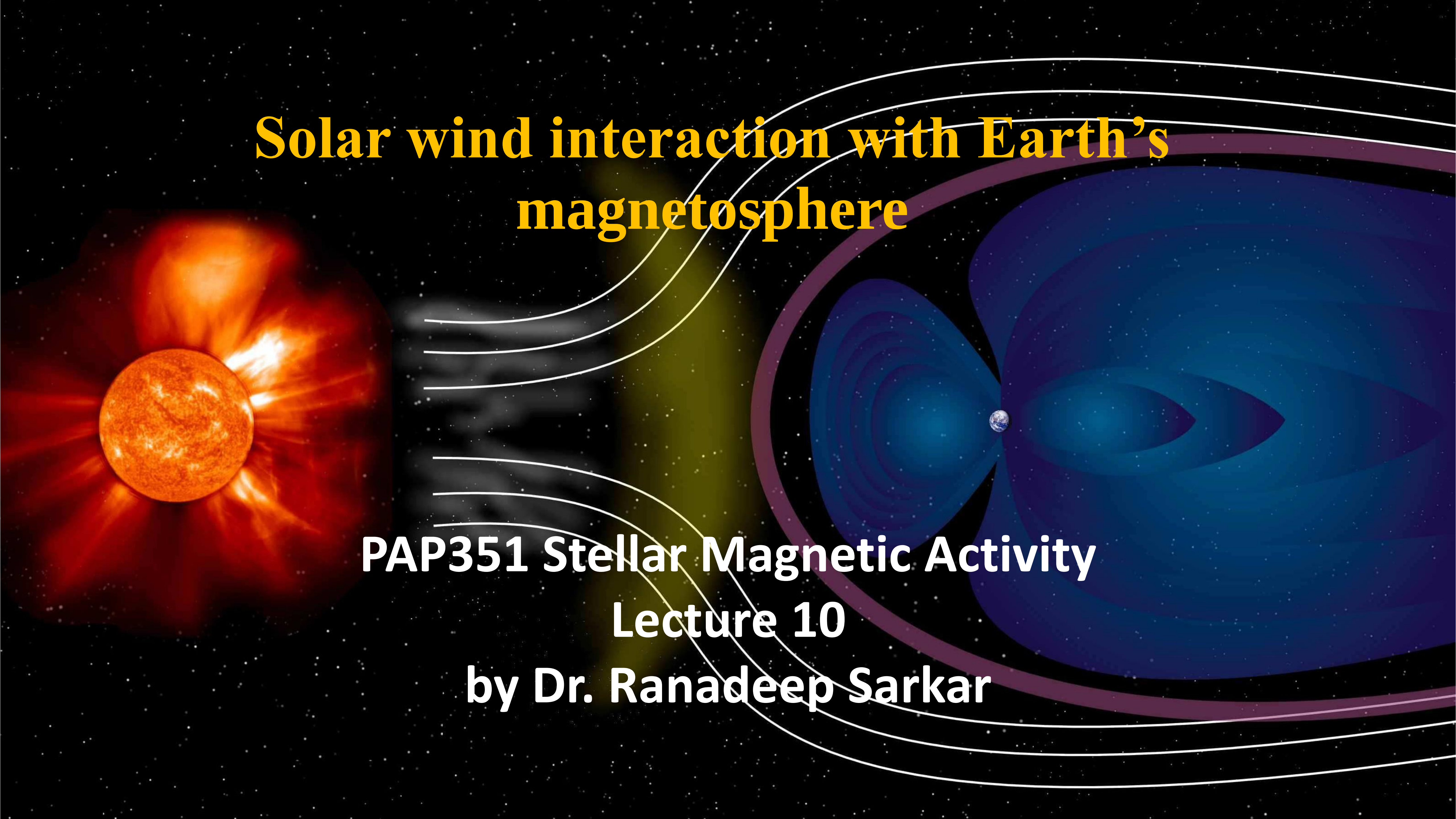


Solar wind interaction with Earth's magnetosphere

PAP351 Stellar Magnetic Activity

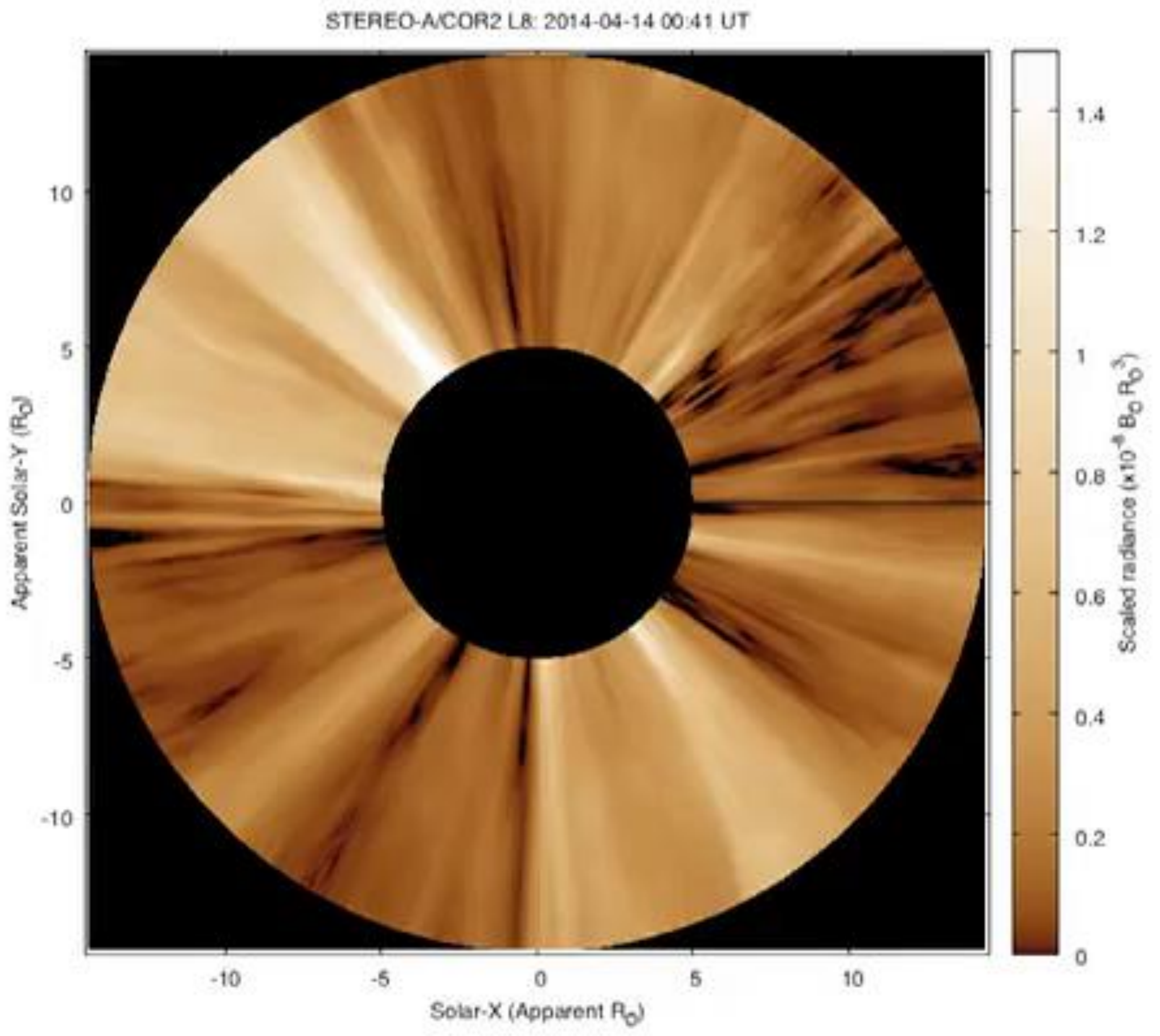
Lecture 10

by Dr. Ranadeep Sarkar

Outline:

- ❑ The Parker’s solar wind
- ❑ The interplanetary magnetic field
- ❑ Transient solar wind
- ❑ Interaction of interplanetary magnetic field and Earth’s magnetosphere
- ❑ Geomagnetic storm and space weather

Solar wind basics



Deforest et al. 2018

- The solar wind is a continuous outflow of magnetized plasma from the Sun
- It is the expansion of the super-hot ($T \sim 10^6$ K) solar atmosphere (i.e. corona) into the solar system
- Flows radially away from the Sun in all directions
- Average composition of H^+ (~95% by mass), He^{2+} (~4%) and heavier ions (~1%)
- Electron component maintains quasi-neutrality
- Two distinct varieties, fast (v ~700 km/s) and slow (v ~300 km/s)
- Drags out the coronal magnetic field to form the interplanetary magnetic field (IMF)

The hydrodynamic model

- Can model the solar wind as a magnetohydrodynamic (MHD) fluid
- Begin with two of the MHD equations:

$$\frac{\partial \rho}{\partial \mathrm{t}} + \nabla \cdot (\rho \mathbf{u}) = 0 \qquad \text{(mass conservation)}$$

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho(\mathbf{u} \cdot \nabla)\mathbf{u} = -\nabla P + \mathbf{j} \times \mathbf{B} + \mathbf{F}_g \qquad \text{(momentum conservation)}$$

ρ – mass density

P – gas pressure

$\mathbf{u}$ – flow velocity

$\mathbf{j} \times \mathbf{B}$ – magnetic force (density)

$\mathbf{F}_g$ – gravitational force (density)

The other ideal MHD equations:

$\mathbf{E} + \mathbf{u} \times \mathbf{B} = 0$	(Ohm's law)
$-\partial \mathbf{B}/\partial t = \nabla \times \mathbf{E}$	(Faraday's law)
$\mu_0 \mathbf{j} = \nabla \times \mathbf{B}$	(Ampere's law)
$\nabla \cdot \mathbf{B} = 0$	(No *B* monopoles)
$d(P/\rho^\gamma)/dt = 0$	(Energy equation)

- Let's assume a steady-state flow ($\partial/\partial t = 0$), a radial flow ($\mathbf{u} = u\hat{r}$)negligible magnetic forces ($\mathbf{j} \times \mathbf{B} = 0$), spherical symmetry so all variables only depend on r …

