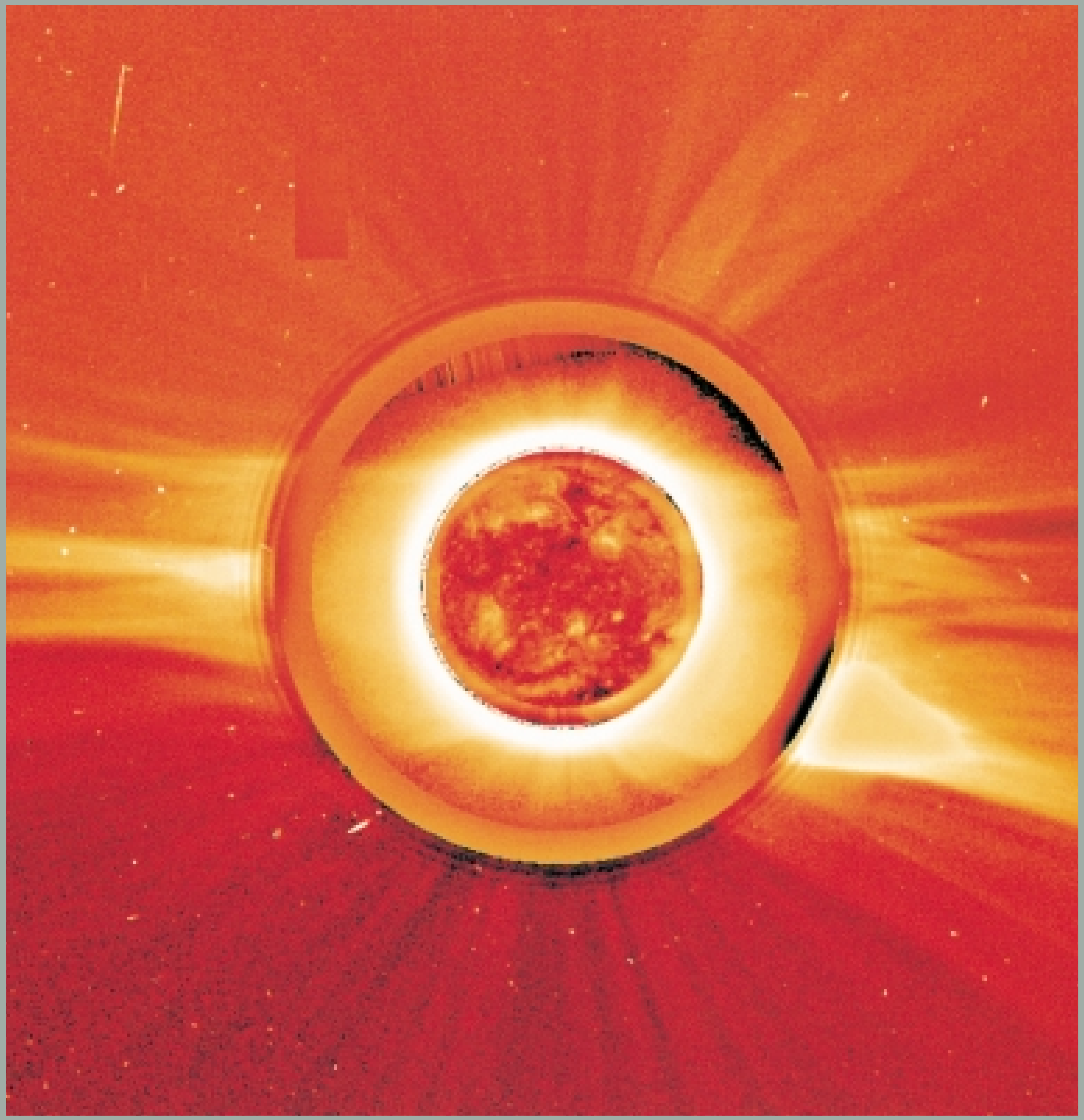
Magnetic Reconnection and Space Weather

Cesar La Hoz

The Arctic University of Norway

Cornell University

Swiss Re



Space weather
Hazard to the Earth?

Swiss Re

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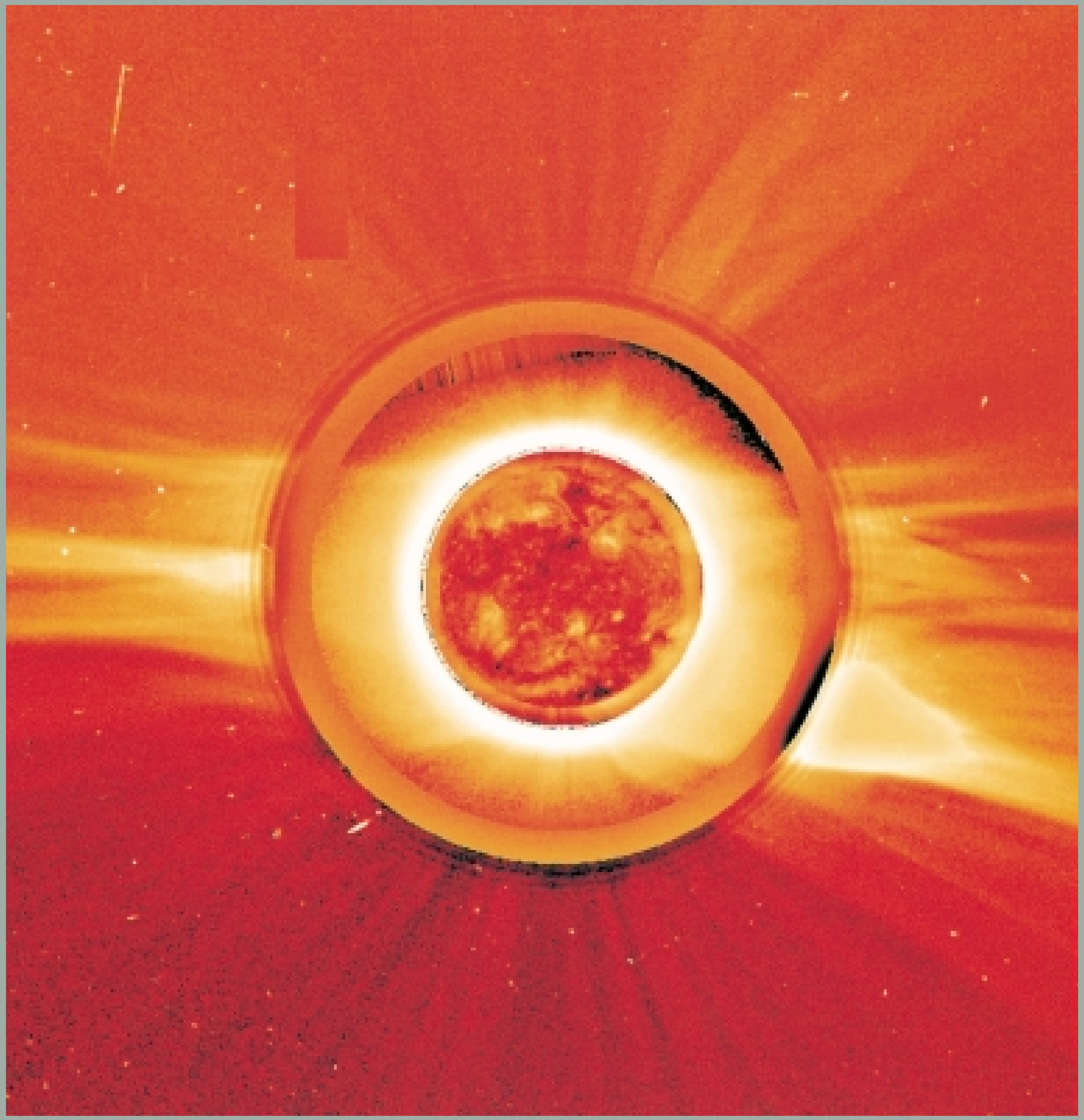

Space weather
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Re-insurance company

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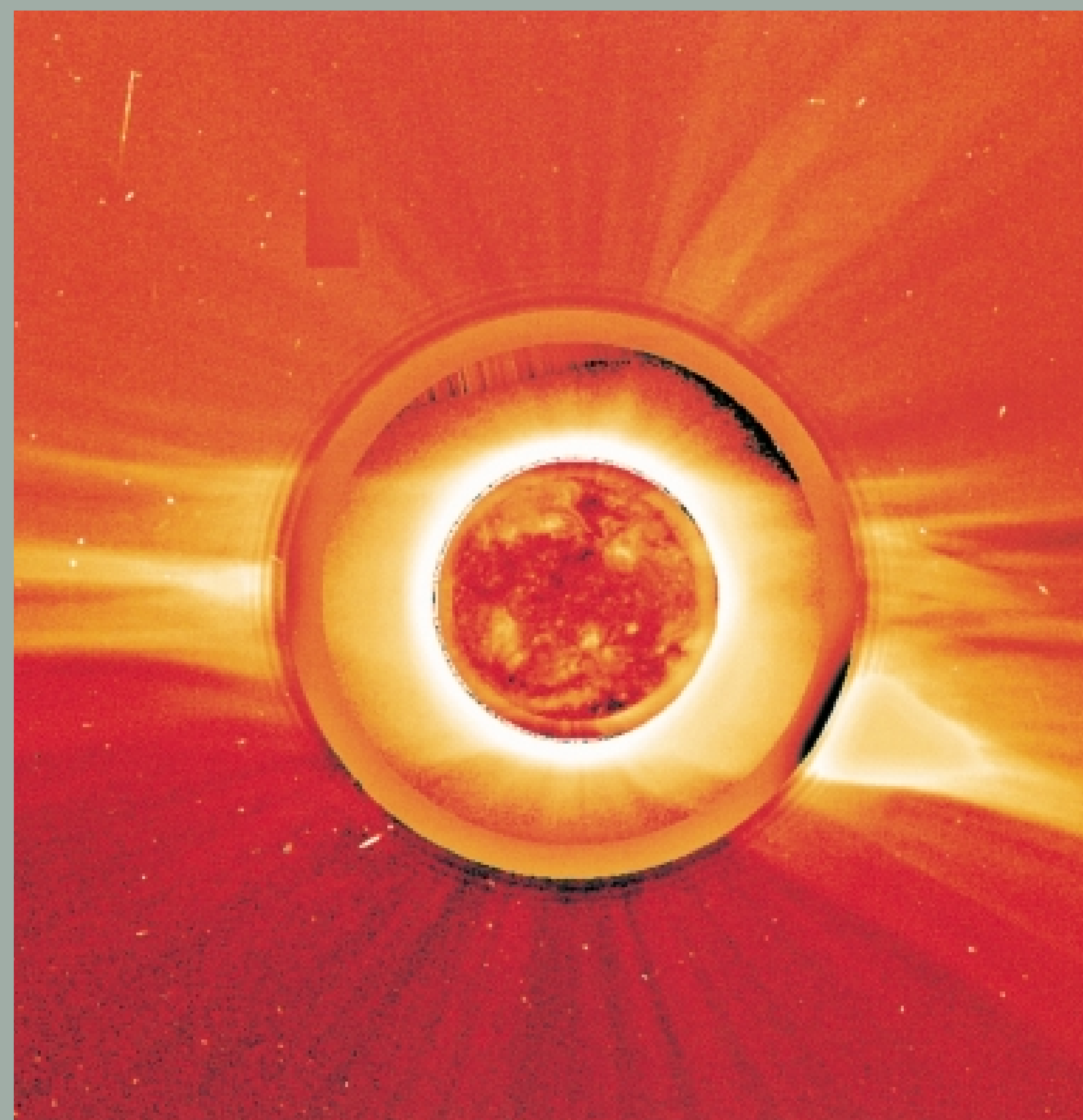

Space weather

Hazard to the Earth?

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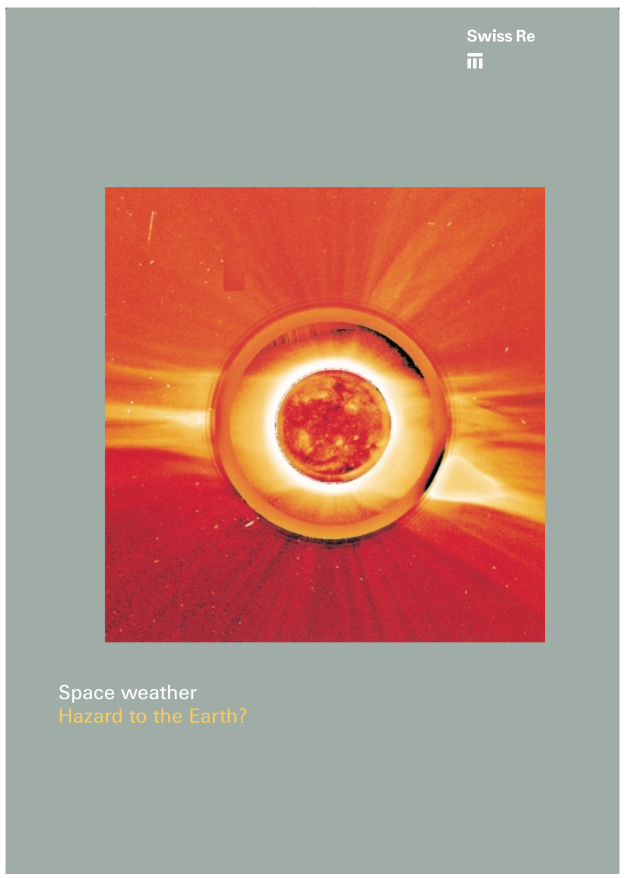

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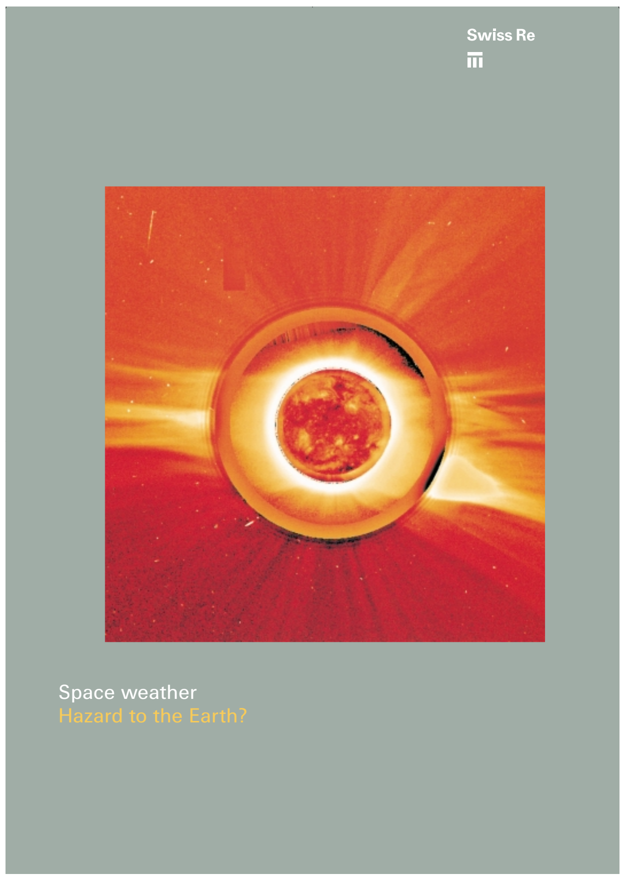

