Why are there Magnetospheres?

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Where are Magnetic Fields important in the Heliosphere?

(place stamp next to region)

- Sun (photosphere to corona)
- Interplanetary space (solar wind)
- Earth's Space Environment
- Ionosphere
- Other Planets' space environments
- Boundary with ISM

Conceptual Framework

- Magnetic Fields are important essentially wherever there are plasmas!
- Magnetic fields contain energy, define plasma boundaries, particle motion and wave propagation (E&M and Alfvénic)
- Basic plasma parameters (Beta, Alfvén Velocity, particle frequencies) depend on B
- We live on a magnetic planet, in a magnetic solar system…. in a magnetic universe.

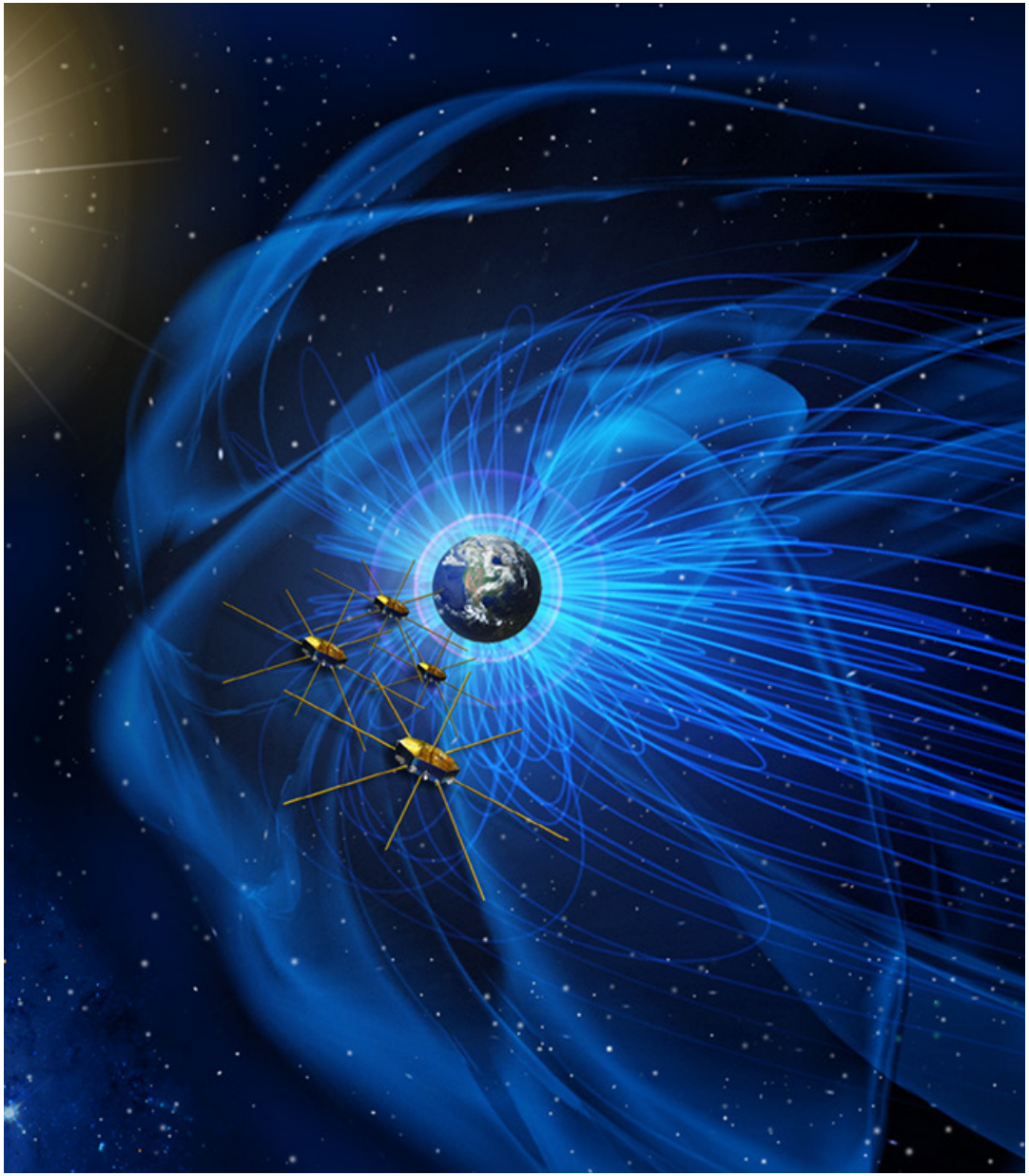
Three fundamental magnetic structures

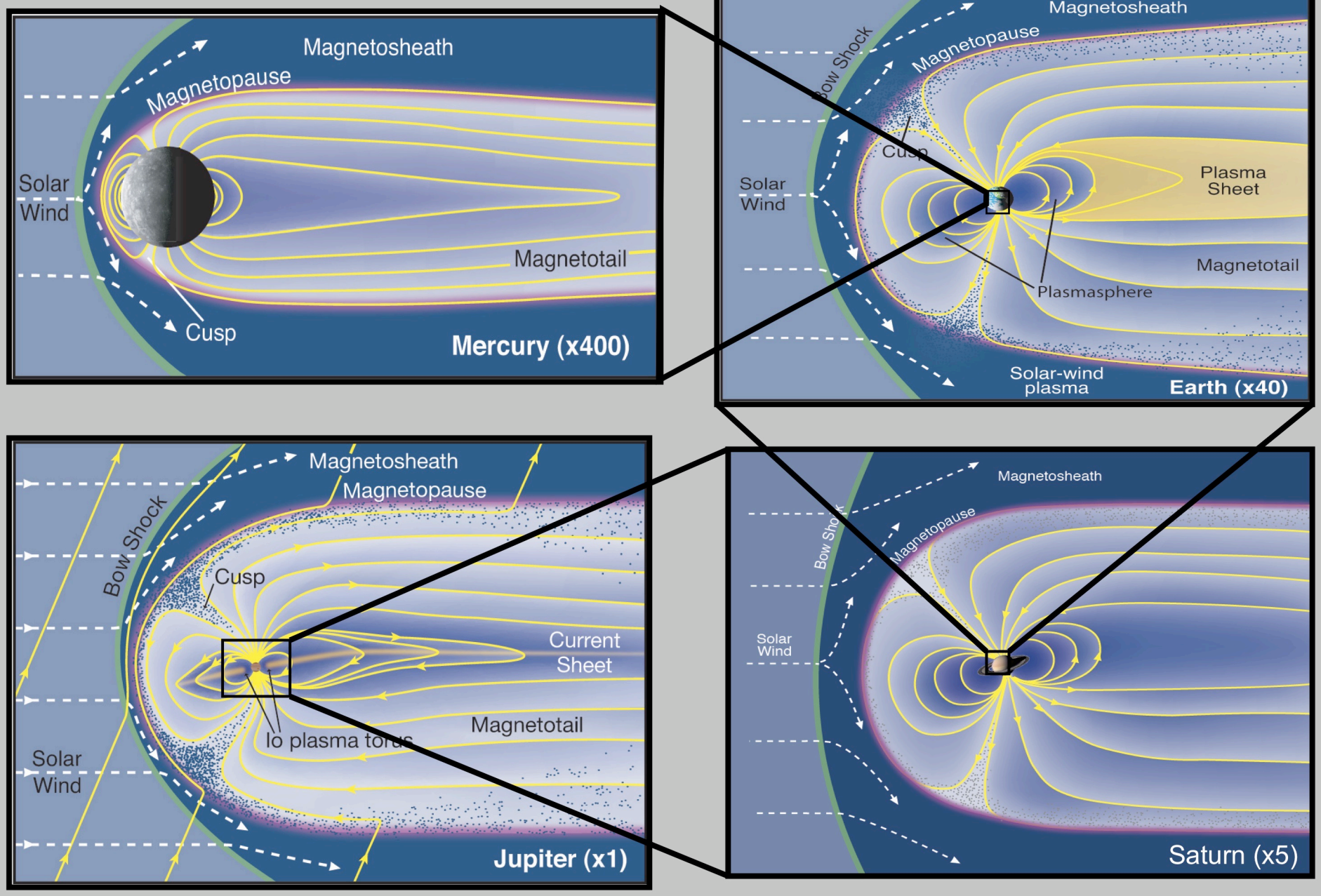
Cavities (magnetospheres)