The hydrostatic solution

$\nabla \cdot (\rho \mathbf{u}) = \frac{1}{r^2}\frac{d}{dr}(r^2 \rho u) = 0$ (mass conservation)

This equation can be re-written to show that the mass flux through a spherical shell centred on the Sun is constant:

$4\pi r^2 \rho u = C$

…

Back to the momentum equation: $\rho \frac{\partial \mathbf{u}}{\partial t} + \rho(\mathbf{u} \cdot \nabla)\mathbf{u} = -\nabla P + \mathbf{j} \times \mathbf{B} + \mathbf{F}_g$

$\mathbf{F}_g = -(GM_S \rho / r^2)\, \hat{r}$ (G is the gravitational constant, M_S is the Sun's mass)

$\nabla P = -(dP/dr)\, \hat{r}$

$\rho u \frac{du}{dr} = -\frac{dP}{dr} - \rho \frac{GM_S}{r^2}$ (momentum conservation)

The hydrostatic solution

Chapman (1957)

Assume the corona is in static equilibrium, $\boldsymbol{u}(\boldsymbol{r}) = \mathbf{0}$ everywhere, the plasma is at rest (*cf.* Earth's atmosphere):

$$0 = -\frac{dP}{dr} - \rho\frac{GM_S}{r^2}$$

Let's solve for P. Begin by assuming isothermal protons and electrons so that $T_e = T_i$

Ideal gas law: $P = nk_B(T_e + T_i) = 2nk_BT$

Mass density: $\rho = n(m_e + m_i) \sim nm_i = Pm_i/2k_BT$

Substituting into the momentum equation:

$$\frac{1}{P}\frac{dP}{dr} = -\frac{GM_Sm_i}{2k_BT}\frac{1}{r^2}$$

The hydrostatic solution

Integrating with limits such that pressure is P_0 at height R_0:

$$P(r) = P_0 \exp\left\{\frac{GM_S m_i}{2k_B T}\left(\frac{1}{r} - \frac{1}{R_0}\right)\right\}$$

... but there is a problem with this solution! Consider what happens when $r \rightarrow \infty$:

$$P(\infty) = P_0 \exp\left(-\frac{GM_S m_i}{2k_B T R_0}\right)$$

At $R_0 = 7 \times 10^8 \mathrm{m}$, $P_0 \sim 0.03 \text{ Pa}$ and $T_0 \sim 10^6 \mathrm{K} \rightarrow P(\infty) = 10^{-7} \mathrm{Pa}$

This is vastly greater than the pressure of the interstellar medium, which is around $10^{-14} \mathrm{Pa}$

→ The solar corona cannot be in static equilibrium because there would be no pressure balance with the interstellar medium

Parker's hydrodynamic solution

Parker (1958)

Assume the solar wind is not static, $u(r) \neq 0$. Let's solve the momentum equation to find u as a function of r.

$$\rho u \frac{du}{dr} = -\frac{dP}{dr} - \rho \frac{GM_S}{r^2} \quad \text{....(1) (momentum conservation)}$$

...

$$P = 2nk_bT \quad \text{(ideal gas law)}$$

$$\frac{\mathrm{d}P}{\mathrm{d}r} = 2k_BT\frac{\mathrm{d}n}{\mathrm{d}r} \quad \text{....(2)}$$

$$\text{Recall, due to mass conservation,} \quad r^2\rho u = \mathrm{k}, \quad \text{where k is constant}$$

$$\rho = \rho(u(r), r) \overset{\text{Chain rule}}{\Rightarrow} \frac{\mathrm{d}\rho}{\mathrm{d}r} = \frac{\partial\rho}{\partial u}\frac{\mathrm{d}u}{\mathrm{d}r} + \frac{\partial\rho}{\partial r}$$

$$\frac{\mathrm{d}\rho}{\mathrm{d}r} = -\frac{k}{u^2r^2}\frac{\mathrm{d}u}{\mathrm{d}r} - \frac{2k}{ur^3} \Rightarrow m_i\frac{\mathrm{d}n}{\mathrm{d}r} = -\frac{k}{u^2r^2}\frac{\mathrm{d}u}{\mathrm{d}r} - \frac{2k}{ur^3} \quad \text{....(3)} \qquad \rho = \mathrm{n}m_i$$

Parker's hydrodynamic solution

Substituting eqn 3 into 2

$$\frac{\mathrm{d}p}{\mathrm{d}r} = -2k_B T n \left(\frac{1}{u}\frac{\mathrm{d}u}{\mathrm{d}r} + \frac{2}{r} \right) \qquad \text{....(4)}$$

Substituting eqn 4 into 1

$$\boxed{\frac{1}{u}\frac{du}{dr}\left(u^2 - \frac{2k_B T}{m_i}\right) = \frac{4k_B T}{m_i r} - \frac{GM_S}{r^2}}$$

Parker's hydrodynamic solution

Let's examine some of the properties of Parker's equation.

The RHS is zero when $\frac{4k_BT}{m_i r} = \frac{GM_S}{r^2}$

$\rightarrow$ can define a critical radius, $r_c = \frac{GM_S m}{4k_BT}$

$$\boxed{\frac{1}{u}\frac{du}{dr}\left(u^2 - \frac{2k_BT}{m_i}\right) = \frac{4k_BT}{m_i r} - \frac{GM_S}{r^2}}$$

Thus at $r = r_c$, $\frac{1}{u}\frac{du}{dr}\left(u^2 - \frac{2k_BT}{m_i}\right) = 0$

This is satisfied with either of two conditions:

(1) $\left(\frac{1}{u}\frac{du}{dr}\right)_{r_c} = 0$ $\rightarrow$ derivative is zero $\rightarrow$ local minimum or maximum of u at $r = r_c$

(2) Alternatively, there is a value of u such that $\left(u^2 - \frac{2k_BT}{m_i}\right)_{r_c} = 0$

$\rightarrow$ defines the sound speed $u_c = \sqrt{\frac{2k_BT}{m_i}} = c_s$

Parker's hydrodynamic solution

These two conditions give four classes of solution for u

If condition (1) is valid -

Class 4: Minimum in u at r_c, $u > u_c$ (supersonic) for all r

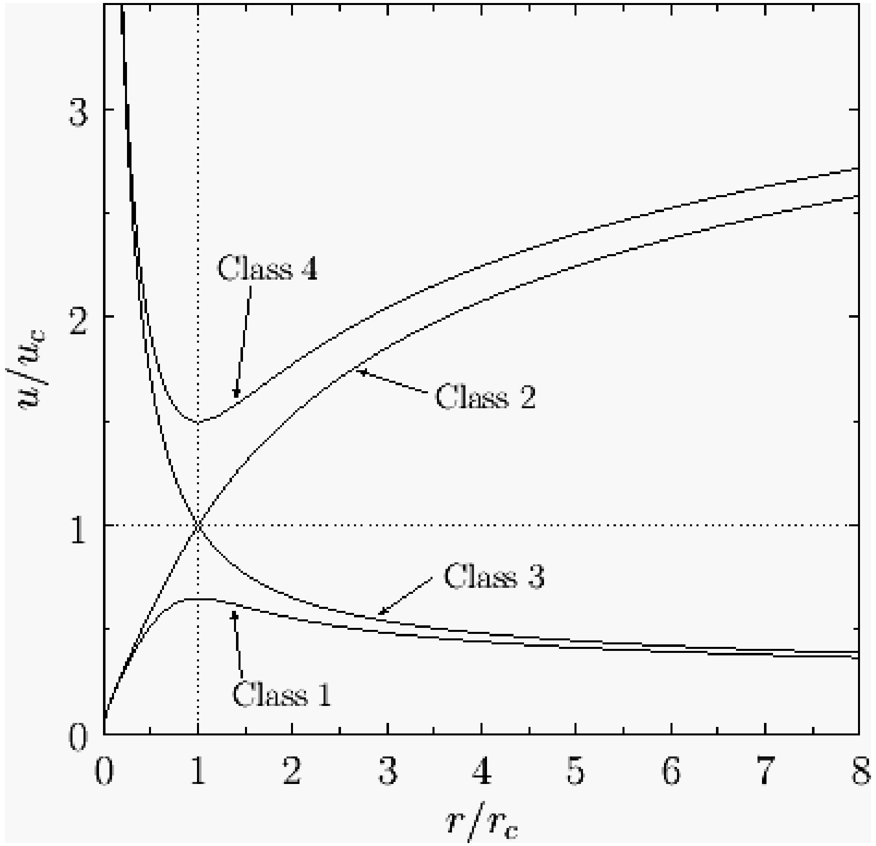
Class 1: Maximum in u at r_c, $u < u_c$ (subsonic) for all r – the 'solar breeze'

If condition (2) is valid -

First recall the Parker equation:

$$\frac{1}{u}\frac{du}{dr}(u^2 - u_c^2) = \frac{4k_BT}{m_i r} - \frac{GM_S}{r^2}$$

If $r < r_c$, RHS is negative; if $r > r_c$, RHS is positive → LHS must have same sign change



Class 3: du/dr negative, $u^2 - u_c^2 > 0$ for $r < r_c$ and $u^2 - u_c^2 < 0$ for $r > r_c$

Class 2: du/dr positive, $u^2 - u_c^2 < 0$ for $r < r_c$ and $u^2 - u_c^2 > 0$ for $r > r_c$

Parker's hydrodynamic solution

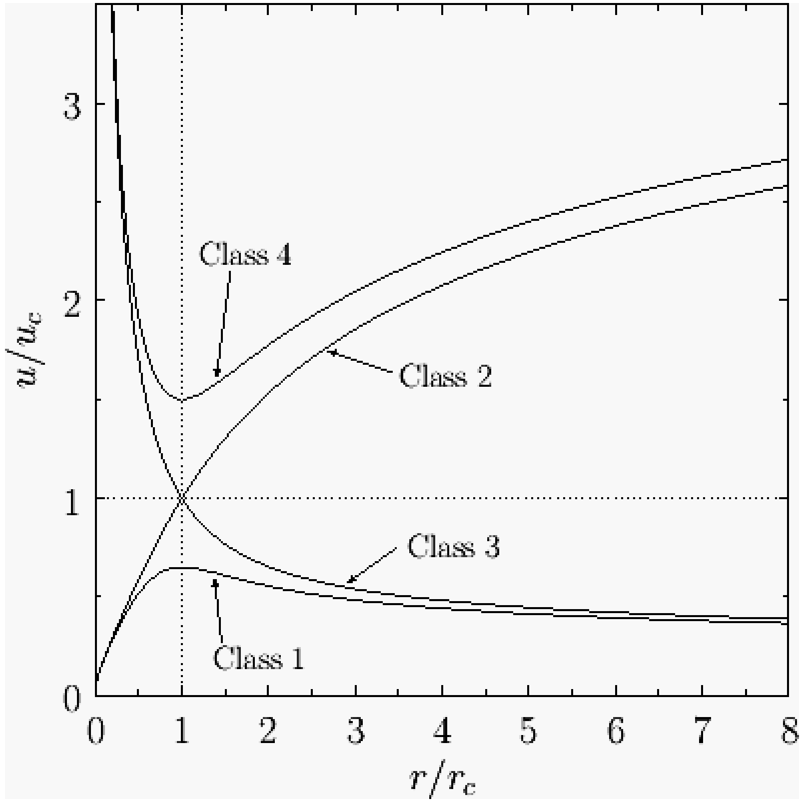
Which solution class is physically valid?