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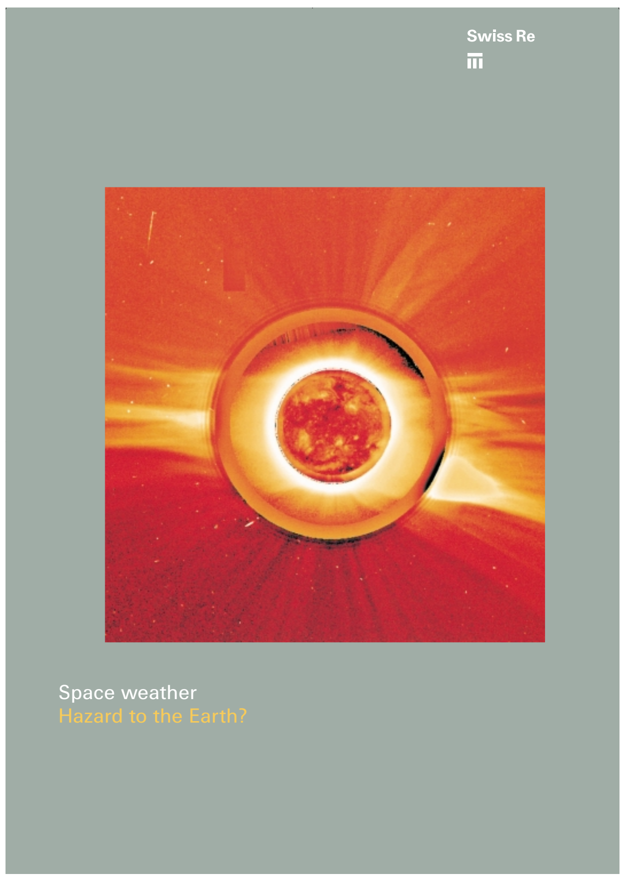

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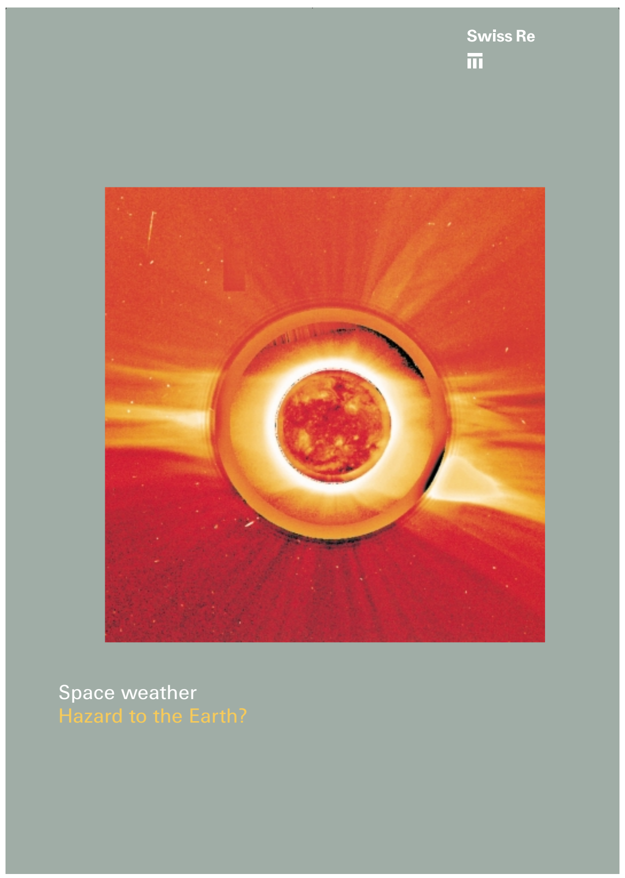

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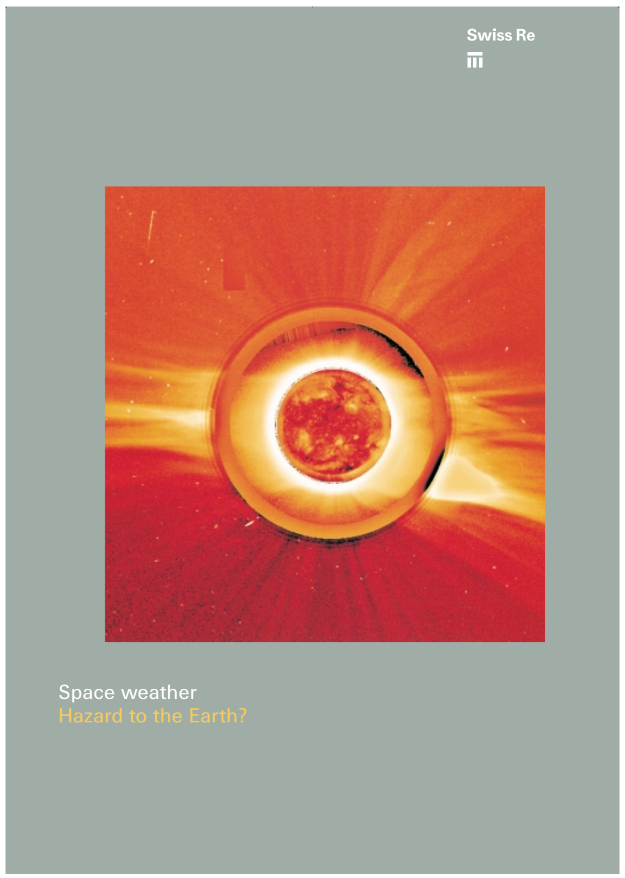

EOS
EOS, TRANSACTIONS, AMERICAN GEOPHYSICAL UNION

VOLUME 92 NUMBER 36
6 SEPTEMBER 2011
PAGES 297–304

Does the Space Environment Affect the Ecosphere?

PAGES 297–298

The Sun is now emerging from a deep and protracted solar minimum, when the power, pressure, flux, and magnetic flux of solar wind were at their lowest levels [*McComas et al.*, 2008; *Schwadron and McComas*, 2008; *Connick et al.*, 2011]. Because of an anomalously weak heliospheric magnetic field and low solar wind pressure, galactic cosmic rays (GCRs)—protons, electrons, and ionized nuclei of elements accelerated to high energies—achieved the highest fluxes observed in the space age (Figure 1) [*Mewaldt et al.*, 2010]. Related observations have shown remarkably rapid changes in the fluxes of energetic neutral atoms (ENAs) used by NASA's Interstellar Boundary Explorer mission to image the global heliosphere surrounding the solar system [*McComas et al.*, 2010]. These changes in ENAs are caused by decreasing solar wind pressure.

Does the recent anomalous deep solar minimum hint at larger changes in store? And how do changing GCR fluxes and conditions on the Sun influence Earth's ecosphere? Given the fact that GCR radiation can damage living tissue, causing cellular mutagenesis, the changing state of the Sun may have serious implications for life on the planet.

Sun, eventually reaching a value at which the solar wind pressure is roughly equal to the LISM pressure. The distance at which the solar wind pressure matches the LISM pressure sets the location of the termination shock, a sharp boundary where the solar wind abruptly transitions from a fast (supersonic) flow to a slower and hotter (subsonic) flow. Beyond this boundary, there is also a contact discontinuity separating the solar wind from the LISM flow, and even farther out there may be a bow shock or a bow wave [e.g., *Opher et al.*, 2009] where the LISM flow begins to be diverted around the heliosphere, a term denoting the volume of space surrounding the Sun caused by these solar wind interactions with the LISM.

These distant interstellar plasma boundaries and the outflowing solar wind partially protect the solar system by regulating the fluxes of GCRs that enter the solar system. GCRs are charged particles with relativistic energies, and they permeate our galaxy; because they are charged, their motions are governed by the magnetic fields they encounter. The most energetic GCRs penetrate even the powerful magnetic fields closest to Earth, ultimately colliding with and producing complex interactions with Earth's massive atmosphere, such as cosmic ray air showers,

Sun, which leads to a temporary buildup of magnetic flux in the heliosphere during solar maximum when CMEs are more frequent [*Owens and Crooker*, 2006; *Schwadron et al.*, 2010]. The strengthened and disordered heliospheric magnetic fields near solar maxima inhibit GCRs from entering the heliosphere. In solar minima the weakened and ordered heliospheric magnetic field allows more GCRs to pass through the heliosphere and into Earth's atmosphere.

Superimposed on the effects of the changing magnetic field are the effects of the solar wind pressure, which has been gradually eroding in successive minima since about 1990 on the basis of data from NASA's Advanced Composition Explorer (ACE) and the Wind spacecraft, as well as on data from the joint NASA–European Space Agency Ulysses spacecraft [e.g., *McComas et al.*, 2008]. As seen in Figure 1c, the solar wind pressure has been dropping since about 2005, which caused the interstellar boundaries to move inward toward the Sun, shrinking the size of the heliosphere over time. The high GCR fluxes recently observed are the combined effect of a smaller heliosphere and decreases in both solar wind and magnetic flux; this weaker solar wind is far less effective in shielding the inner heliosphere from GCRs.

Large changes in the LISM may also have dramatic effects on the heliosphere and its ability to modulate GCRs. Passage of the solar system through a typical enhancement (by a factor of 10) in the density of the LISM causes the entire heliosphere to shrink to about a

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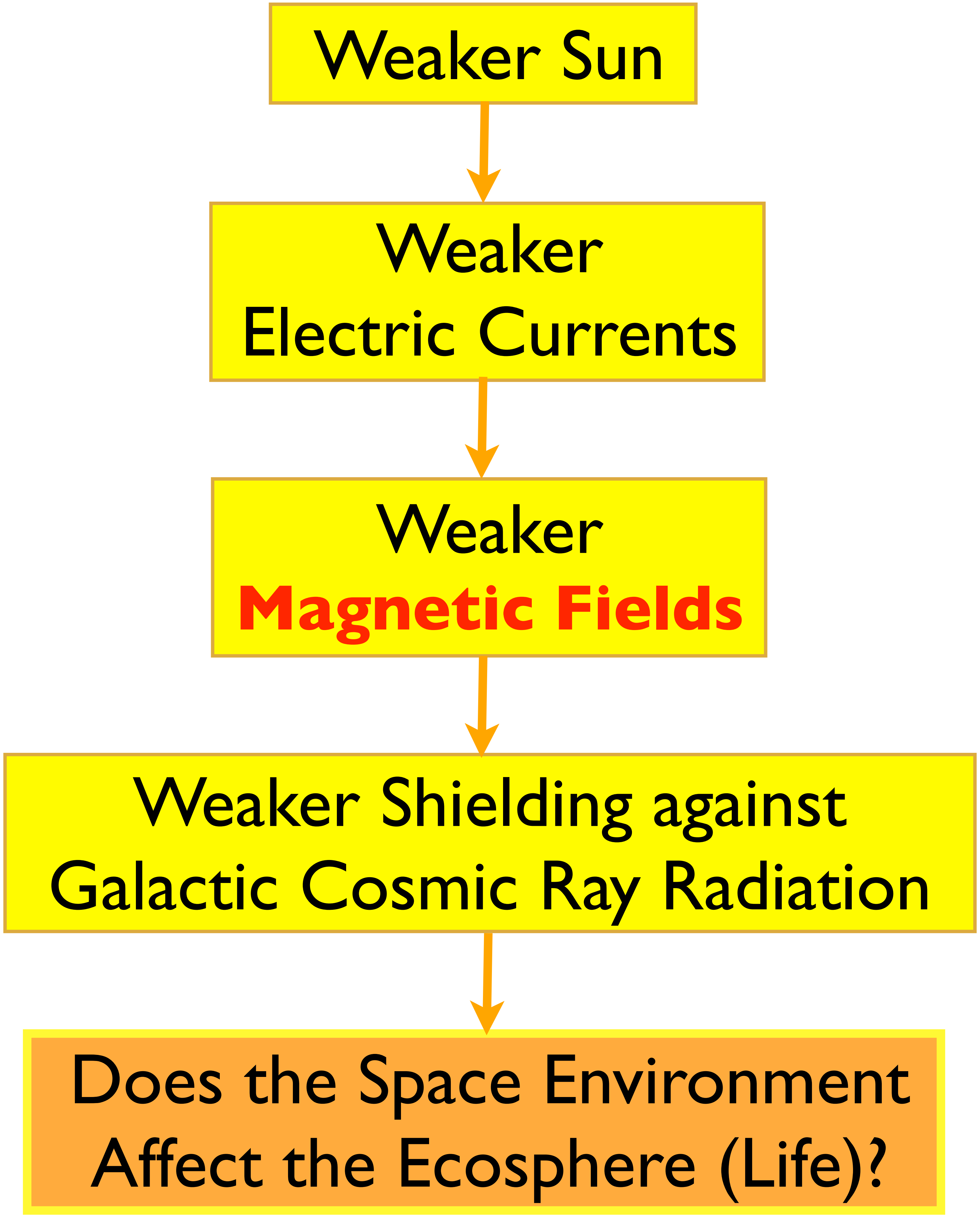
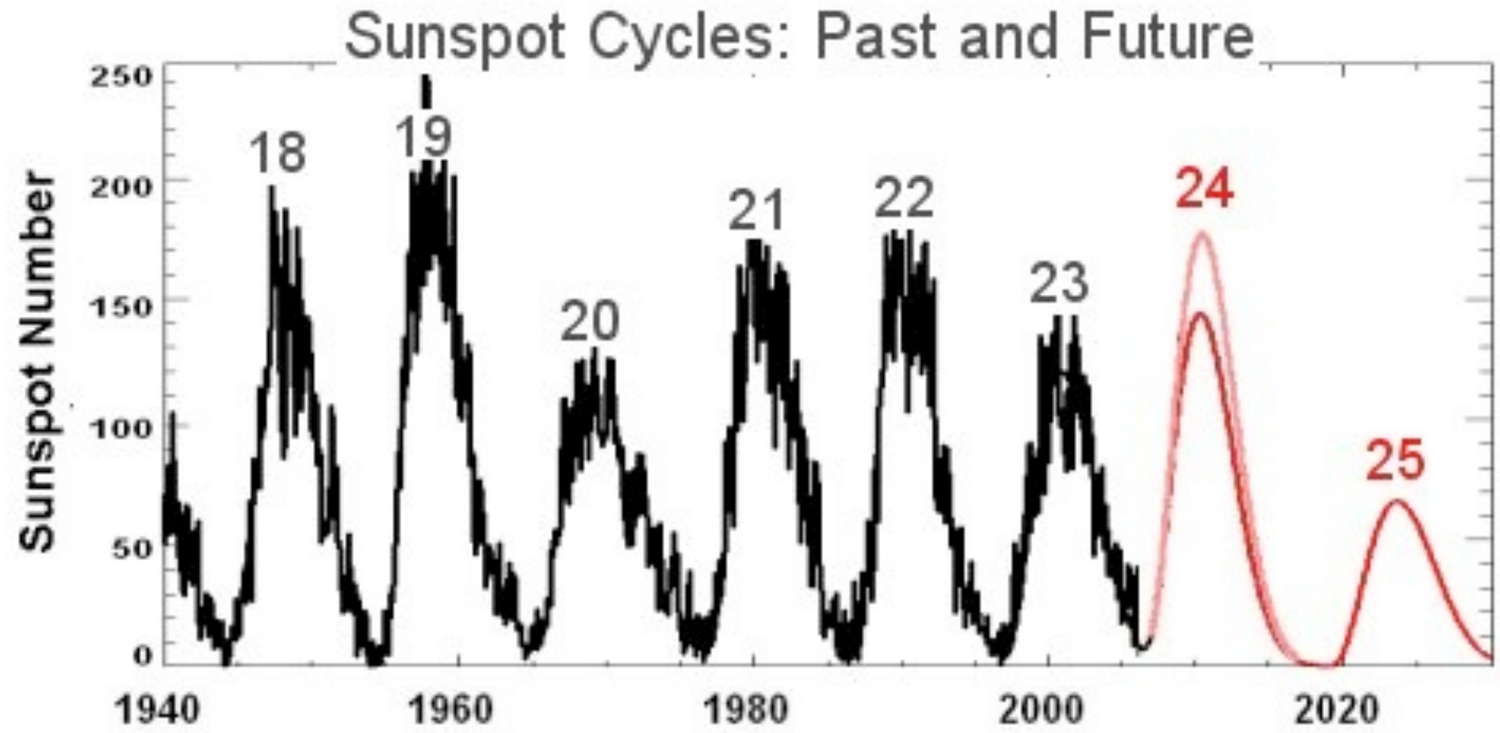
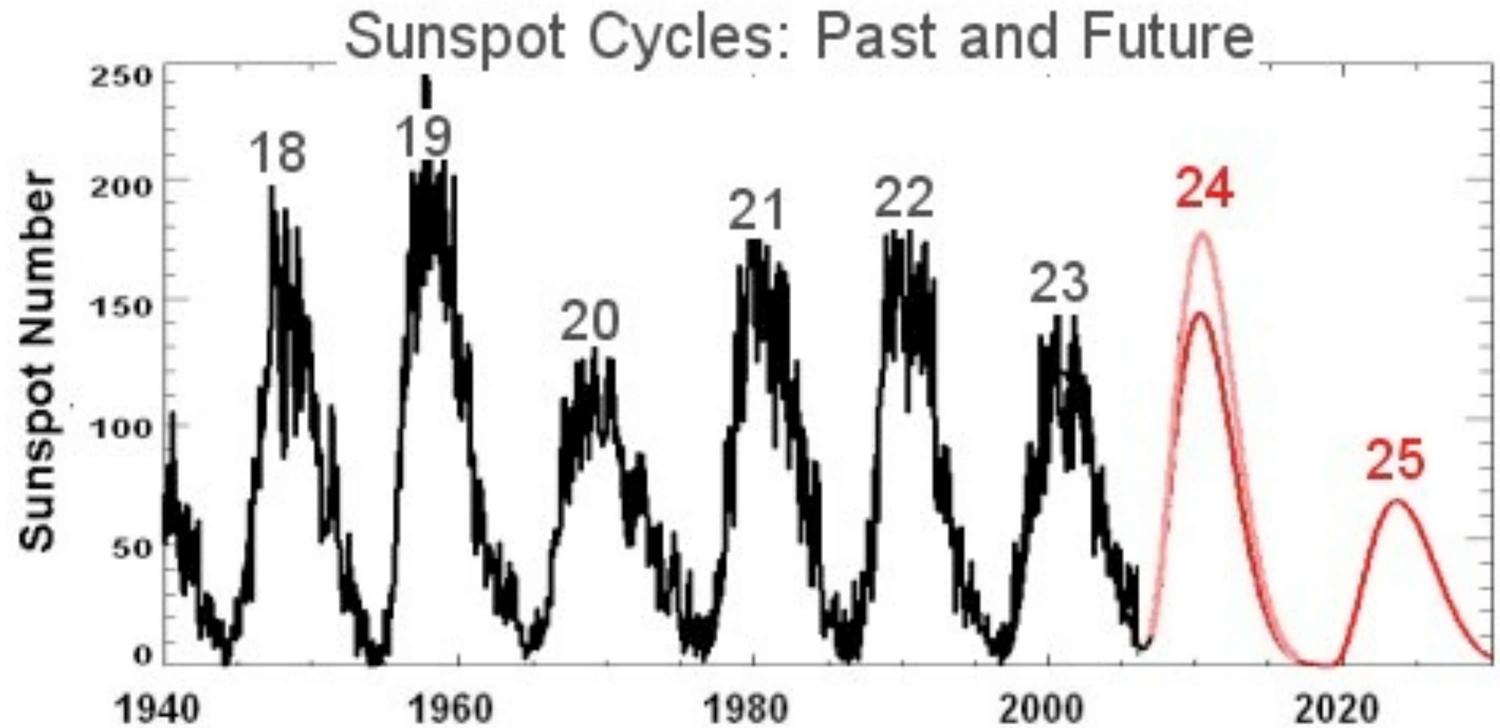