Current Sheets

Flux Tubes

Moldwin et al., 2009



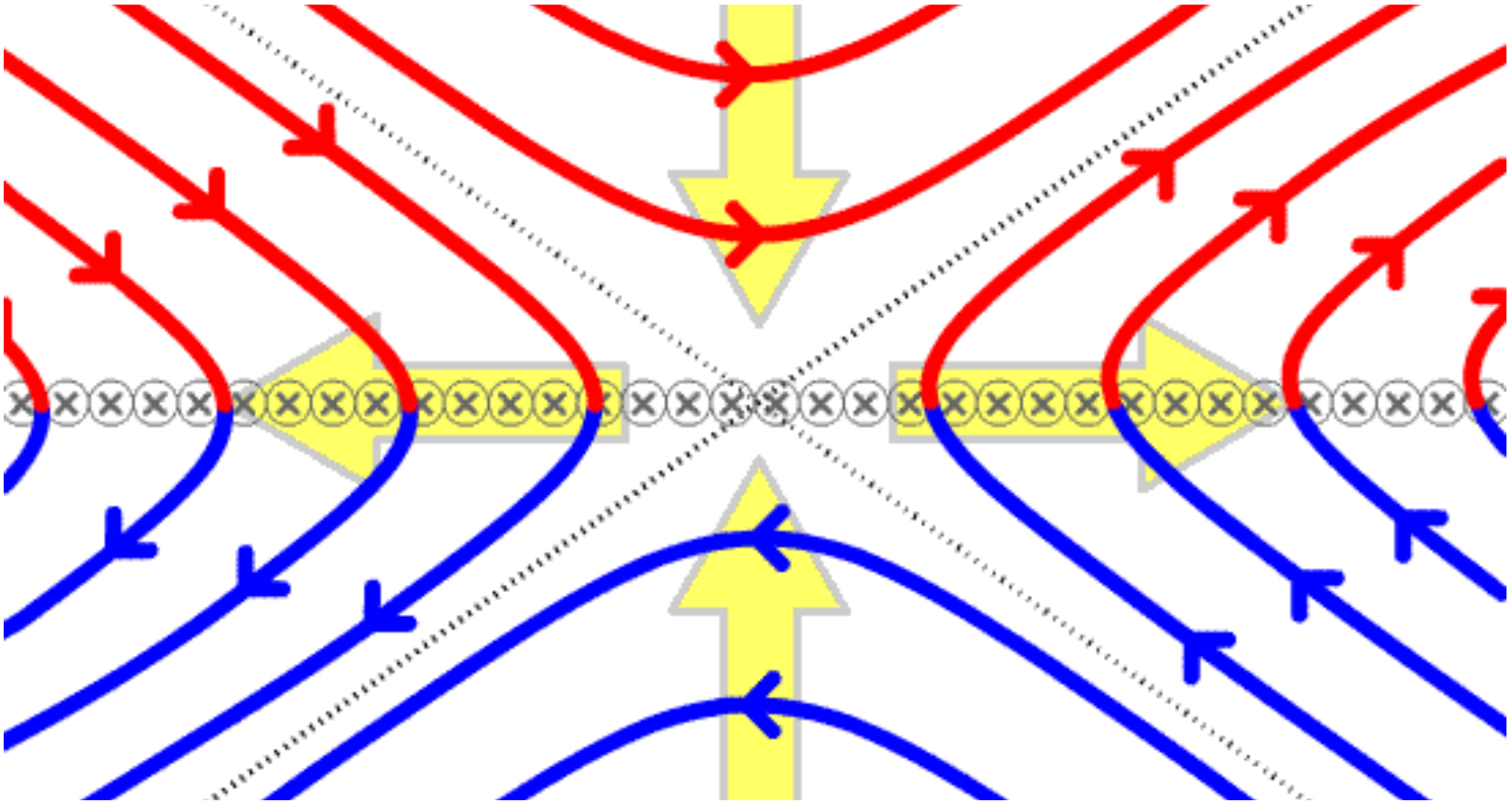

Magnetosheath
Magnetopause
Solar
Wind
Magnetotail
Cusp
Mercury (x400)
Bow Shock
Cusp
Plasma
Sheet
Plasmasphere
Solar-wind
plasma
Earth (x40)
Bow Shock
Current
Sheet
Io plasma torus
Jupiter (x1)
Saturn (x5)