Class 4: Very high supersonic speed below r_c, minimum at r_c, then rises again → unphysical

Class 1: The 'solar breeze'; quasi-static for $r \to \infty$, same problem as with Chapman model

Class 3: Unphysical in the same manner as Class 4 (*cf.* stellar accretion)

Class 2: The real solar wind



The supersonic solar wind

- Class 2 solution:

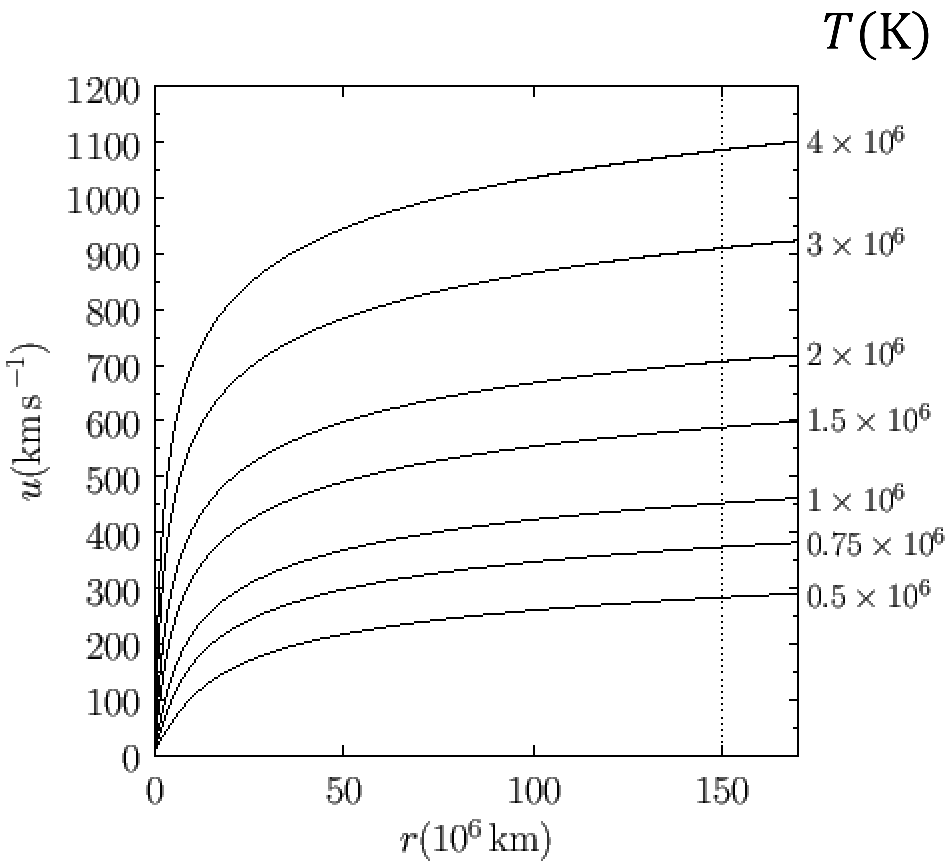
$$u^2 - \frac{2k_BT}{m_i}\left[1 + \ln\left(\frac{m_i u^2}{2k_BT}\right)\right] = \frac{8k_BT}{m_i}\ln\left(\frac{r}{r_c}\right) + 2GM_S\left(\frac{1}{r} - \frac{1}{r_c}\right)$$

- Typically $r_c \sim 5.8\,R_S \sim 0.03$ au, $u_c \sim 130$ km/s
- The solar wind is supersonic → r_c defines an 'information horizon': beyond r_c, waves (at speed u_c) cannot travel from the solar wind back to the corona because the plasma is travelling away from the Sun faster than the waves can propagate
- u is controlled by two parameters, M_S and T:
    - M_S determines the extent to which the atmosphere is gravitationally bound
    - T determines the internal energy of the atmosphere, and so its ability to overcome gravity and escape
    - Much cooler and/or more massive stars would not have a stellar wind

The supersonic solar wind

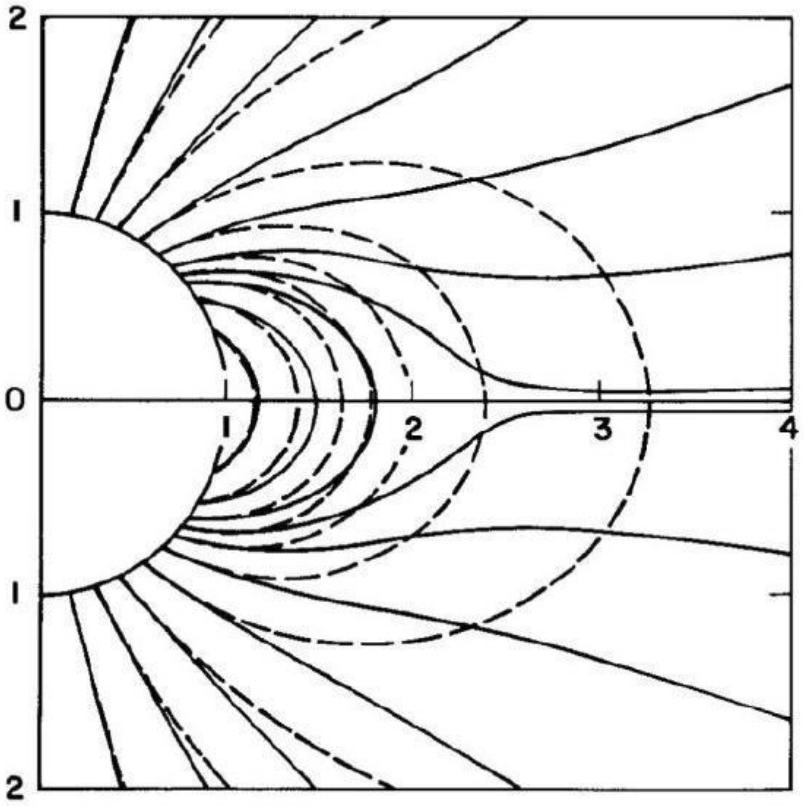
The T dependence of u (for constant M_S) →

We have modelled the solar wind as an isothermal (i.e. constant T) plasma



The coronal magnetic field

- Radial flow of plasma drags out closed-field regions around the equator
- Drawn-out loops at the equator form the 'streamer belt'
- B-field becomes increasingly radial with height
- At a certain distance above the photosphere, R_0, the B-field becomes entirely radial
- $R_0 \sim 2 - 2.5\, R_S$; all field lines threading the surface defined by R_0 are radial; this is the 'source surface'



Dashed lines show equivalent dipole field

Figure adapted from Pneuman and Kopp 1971

The interplanetary magnetic field

- We now consider what happens to the magnetic field beyond the source surface at R_0: how is the interplanetary magnetic field (IMF) structured?
- Some assumptions:
  - Purely radial B-field at the source surface
  - The solar wind outflow is purely radial, has a constant speed, and is uniform at all longitudes and latitudes
  - The field line footpoints are fixed to the solar surface (photosphere)
  - The Sun rotates; once a frozen-in plasma/magnetic field parcel leaves the source surface, it does not co-rotate with the Sun
- This combination of solar rotation and radial outflow produces a magnetic field with an Archimedean spiral pattern in interplanetary space → the Parker spiral