Weaker Sun
Weaker Electric Currents
Weaker **Magnetic Fields**
Weaker Shielding against Galactic Cosmic Ray Radiation
Does the Space Environment Affect the Ecosphere (Life)?



Sunspot Cycles: Past and Future
Sunspot Number
250
200
150
100
50
0
1940
1960
1980
2000
2020
18
19
20
21
22
23
24
25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22
23
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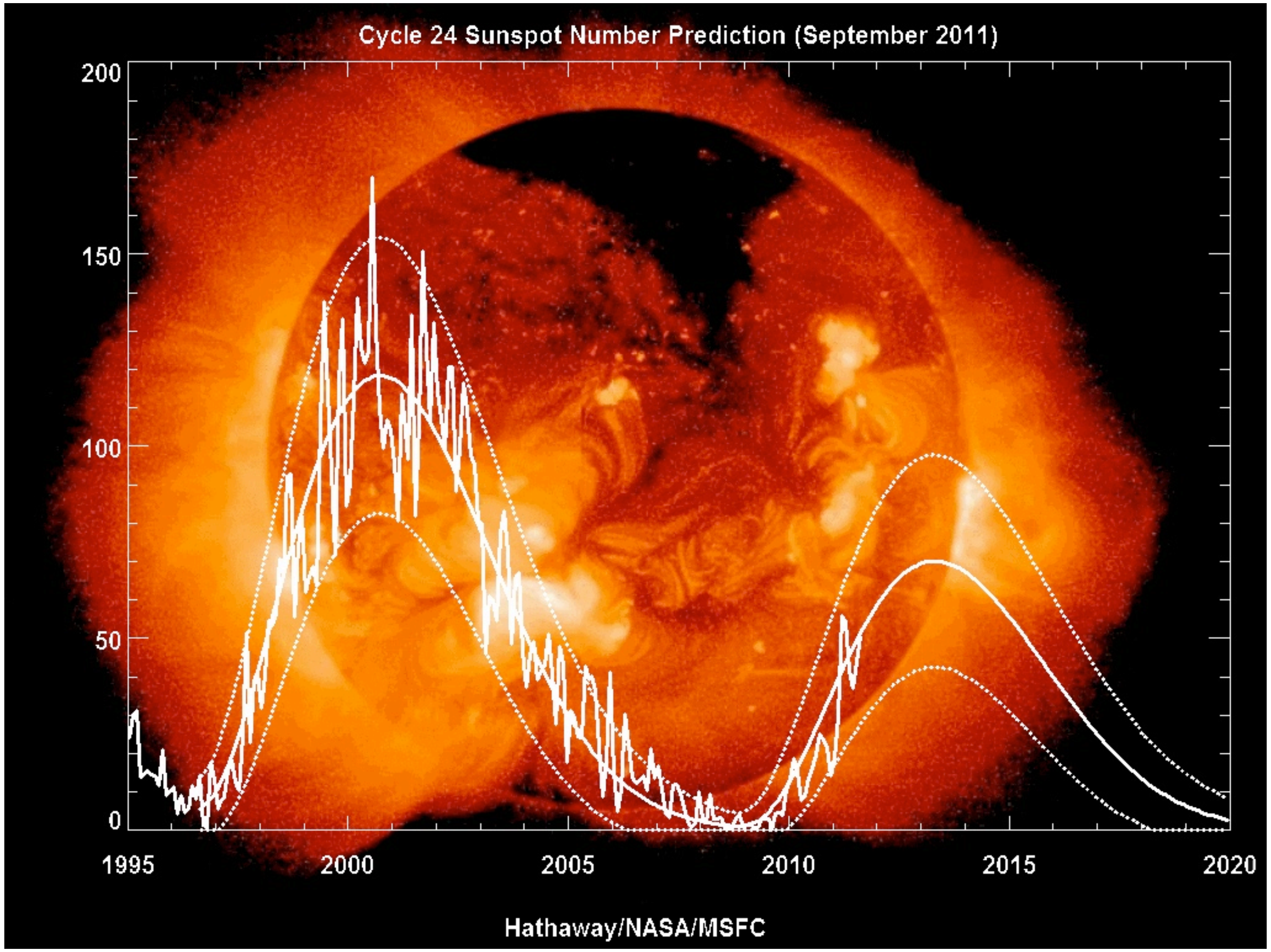
Cycle 24 Sunspot Number Prediction (September 2011)
200
150
100
50
0
1995
2000
2005
2010
2015
2020
Hathaway/NASA/MSFC

Reconnection Accounts for of most Space Weather
The Largest Variations
Low Probability High Risk Events

Magnetic Reconnection is almost certainly the energy release mechanism in:

- Solar flares and Coronal Mass Ejections (CME's)
- Geomagnetic storms and substorms

Without Reconnection Space Weather Uneventful

Ingredients

Magnetic Field Pressure & Tension

Magnetic Field Convection & Diffusion

Magnetohydrodynamics (MHD) Equations

Moments of the Kinetic Equation & Maxwells Equations

$$\partial_t \rho_m + \nabla \cdot (\rho_m \mathbf{V}) = 0$$ **Mass Conservation**

$$\rho_m \mathrm{d}_t \mathbf{V} = \mathbf{J} \times \mathbf{B} - \nabla P$$ **Momentum Conservation**

force/volume

$$\mathbf{J} = \sigma(\mathbf{E} + \mathbf{V} \times \mathbf{B})$$ **Ohm's Law**

$$\mathrm{d}_t (P \rho_m^{-\gamma}) = 0$$ **Equation of State**

$$\nabla \times \mathbf{B} = \mu_o \mathbf{J}$$ **Ampère's Law**

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

$$\nabla \times \mathbf{E} = -\partial_t \mathbf{B}$$ **Faraday's Law**

$$\nabla \cdot \mathbf{E} = 0$$ **Gauss's Law**

Maxwell

The Lorentz Force: Magnetic Pressure & Tension

$\mathbf{J} \times \mathbf{B}$ is the Lorentz force density (force/volume) on the plasma

☆ $$\underbrace{\mathbf{J} \times \mathbf{B}}_{\text{force/volume}} = \frac{1}{\mu_o}(\mathbf{B} \cdot \nabla)\mathbf{B} - \nabla\left(\frac{B^2}{2\mu_0}\right)$$

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psswrd: 1302

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$$\overleftrightarrow{\mathbf{T}} = \begin{pmatrix} B^2/2\mu_o & & \\ 0 & & \\ 0 & 0 & -B^2/2\mu_o \end{pmatrix}$$

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$$= \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -B^2/\mu_o \end{pmatrix} + \begin{pmatrix} B^2/2\mu_o & 0 & 0 \\ 0 & B^2/2\mu_o & 0 \\ 0 & 0 & B^2/2\mu_o \end{pmatrix}$$

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Magnetic Pressure
isotropic

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Magnetic Tension
field-aligned

Magnetic Pressure
isotropic

Magnetic Tension & Pressure

$$\mathbf{J} \times \mathbf{B} = \frac{1}{\mu_o}(\mathbf{B} \cdot \nabla)\mathbf{B} - \nabla\left(\frac{B^2}{2\mu_0}\right)$$

Magnetic Tension & Pressure

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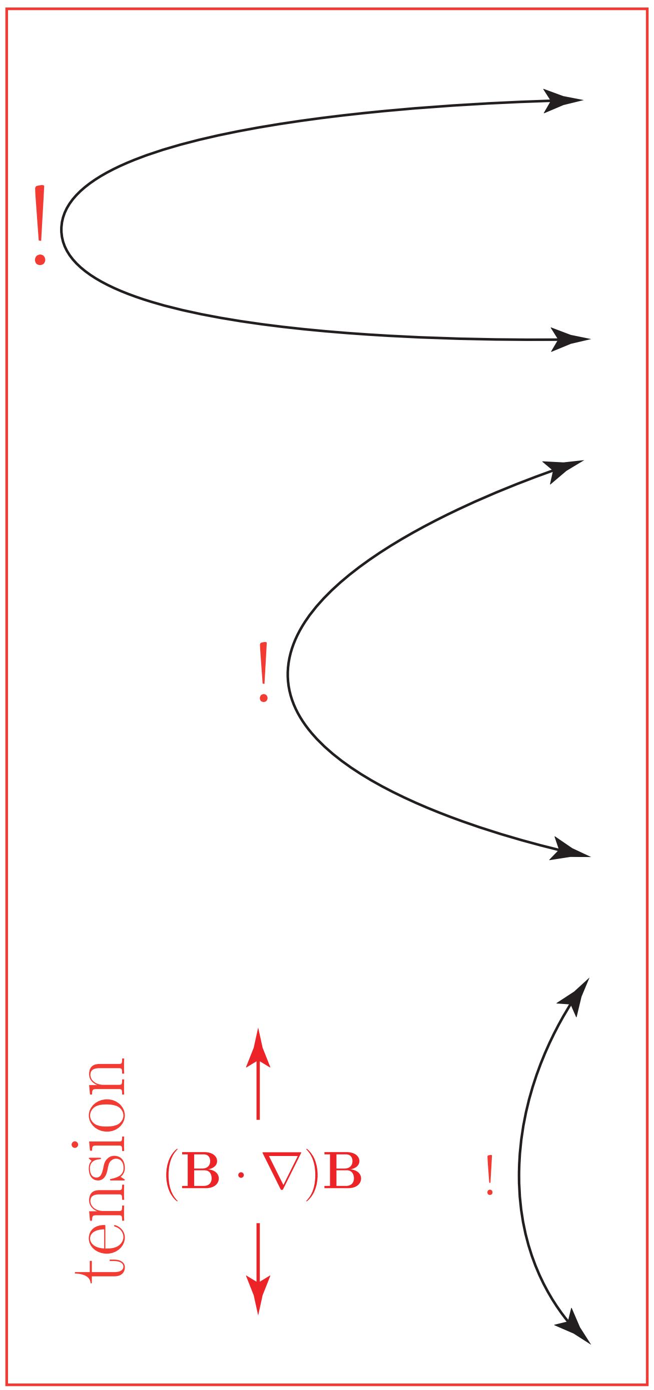
Tension