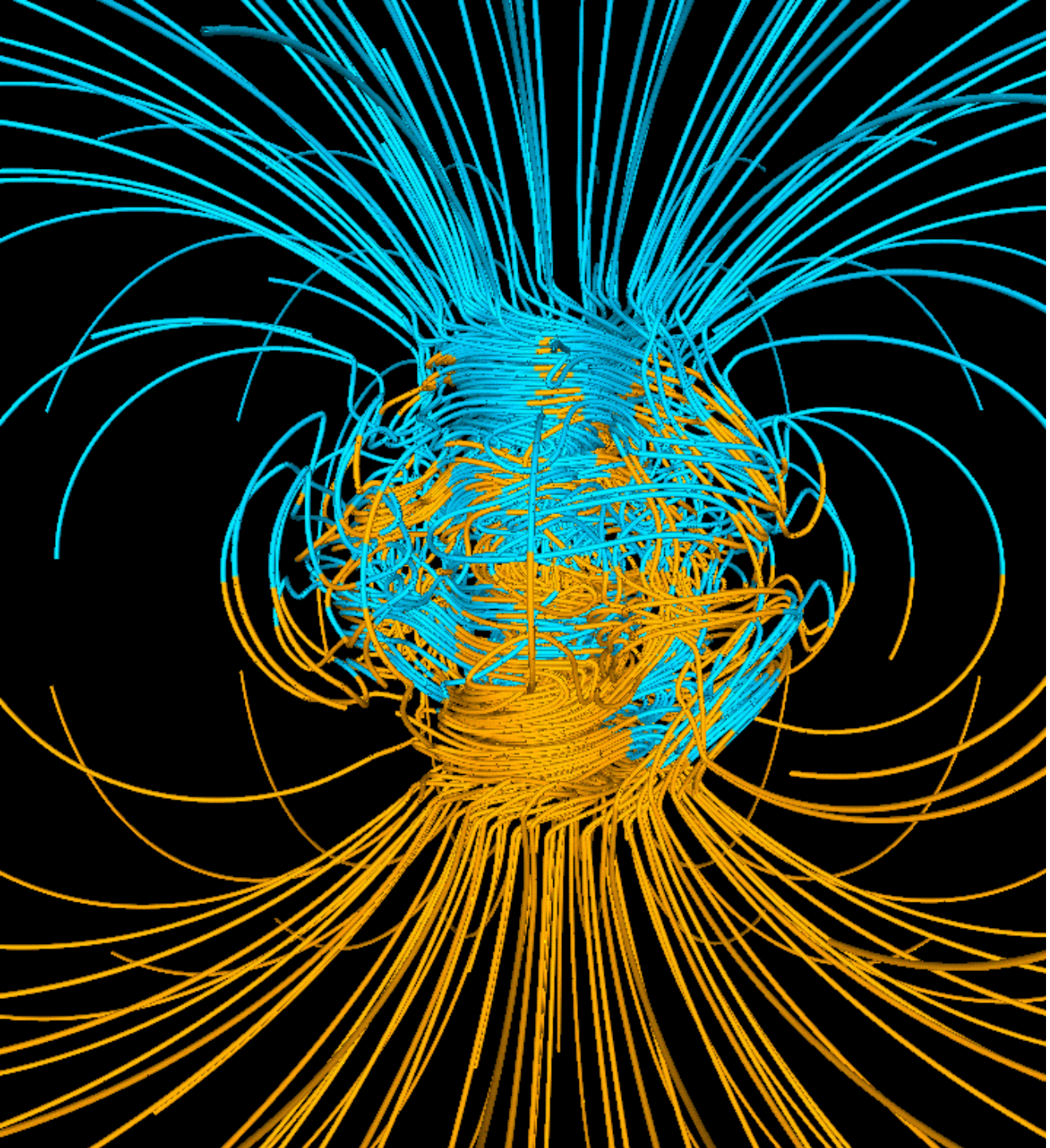
Magnetic Energy Evolution

$$U = \frac{B^2}{2\,\mu_0}.$$

$$\frac{\partial \mathbf{B}}{\partial t} = \eta \nabla^2 \mathbf{B} + \nabla \times (\mathbf{u} \times \mathbf{B})$$

RXN is the conversion of magnetic energy and change in topology of field





Creation and destruction of magnetic energy, flux, fields, pressure, tension gives rise to heliophysics structure and dynamics.