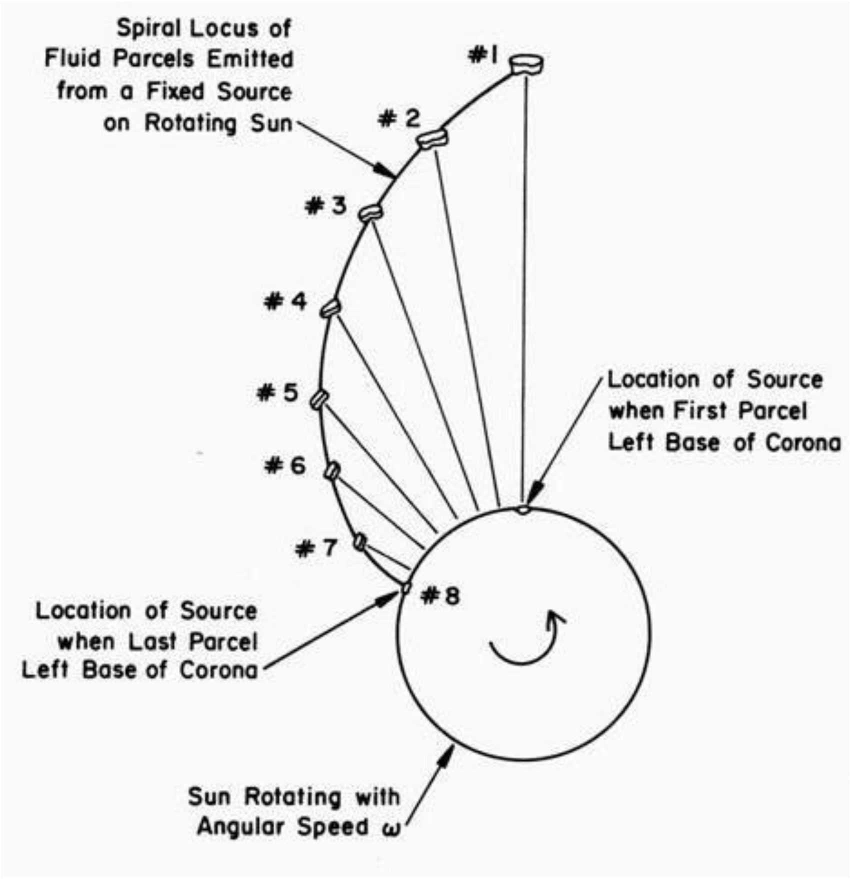
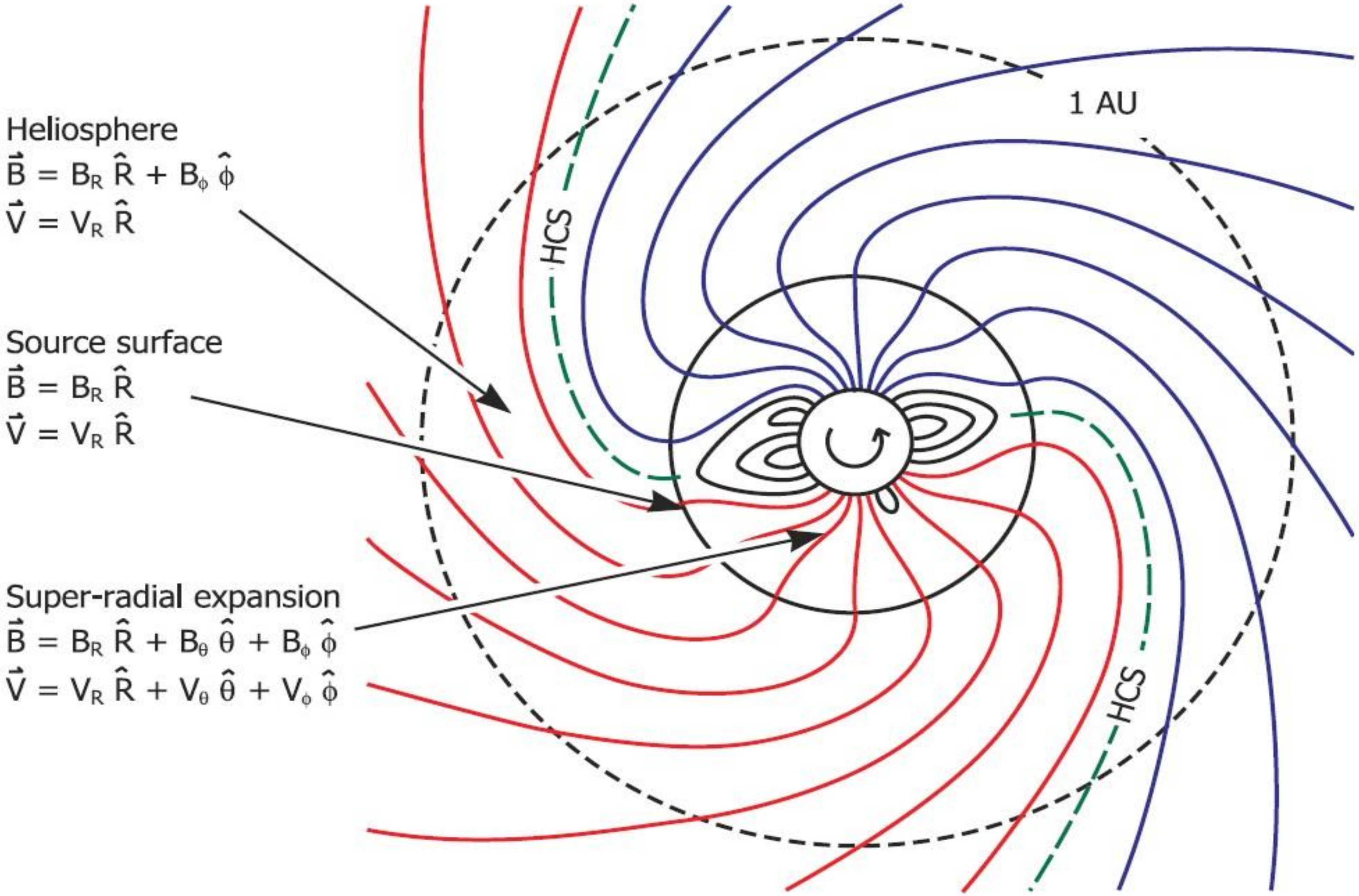


Figure credit: Kivelson and Russell 1995

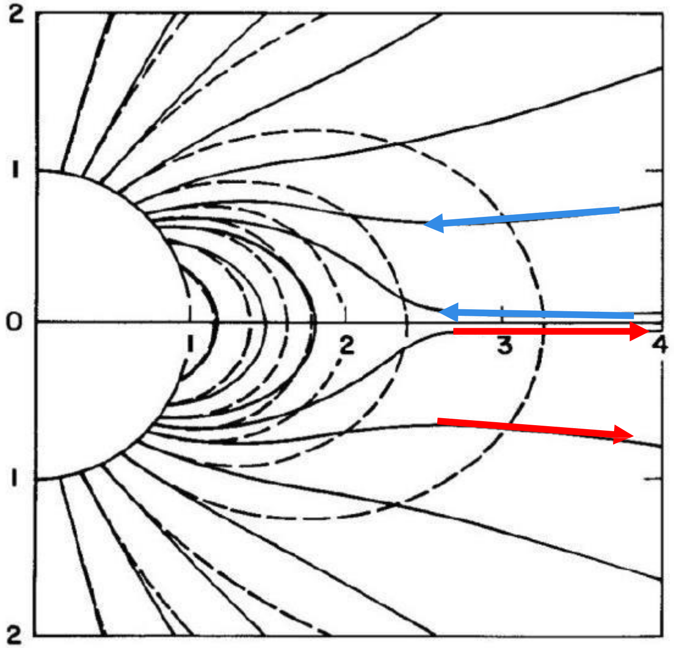
The Parker spiral

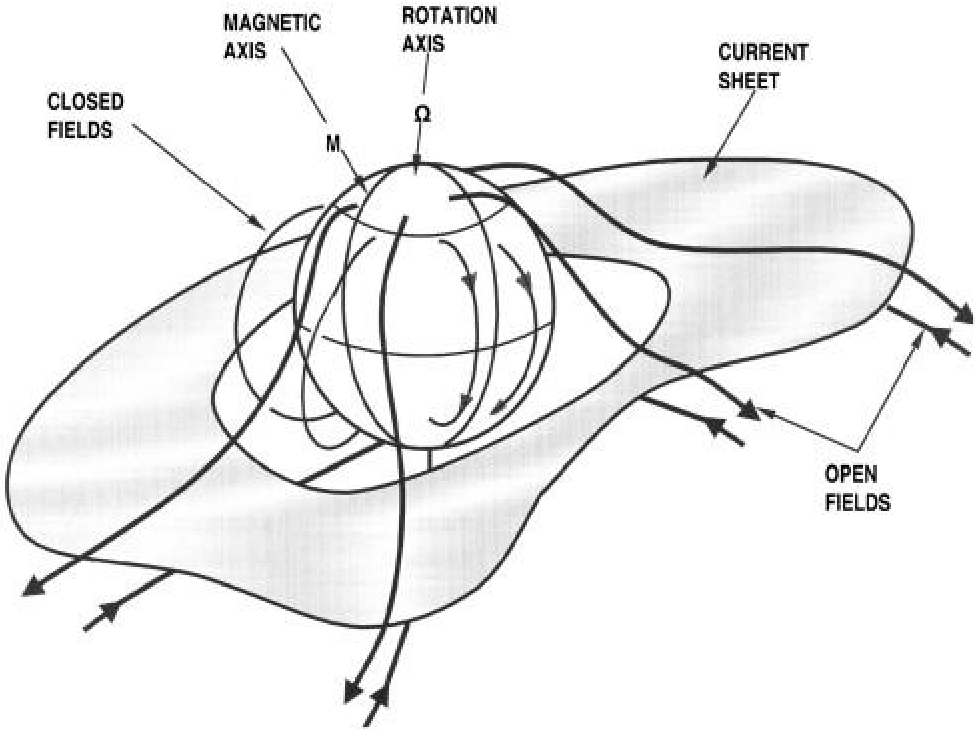


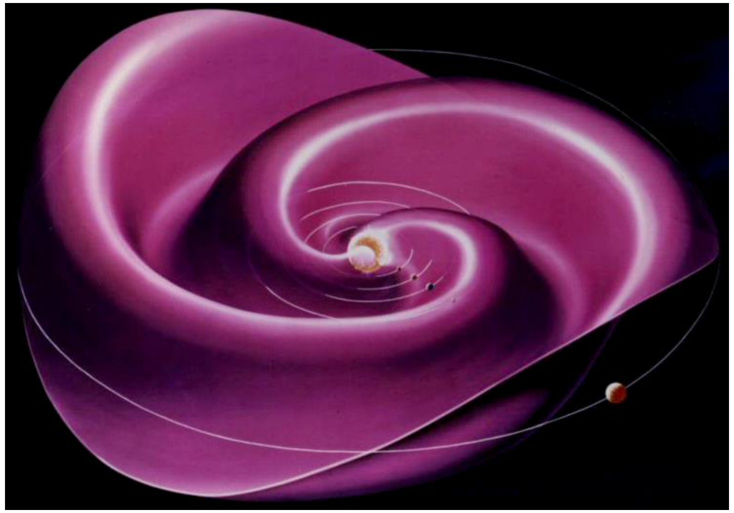
The spiral in the equatorial plane ($\theta = 90°$)

