Sun-planet connection

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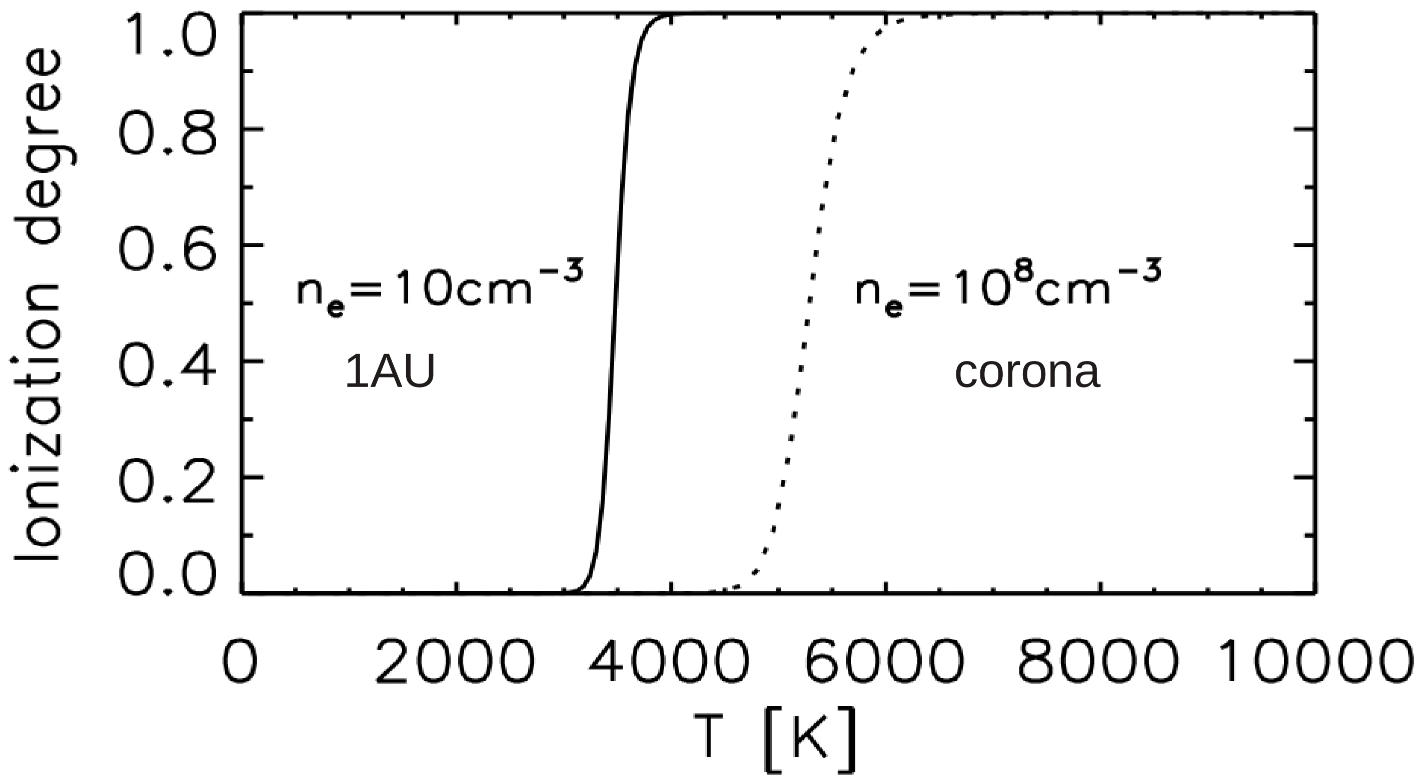
Ionization of atomic hydrogen gas

$H \rightarrow p + e^-$



13.6 eV = 158 000 K

Other ionization sources?

Magnetohydrodynamics

Flow velocity evolution

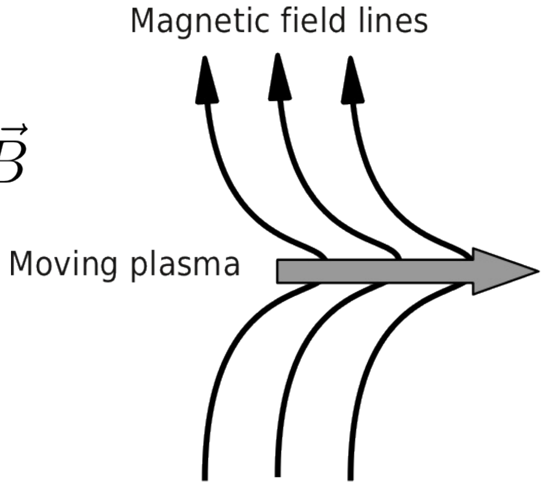
$$\rho\partial_t\vec{v} + \rho\vec{v}\cdot\nabla\vec{v} = -\nabla p_{\rm th} + \rho\nu\nabla^2\vec{v} + \vec{j}\times\vec{B} + \rho\nabla\Phi$$

Simplified pressure balance

$$\nabla\left(\frac{1}{2}\rho v^2 + p_{\rm th} + \frac{B^2}{2\mu_0} + \rho\Phi\right) = 0$$

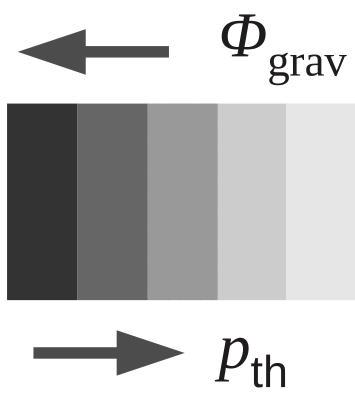
Magnetic field evolution

$$\partial_t\vec{B} = \nabla\times(\vec{v}\times\vec{B}) + \frac{1}{\mu_0\sigma}\nabla^2\vec{B}$$