Magnetohydrodynamic Equations

$$\frac{\partial n}{\partial t} + \nabla \cdot (n\mathbf{v}) = 0$$

$$\frac{\partial (nm\mathbf{v})}{\partial t} + \nabla \cdot (nm\mathbf{v}\mathbf{v}) = -\nabla \cdot \mathbf{P} + \rho\mathbf{E} + \mathbf{j} \times \mathbf{B}$$

$$\mathbf{E} + \mathbf{v} \times \mathbf{B} = \eta\mathbf{j} + \frac{1}{ne}\mathbf{j} \times \mathbf{B} - \frac{1}{ne}\nabla \cdot \mathbf{P}_e + \frac{m_e}{ne^2}\frac{\partial \mathbf{j}}{\partial t}$$

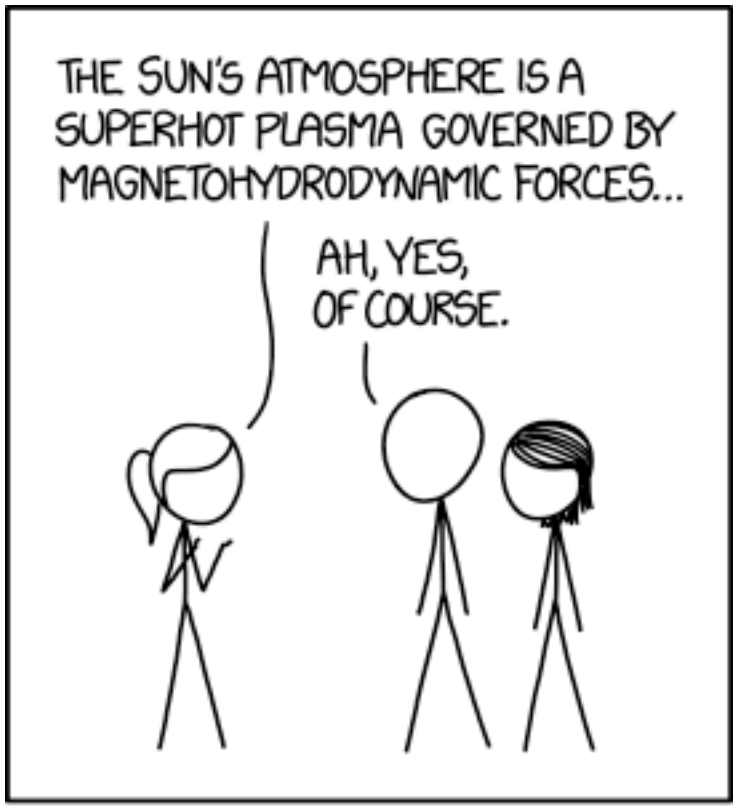
$$\nabla \times \mathbf{B} = \mu_0\mathbf{j} + \mu_0\epsilon_0\frac{\partial \mathbf{E}}{\partial t}$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \cdot \mathbf{B} = 0$$

Mass density (density and composition)
Velocity
Pressure (gas (nkT) and magnetic (B) and ram (ρV^2)
Fields E, B (DC and AC and waves)
Add Energy and radiation, chemistry etc.

You've seen these all last week….



WHENEVER I HEAR THE WORD "MAGNETOHYDRODYNAMIC" MY BRAIN JUST REPLACES IT WITH "MAGIC."

Origin and Evolution

- Where do magnetic fields come from?

DYNAMO THEORY (from Gill)

Branch of magnetohydrodynamics which deals with the self excitation of magnetic fields in large rotating bodies comprised of electrically conducting fluids.

Earth's Core:

Inner Core:

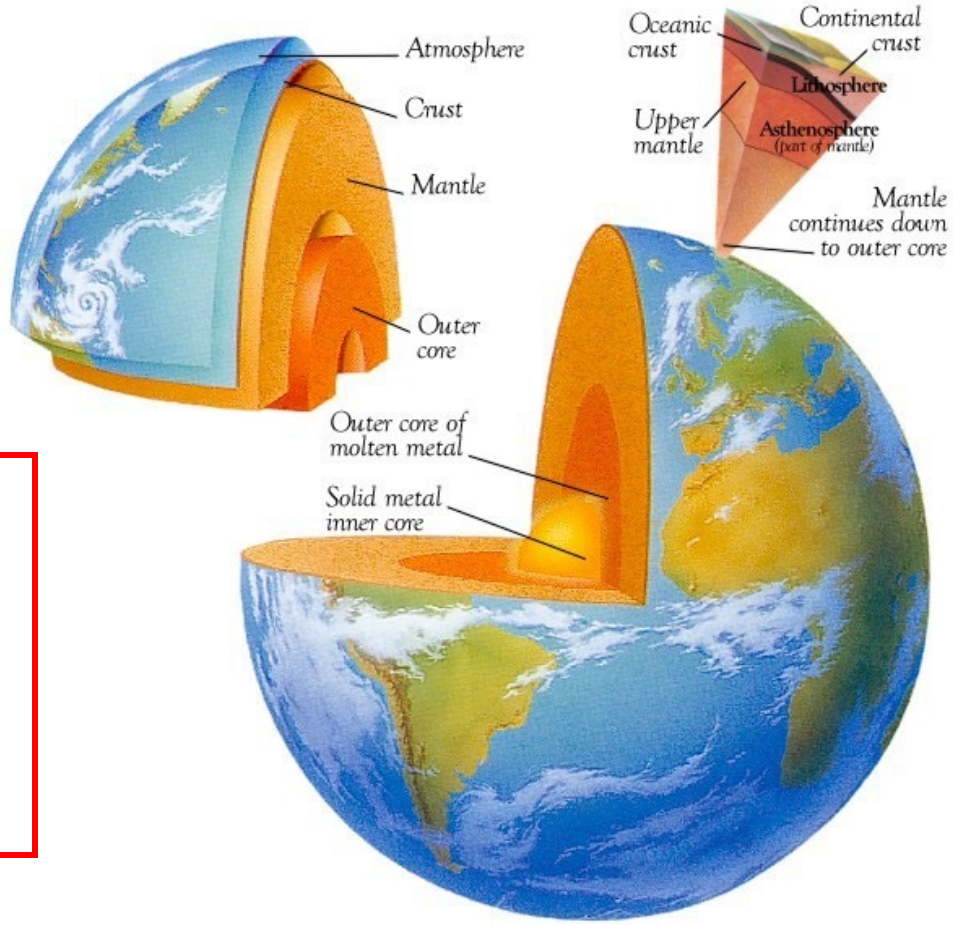
$R_{Inner\ Core} \approx 0.19 R_{\oplus}$

Iron & Nickel Alloy

Outer Core:

$R_{Outer\ Core} \approx 0.55 R_{\oplus}$ Molten

Iron and admixture of silicon, sulphur, carbon



REQUIREMENTS FOR GEODYNAMO

1) CONDUCTING MEDIUM

Large amount of molten iron in outer core: comparable to 6 times the volume of the Moon

2) THERMAL CONVECTION

- Inner core is hotter than the mantle
- Temperature difference results in thermal convection.
- Blobs of conducting fluid in outer core rise to the mantle
- Mantle dissipate energy through thermal radiation
- Colder fluid falls down towards the centre of the Earth

MATHEMATICAL FRAMEWORK

Most important equation in dynamo theory:

MAGNETIC INDUCTION EQUATION

$$\frac{\partial \vec{B}}{\partial t} = \nabla \times (\vec{u} \times \vec{B}) + \eta \nabla^2 \vec{B}$$

Where η is the magnetic diffusivity

First term: $\nabla \times (\vec{u} \times \vec{B})$

$\Rightarrow$

Buildup or Breakdown of magnetic field (Magnetic field instability)

Second term: $\eta \nabla^2 \vec{B}$

$\Rightarrow$

Rate of decay of magnetic field due to Ohmic dissipations

MATHEMATICAL FRAMEWORK

Quantitative measure of how well the dynamo action will hold up against dissipative effects is given by the Reynolds number

$$R_m \equiv \frac{\nabla \times (\vec{u} \times \vec{B})}{\eta \nabla^2 \vec{B}} \approx \frac{u_o L}{\eta}$$