Figure credit: Owens and Forsyth 2013

The heliospheric current sheet





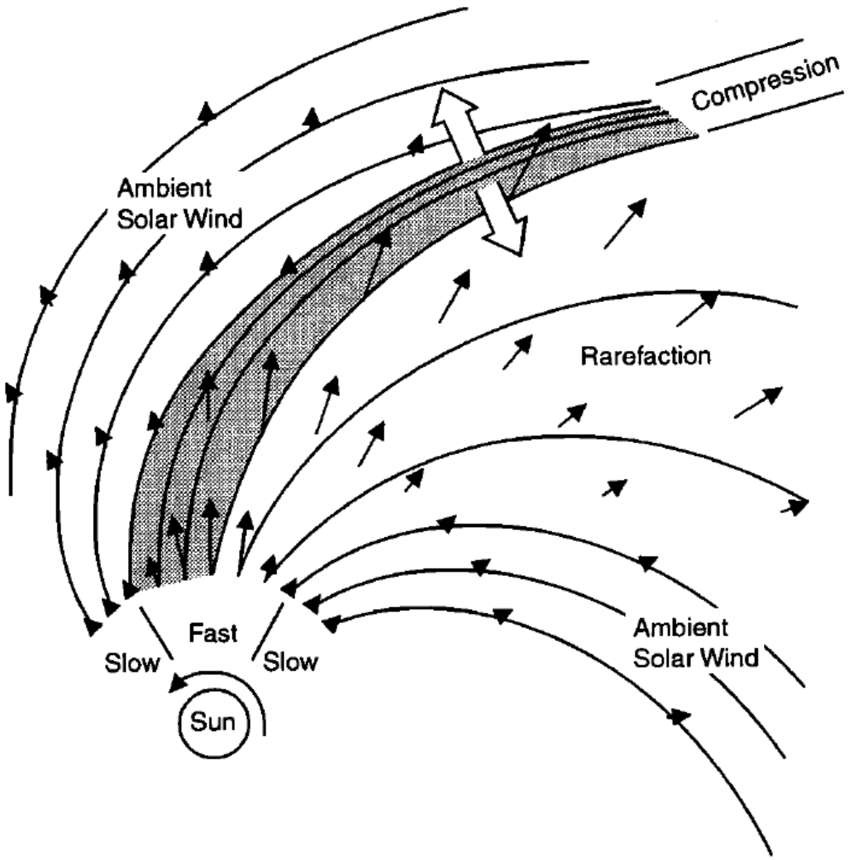


- Field lines of opposite polarity are in close proximity near the magnetic equator → a current sheet forms between the oppositely-directed field lines
- Extends from the tip of the streamer belt into interplanetary space
- Offset bet<u>w</u>een the magnetic (dipole) axis and rotation axis warps the sheet …

Figure credits: Pneuman and Kopp 1971; Smith 2010

Corotating interaction regions (CIRs)

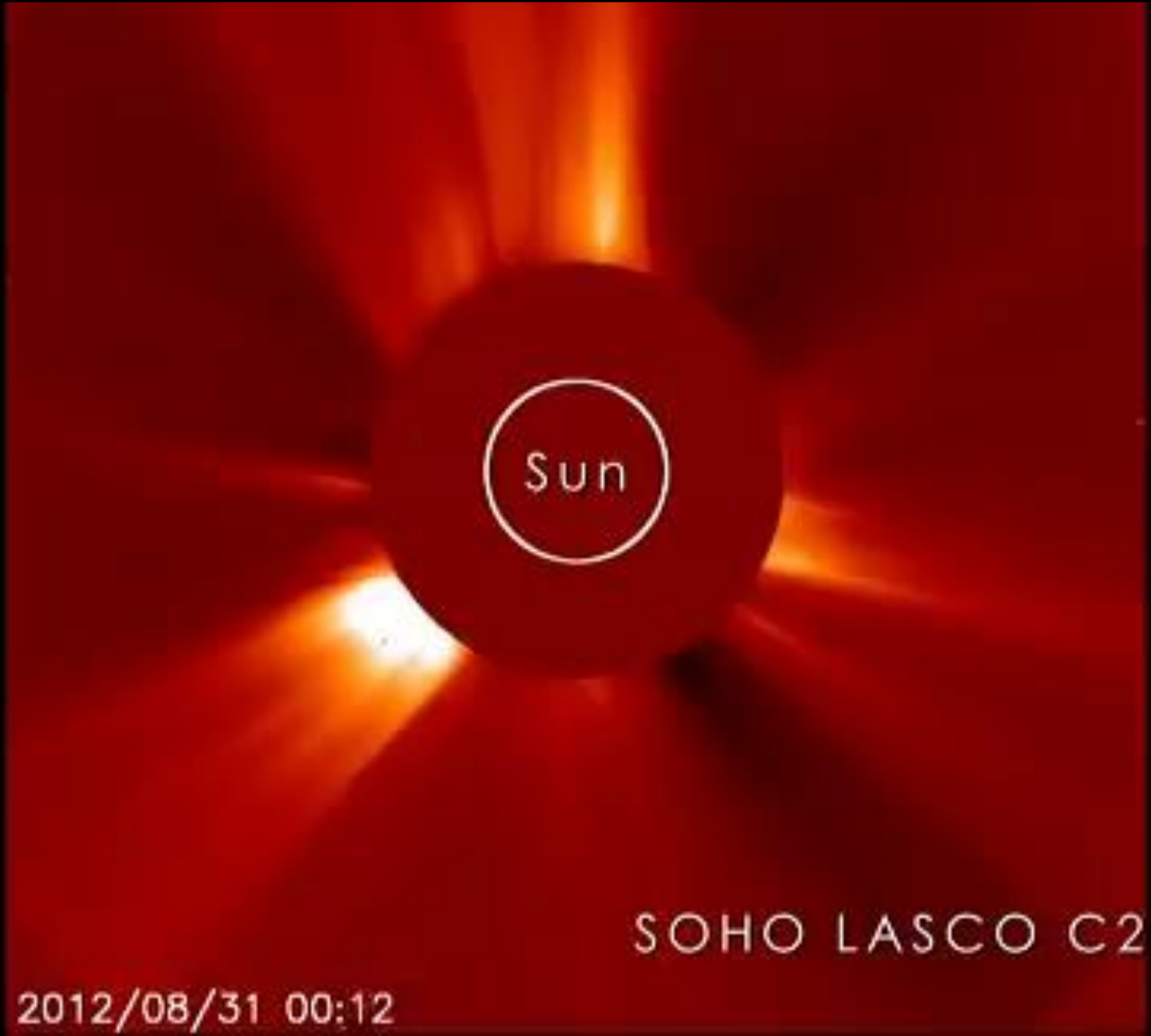
- Along the radial flow lines, fast wind progressively catches up with slow wind ahead
- A compression region forms as the fast wind runs into the back of the slow → this is known as a corotating interaction region (CIR)
- Fast wind runs ahead of slow wind behind it → a rarefaction (i.e. low-density) region forms behind fast wind
- CIRs corotate with the Sun: they are observed every 27 days (i.e. the solar rotation period) by observers near the SE plane