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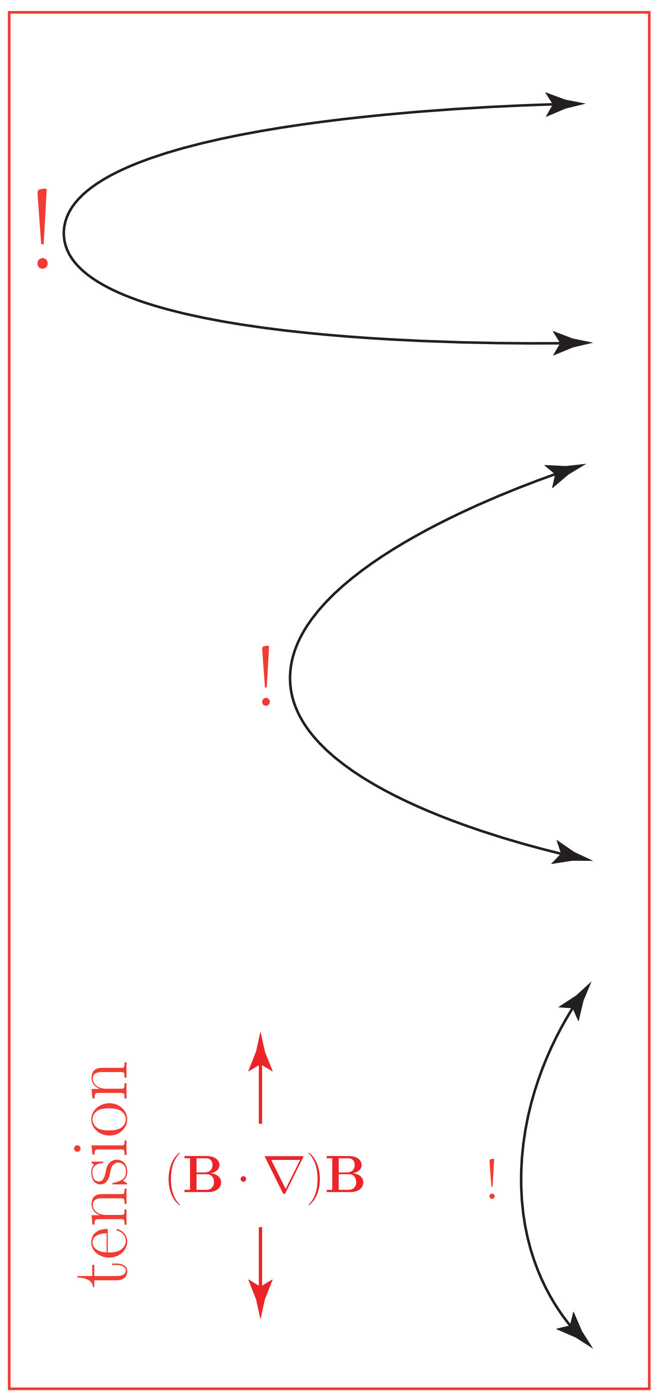
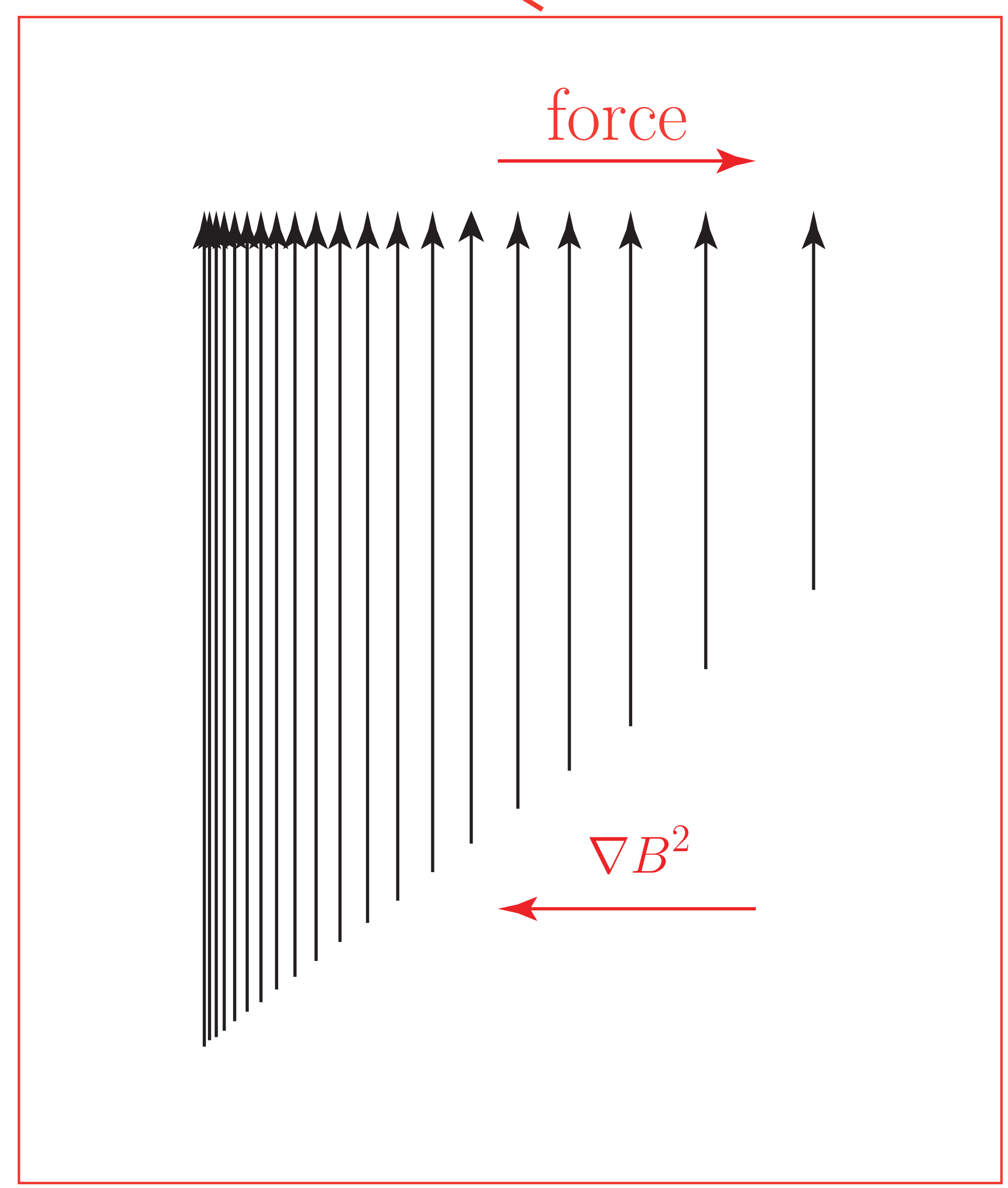


Pressure



Magnetic Tension & Pressure

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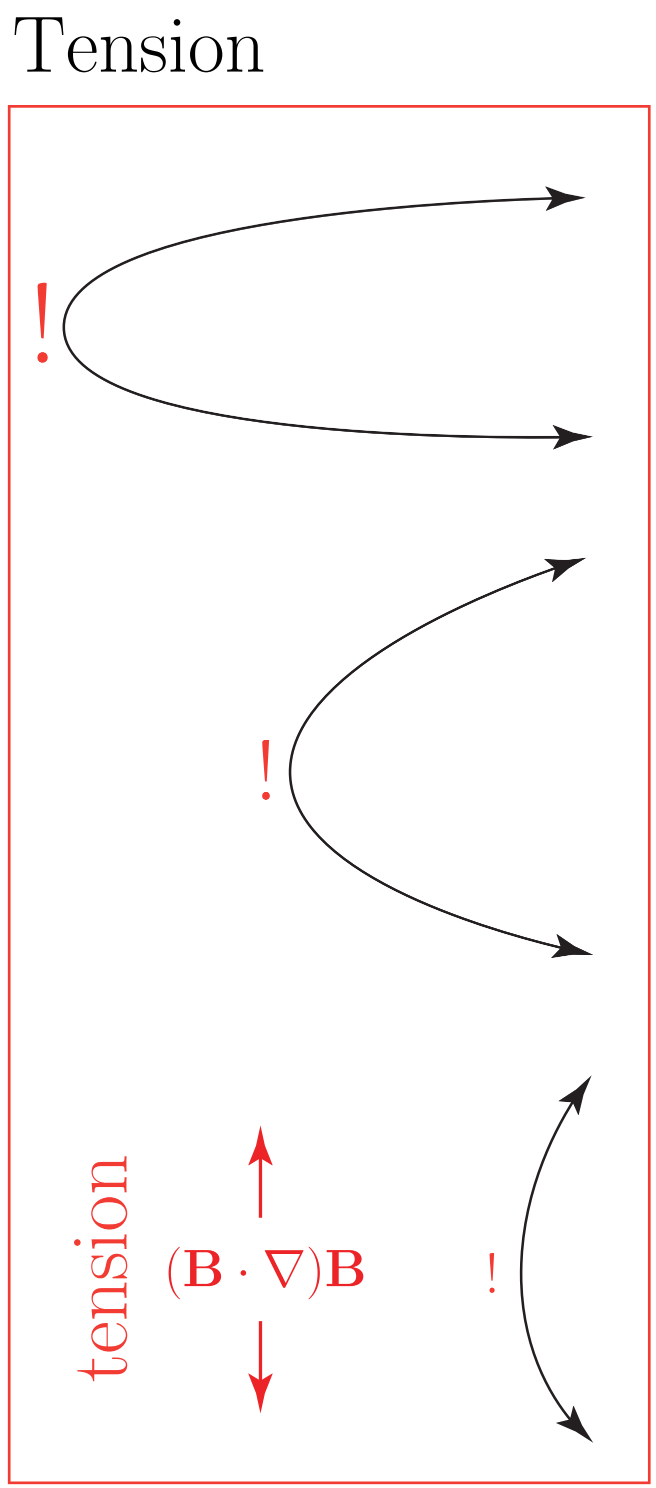
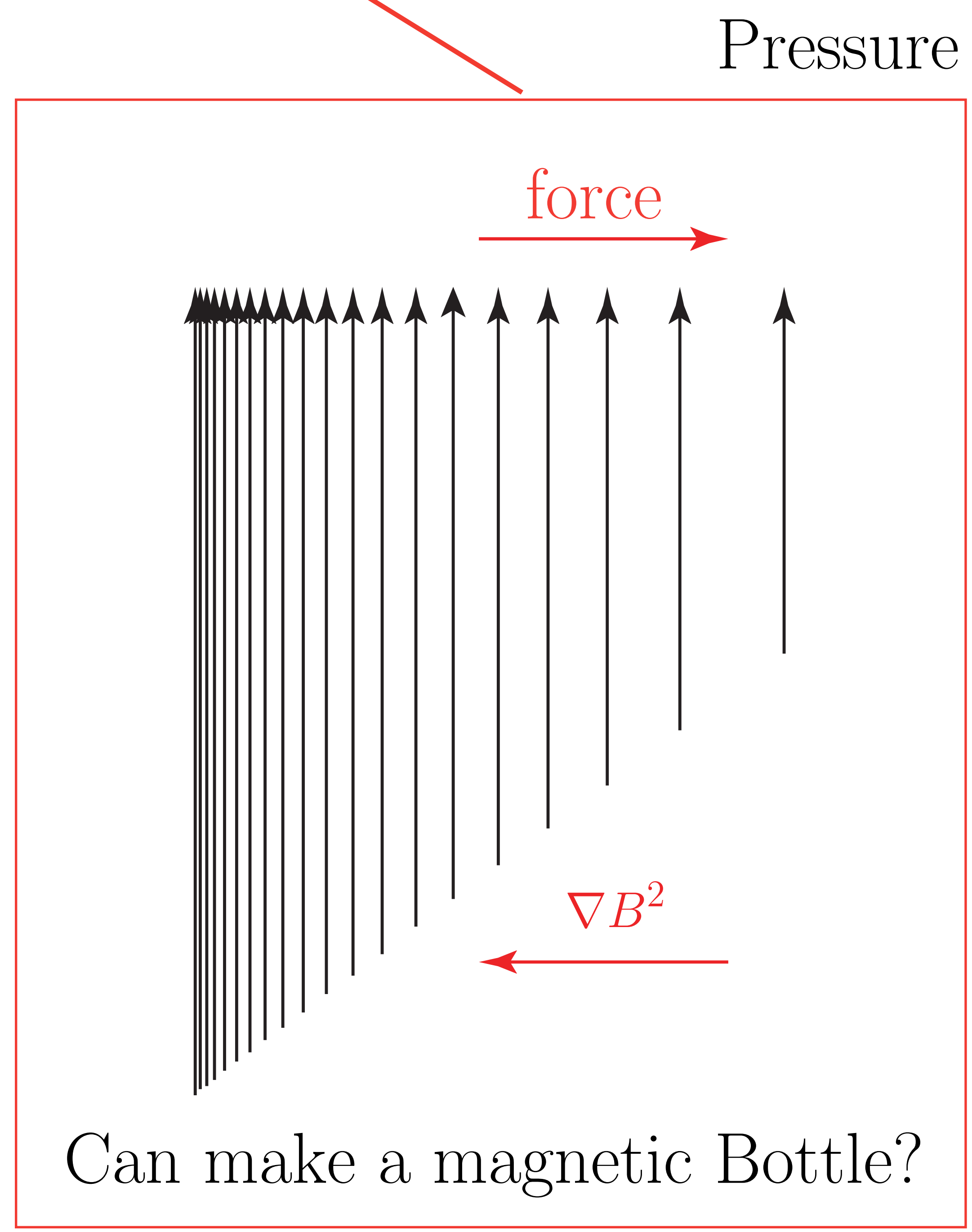
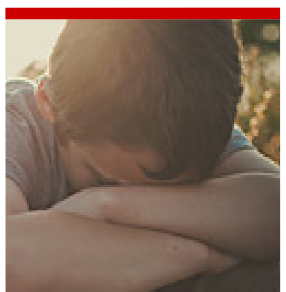




TIME Magazine U.S.

Science: Magnetic Bottle

Monday, June 18, 1956



Project Sherwood, the secret U.S. program to achieve controlled thermonuclear (atomic fusion) power, came ever so slightly into the open last week. After attending a secret conference of 350 Sherwood men at Gatlinburg, Tenn., Dr. Edward Teller, leading authority on thermonuclear processes, delivered a complicated paper before an unclassified meeting of the American Nuclear Society at Chicago.

Teller's speech did not give the present status of U.S. thermonuclear research, but it did give a great deal of background, new to most outsiders, about the path (or one of the paths) that Project Sherwood is following.

Small Star. In the stars, said Teller, thermonuclear reactions are possible because the great mass of the star provides a gravitational field that holds the reacting gases together, even though their temperature may be very high. Human scientists have better nuclear fuel than the stars have, but they cannot hold their gases together gravitationally. No material container can do the trick, either; its walls would be melted instantly if they came in contact with reacting gases at the necessary high temperature.

