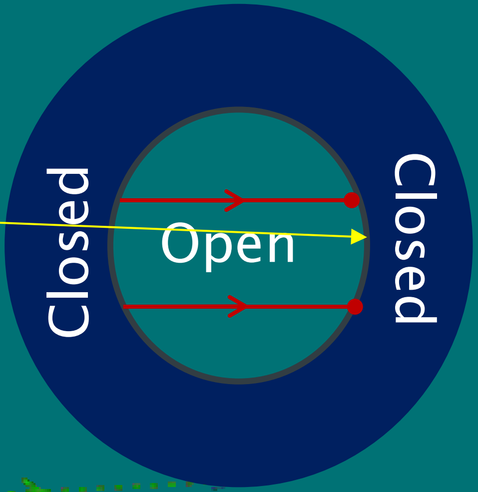
“Open” flux is “closed”

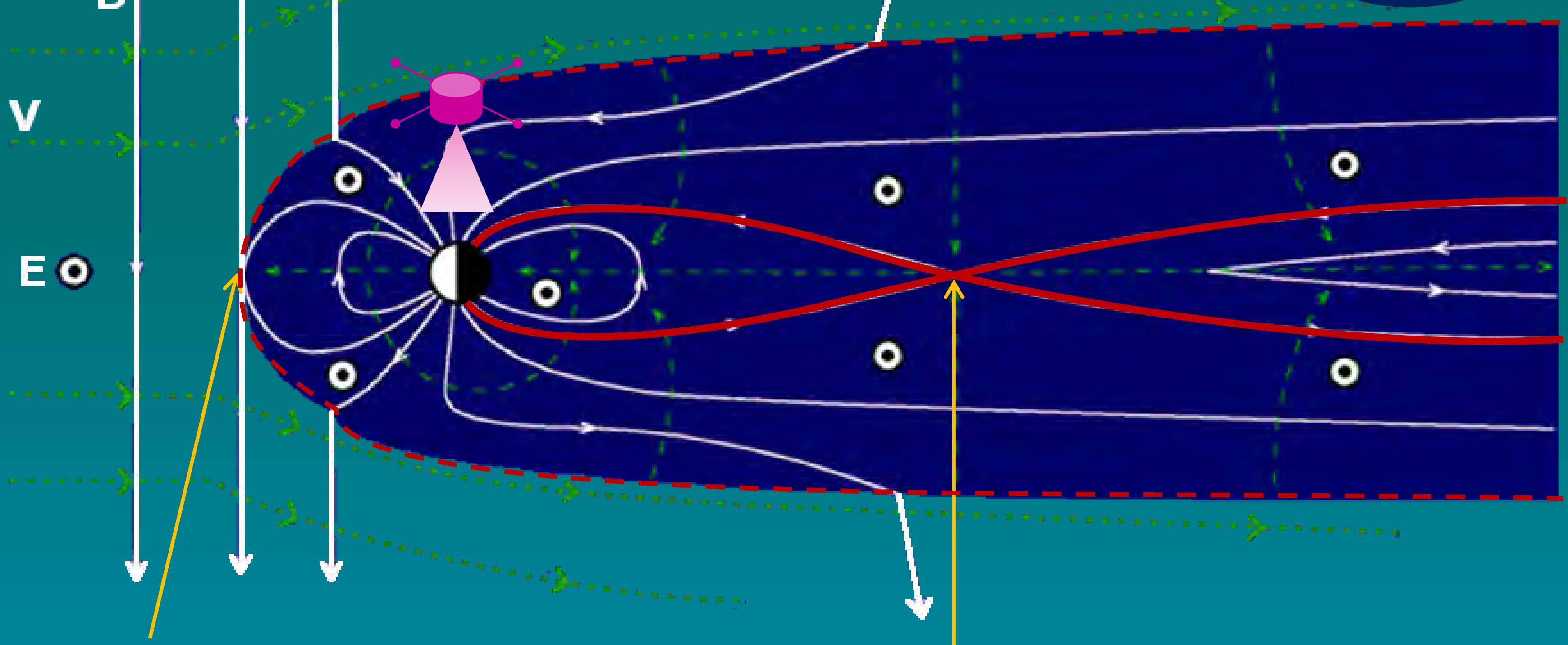
The Dungey cycle

Tail reconnection occurs explosively in a process known as the **substorm** - Earth's most intense aurorae occur here


Sun







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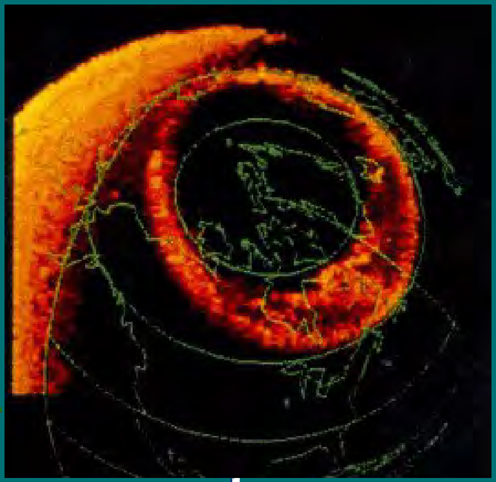
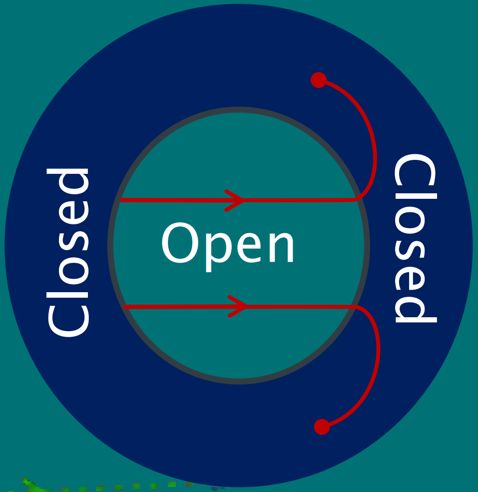
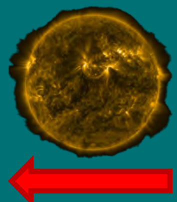
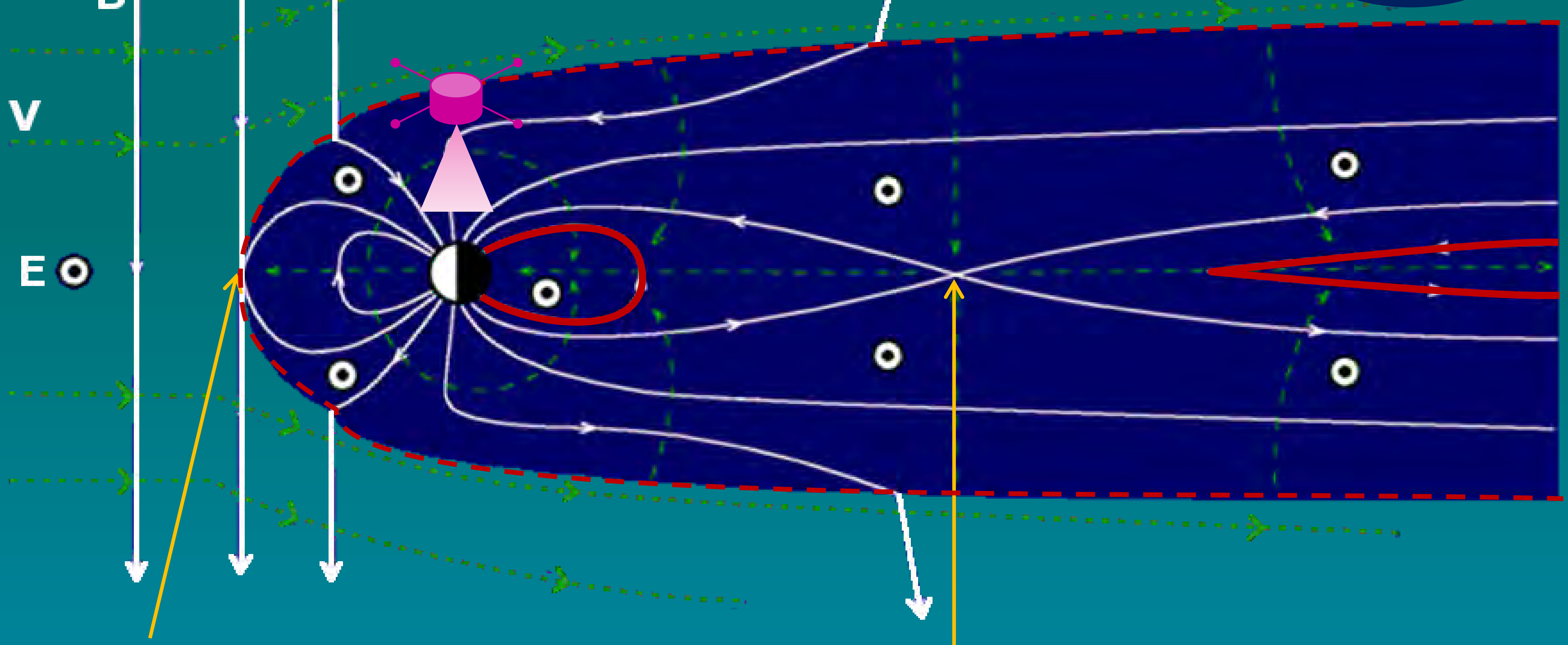
The Dungey cycle