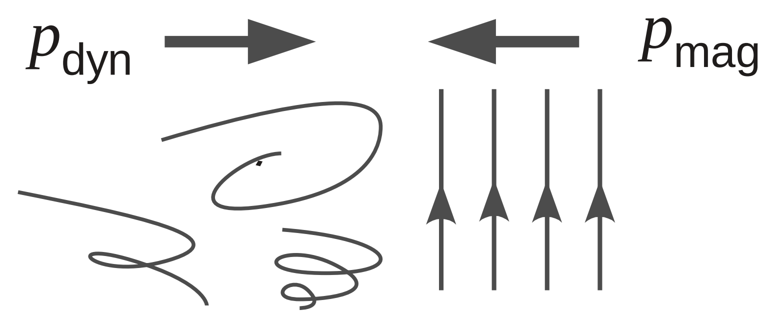


Pressure balance realizations

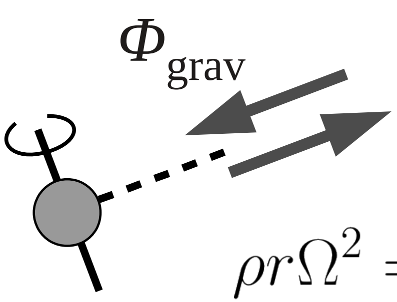
(a) Hydrostatic equilibrium



(b) Hydromagnetic equilibrium

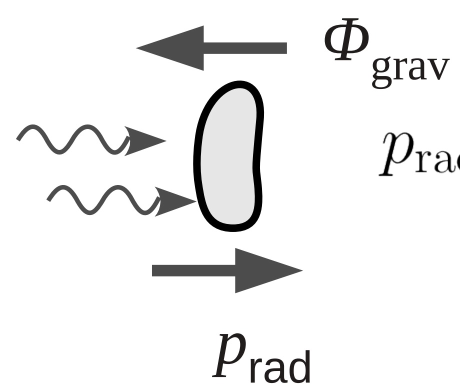


(c) Rotating body



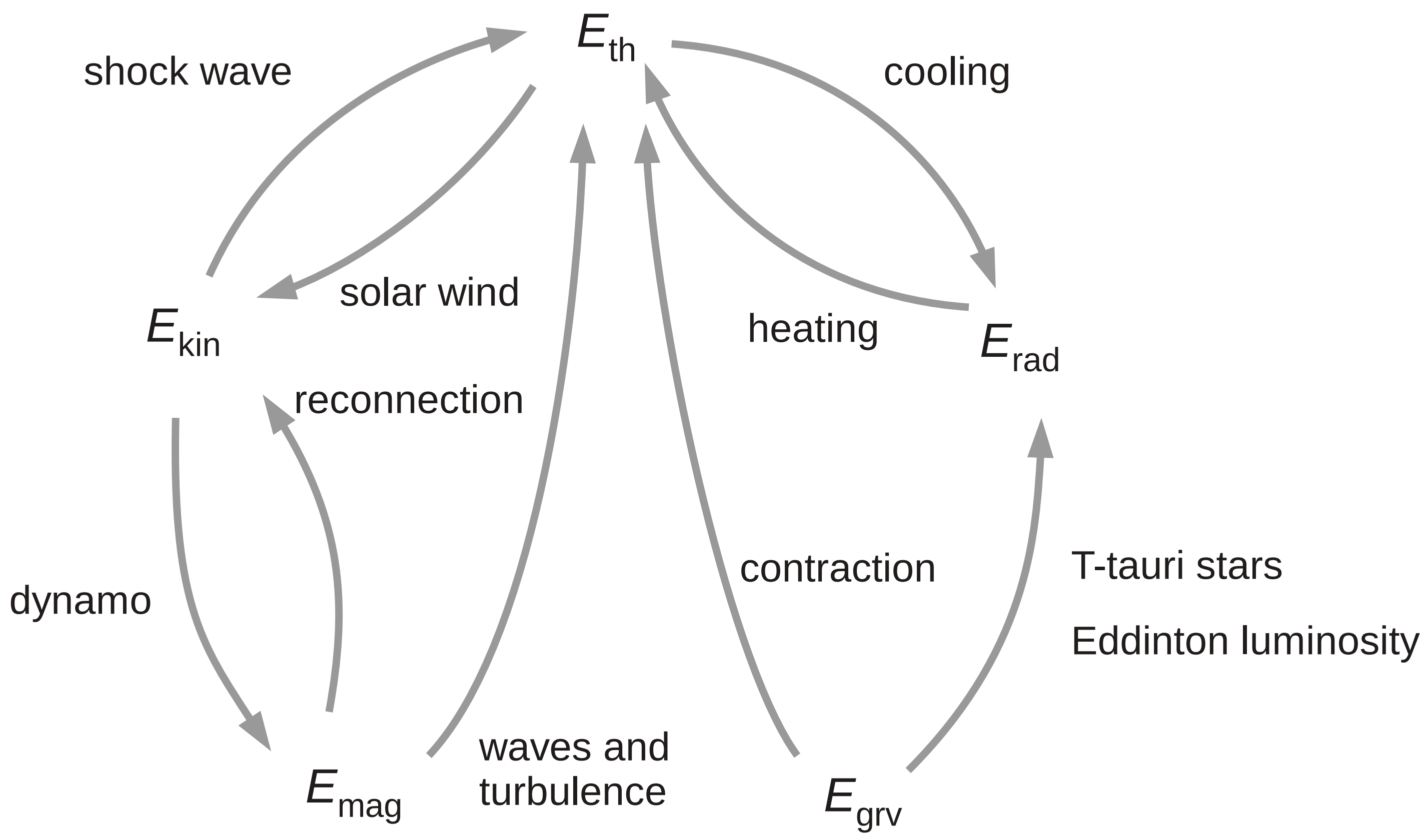
$$\rho r \Omega^2 = \nabla_\perp \left(\frac{1}{2} \rho r^2 \Omega^2 \right)$$

(d) Radiative transfer



$$p_{\mathrm{rad}} = \frac{I_{\mathrm{photon}}}{c} = \frac{1}{c} \frac{\mathrm{Power[W]}}{\mathrm{Area[m^2]}}$$

Energy conversion processes



Heat energy transport

$$F_{\mathrm{total}} = F_{\mathrm{rad}} + F_{\mathrm{cnv}} + F_{\mathrm{cnd}} = \frac{L\,[\mathrm{W}]}{4\pi r^2\,[\mathrm{m}^2]}$$

$$F_{\mathrm{rad}} = -\kappa_{\mathrm{rad}} \nabla T$$

$$F_{\mathrm{cnv}} = \kappa_{\mathrm{cnv}} \left(\frac{d(\log T)}{d(\log P)} - \left[\frac{d(\log T)}{d(\log P)} \right]_{\mathrm{ad}} \right)^{3/2}$$

$$F_{\mathrm{cnd}} = -\kappa_{\mathrm{cnd}} \nabla T$$

Caveat! Additional energy loss due to neurtino escape

Exercise

Is the electrical conductivity in interplanetary plasma (at 1 AU) better than that of iron Fe (10^7 Ω^{-1} m^{-1})?

How many meaningful units are there for expressing pressure?

Solution

Is the electrical conductivity in interplanetary plasma (at 1 AU) better than that of iron Fe (10^7 Ω^{-1} m^{-1})?

The resistivity formula ($\eta = \sigma^{-1} = m_e \nu_c / n_e e^2$) using n_e= 10 cm $^{-3}$ and ν_c = 10^{-7} Hz (T_e = 0.3 MK) yields σ = 10^6 Ω^{-1} m^{-1}.
It is less conductive than iron but is almost on the same order.

How many meaningful units are there for expressing pressure?

Pa (pascal)
N/m^2 (force per area)
J/m^3 (energy density)
kg ms^{-1} / m^2 s (momentum flux)

Heat production

Solar luminosity $L_\odot = 4 \times 10^{26}\,[\mathrm{W}]$

from gravitational contraction $\tau_{grv} = \dfrac{GM^2}{RL_\odot} = 10^7\,[\mathrm{yr}]$

from nuclear fusion $\tau_{fsn} = \dfrac{(\mathrm{fuel\ amount})}{(\mathrm{consumption\ rate})} = 10^{11}\,[\mathrm{yr}]$