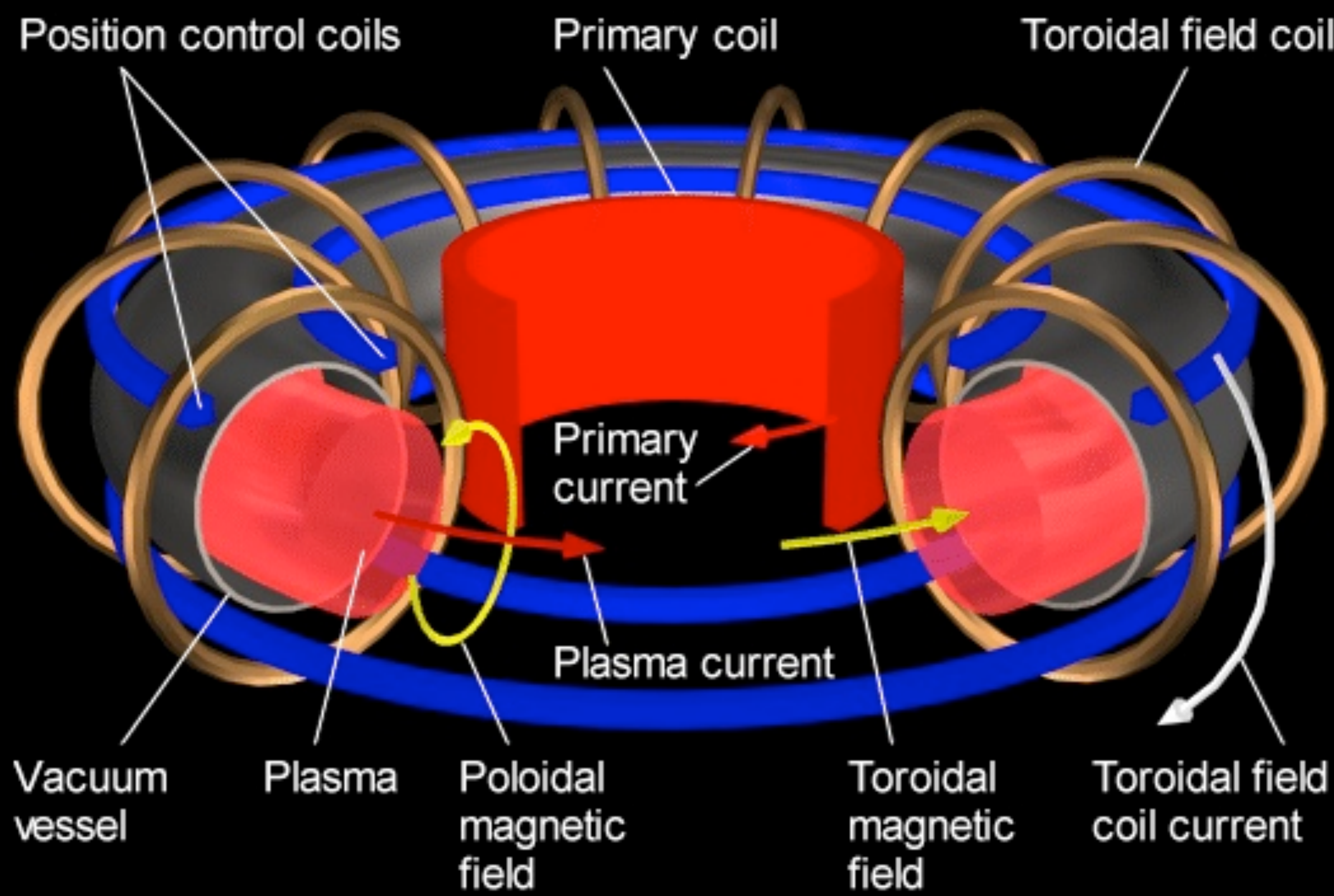
One way to create a "small star" that reacts at enormous temperature without touching anything material is to confine the gases in a "magnetic bottle." Teller explained that the gases would be completely ionized by the heat. All the particles in them would have electric charges, and would be strongly influenced by a magnetic field. If the field could be made strong enough, the particles would spiral tightly in it, keeping away from vulnerable walls of the material container.

Tricky Balance. Leakproof magnetic bottles, Physicist Teller pointed out, are not easy to construct. The magnetism must be just strong enough to confine the ionized gases at the right density and temperature, and keep them confined long enough for a reaction to take place. The reaction would release energy and raise the temperature, so the magnetic field must grow stronger when necessary to keep things in balance. Power must be drawn out of the system without disturbing its tricky balance.

Teller did not tell in detail how this could be done, but he gave a long chain of complex equations showing how energy is released in reacting gases (deuterium or tritium), and how energy escapes from the system. He gave a few general hints about how the lines of magnetic force affect and confine the moving ions. He did not sound lightly confident; repeatedly, he pointed to serious difficulties.

But Teller believes that the job can be done, given enough time and effort. "I am confident," he said, "that controlled thermonuclear reactors will eventually be constructed. I do not believe that the power derived from such reactors will compete at an early date with conventional energy sources or with fission [uranium] reactors."

Magnetic Bottle in Thermonuclear Fusion
The Tokamak



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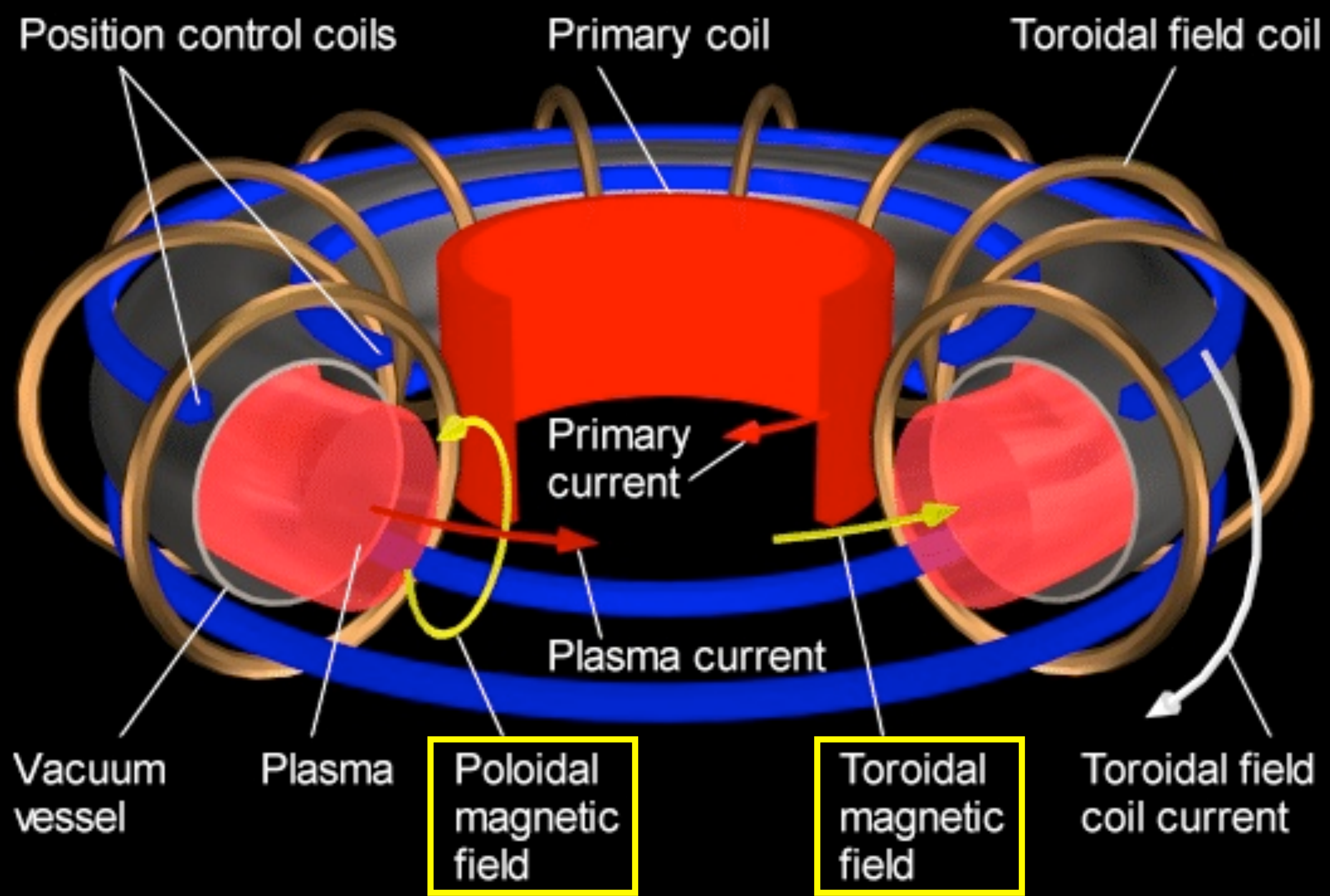
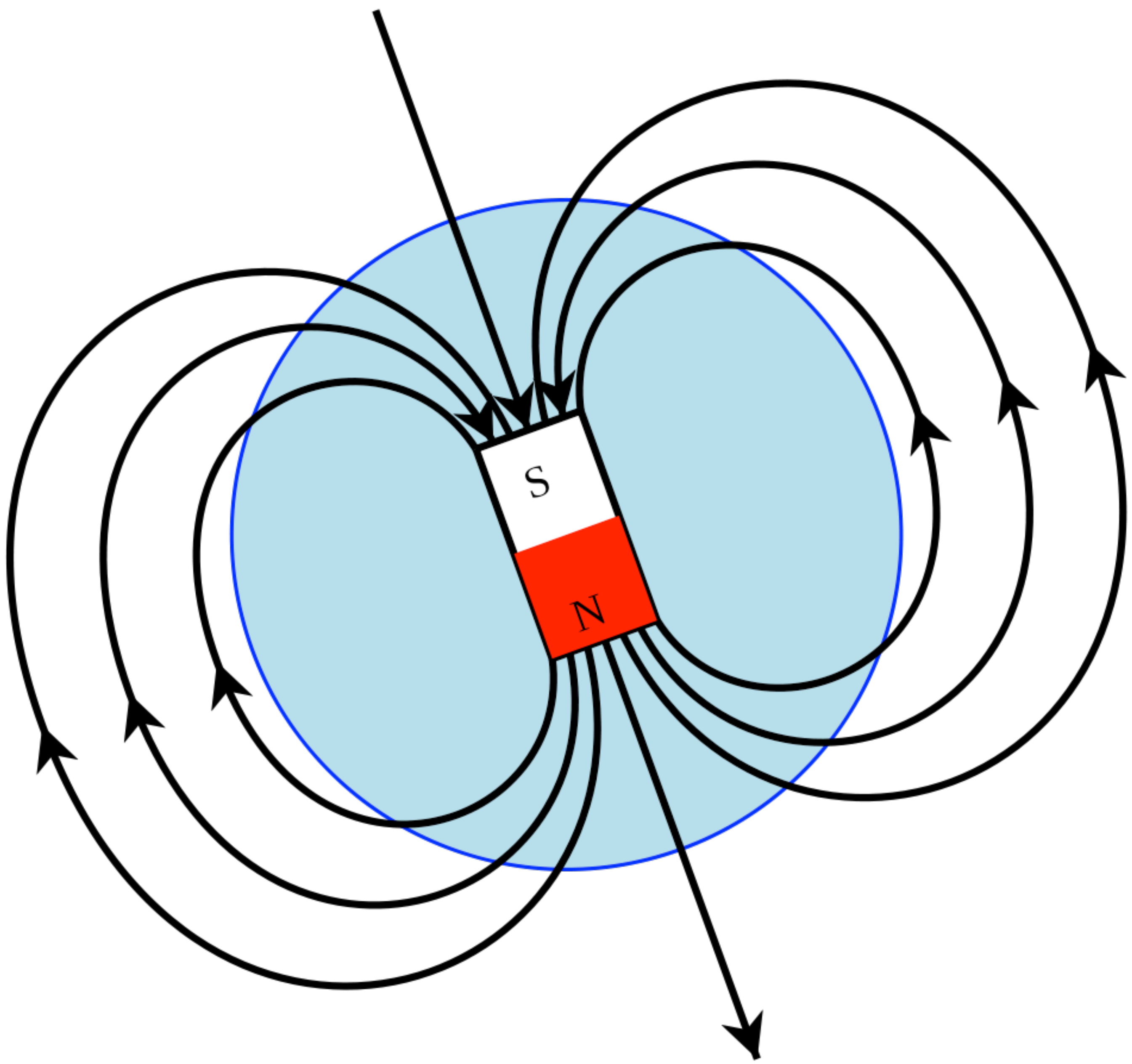


The Earth's Magnetic Field is Dipolar

Like that of a bar magnet



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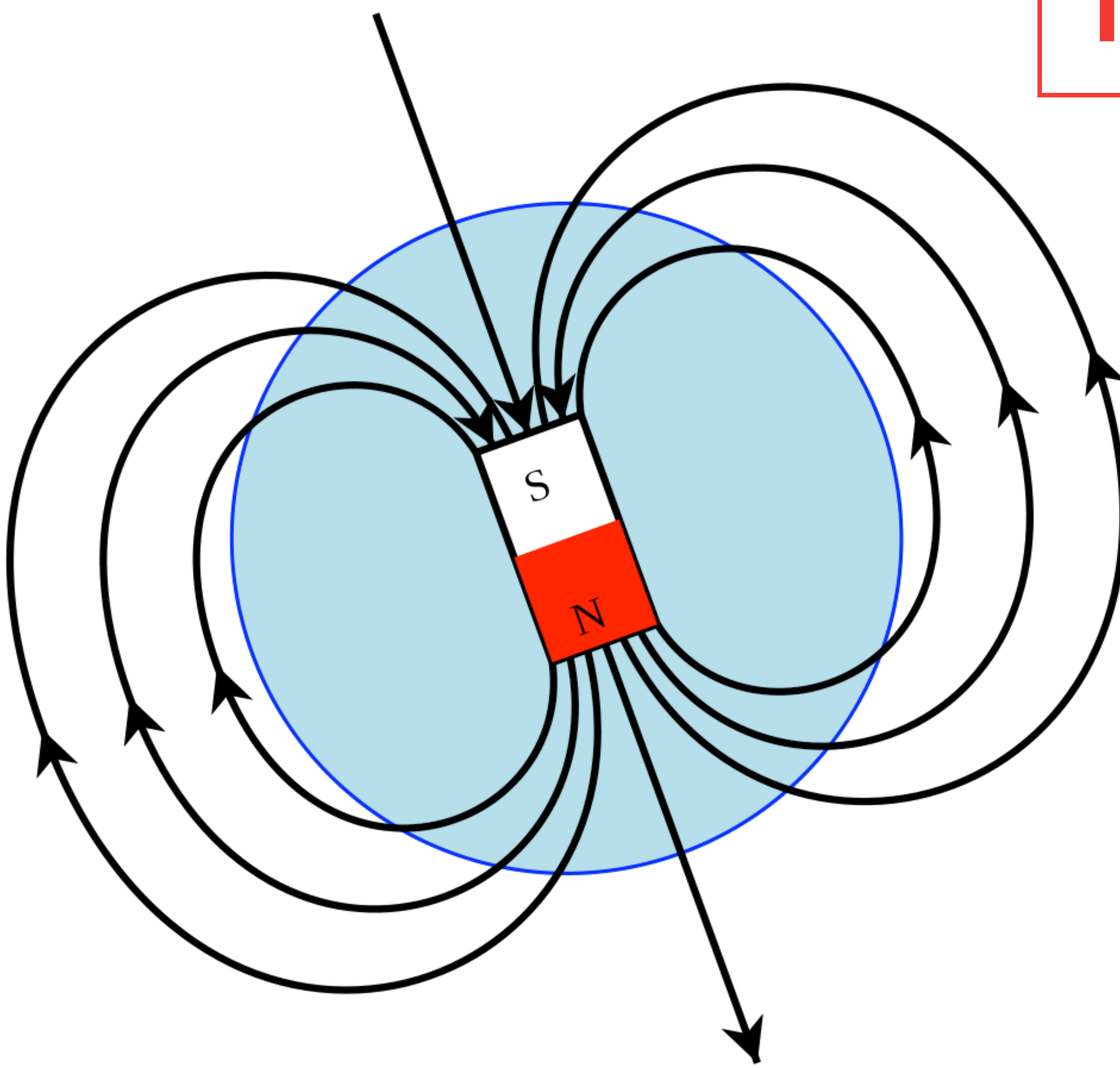
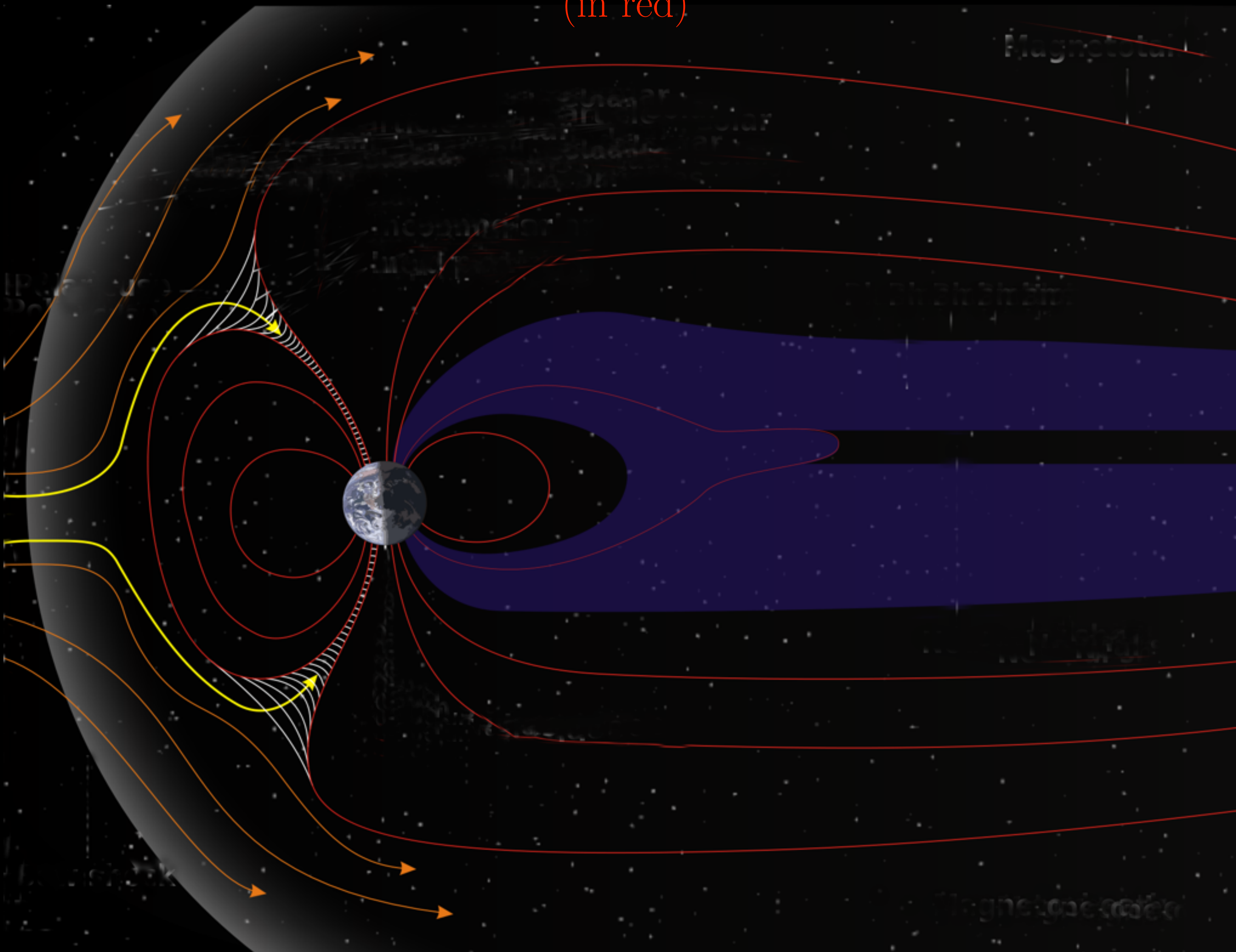
Is it ???