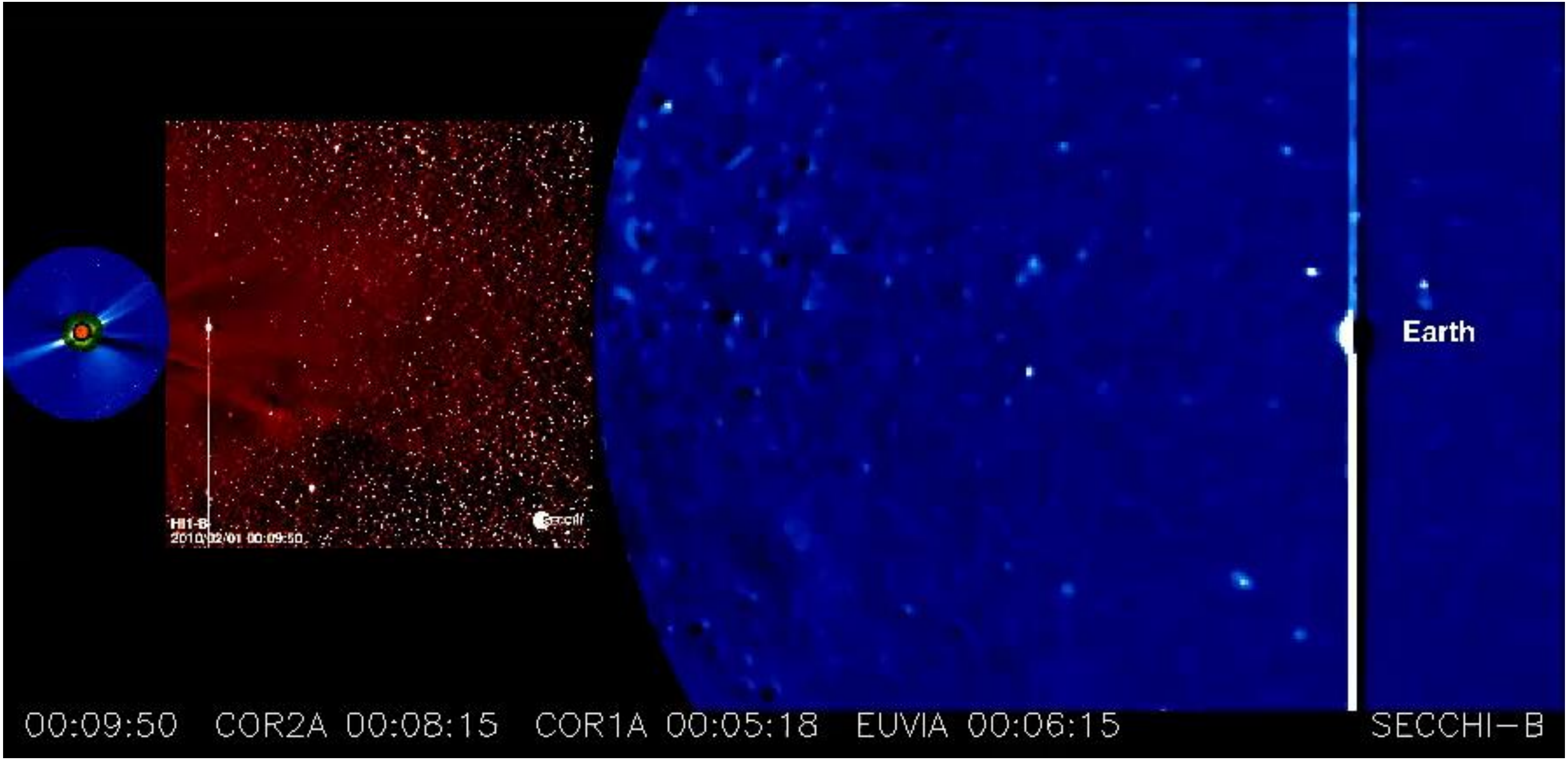
In the solar equatorial plane

Figure credit: Pizzo 1985

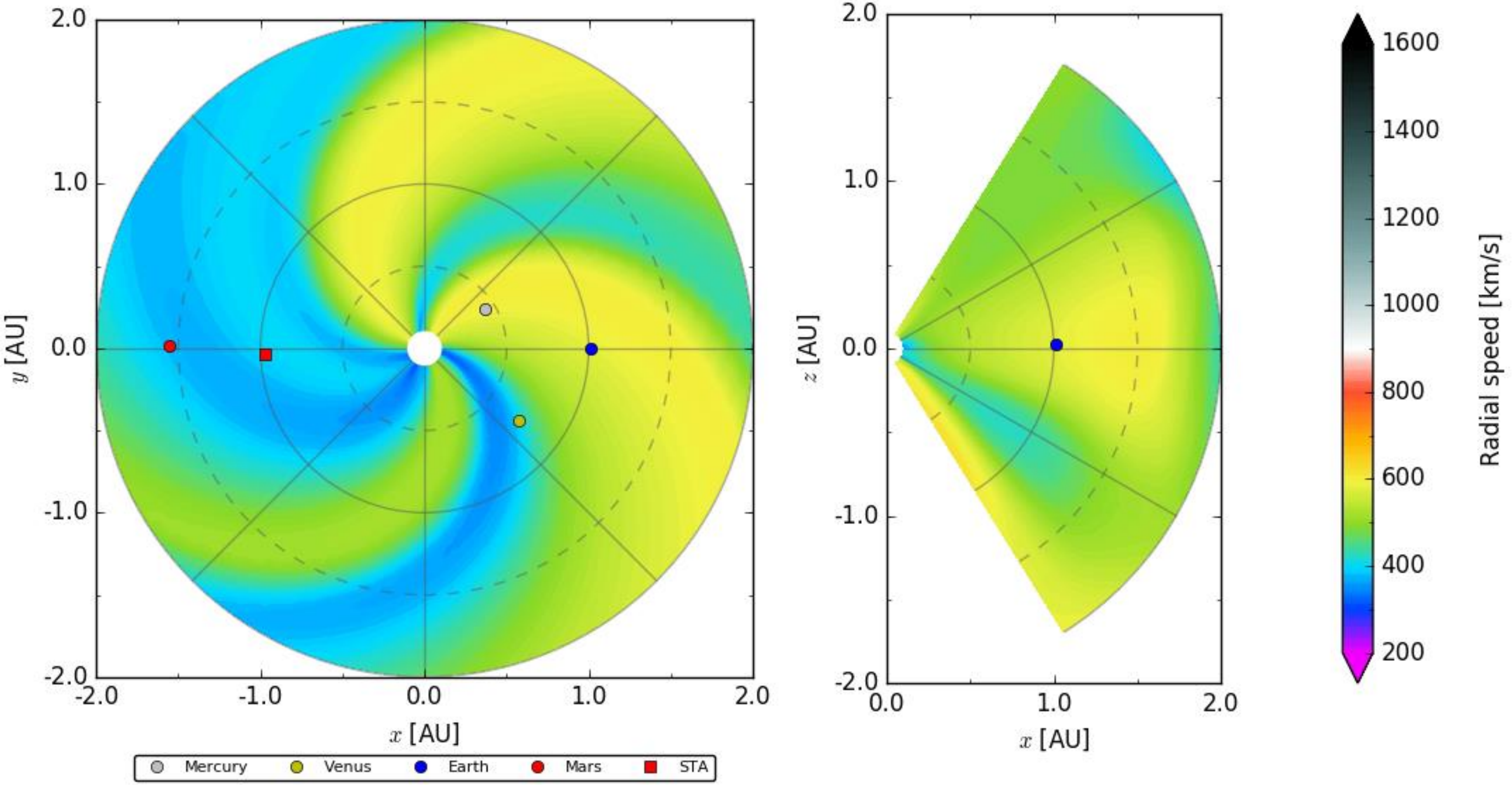
Transient solar wind: Coronal mass ejections (CMEs)



Solar eruption propagating towards Earth

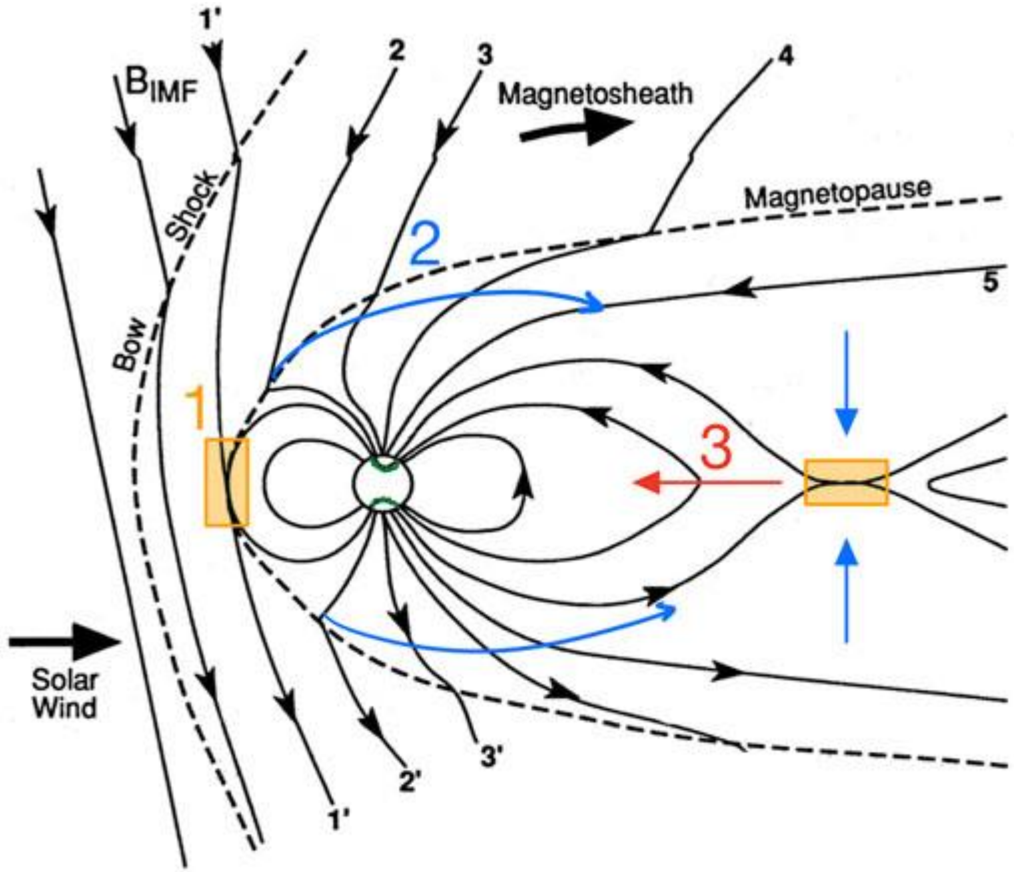


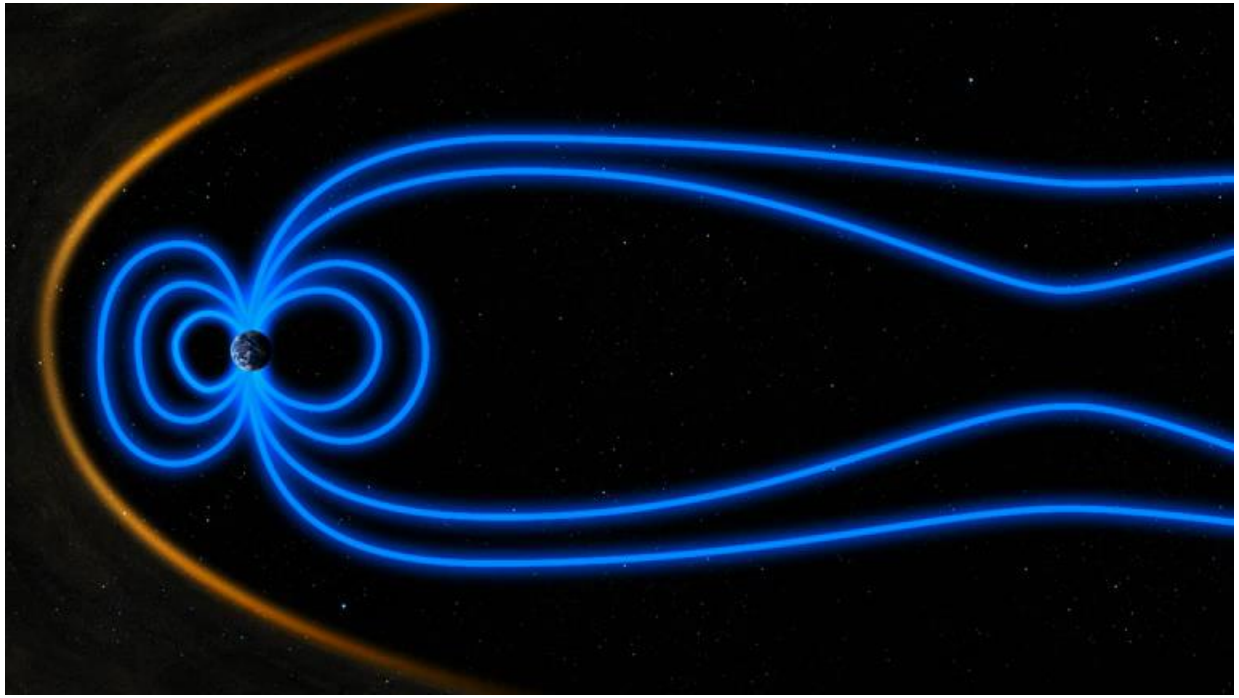
Heliospheric MHD simulation with EUHFORIA