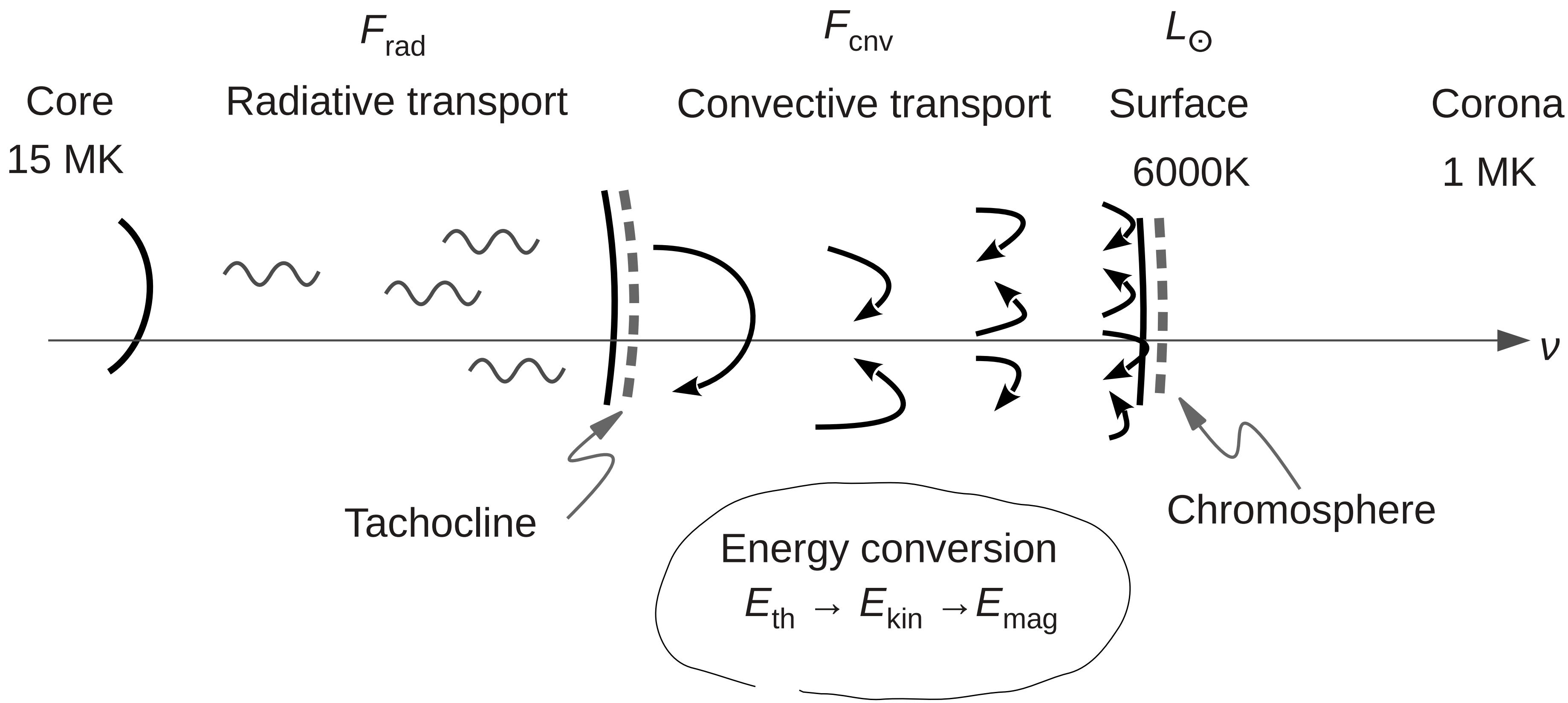
Is the core hot enough for fusion? … Yes but only possible through tunnel effect

Reaction process $4p \rightarrow {}^4\mathrm{He} + 2e^+ + 2\nu_\mathrm{e} + Q(26\,\mathrm{MeV})$

(pp-chain, CNO-cycle)

neutrinos heat

Heat transfer to the surface



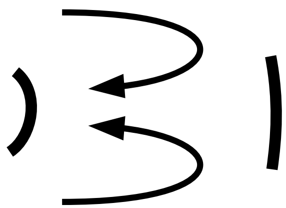
Model construction

- Spherical symmetry
- Hydrostatic equilibrium
- Equation of state?

Excursion to astrophysics

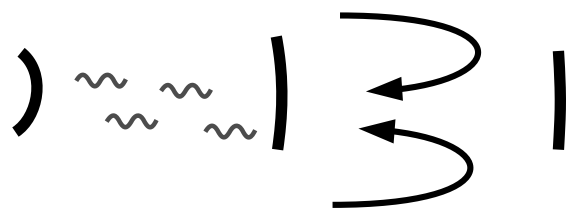
Main sequence stars

Low-mass (M)
red dwarf, 0.1-0.5 $M_\odot$



core - conv

Sun-like (G)
0.5-1.5 $M_\odot$



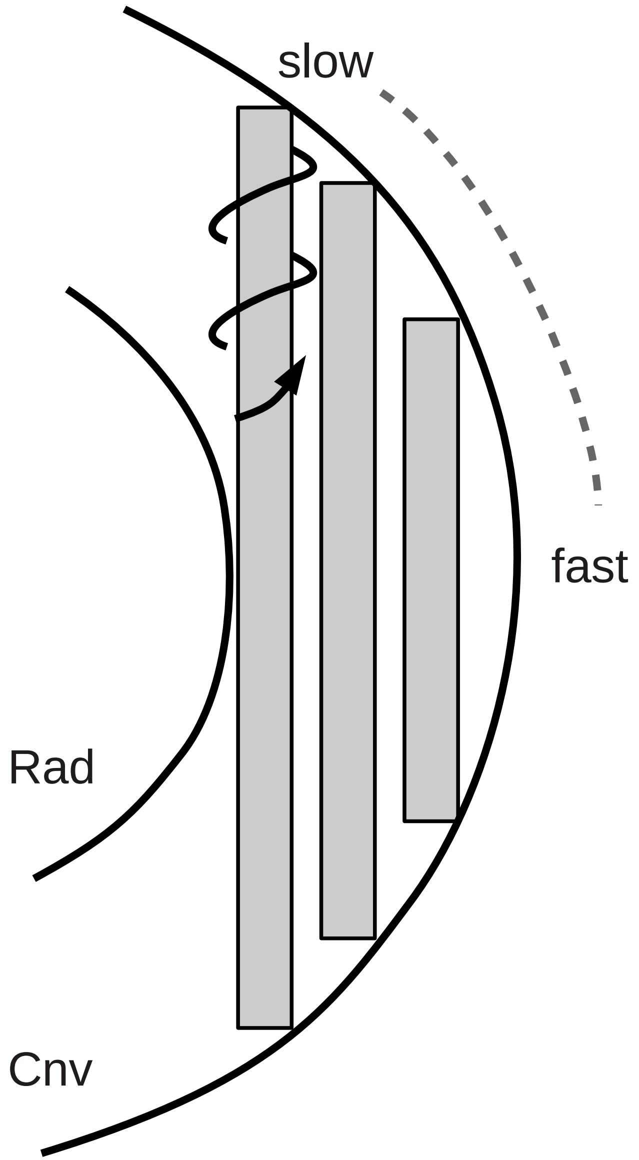
core - rad - conv

High-mass (O,B)
1.5 $M_\odot$ or higher

core+conv - rad

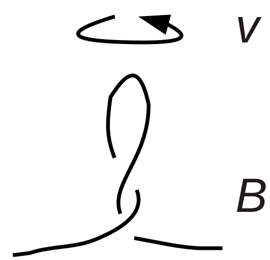
High-mass stars live much shorter although they have more fuel. Why?