The Earth's Magnetic Field is NOT Dipolar

(in red)



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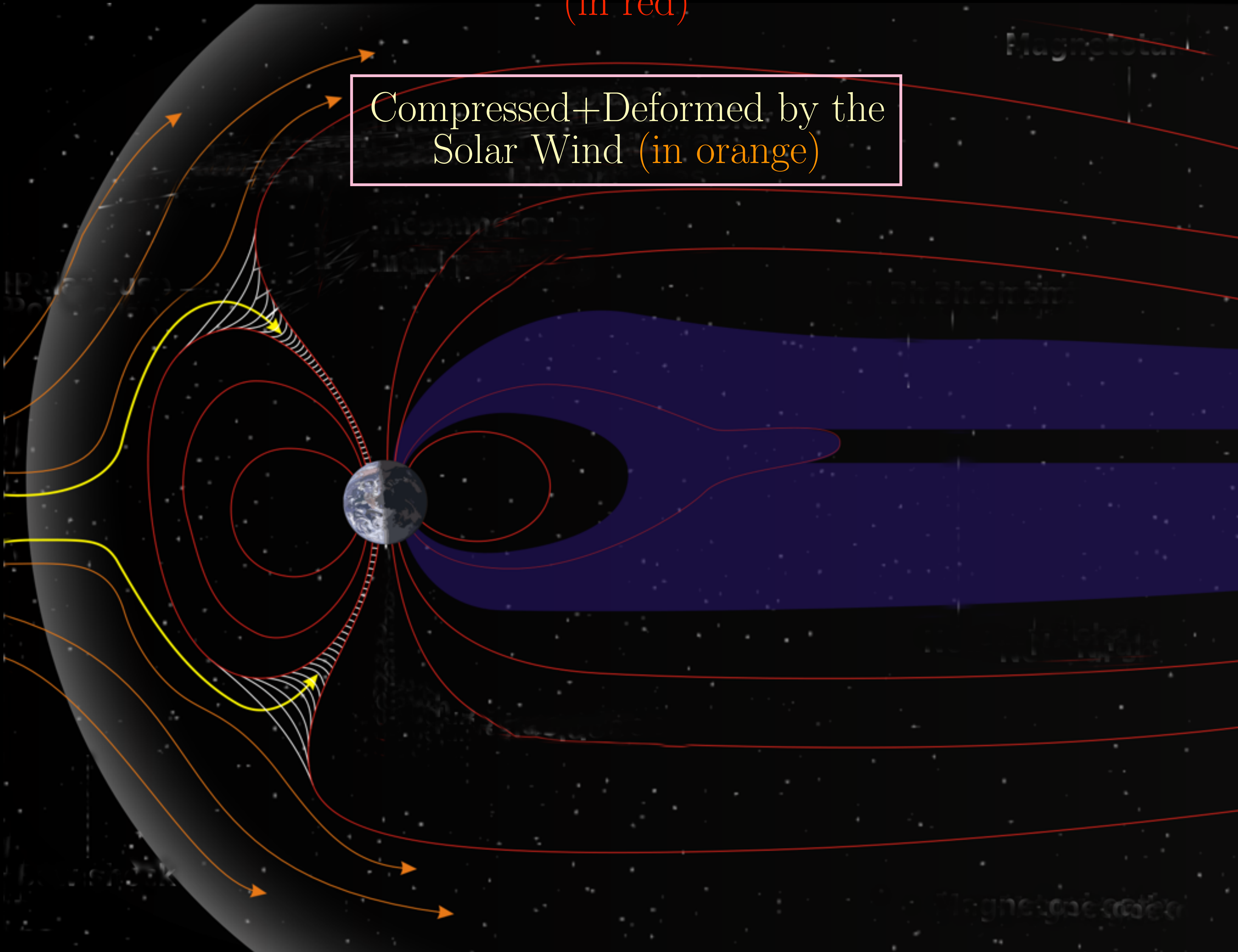

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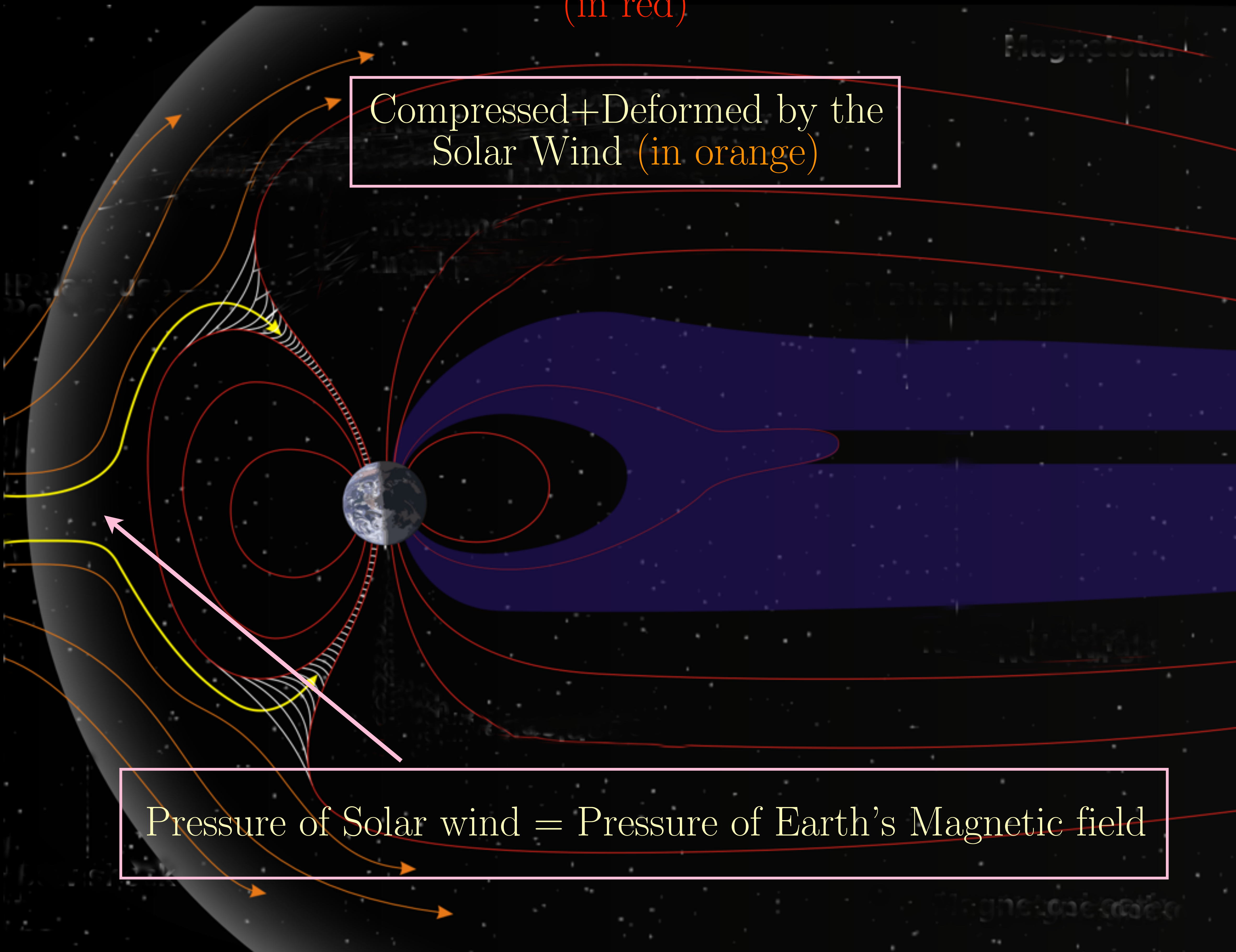

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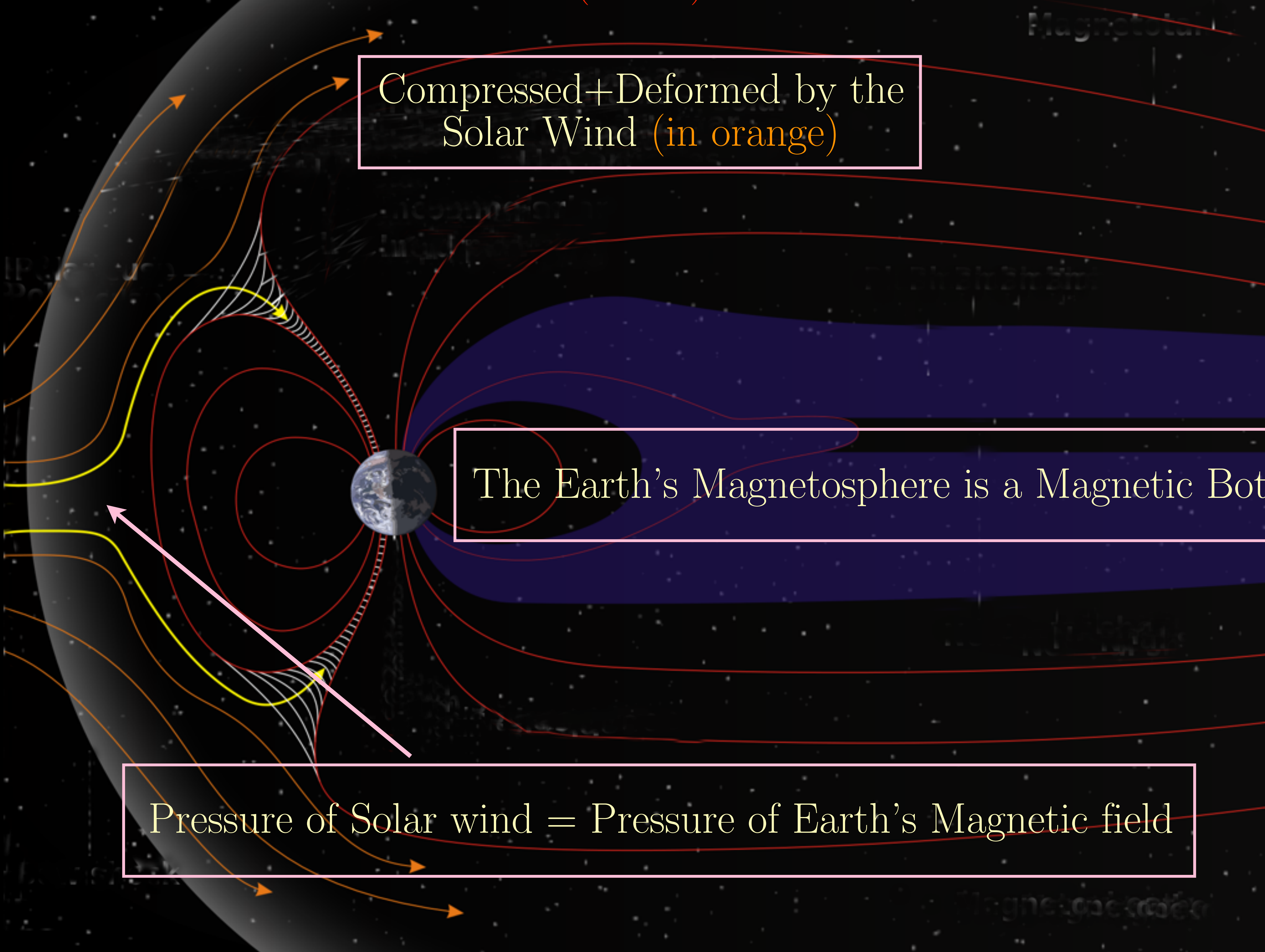

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Earth's "Magnetic Tail" – Magnetotail, Shaped by the Solar Wind

Our Sun throws off dense clouds of super-hot gas that sail across the solar system and slam into Earth at a million miles per hour!

The Earth's magnetic field looks something like a comet with Earth at the head of the comet and a long (million-mile) magneto-tail flowing out behind Earth.