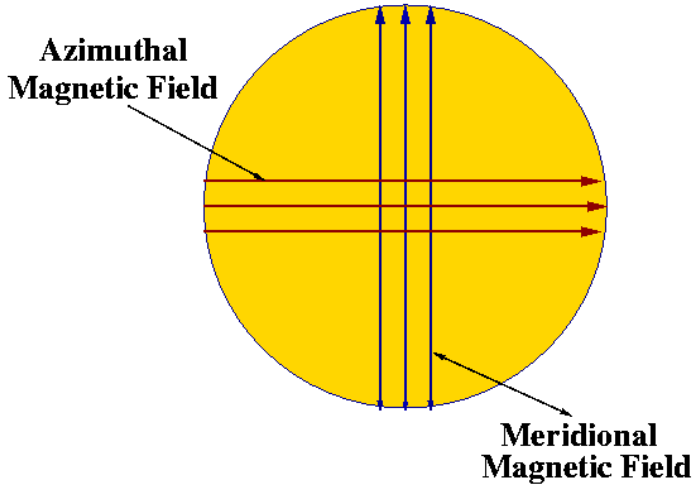
where u_o is the velocity scale and L is the characteristic length scale of the velocity field

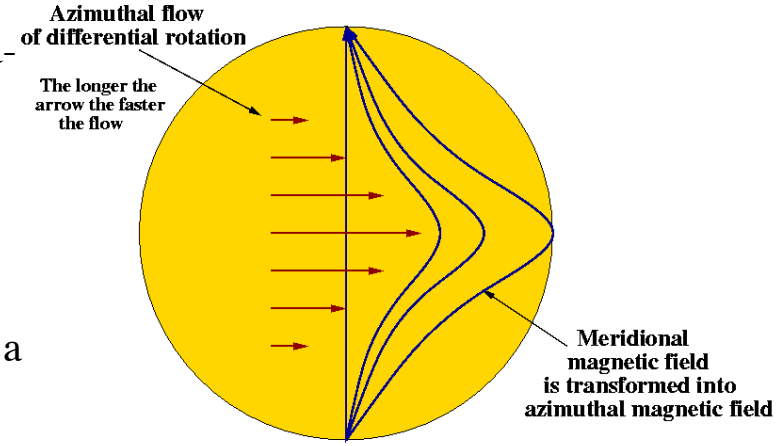
For any dynamo action $R_m > 1$

Otherwise, the decay term would dominate and the dynamo would not sustain

Solar Dynamo: Concept

- The flow of the plasma has to fulfill certain properties for the dynamo to work:
  - The flow has to be turbulent. A laminar flow does not work.
  - The flow has to be fully three-dimensional.
  - The flow has to be helical.
- First, the solar differential rotation stretches the magnetic field and winds it around the Sun. This stretching takes a meridional magnetic field and stretches it into a azimuthal magnetic field. The effect of stretching the magnetic field by differential rotation is often referred to as the omega-effect.
- Next we need to do the opposite. This is done by the alpha-effect which is due to the interaction of convection and rotation. The alpha-effect basically takes the azimuthal magnetic field generated by the omega-effect and transforms it back into meridional flow.
- Exactly how this works is at present not well understood. This complicated stretching, twisting and folding requires a complicated flow.





The Alpha-Omega Dynamo

- Induction equation $\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}) + \eta_m \nabla^2 \mathbf{B}$

- Magnetic field and velocity are expressed as the sum of toroidal and poloidal components $\mathbf{B} = B_\varphi \mathbf{e}_\varphi + \mathbf{B}_p \qquad \mathbf{u} = u_\varphi \mathbf{e}_\varphi + \mathbf{u}_p$

- Toroidal component of the induction equation
$\frac{\partial B_\varphi}{\partial t} + R\left(\mathbf{u}_p \cdot \nabla\right)\left(\frac{B_\varphi}{R}\right) = R\left(\mathbf{B}_p \cdot \nabla\right)\left(\frac{u_\varphi}{R}\right) + \eta_m \left(\nabla^2 - \frac{1}{R^2}\right) B_\varphi$
- Toroidal field is generated by the shear of the toroidal velocity (omega effect)
- Poloidal component
$\frac{\partial A_p}{\partial t} + \left(\frac{\mathbf{u}_p}{R} \cdot \nabla\right)(RA_p) = \eta_m \left(\nabla^2 - \frac{1}{R^2}\right) A_p \qquad \mathbf{B}_p = \nabla \times (A_p \mathbf{e}_\varphi)$
- There is no generation of poloidal field!