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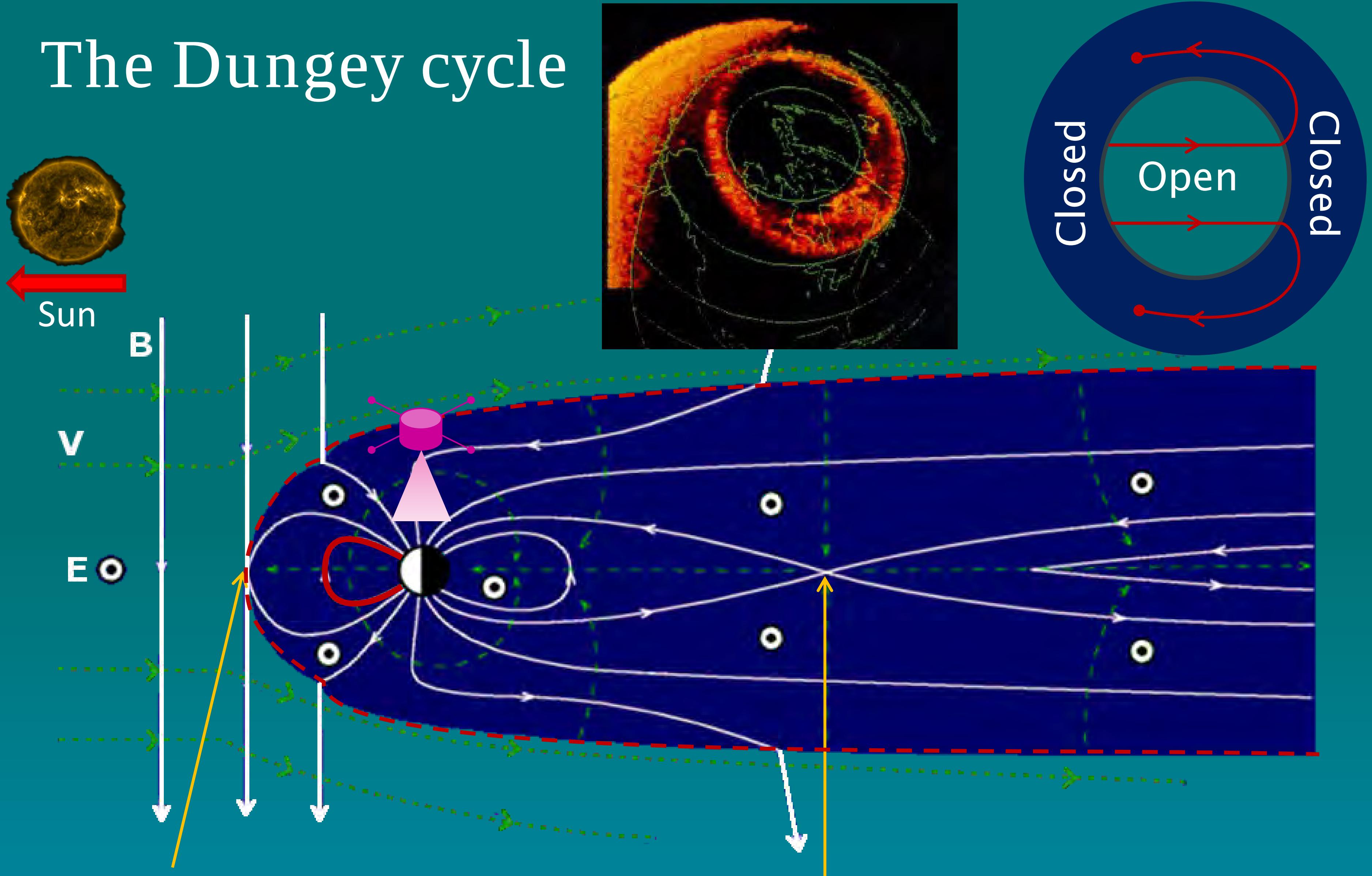
The Dungey cycle



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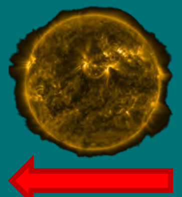
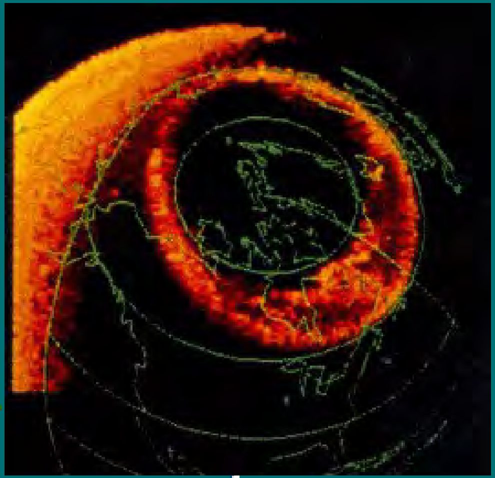
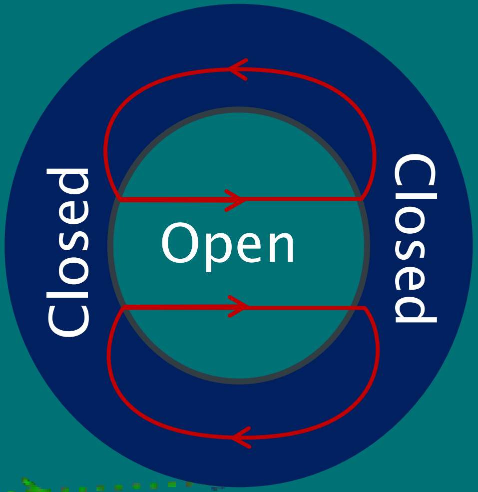
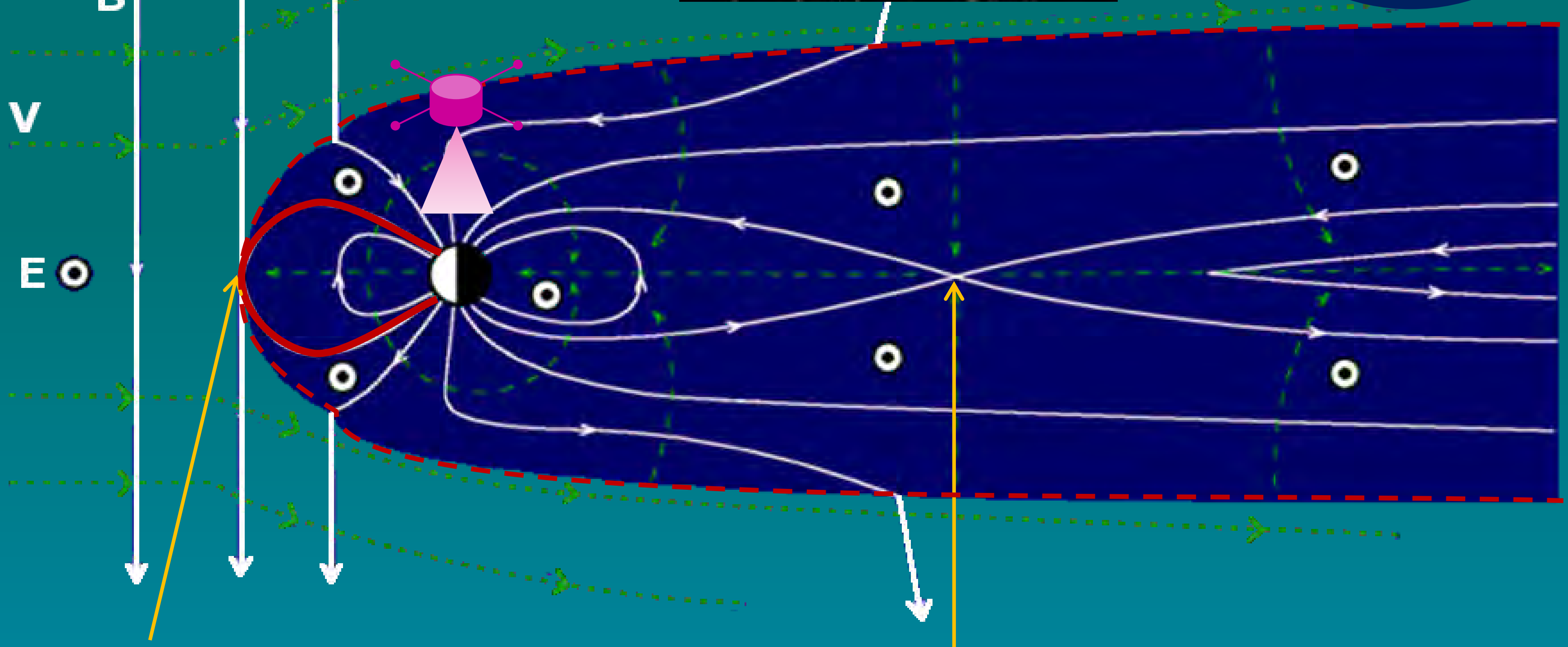


Sun







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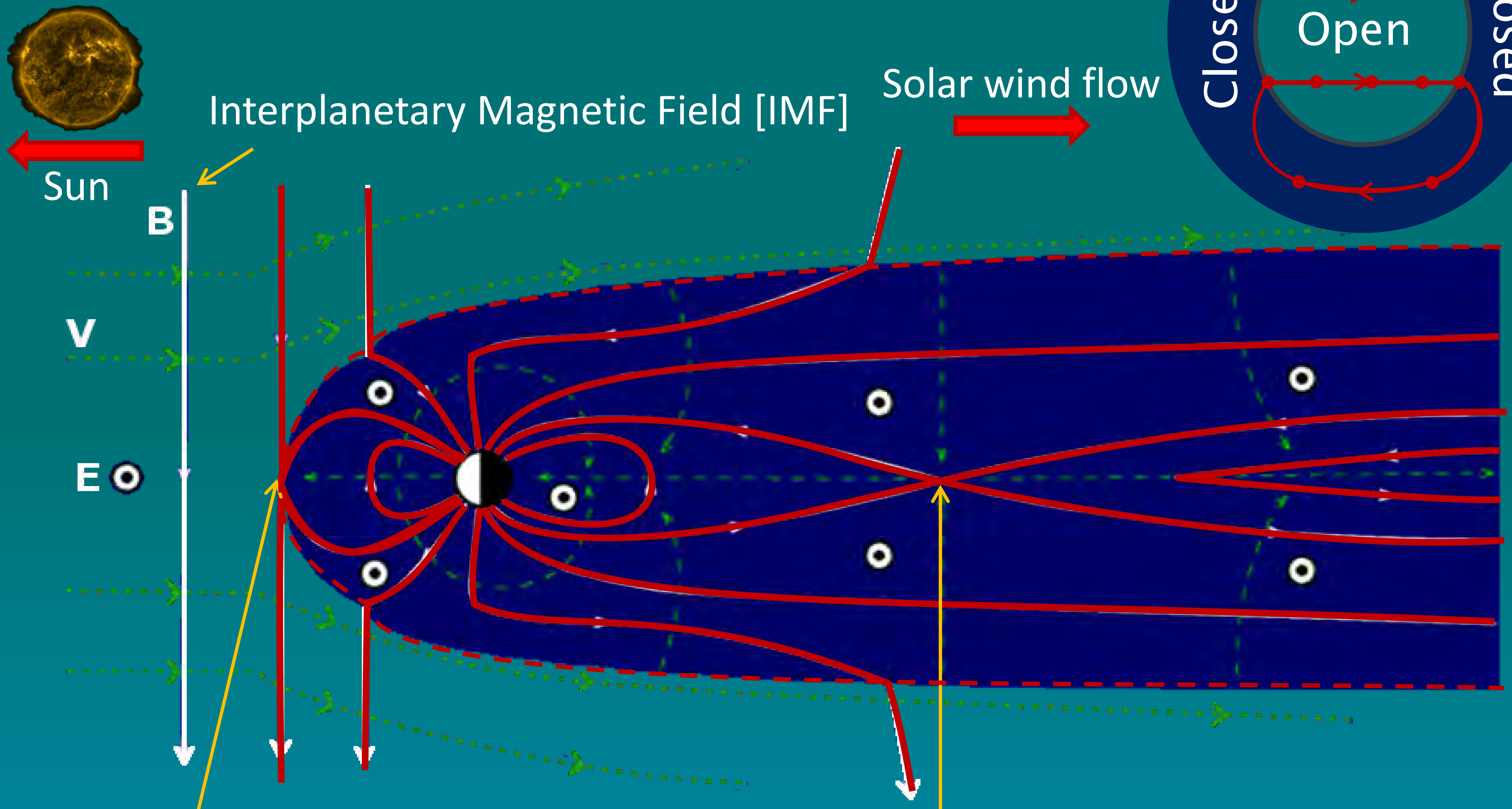