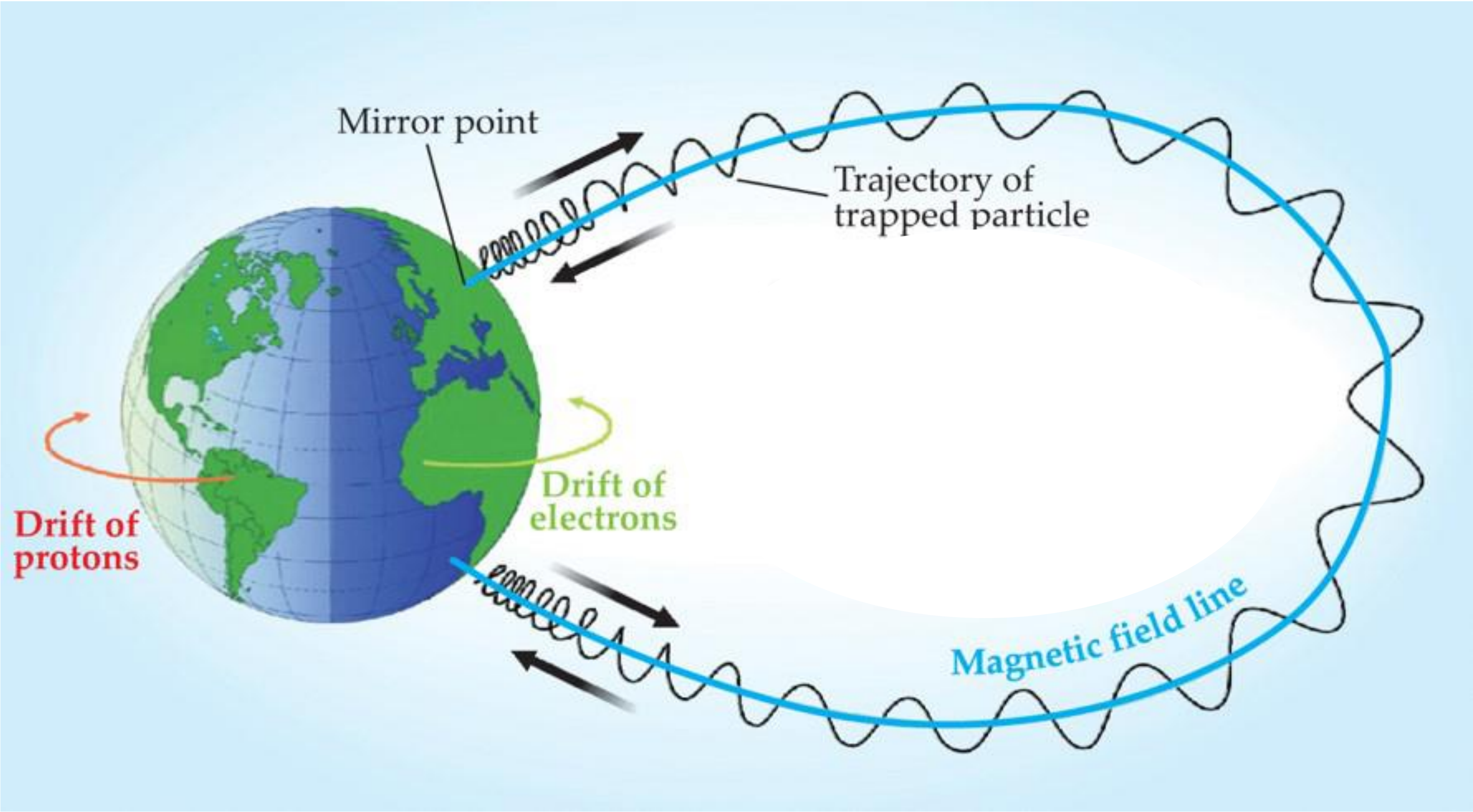
Credit: J. Pomoell

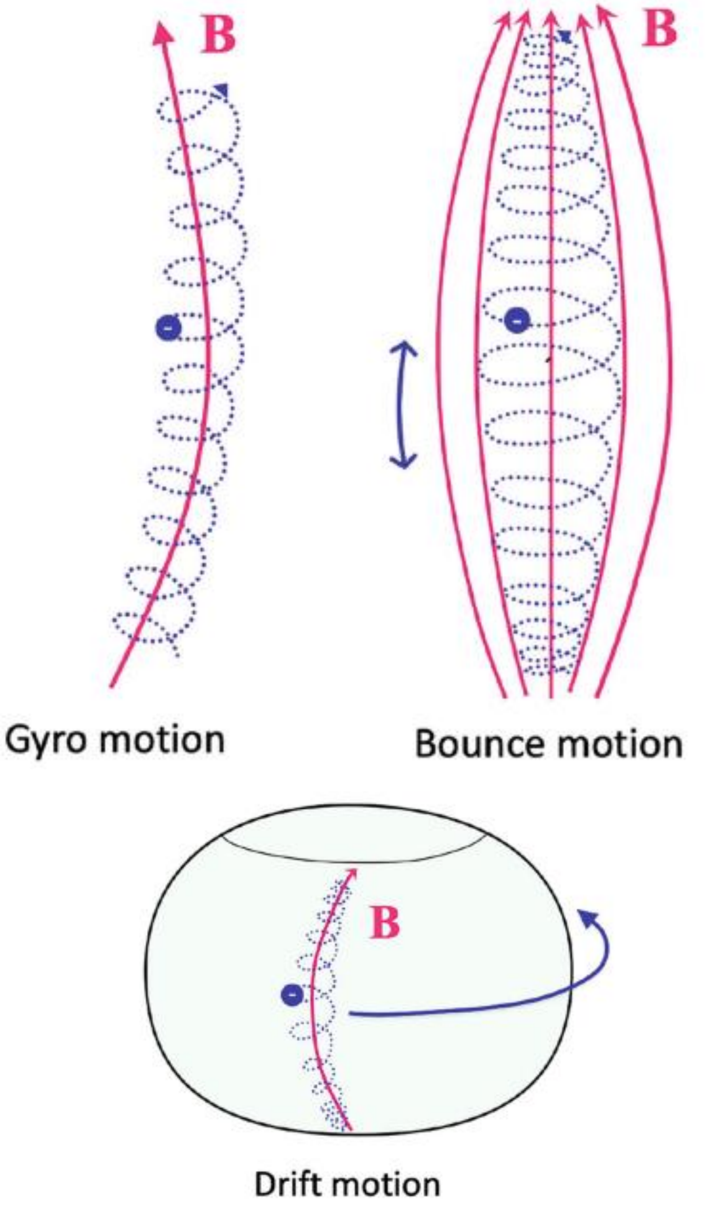
Dayside and nightside magnetic reconnection