Convection zone



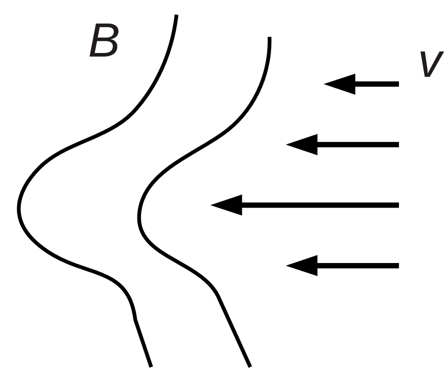
Buoyancy + Coriolis effect → Taylor column

Twisting magnetic field lines (“alpha”)



Differential rotation

Stretching field lines (“Omega”)



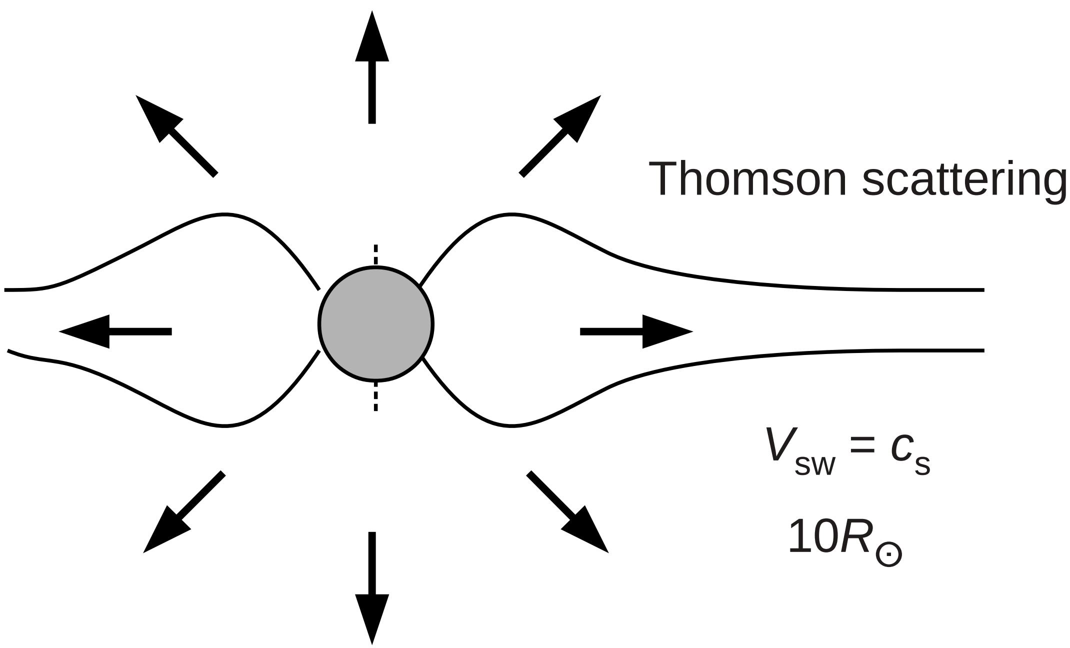
Cause of 11-year (or 22-year) perioditicy?

Corona

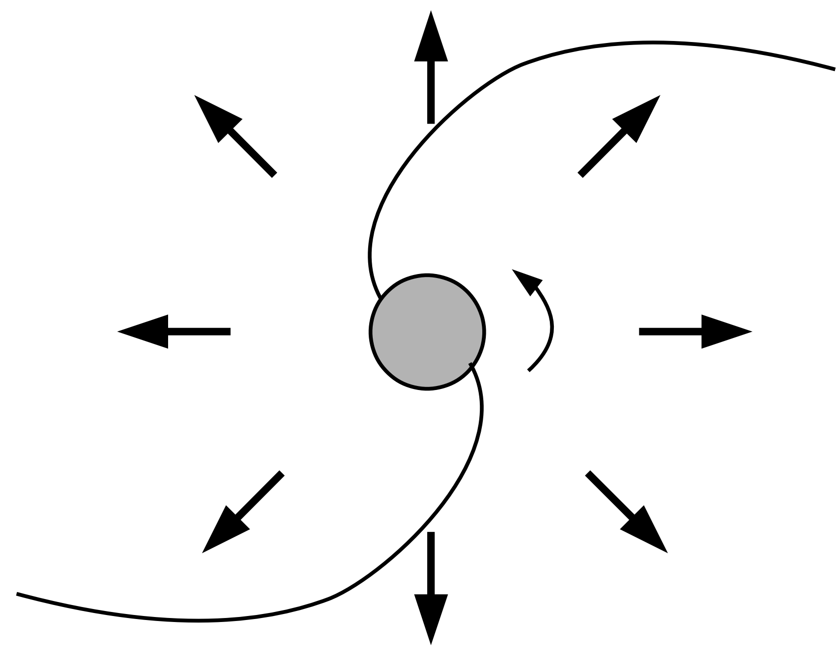
Proposed heating mechanisms: shock waves, nanoflares, Alfven waves, ...

Thermal expansion of coronal gas → solar wind ($E_{th} \rightarrow E_{kin}$)