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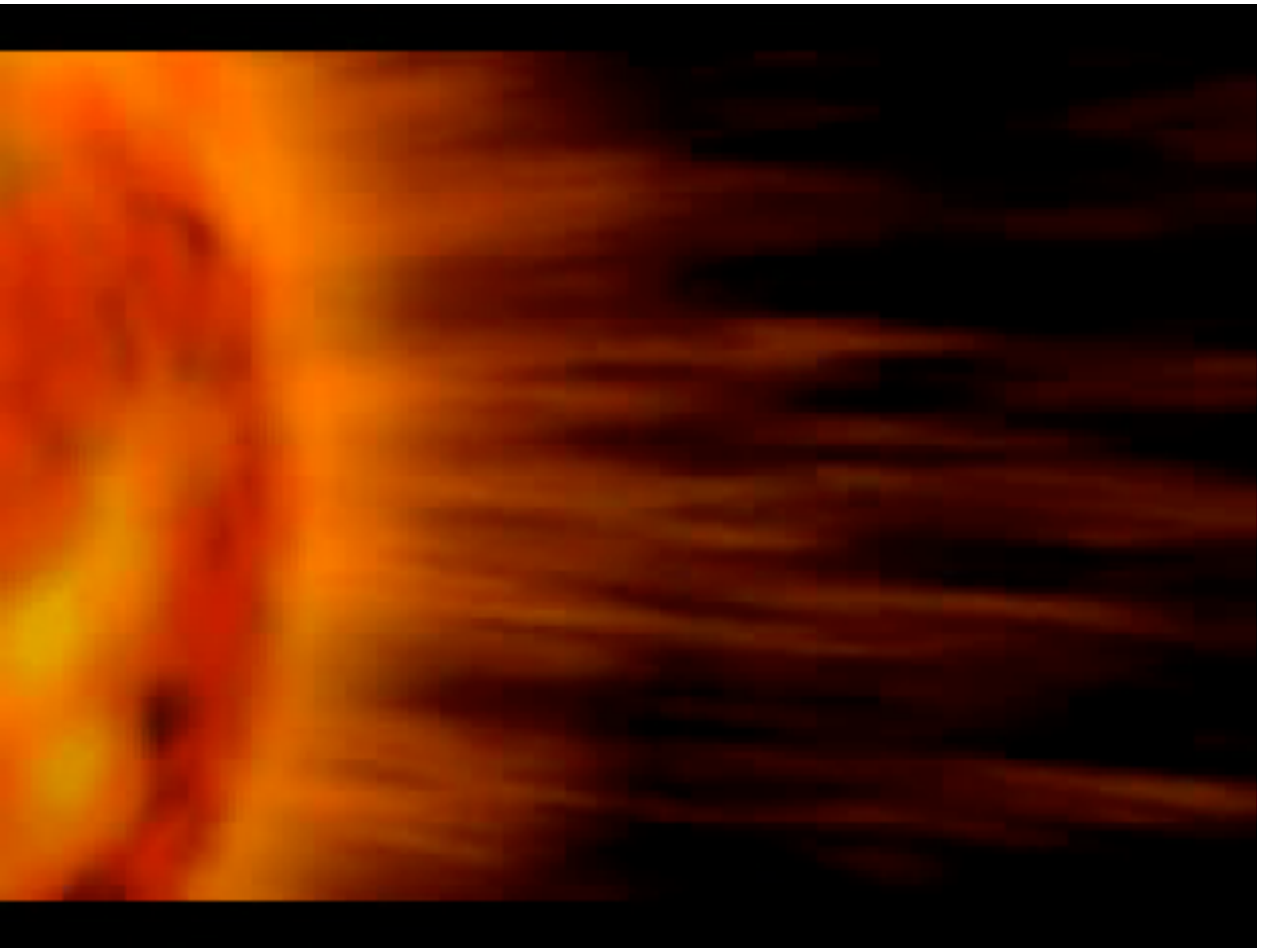

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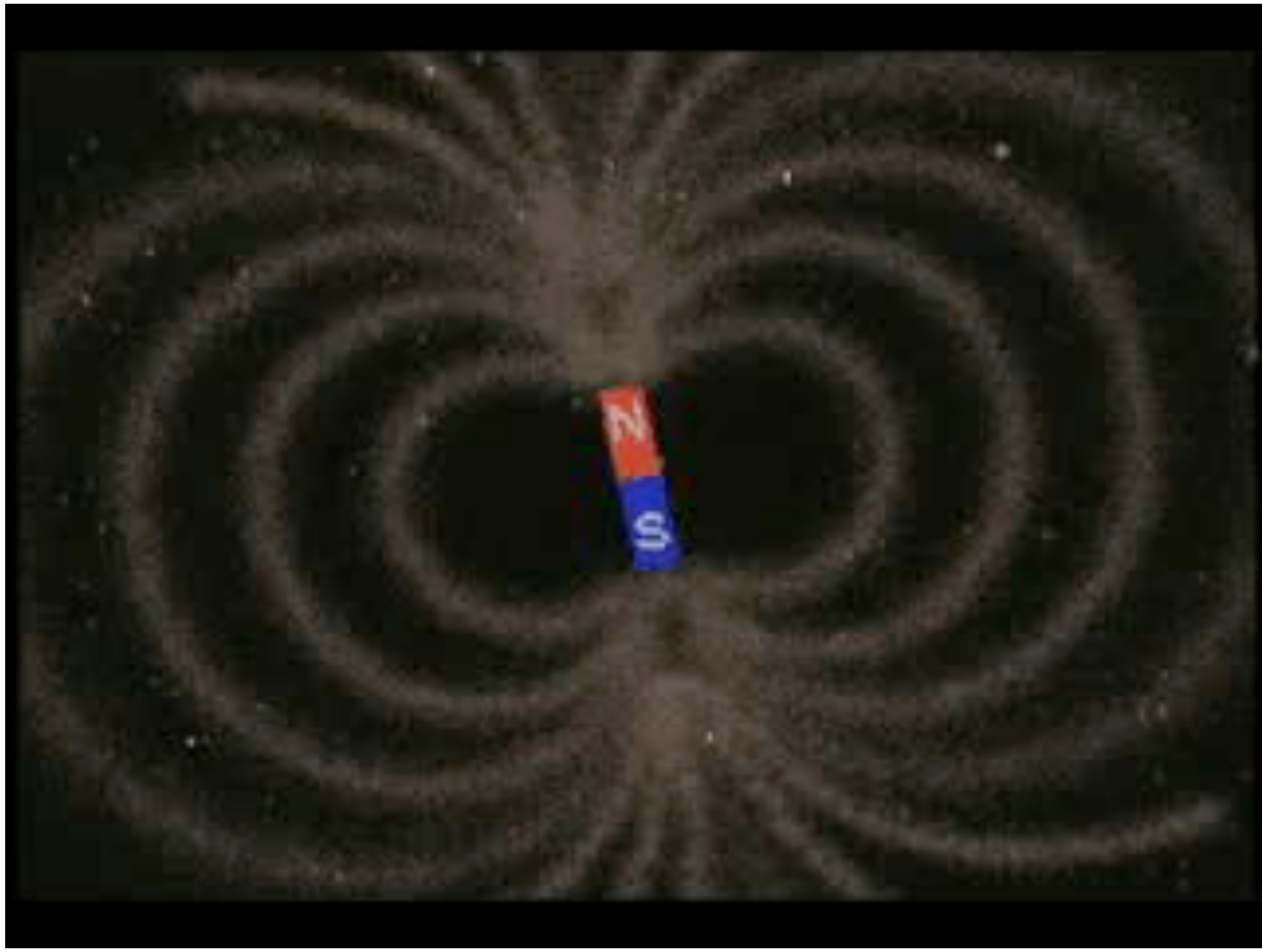

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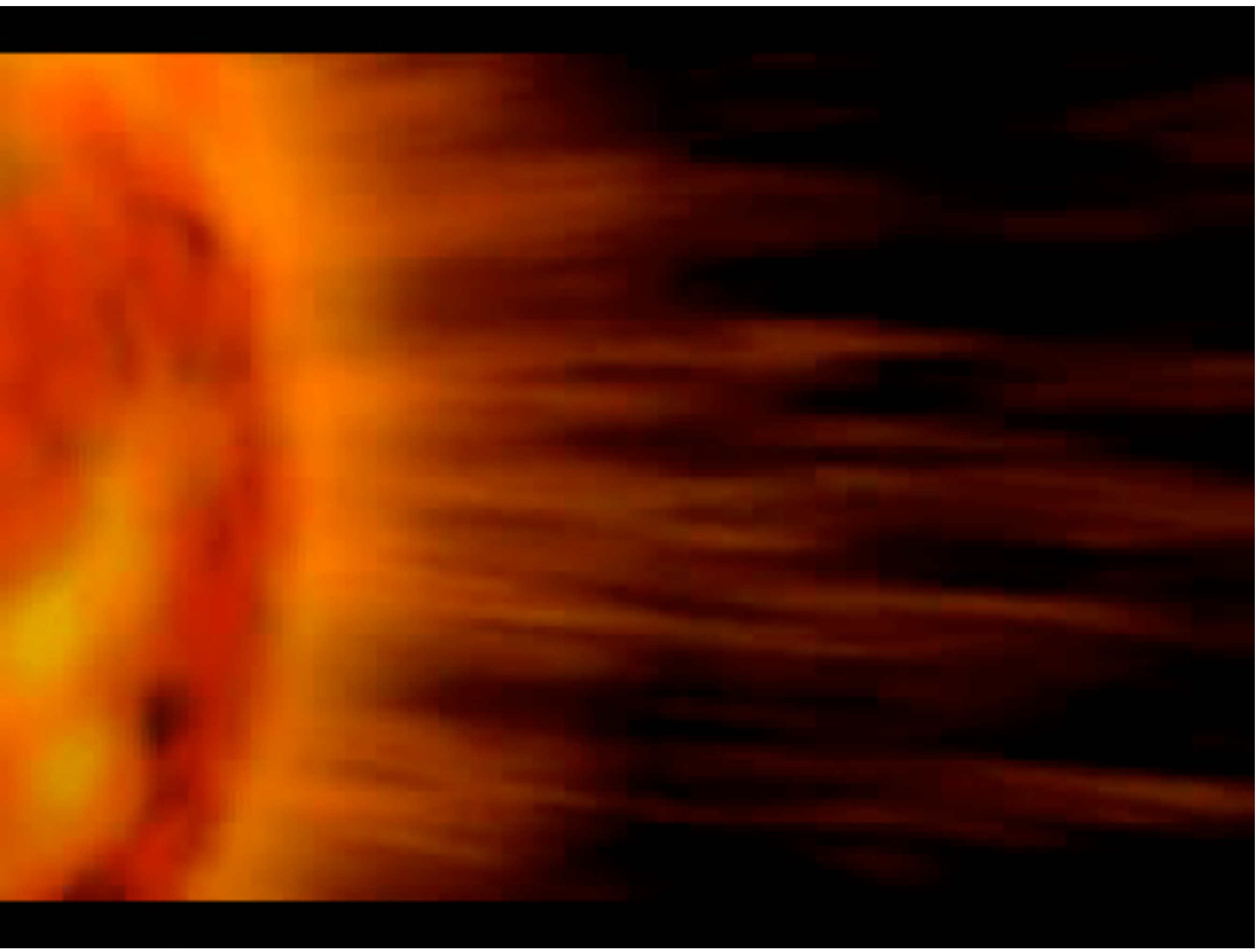

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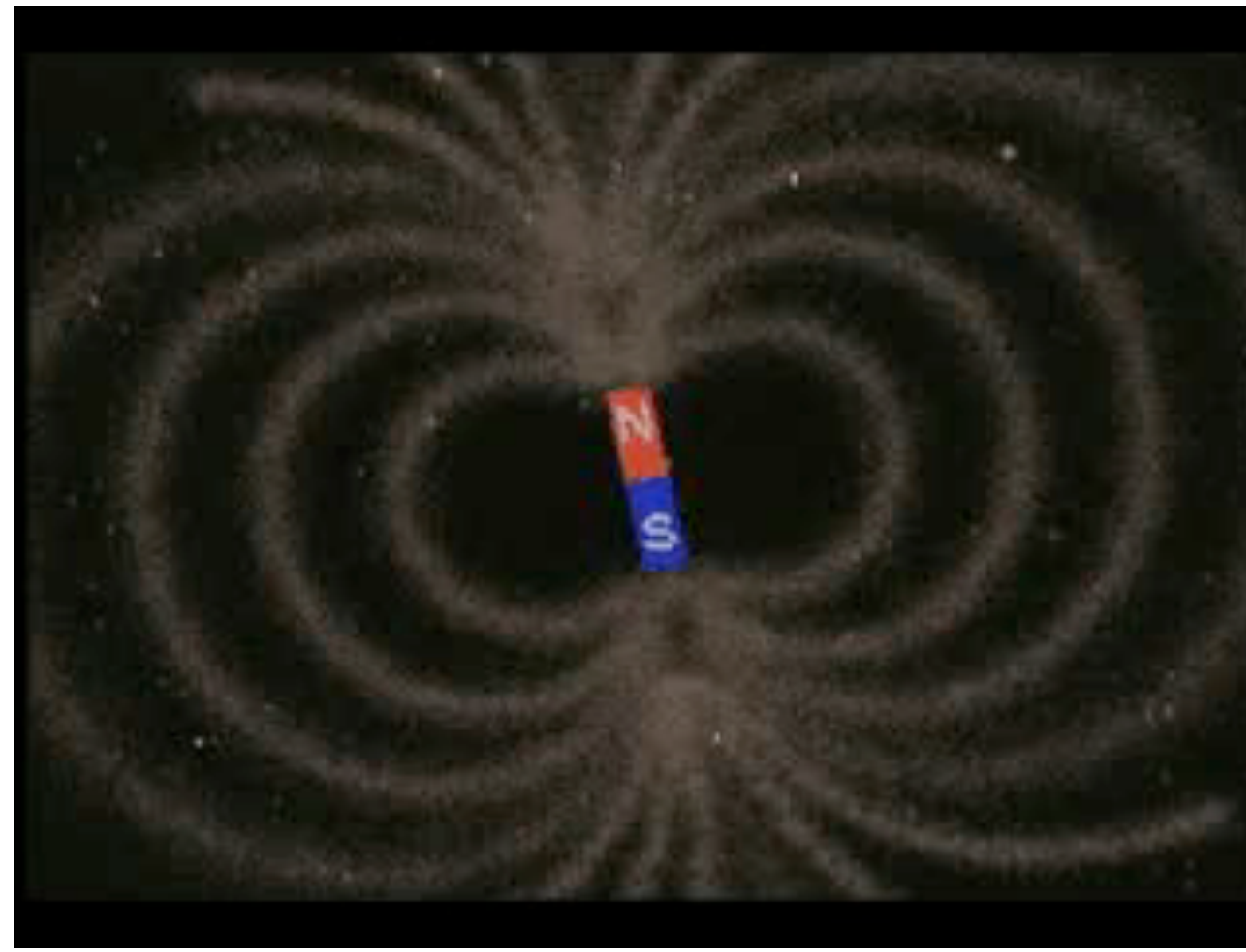

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Magnetic Field Convection & Diffusion

Take the curl of the MHD Ohm's law and apply Faraday's law

$$\partial_t \mathbf{B} = \nabla \times (\mathbf{V} \times \mathbf{B}) + \frac{1}{\mu_o \sigma} \nabla^2 \mathbf{B}$$