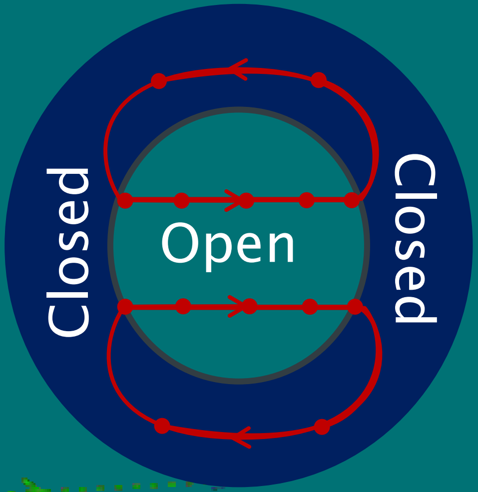

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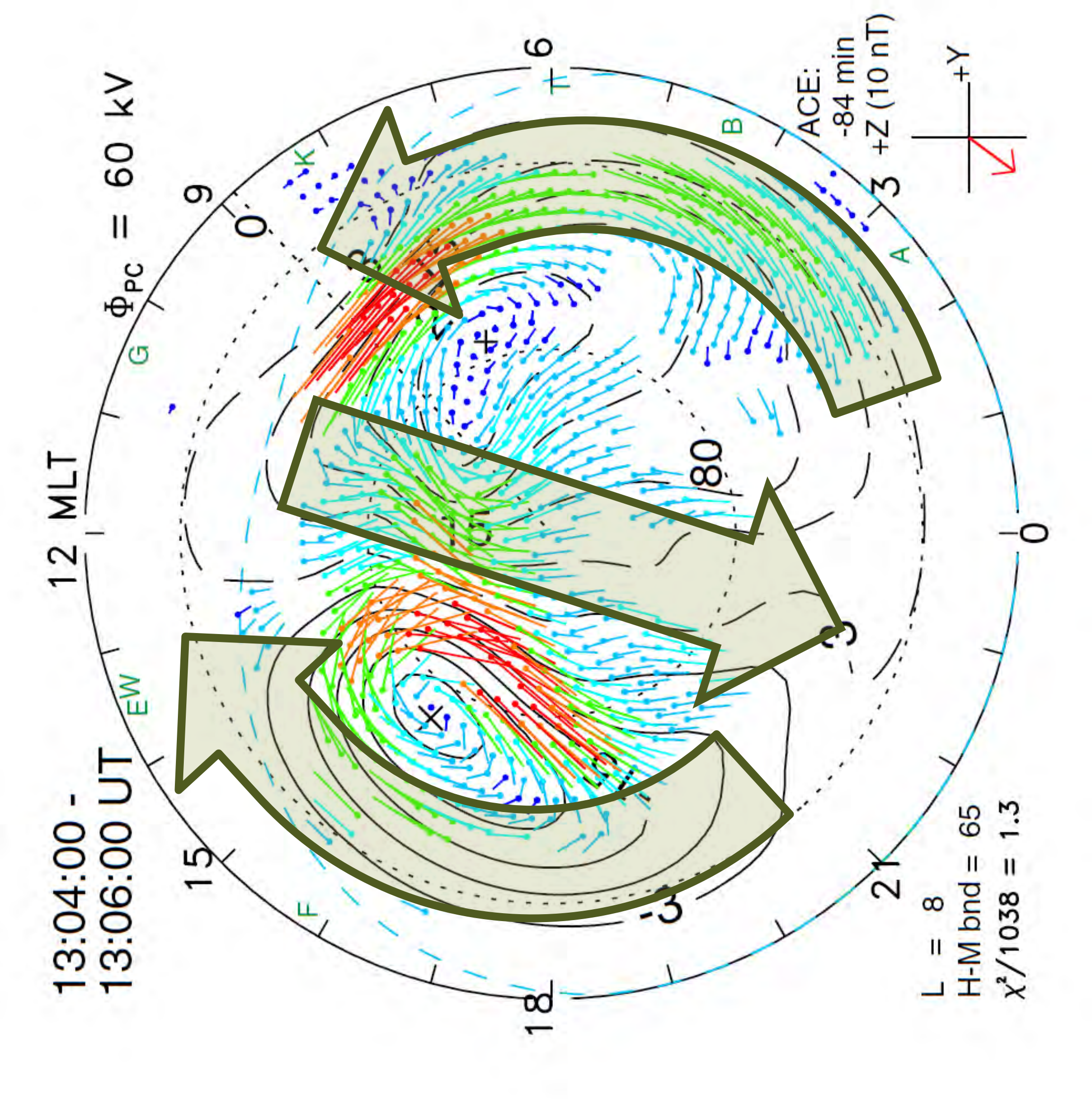
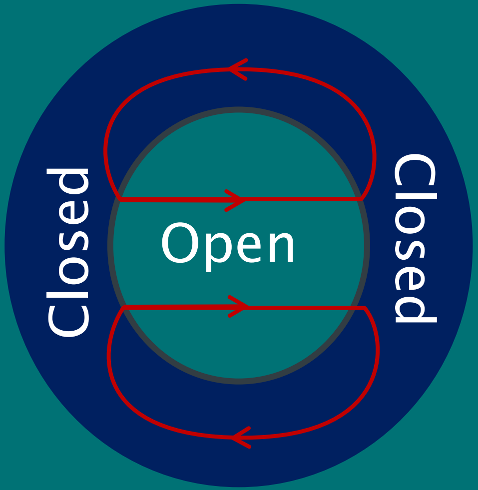
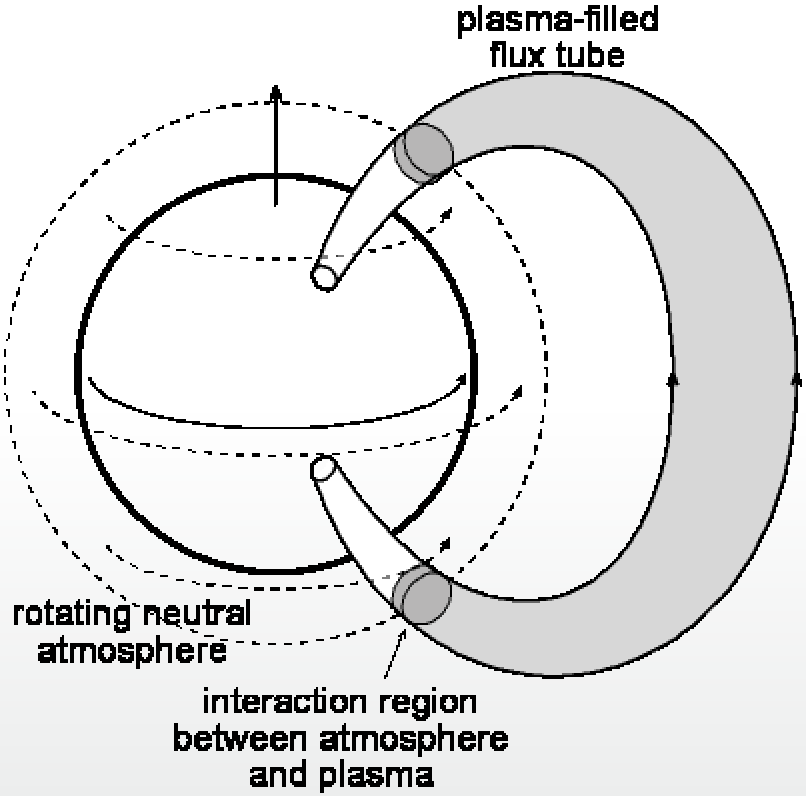
The Dungey cycle