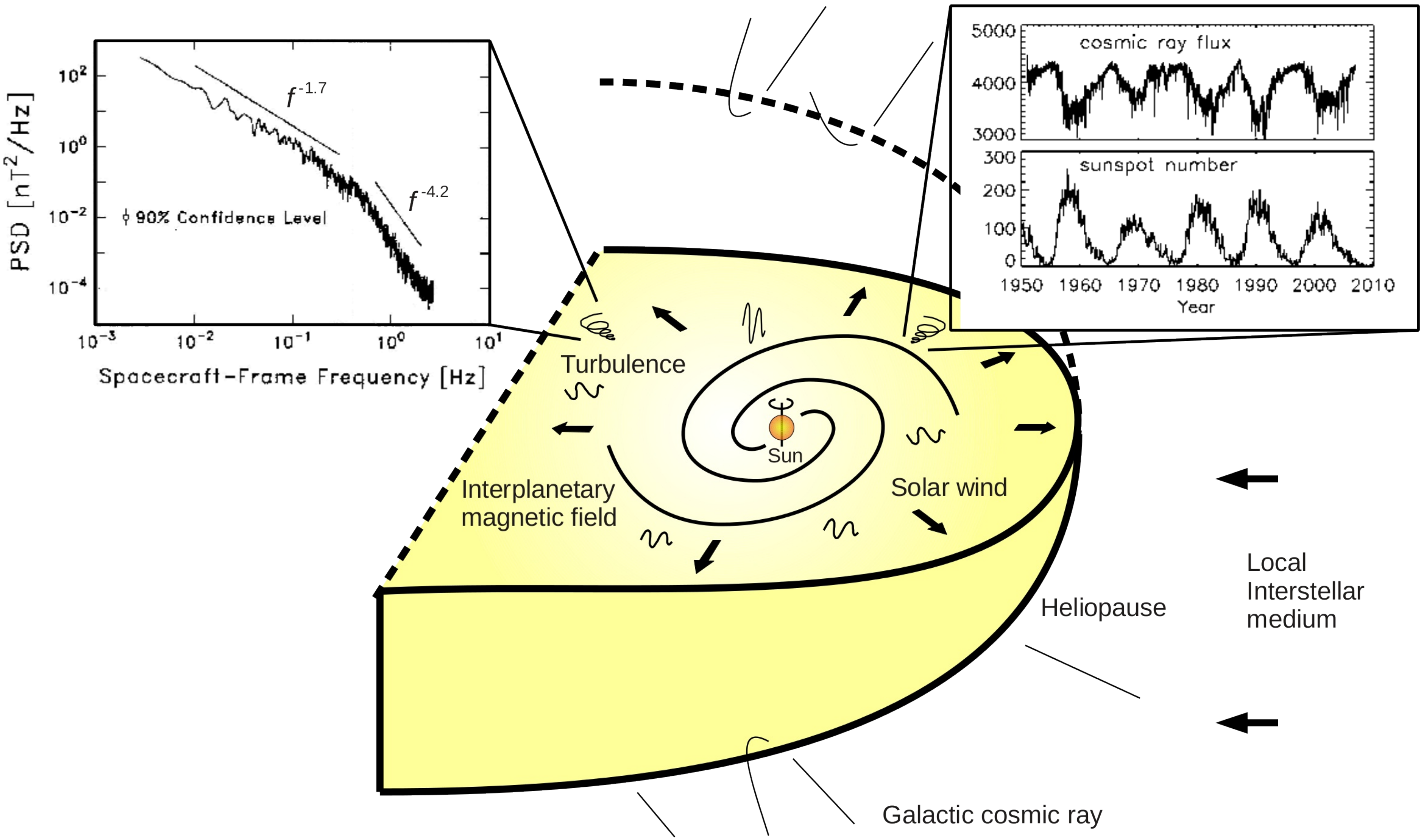
Slice along the rot axis



Slice cutting the rot axis



Heliosphere



Exercise

1. Estimate the lifetime of the sun.

2. Is the number density of solar neutrino coming to Earth higher than 1 cm^{-3}?

Solution

1. Estimate the lifetime of the sun.

(Fuel amount) = ($M_\odot$ / m_p) [protons] x 26/4 [MeV] x 1.6 x 10^{-13} [J/MeV]
(Consumption rate) = $L_\odot$ = 4 x 10^{26} [J/s]
(Lifetime) = (Fuel) / (Consumption) = 2.9 x 10^{18} [s] = 0.9 x 10^{11} [yr]

2. Is the number density of solar neutrino coming to Earth higher than 1 cm^{-3}?

Use solar constant and reaction rate (2 neutrinos per 26 MeV).
Neutrino number flux is
F = 1.36 x 10^3 [J/m^2s] / (13 [MeV] x 1.6 x 10^{-13} [J/MeV])
= 6.5 x 10^{10} [particles / cm^2s]
Number density (on using the light speed c) is
$n = F/c$ = 2.18 x 10^6 [particles m^{-3}] = 2.18 [particles cm^{-3}].

It is slightly more than one particle per cm^3.

Earth's magnetic field boundary

$$B \propto \frac{1}{r^3}$$

$$\frac{B}{B_{\rm srf}} = \left(\frac{R}{R_{\rm srf}}\right)^{-3}$$

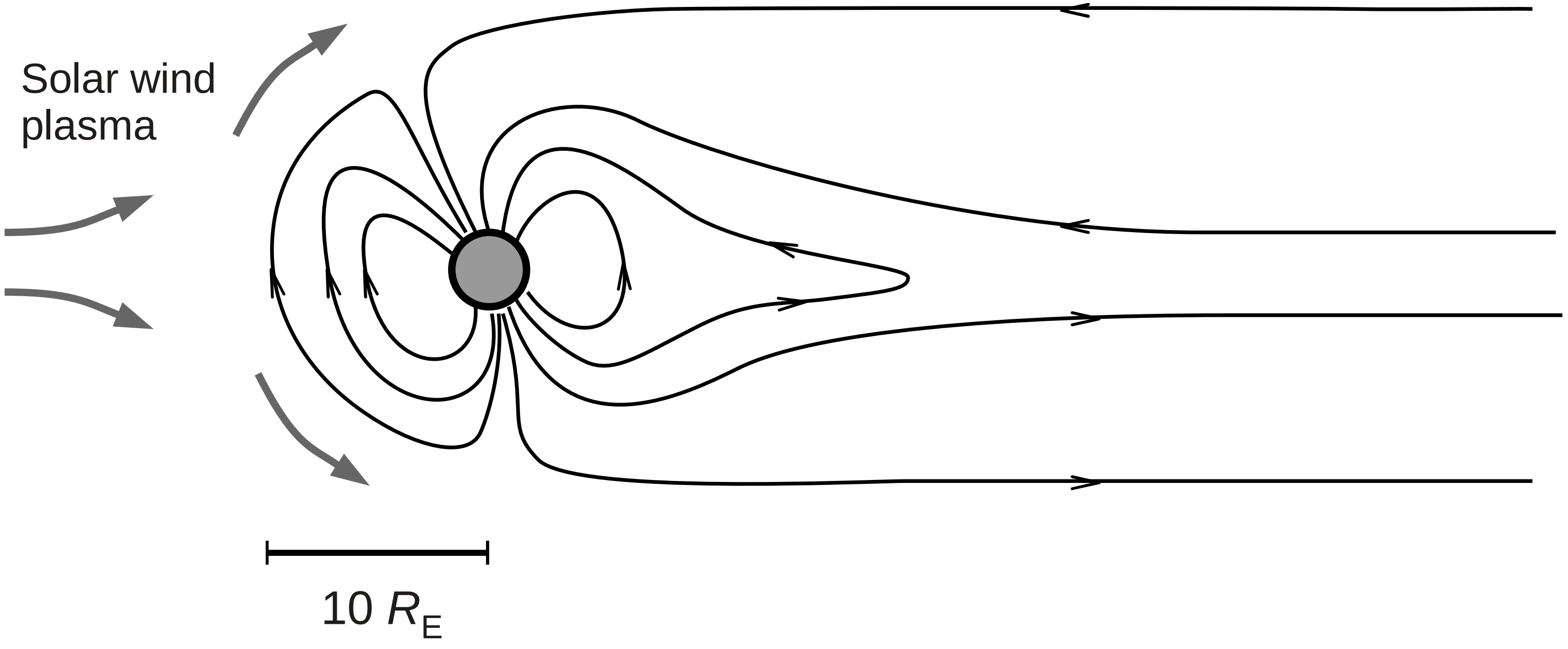
$$\frac{1}{2}\rho v^2 = \frac{B_{\rm mp}^2}{2\mu_0}$$

$$\frac{R_{\rm mp}}{R_{\rm srf}} = \left(\frac{B_{\rm srf}^2}{\mu_0 \rho v^2}\right)^{\frac{1}{6}} = 10\, R_{\rm E}$$

Time scale of reaction against solar wind change?