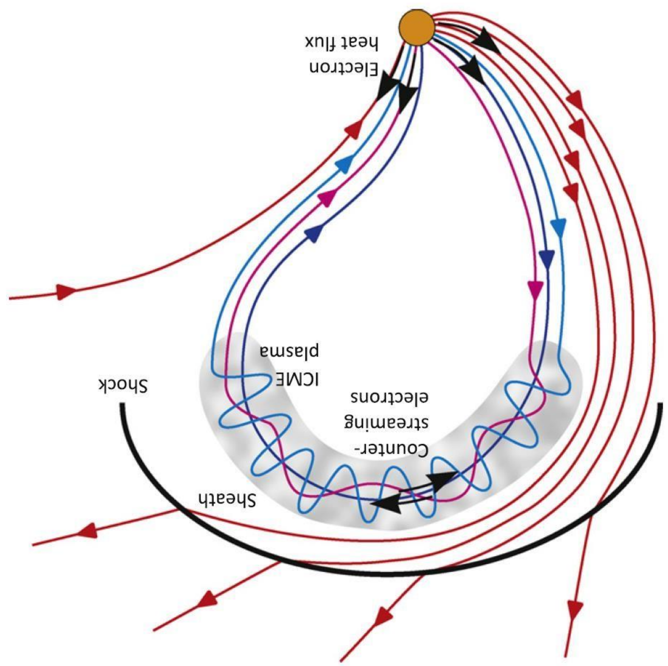


Formation of ring current

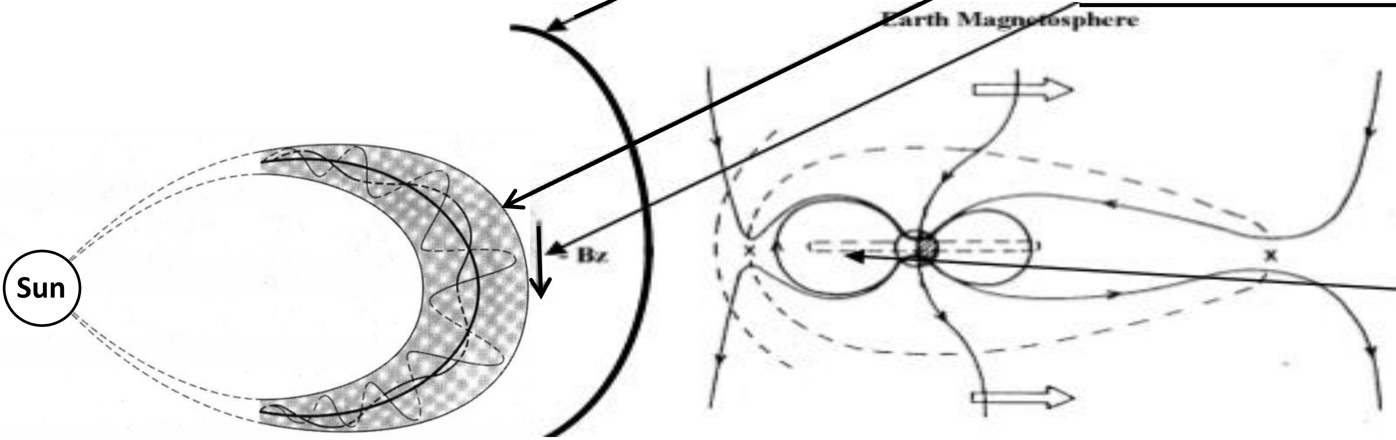




Sun-Earth connection

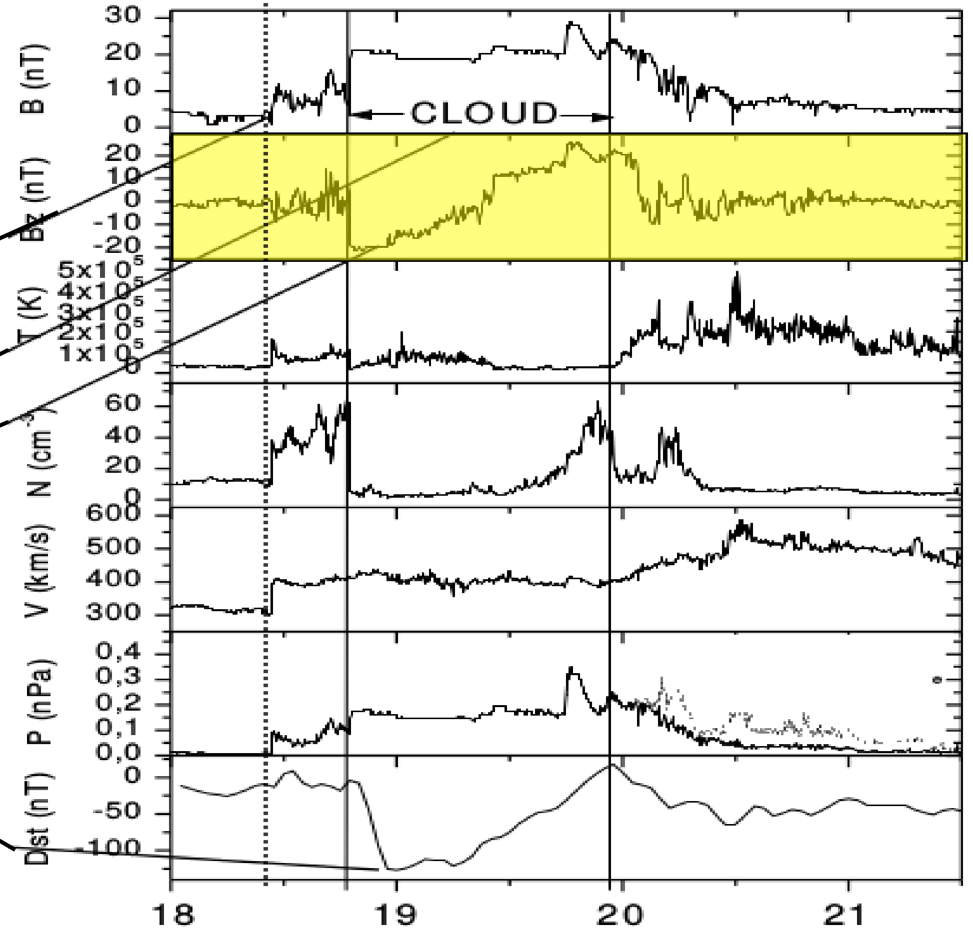


CME Arrival at Earth



Gonzalez & Tsurutani 2005, Gopalswamy 2006

In situ observations

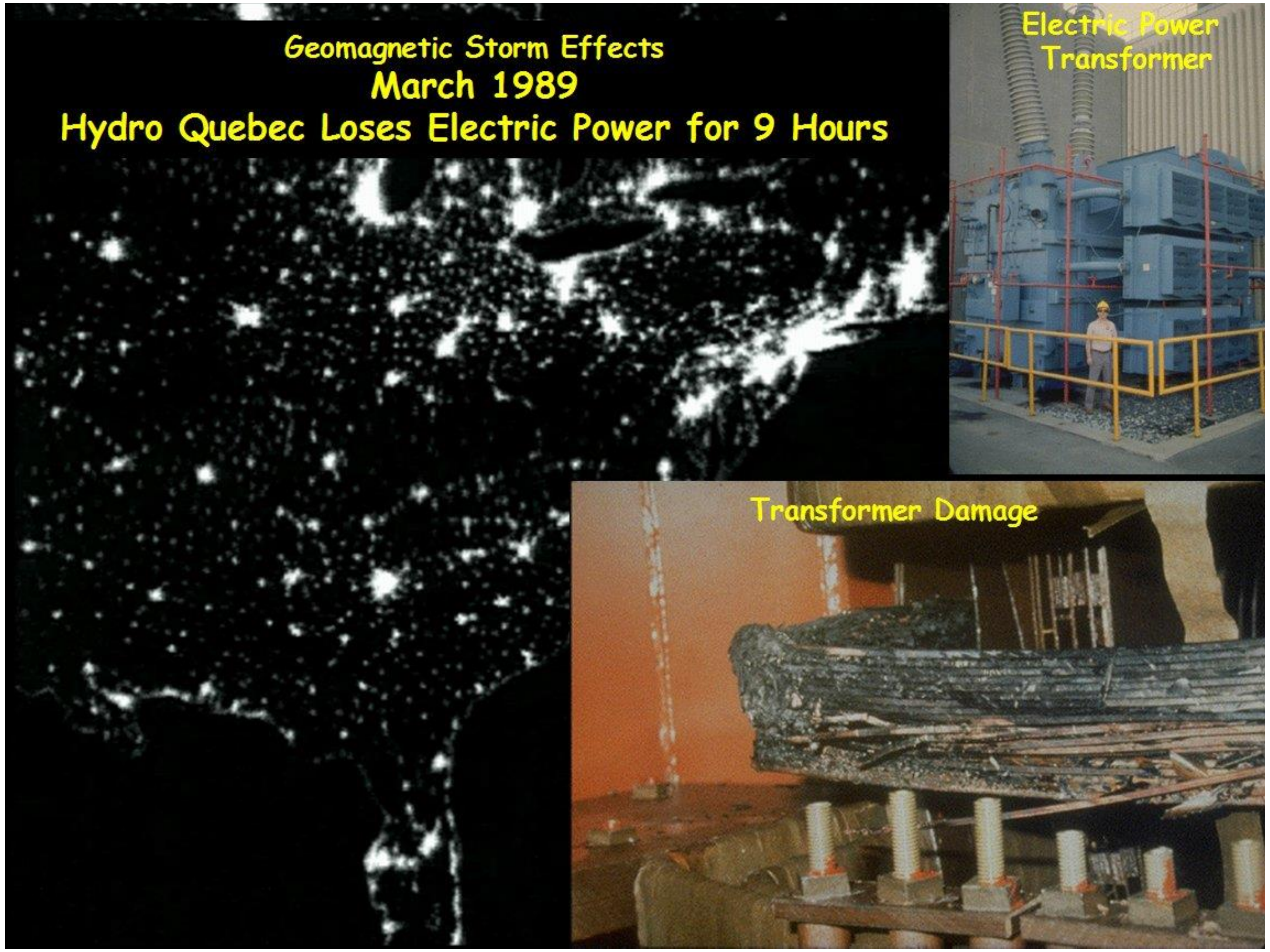


October 1995 Lepping et al. 1997

Effects of geo-magnetic storms

Beauty

Beast



“the day the sun brought darkness”

Effects of geo-magnetic storms

Recent loss of Starlink Satellites

Solar storms can damage the satellites

Consequences:

- Disruption in communication and navigation system
- GPS signal lost

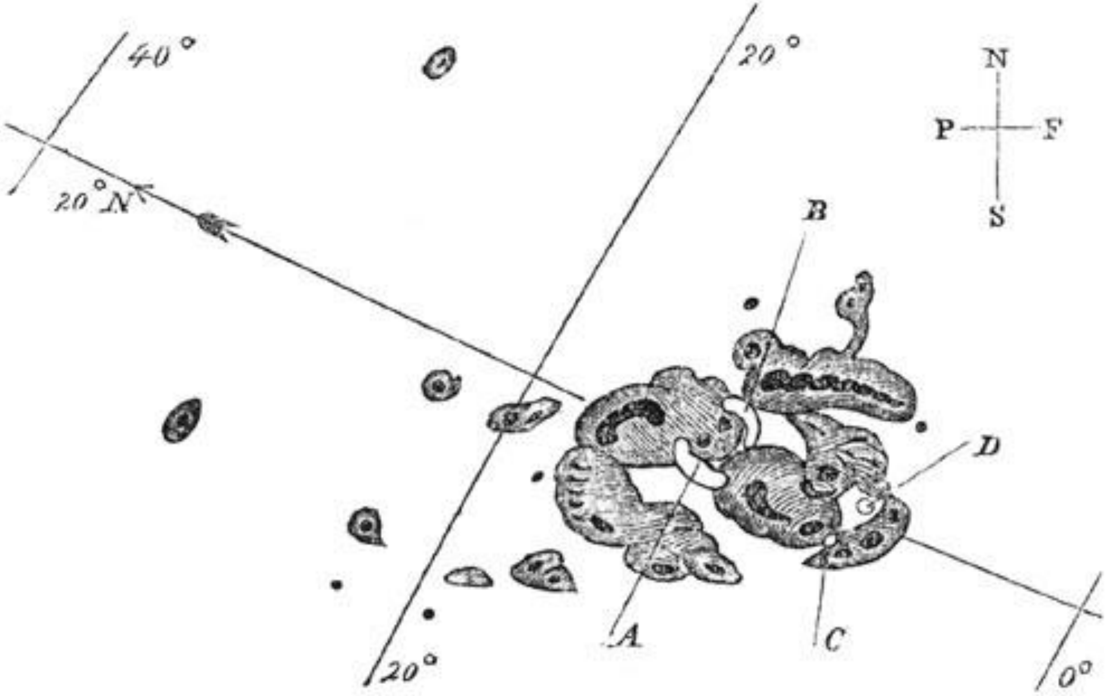
Effects of geo-magnetic storms

Carrington storm (An extreme space weather event)

The white light solar flare on 1 September 1859 was followed by an intense magnetic on 1-2 September 1859

The biggest magnetic storm in the recorded history

The mid latitude areas over the United States and Europe faced electrical shocks and fires by electrical arcing from telegraph wires.



Sunspots of 1 September 1859, as sketched by Richard Carrington

Carrington-like event may cause $2.6 trillion economical loss in the electrical and power-grid industry alone

Learning outcome:

- ❑ Understand that the solar wind outflow is ultimately driven by the high temperatures in the corona
- ❑ Be able to derive Parker’s hydrodynamic solar wind equation
- ❑ Understand the space weather drivers: CIRs and CMEs
- ❑ Understand the day-side and night-side magnetic reconnection at Earth’s magnetosphere
- ❑ Understand the consequences of geo-magnetic storms