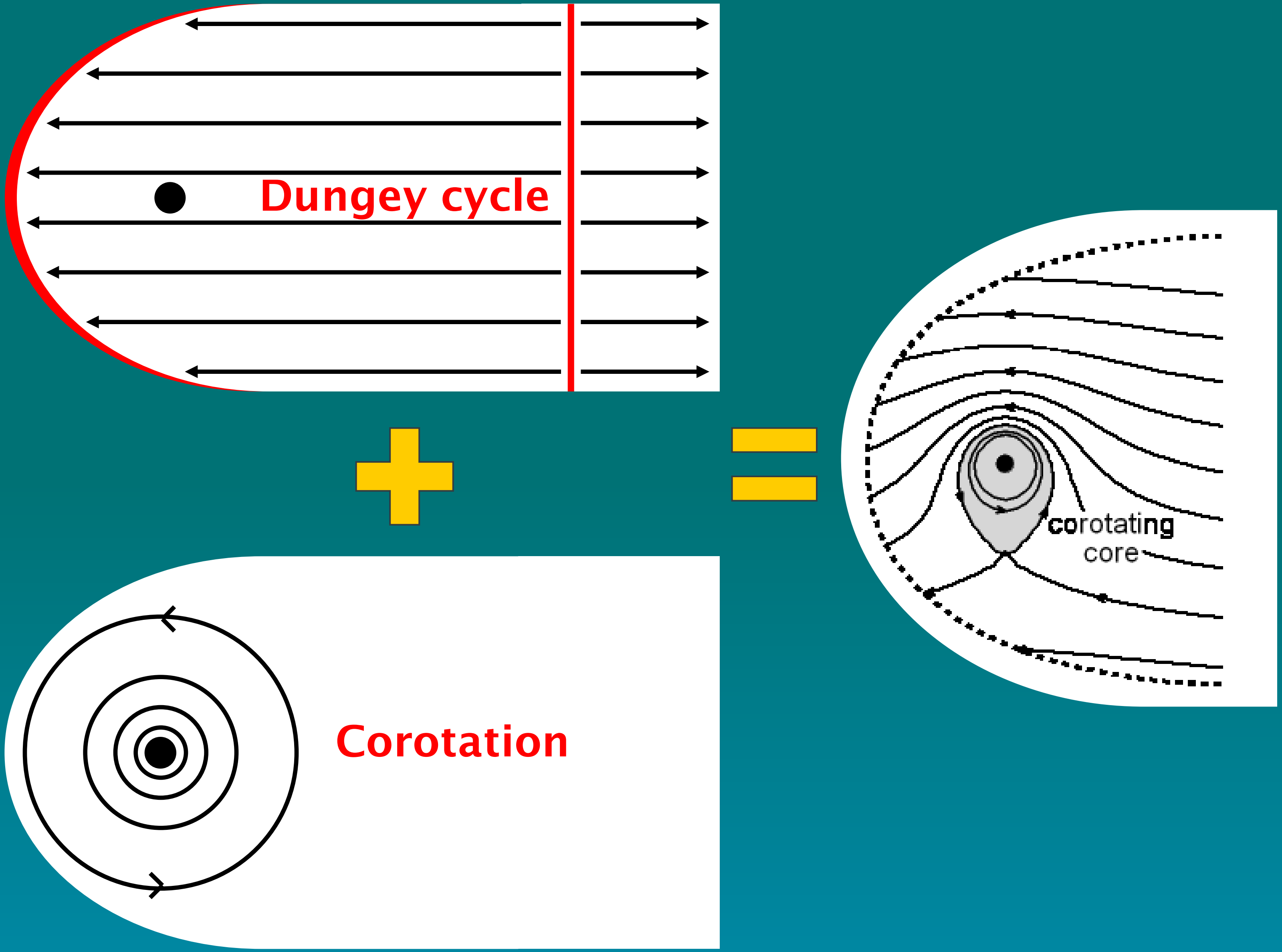




Corotation

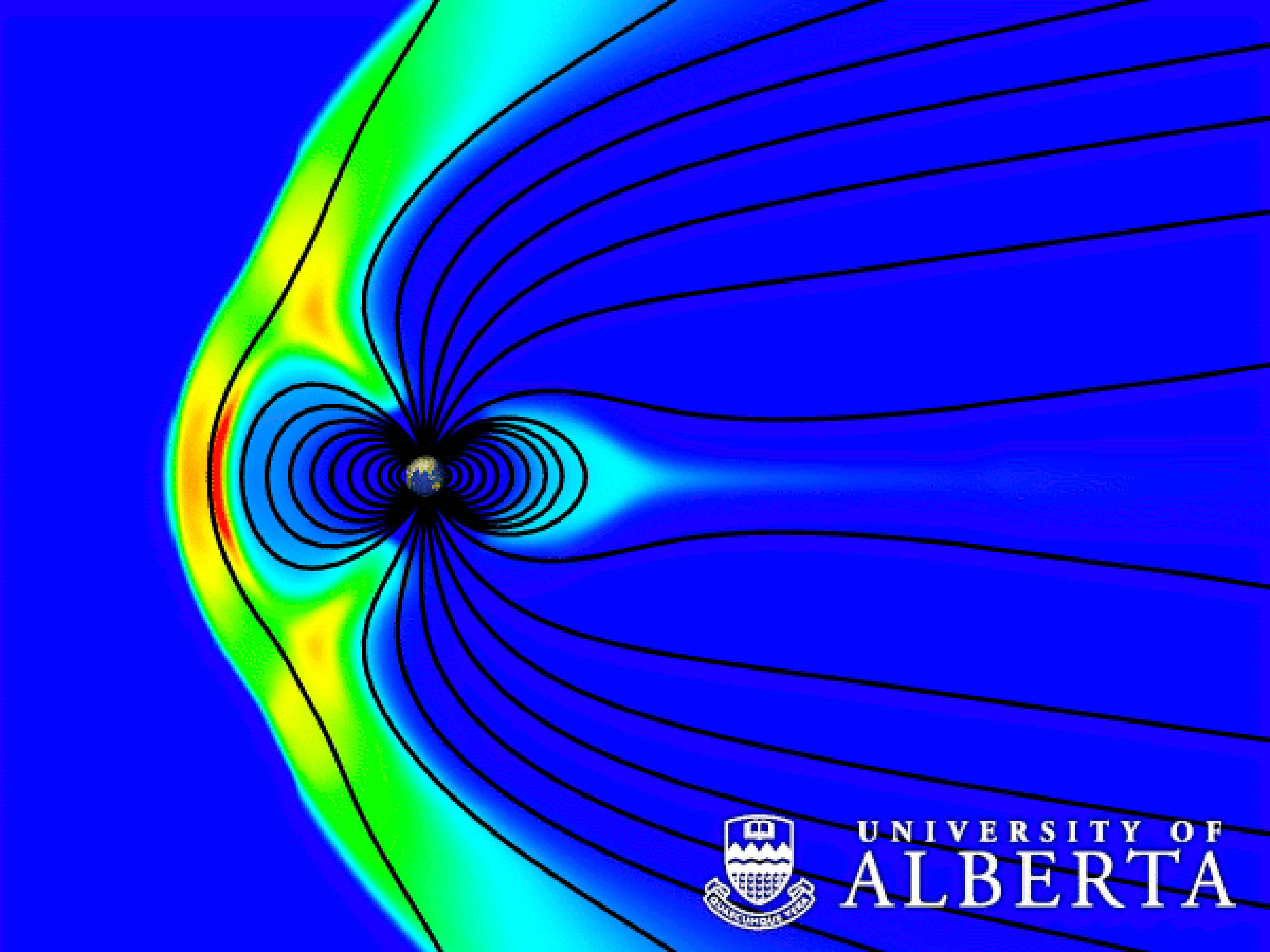


- The rotation of the planet also imparts momentum to the magnetospheric plasma
- Ionospheric plasma is frictionally coupled to the neutral atmosphere
- The magnetic field lines, frozen to this plasma, attempt to rotate with the planet
- In turn, the magnetospheric plasma is frozen to the corotating magnetic field



Dungey cycle

Corotation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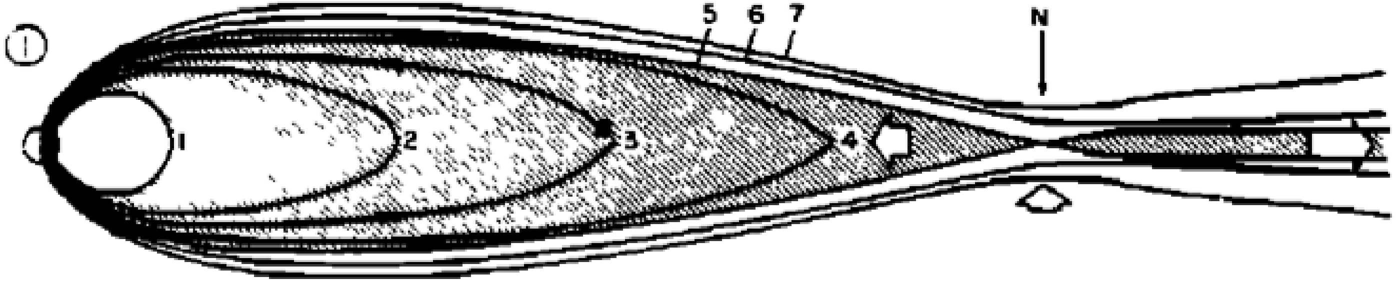
ALBERTA

Time-dependent convection: Substorms

- Stage 1: Growth phase

Hones (1984)



Dayside reconnection rate increases

Magnetotail B field becomes more stretched

Tail current increases

Convection (polar cap **E** field) increases

Lobe magnetic field becomes stronger – build-up of stored energy in tail

Tail reconnection may occur, but dayside reconnection dominant

Polar cap expands equatorwards*

Plasma sheet squeezed and thins

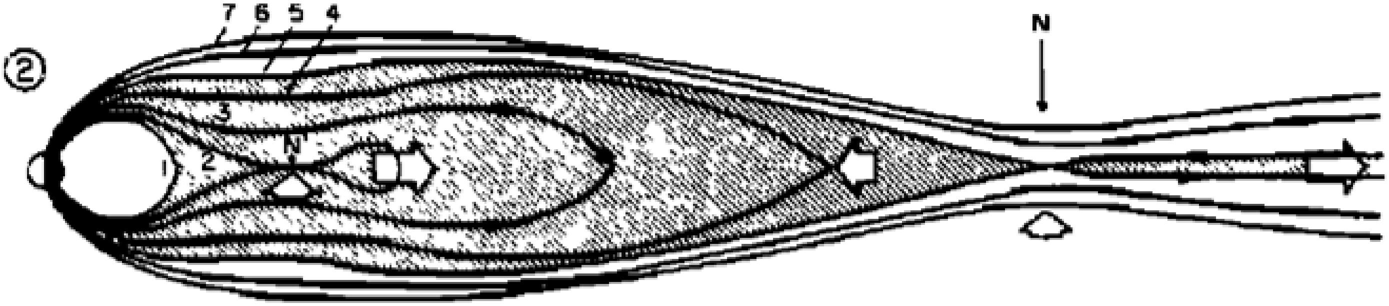
Typically lasts up to ~1 hour (at Earth)

* As dayside reconnection rate >> nightside rate

Time-dependent convection: Substorms

- Stage 2: Expansion phase

Hones (1984)



Dramatic reconfiguration of the magnetotail

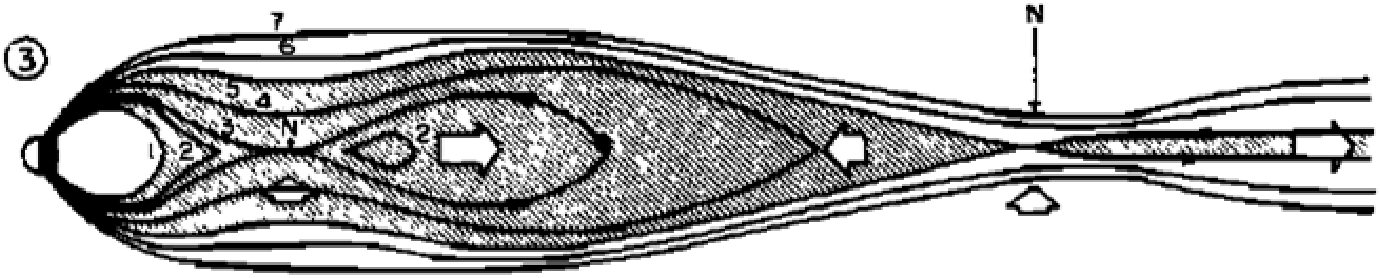
New reconnection line forms (Near-Earth Neutral Line)