Magnetosphere

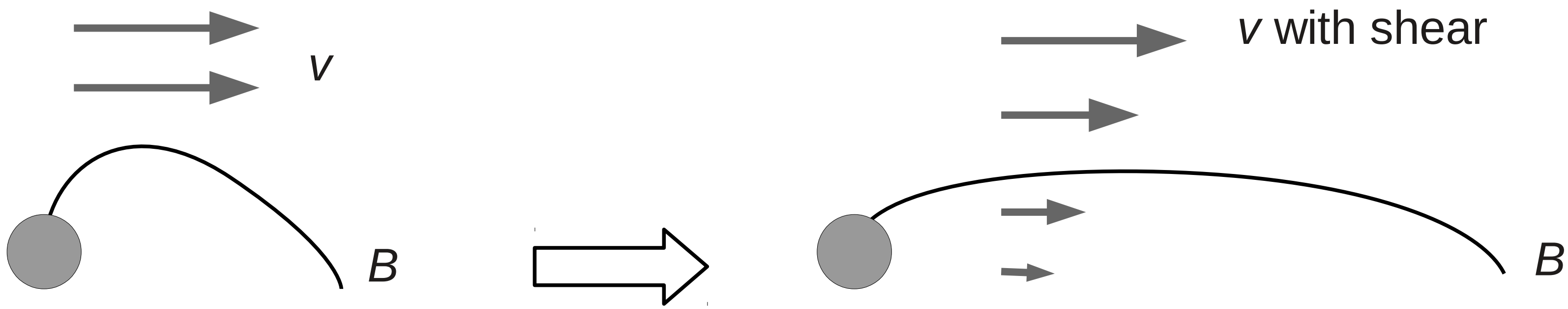
Equlibrium picture



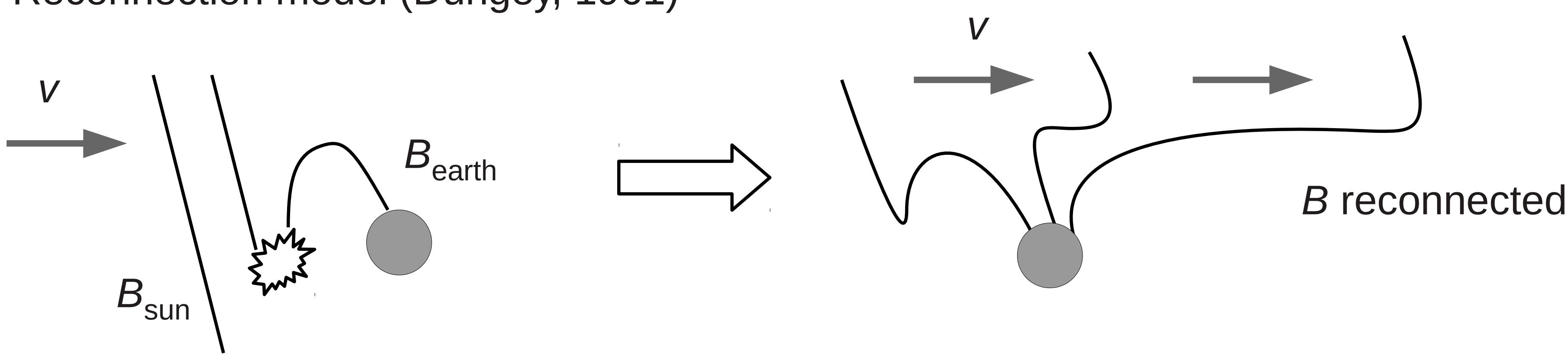
- How does the tail form? - Friction model vs. reconnection model
- Where is the pressure balance applicable? And what kind of pressure?

Magnetic field transport

Friction model (Axford & Hines, 1961)

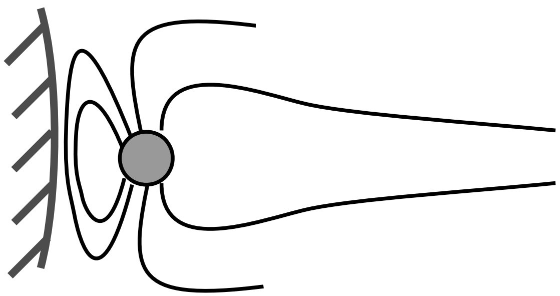


Reconnection model (Dungey, 1961)



Magnetospheric dynamics

Geomagnetic storm



compression

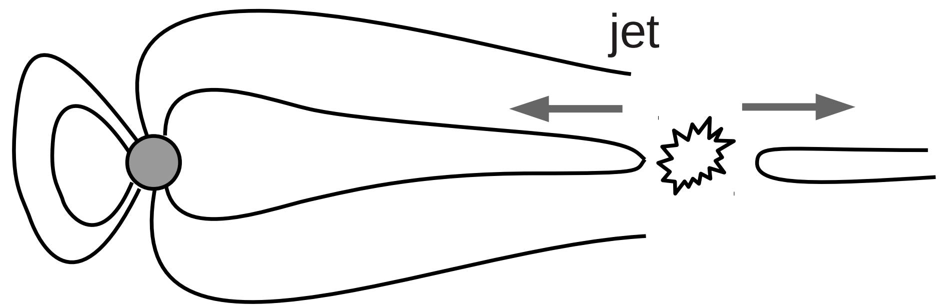
Phenomenon with sudden increase of solar wind pressure (CME, CIR)

Dayside compression ~ minutes

Nightside compression ~ hours

Recovery ~ days

Auroral substorm



reconnection

Phenomenon with the southward direction of interplanetary magnetic field

Dayside reconnection ~ minutes

Tail reconnection ~ 40 minutes after dayside reconnection

Recovery ~ hours

Exercise

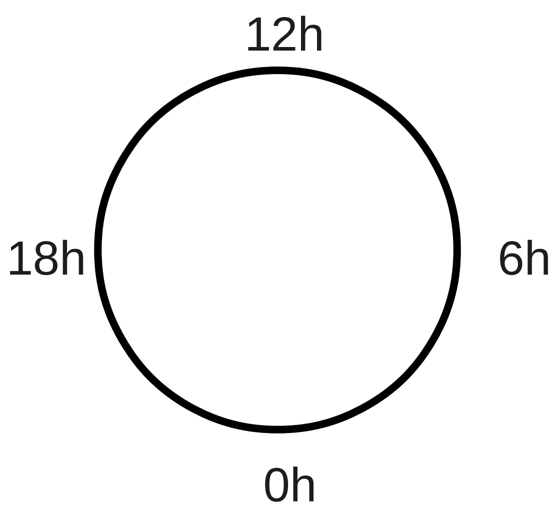
1. What can be used as a proxy of past Earth climate and solar activity on the time scale from 1000 to 10,000 years?