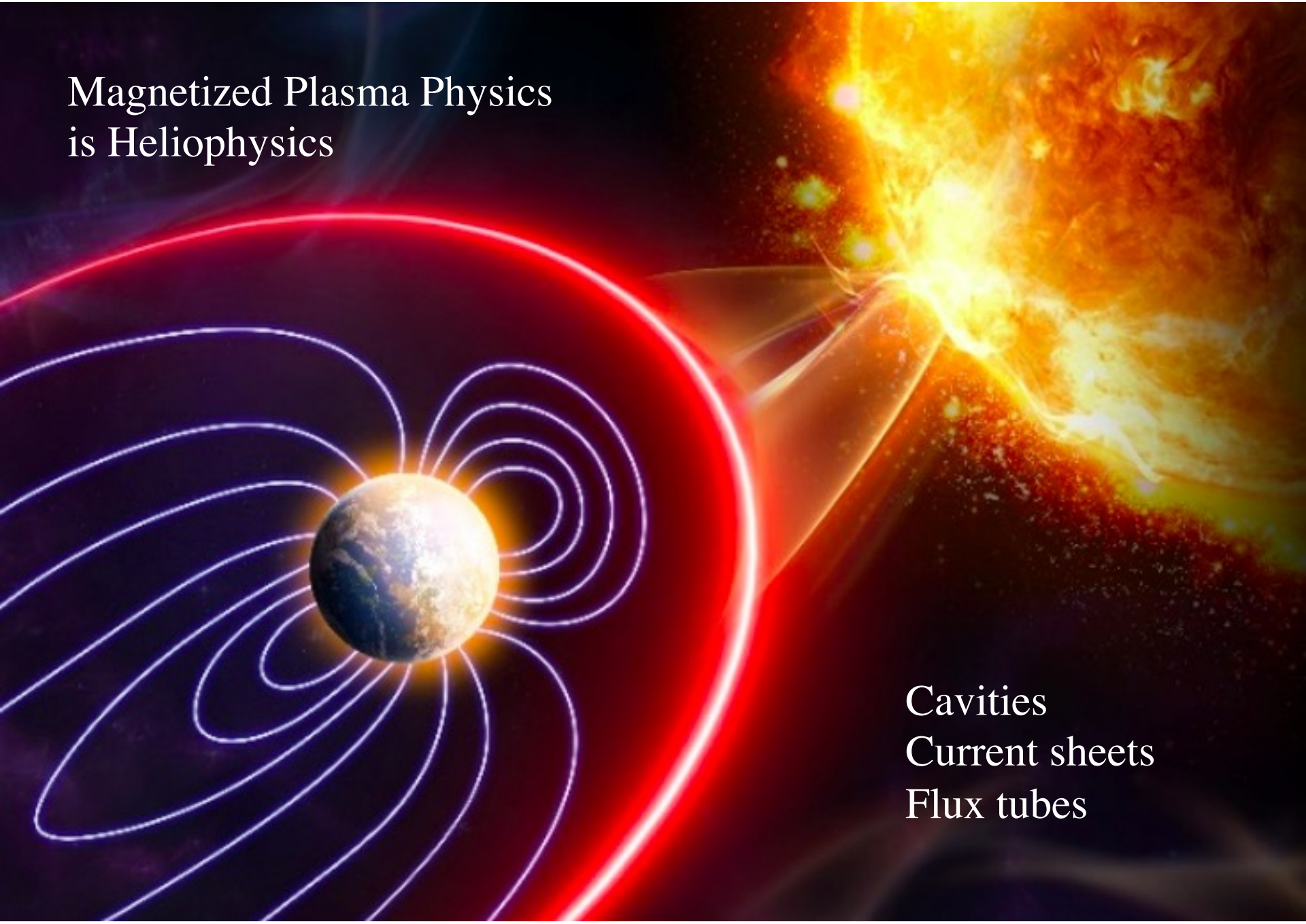
- Alpha effect (Parker): $E_\phi = \alpha B_\phi$

$\frac{\partial A_p}{\partial t} + \left(\frac{\mathbf{u}_p}{R} \cdot \nabla\right)(RA_p) = \alpha B_\varphi + \eta_m \left(\nabla^2 - \frac{1}{R^2}\right) A_p$

- This dynamo works!

Besides Dynamo, what creates a magnetic field in general?

- Lode stone
- Moving charge/dipole moment (qv)
- Electrical current ($j = nqv$)
- Time varying electric field


Magnetized Plasma Physics
is Heliophysics
Cavities
Current sheets
Flux tubes