Excess magnetic flux in magnetotail reconnected at NENL

Time-dependent convection: Substorms

- Stage 2: Expansion phase

Hones (1984)



Dramatic reconfiguration of the magnetotail

New reconnection line forms (Near-Earth Neutral Line)

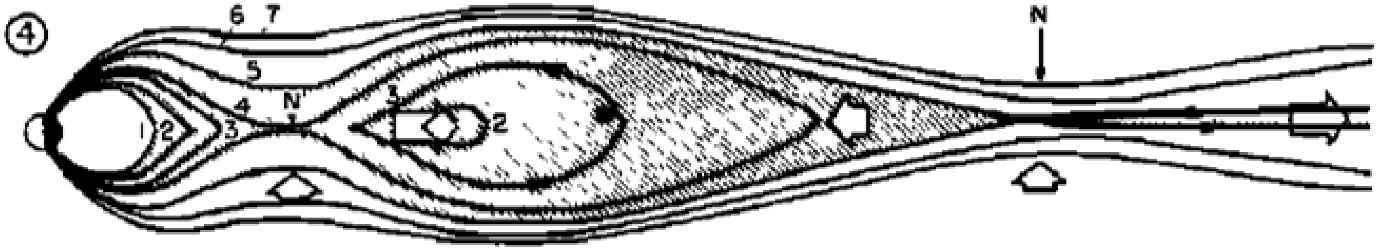
Excess magnetic flux in magnetotail reconnected at NENL

Field lines between reconnection lines form a plasmoid (closed loops) – ejected downtail

Time-dependent convection: Substorms

- Stage 2: Expansion phase

Hones (1984)



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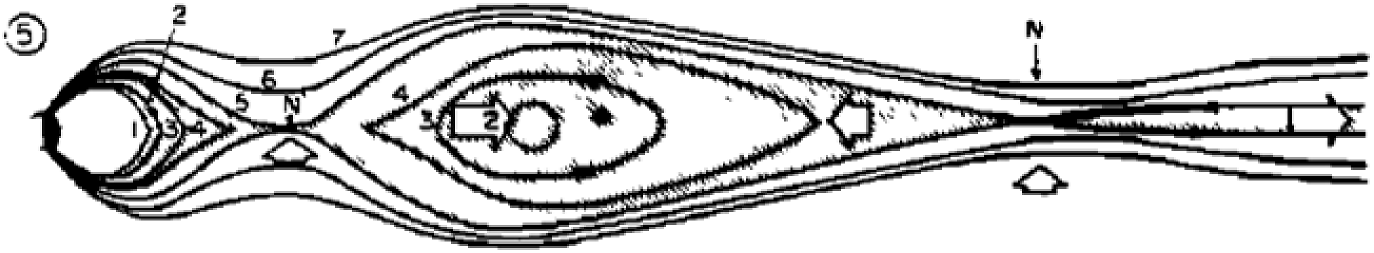

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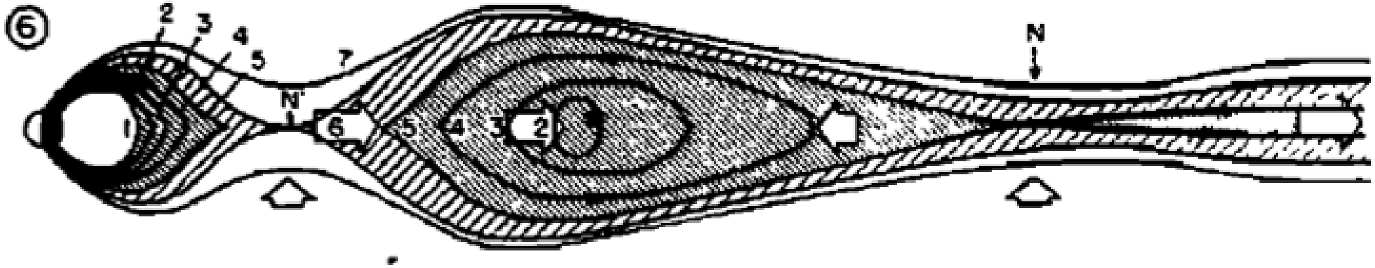

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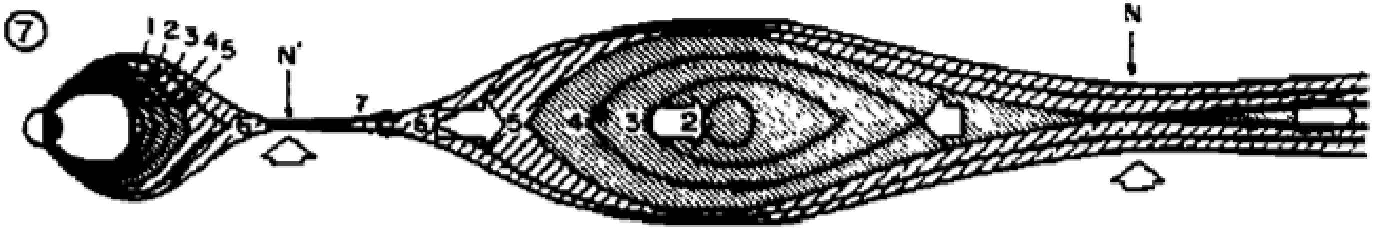

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Dramatic reconfiguration of the magnetotail

New reconnection line forms (Near-Earth Neutral Line)

Excess magnetic flux in magnetotail reconnected at NENL

Field lines between reconnection lines form a plasmoid (closed loops) – ejected downtail

Field lines earthward of NENL become more dipolar

Results in diversion of cross-tail current into ionosphere (substorm current wedge)

Spectacular auroral displays near midnight!

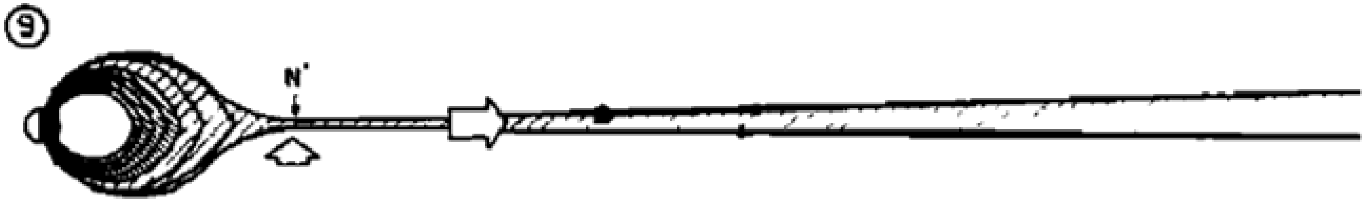
Lobe magnetic field strength decreases

Typically lasts up to 30-60 mins (at Earth)

Time-dependent convection: Substorms

- Stage 3: Recovery phase

Hones (1984)



Auroral bulge fades

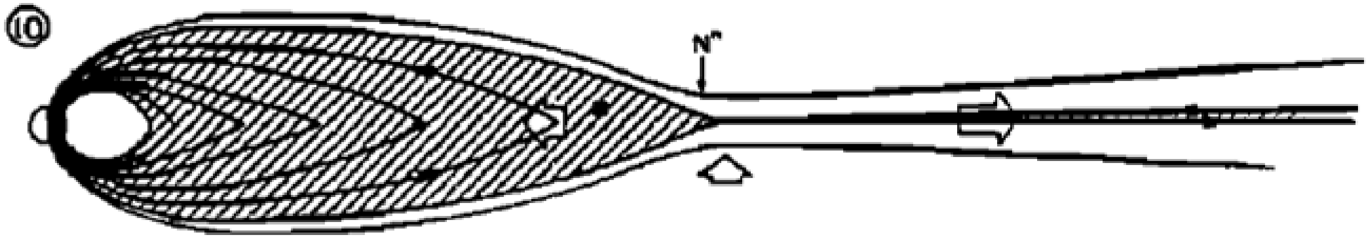
Substorm current wedge weakens

Near Earth Neutral Line retreats downtail

Time-dependent convection: Substorms

- Stage 3: Recovery phase

Hones (1984)



Auroral bulge fades

Substorm current wedge weakens

Near Earth Neutral Line retreats downtail

Plasma sheet thickens

Tail currents and fields ‘relax’ to undisturbed state

Typically lasts about 1-2 hours (at Earth)