Earth climate …

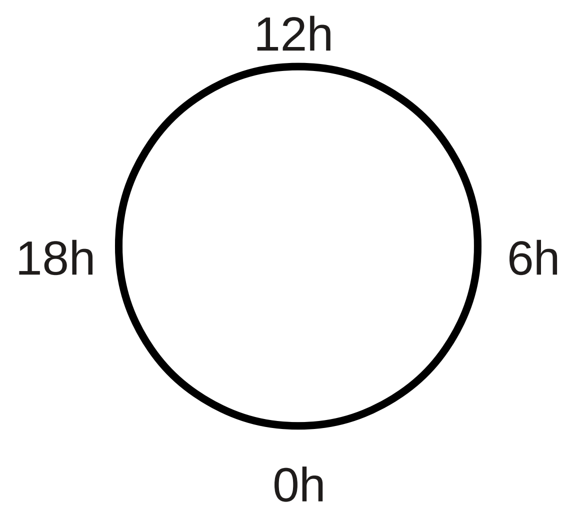
Solar activity …

2. Draw footprint motion of Earth's magnetic field line in the arctic region.

Friction model



Reconnection model



viewed from north pole axis to the ionosphere

Solution

1. What can be used as a proxy of past Earth climate and solar activity on the time scale from 1000 to 10,000 years?

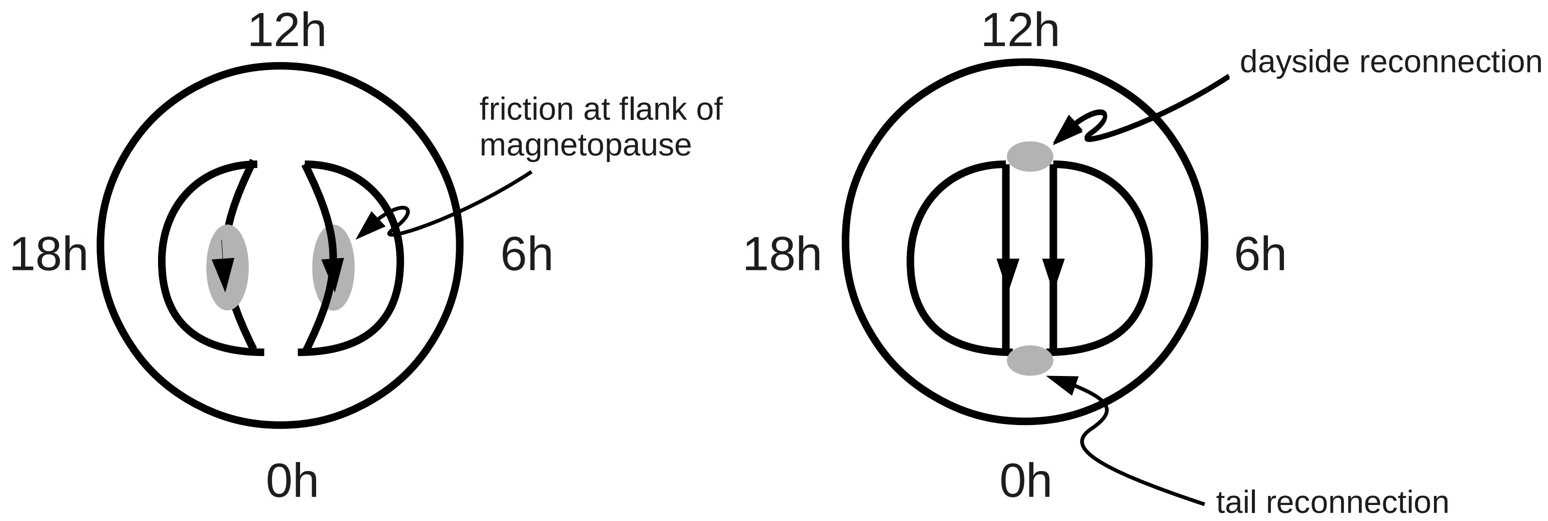
Earth climate … Oxygen 18 isotope abundance in stalagmite

Solar activity … Carbon 14 isotope abundance in tree ring

(*Neff et al*., Nature, 411, 290, 2001)