Ends when magnetosphere has returned to quiet state

If dayside driving still present, could lead into new growth phase

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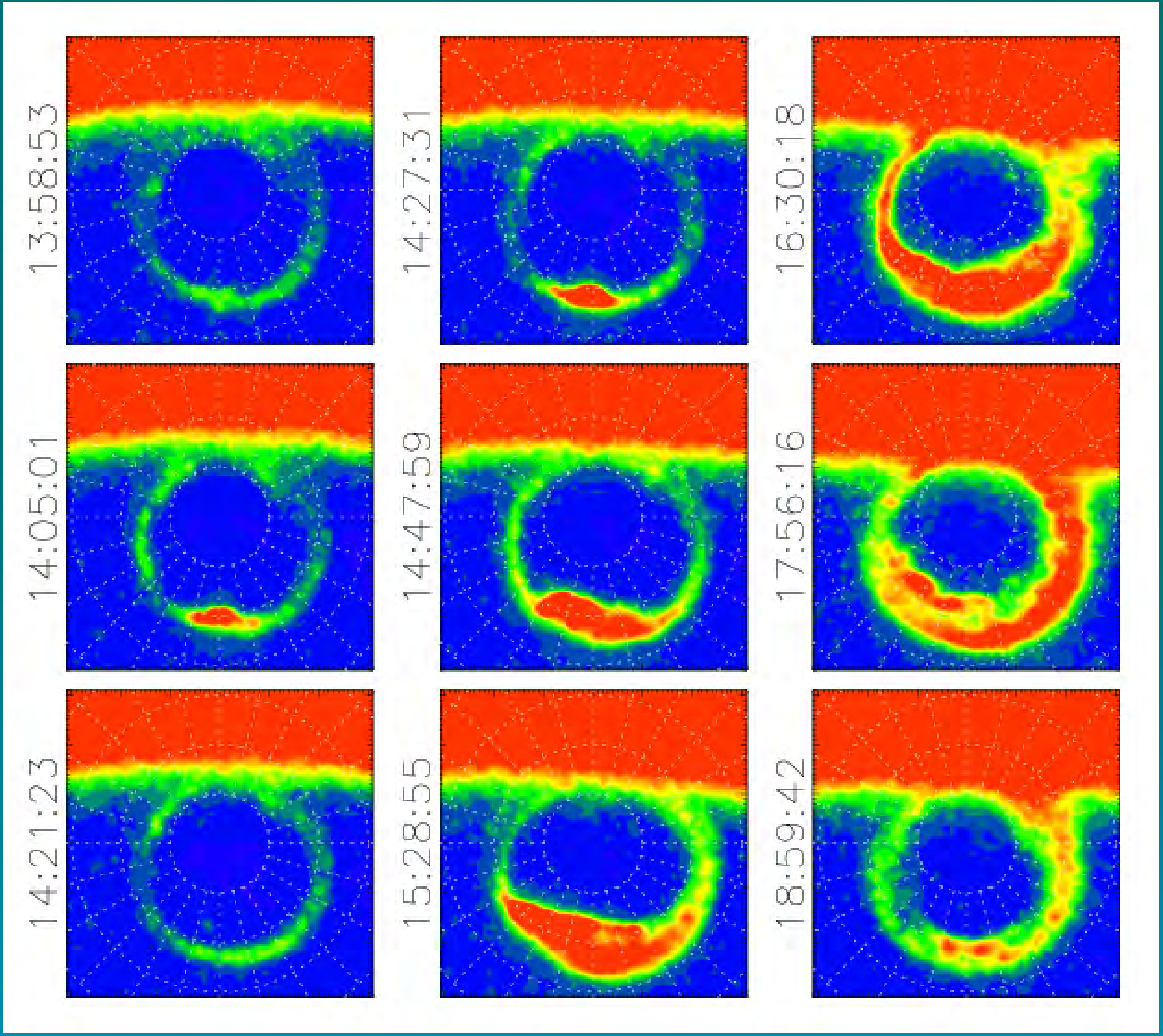
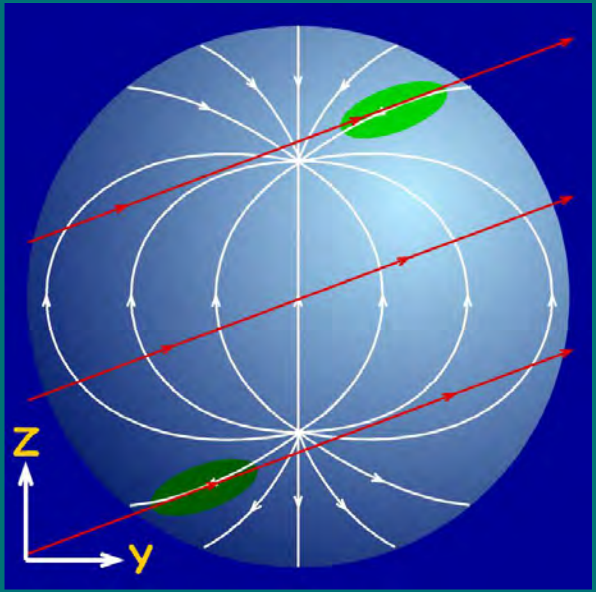
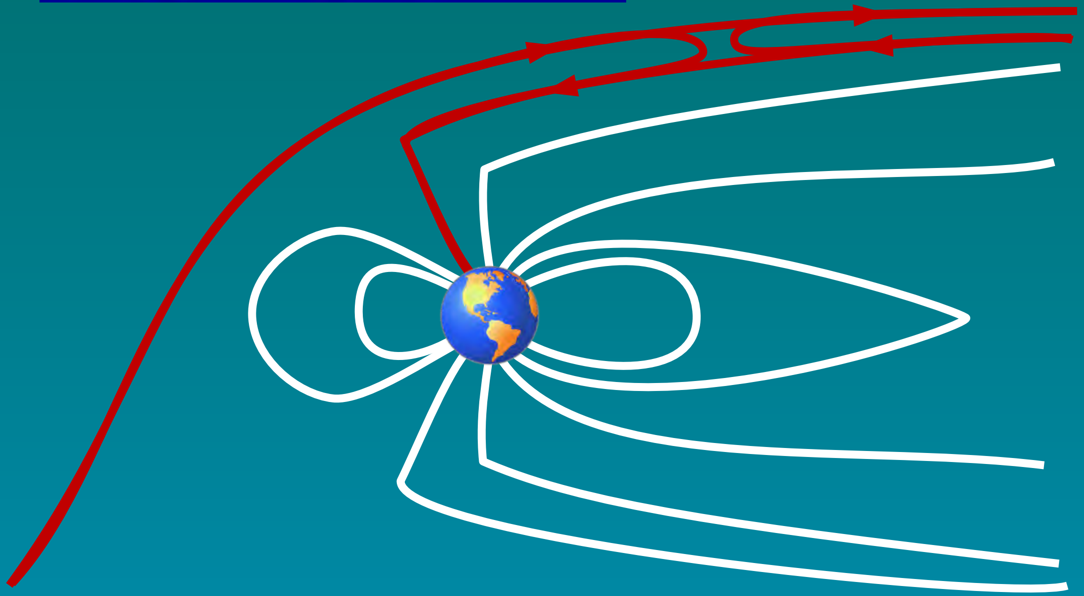
The auroral substorm

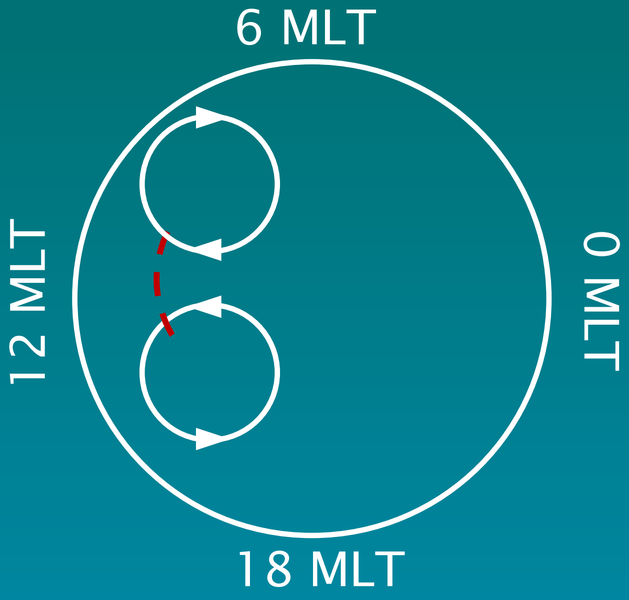


Northward IMF: Lobe reconnection



No change in field line topology, so no addition of flux to polar cap





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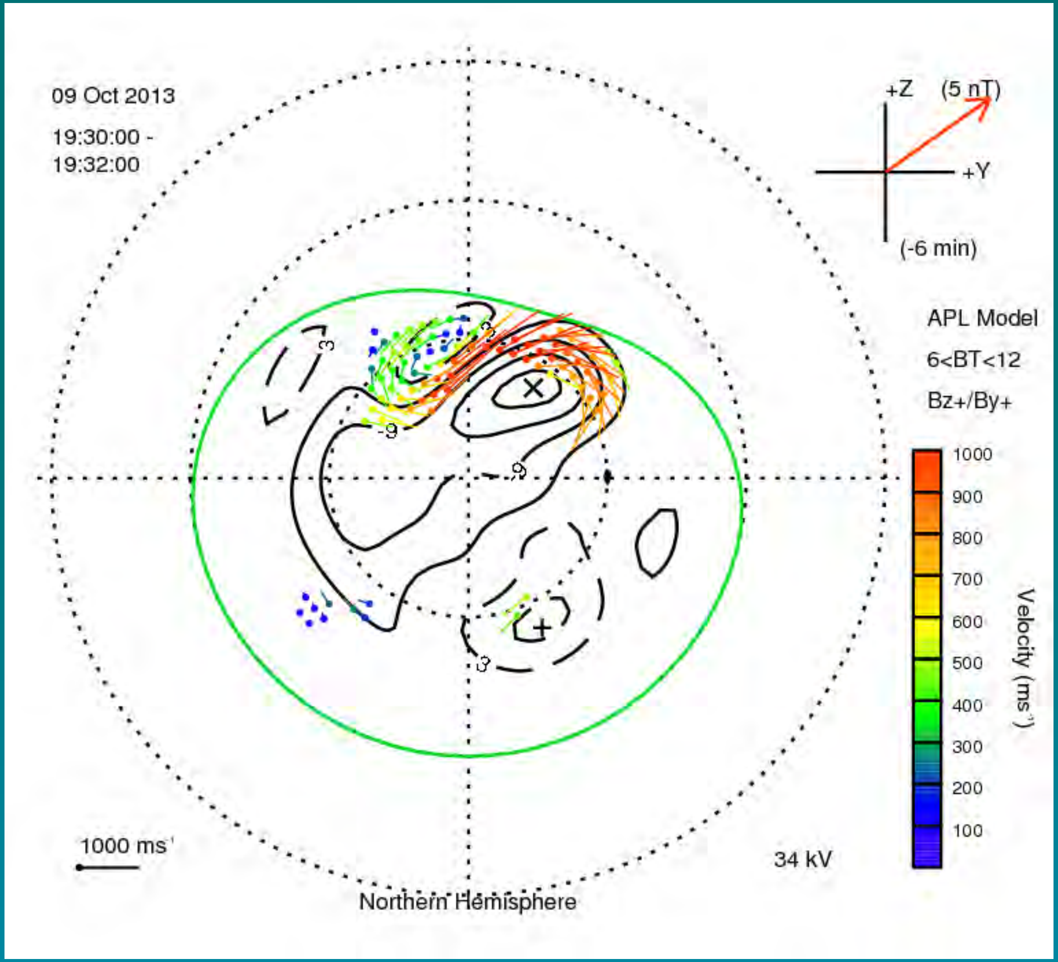

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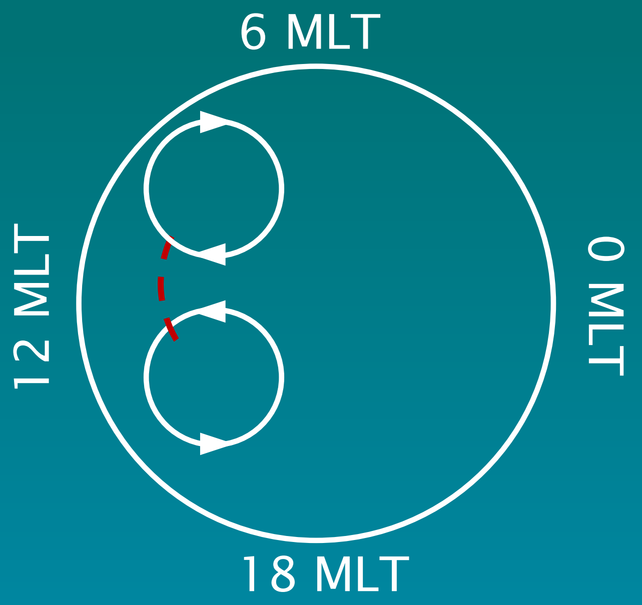
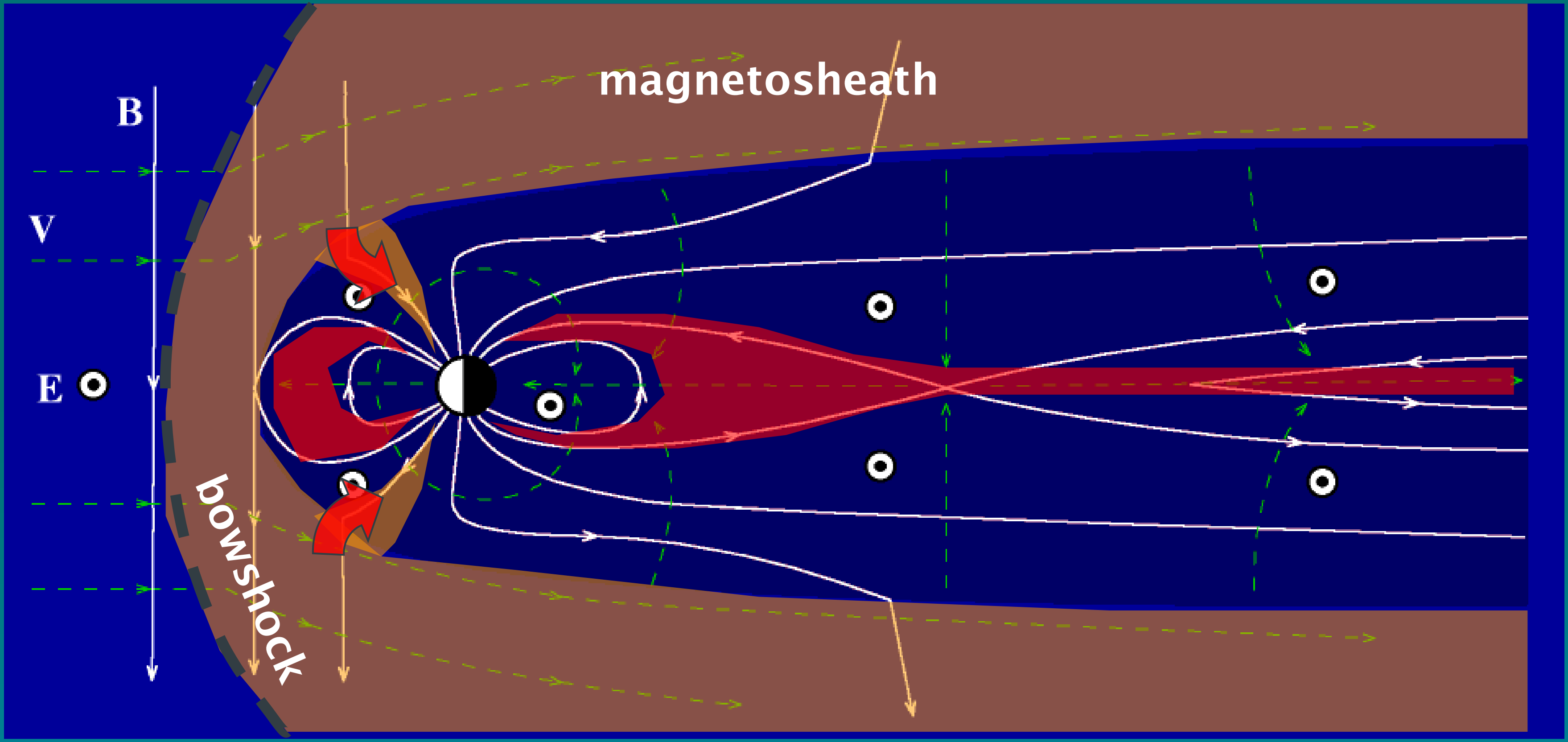


Plasma populations in the magnetosphere



The solar wind (mainly H$^+$ and e$^-$) populates the hot, low density (~ 1 cm^{-3}) "plasma sheet"

This is in pressure balance with the very low density (~0.01 cm^{-3}) lobes

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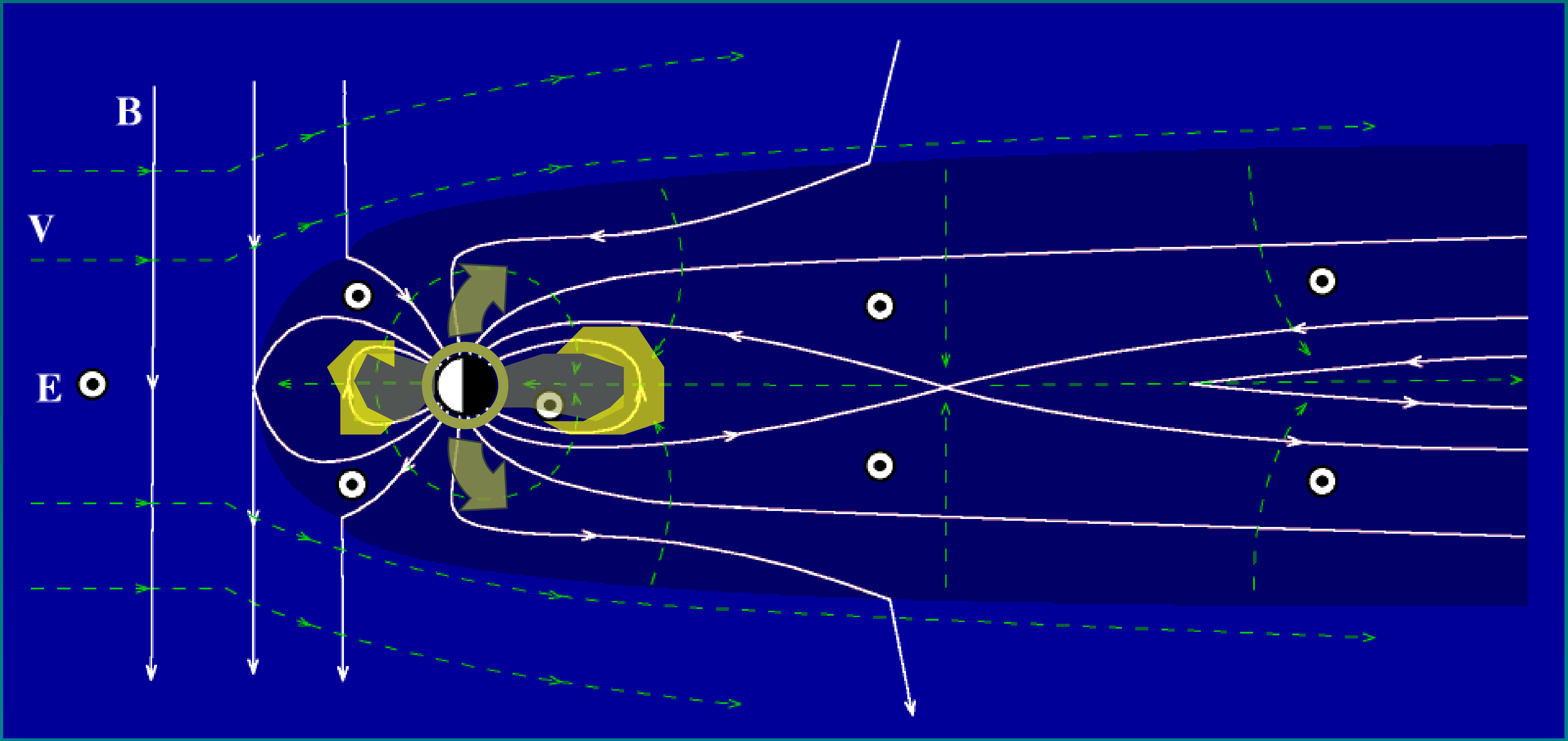
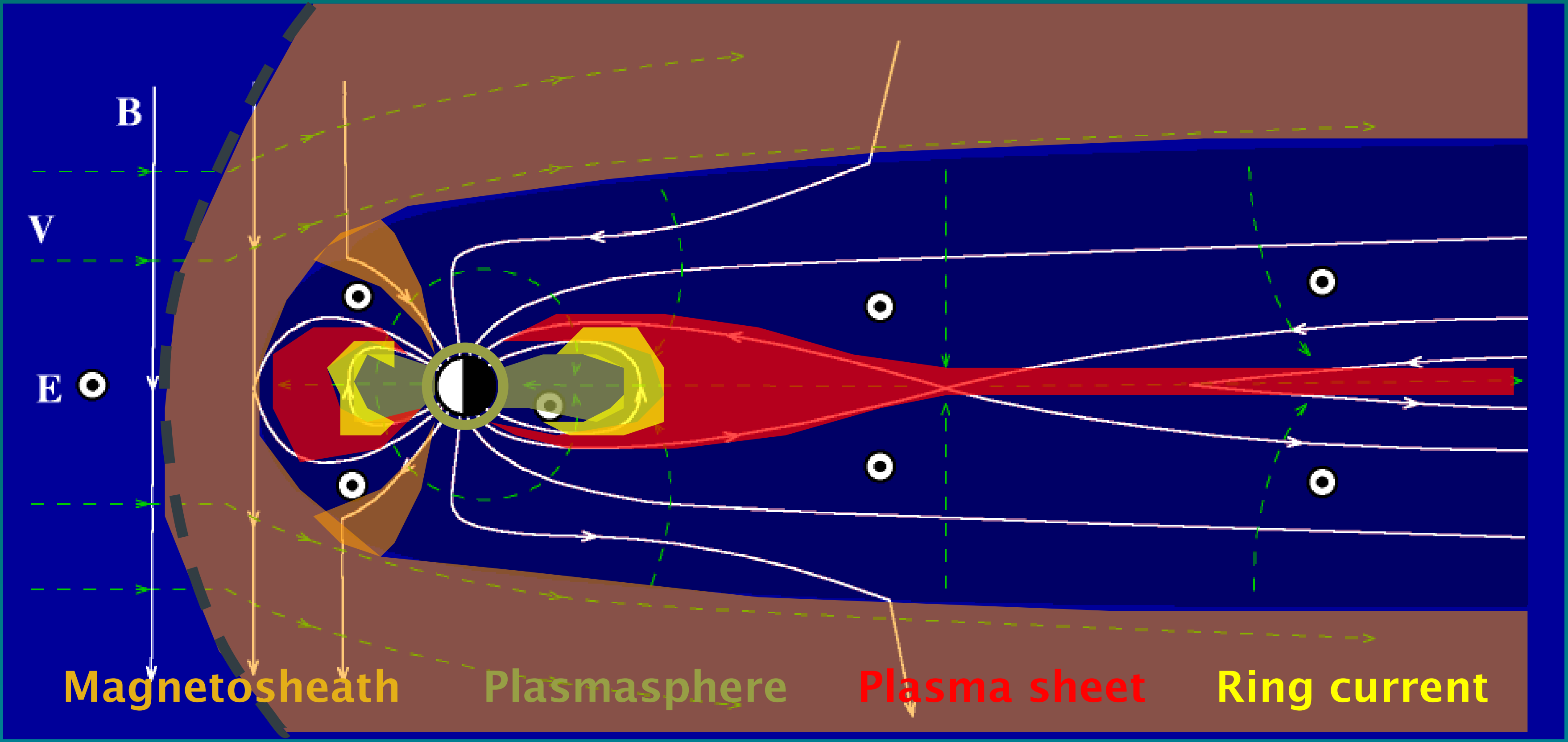
Plasma populations in the magnetosphere