2. Draw footprint motion of Earth's magnetic field line in the arctic region.

Friction model　　　　Reconnection model

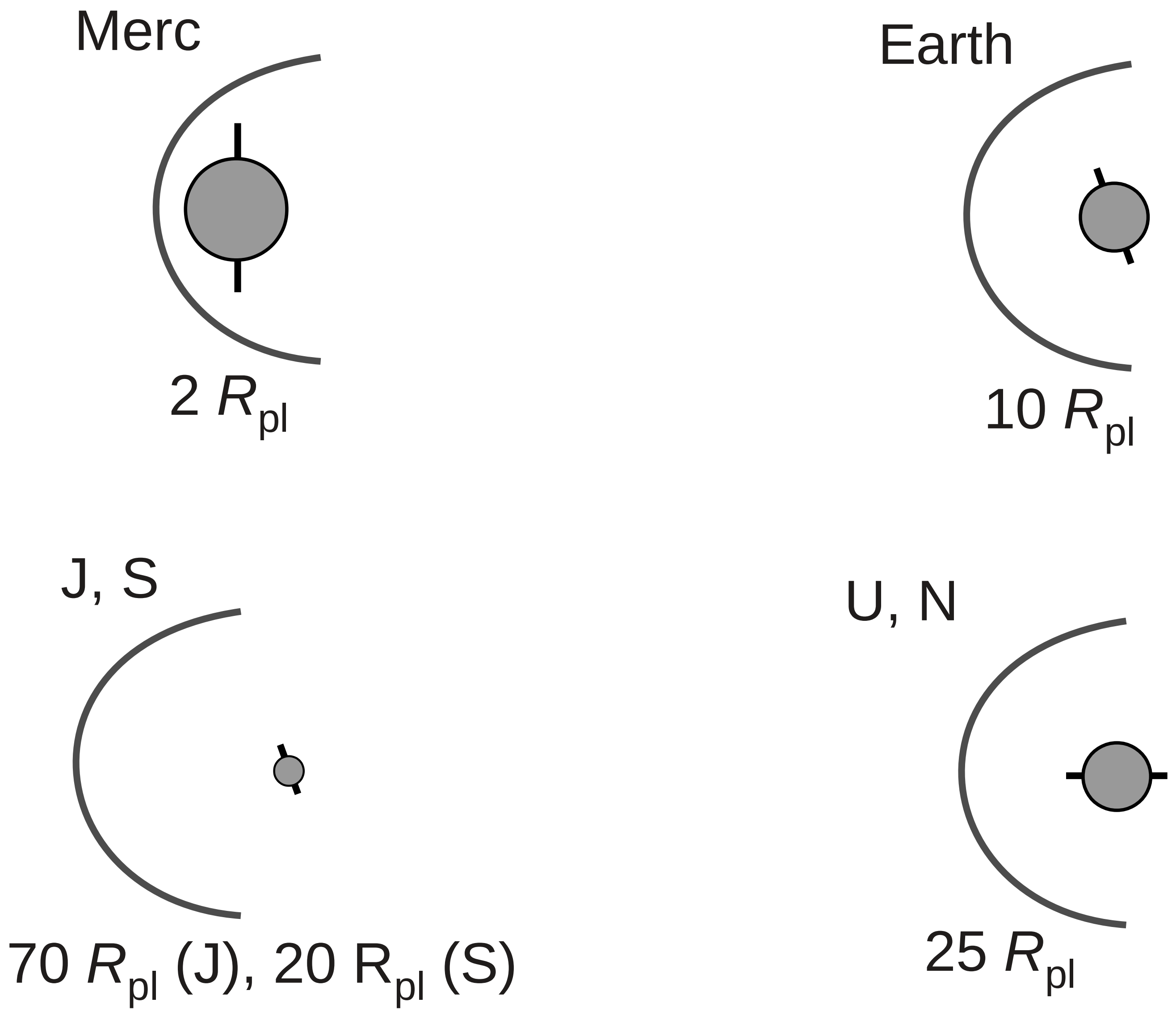


viewed from north pole axis to the ionosphere

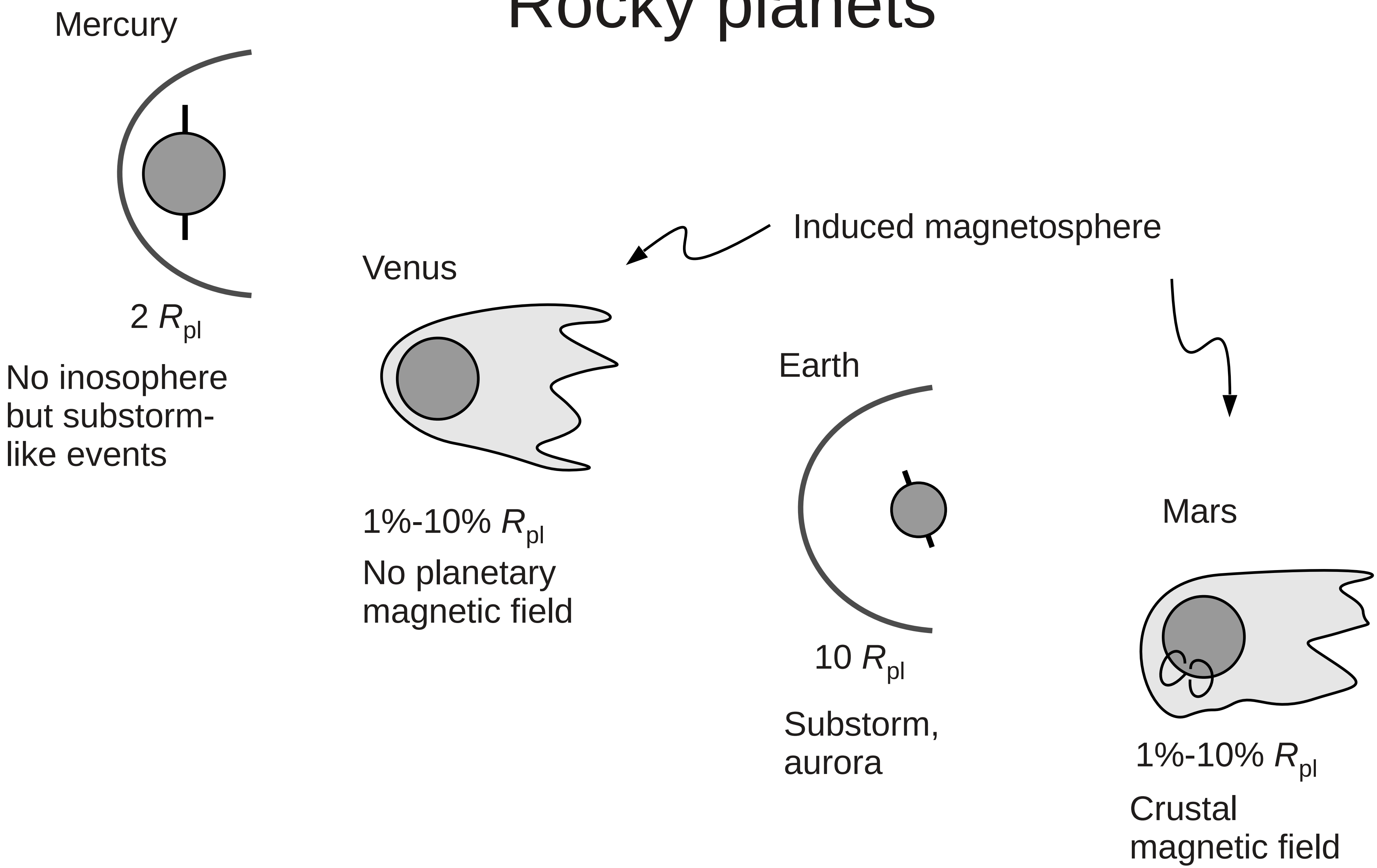
Obstacle types

	Magnetized body	Umagnetized body
With atmosphere	Earth Gas giants (J, S) Icy planets (U, N) Ganymede	Venus, Mars Titan, Enceladus
Without atmosphere	Mercury	Earth moon

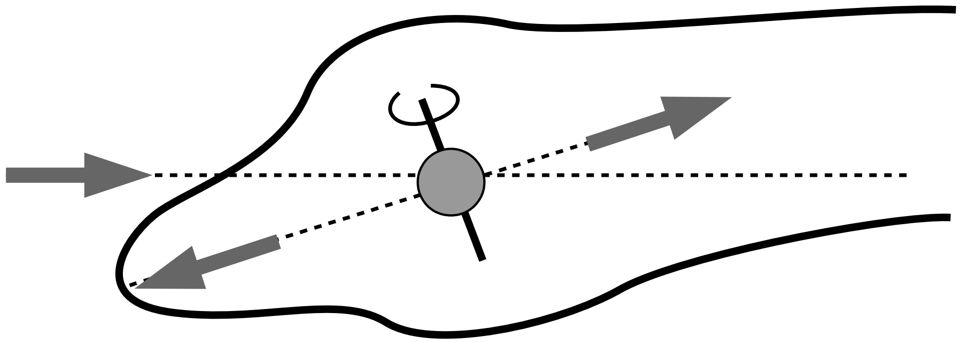
Dipole axis and magnetosphere size



Rocky planets



Gas giants (Jup,Sat)



Centrifugal force

$$\frac{\rho v^2}{r}\vec{e}_\perp = \rho r \Omega^2 = \nabla_\perp \left(\frac{1}{2} \rho r^2 \Omega^2 \right)$$

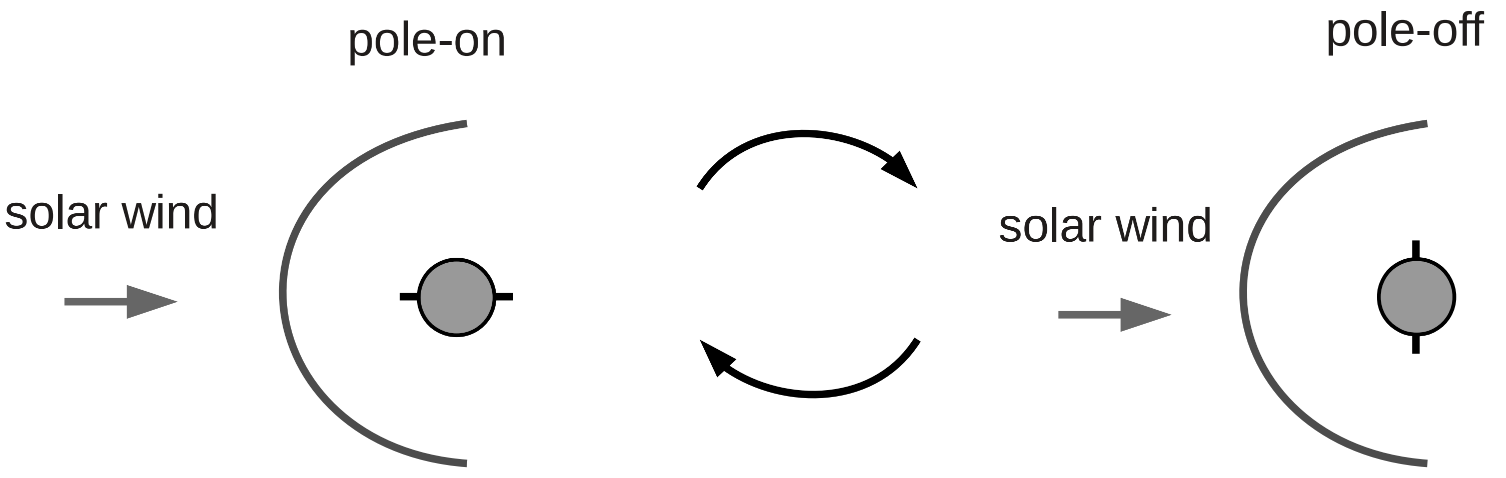
Liquid, metalic hydrogen envelope?

10-hour rotation

Satellites as plasma source (Io, Enceladus)

Aurora, radio wave, synchrotron emission

Icy planets (Ura, Nep)



Planet formation beyond ice limit

Large tilt angle → pole-on magnetosphere

Aurora, radio wave emission