The ionosphere populates the cold, high density (~ 100 cm-3) “plasmasphere” (say, O+ and e-)

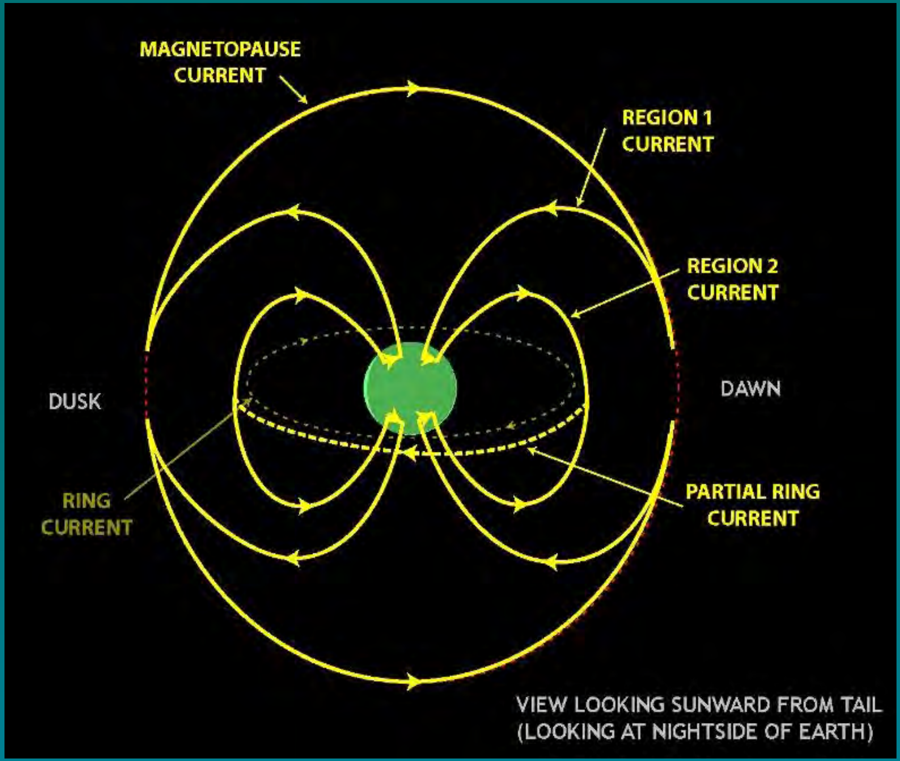
Outside of this region, very high energy particles comprise the Van Allen belts

Plasma populations in the magnetosphere

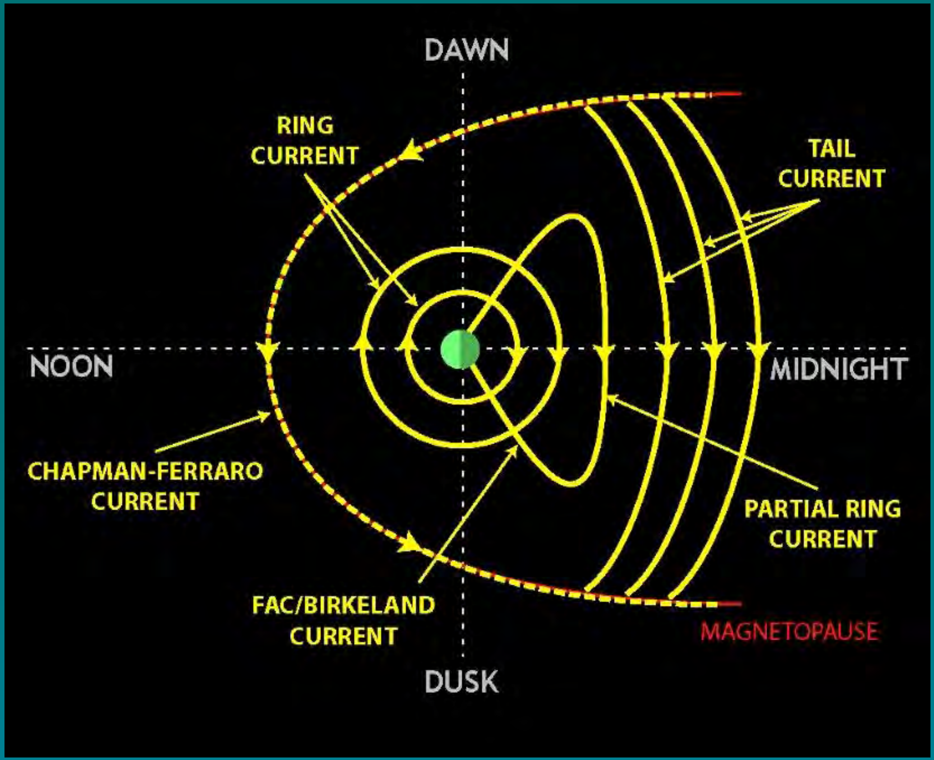


Magnetosheath Plasmasphere Plasma sheet Ring current

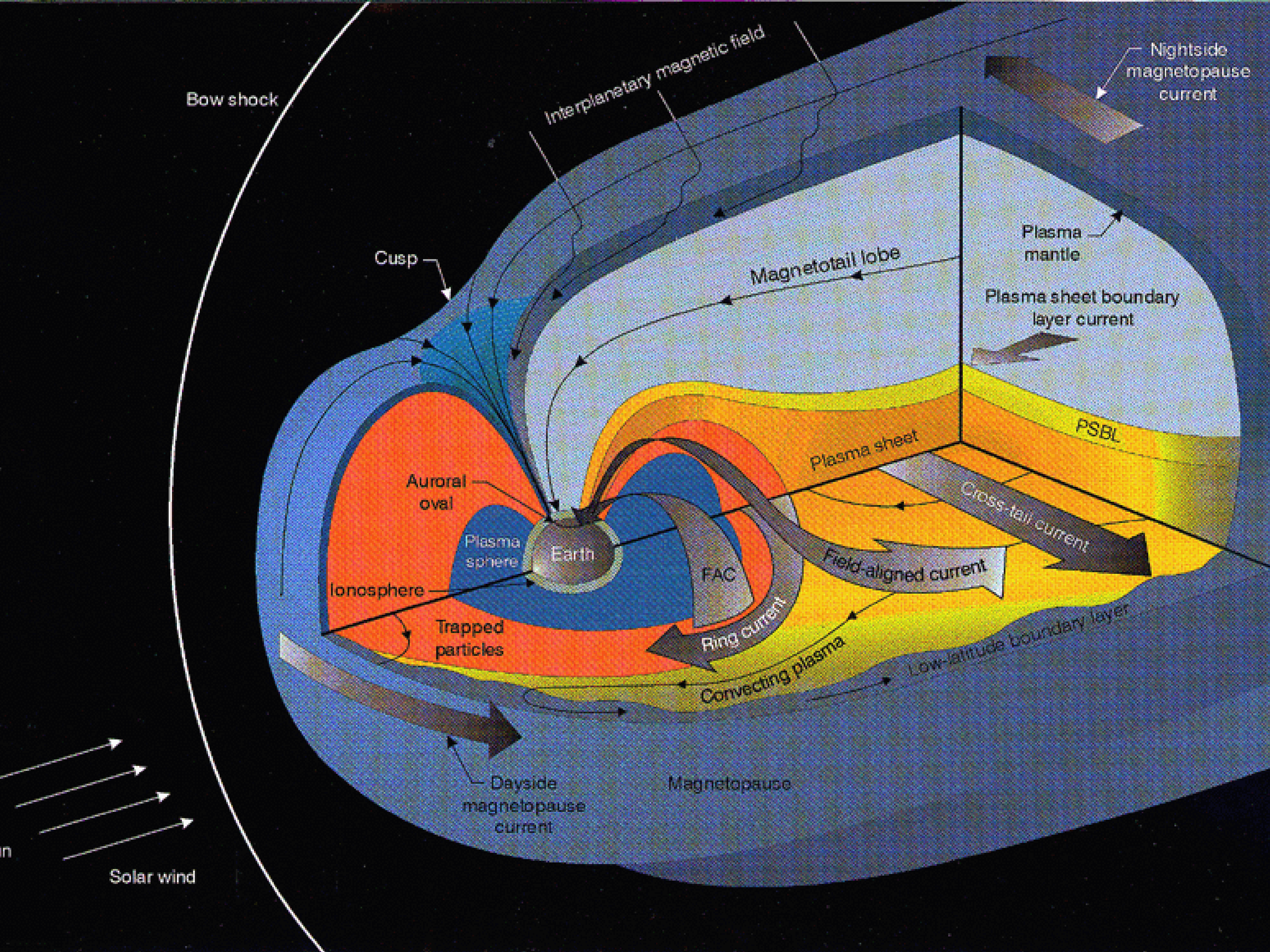
Magnetospheric currents



VIEW LOOKING SUNWARD FROM TAIL (LOOKING AT NIGHTSIDE OF EARTH)



For more info, see Cowley (2000) – Geophysical Monograph 118


Bow shock
Interplanetary magnetic field
Nightside magnetopause current
Cusp
Magnetotail lobe
Plasma mantle
Plasma sheet boundary layer current
PSBL
Plasma sheet
Auroral oval
Plasma sphere
Earth
FAC
Cross-tail current
Field-aligned current
Ionosphere
Trapped particles
Ring current
Convecting plasma
Low-latitude boundary layer
Dayside magnetopause current
Magnetopause
Solar wind

STFC Advanced Summer School 2018

- Follows on from this school
- Topics in all areas of solar system plasma physics
- Provisionally 10th-14th September 2018 in Southampton
- Will be advertised on UKSP and MIST mailing lists – keep an eye out!

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