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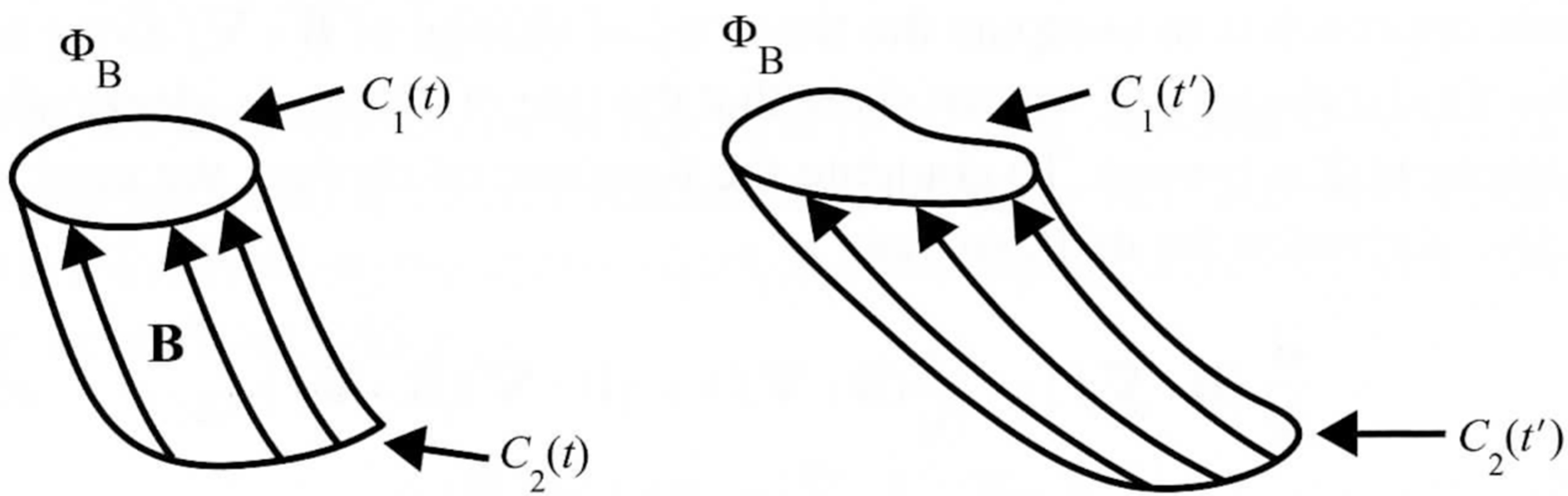
Conductor	**Diffusion**	**time**
Copper sphere	10^{-1}	sec
Fusion machine	10	sec
Earth's molten core	10^{4}	years
Interior of the Sun	10^{10}	years

The Frozen Magnetic Field Theorem

$$R_m \gg 1$$

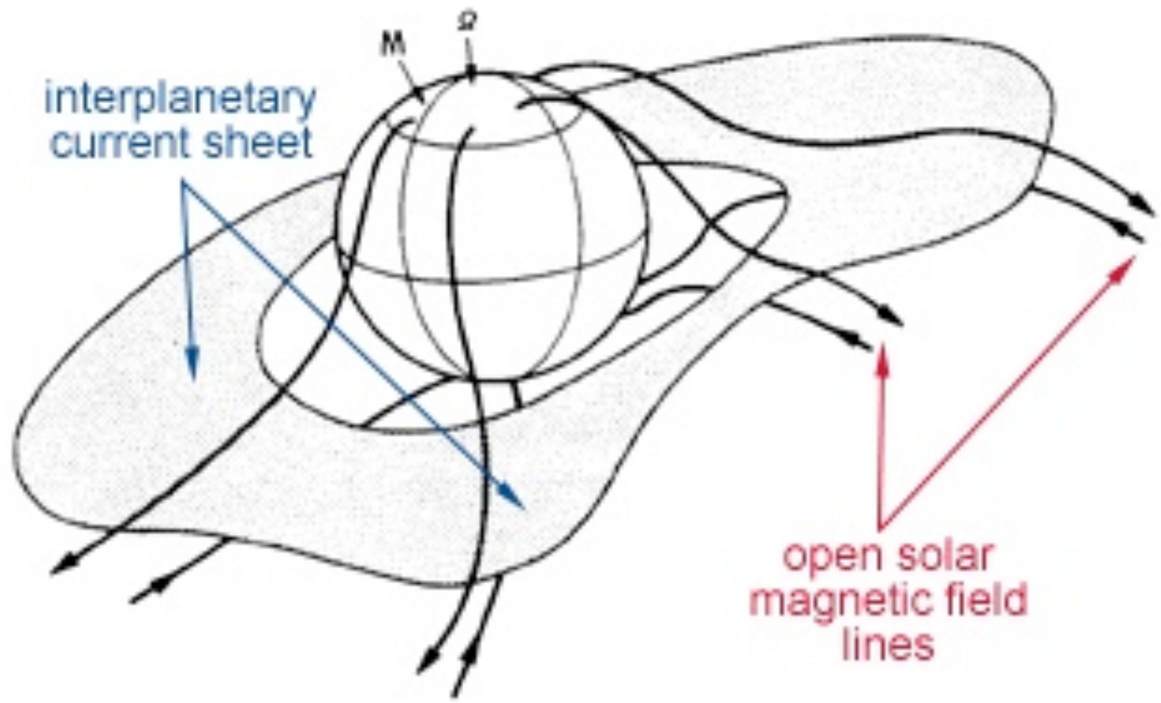
$$\partial_t \mathbf{B} = \nabla \times (\mathbf{V} \times \mathbf{B})$$

$t' > t$



The contours C may deform as time passes, but the plasma and the magnetic flux it encloses both remain invariant as a function of time.

Interplanetary Magnetic Field (IMF)
Its Source are Solar Electric Currents



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Plasma and Magnetic Field are Frozen

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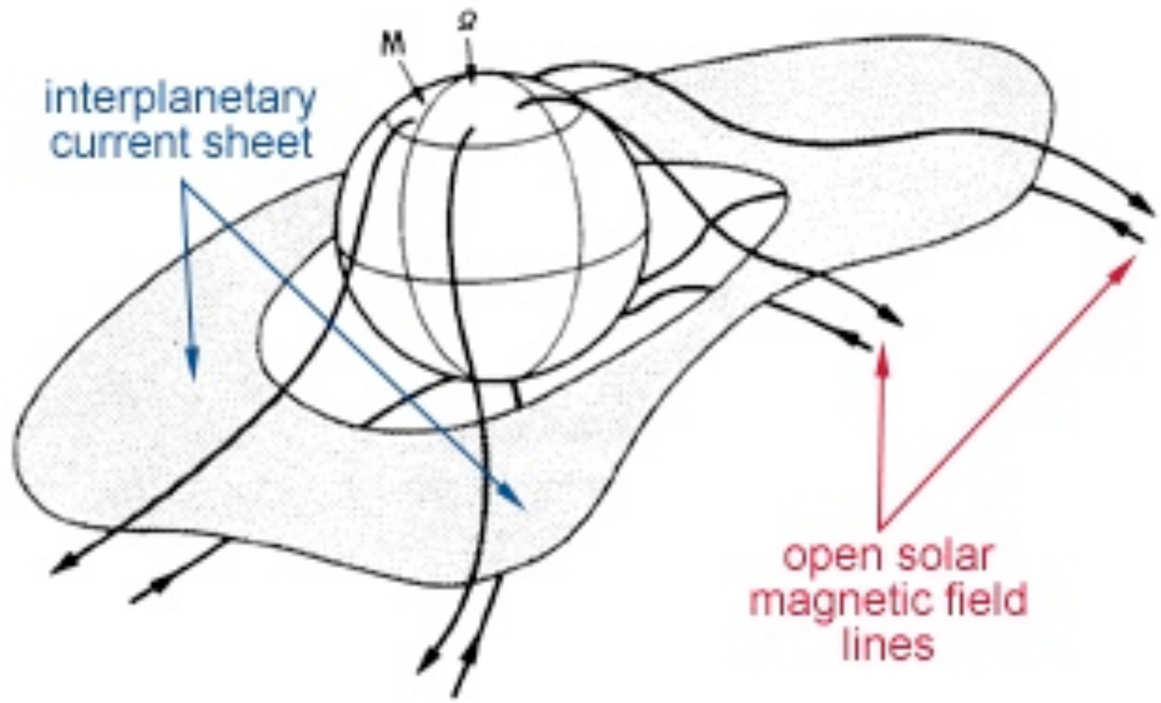

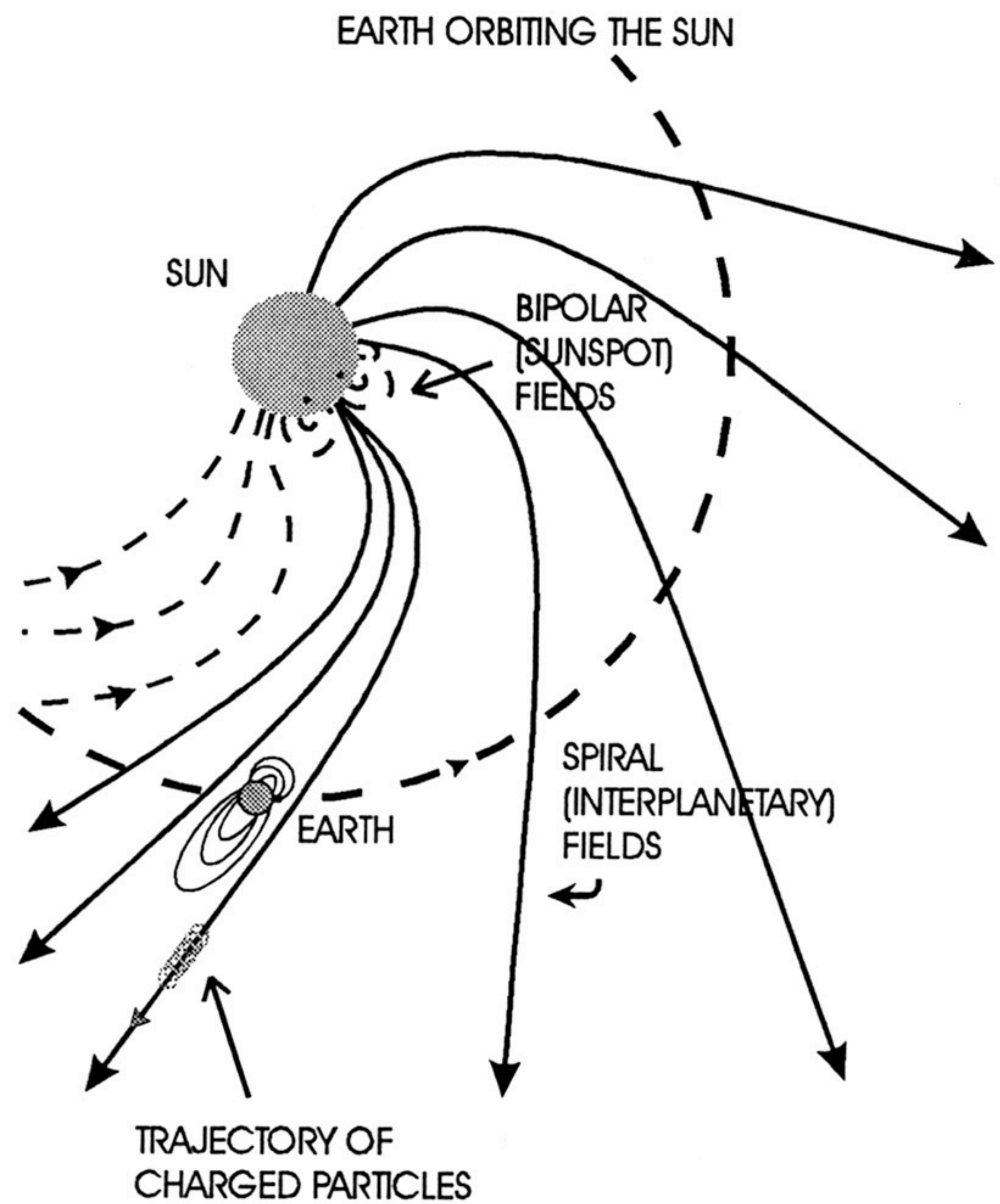

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Solar Magnetic Field–Vertical

A.K.A. Interplanetary Magnetic Field, IMF

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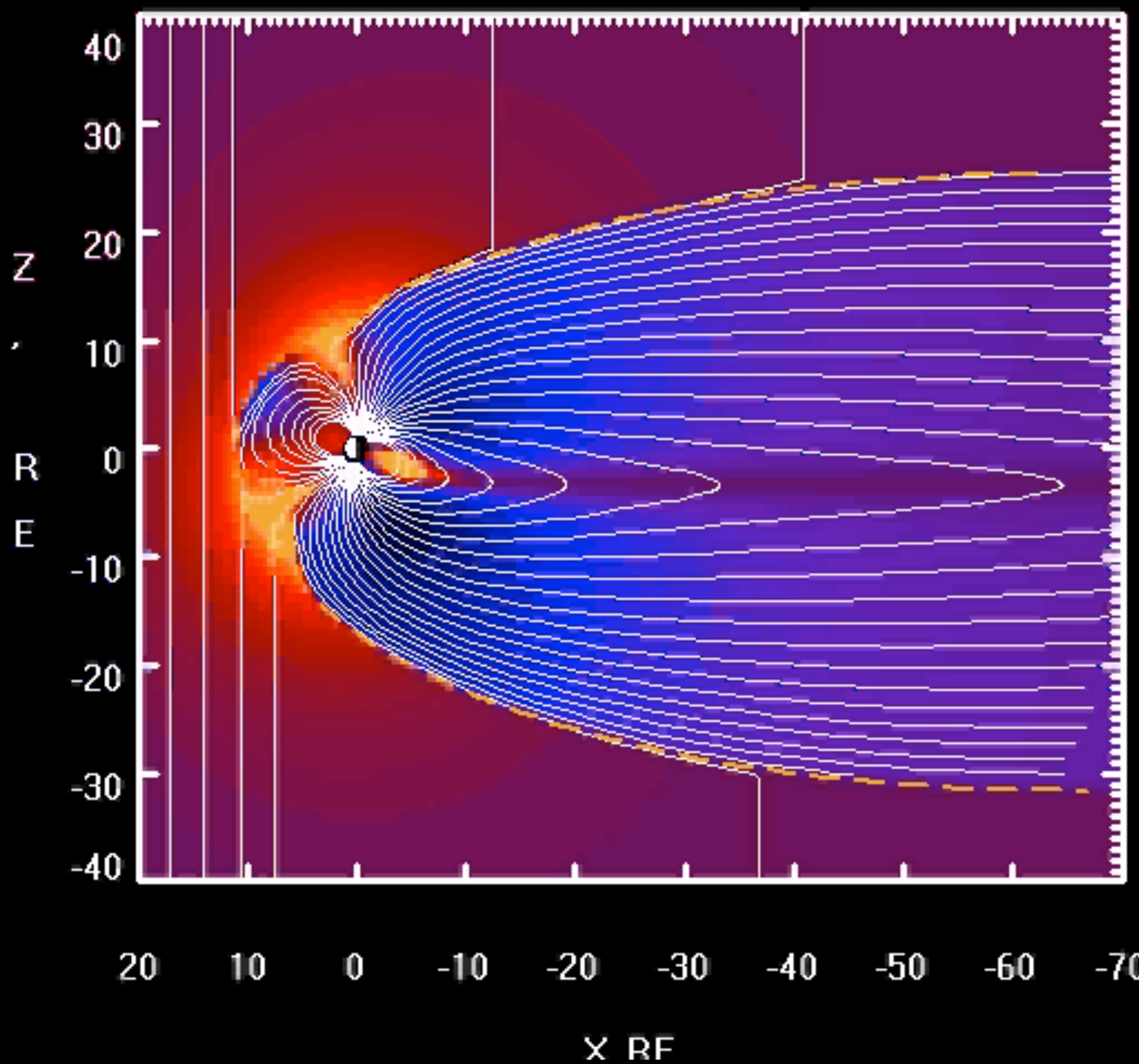
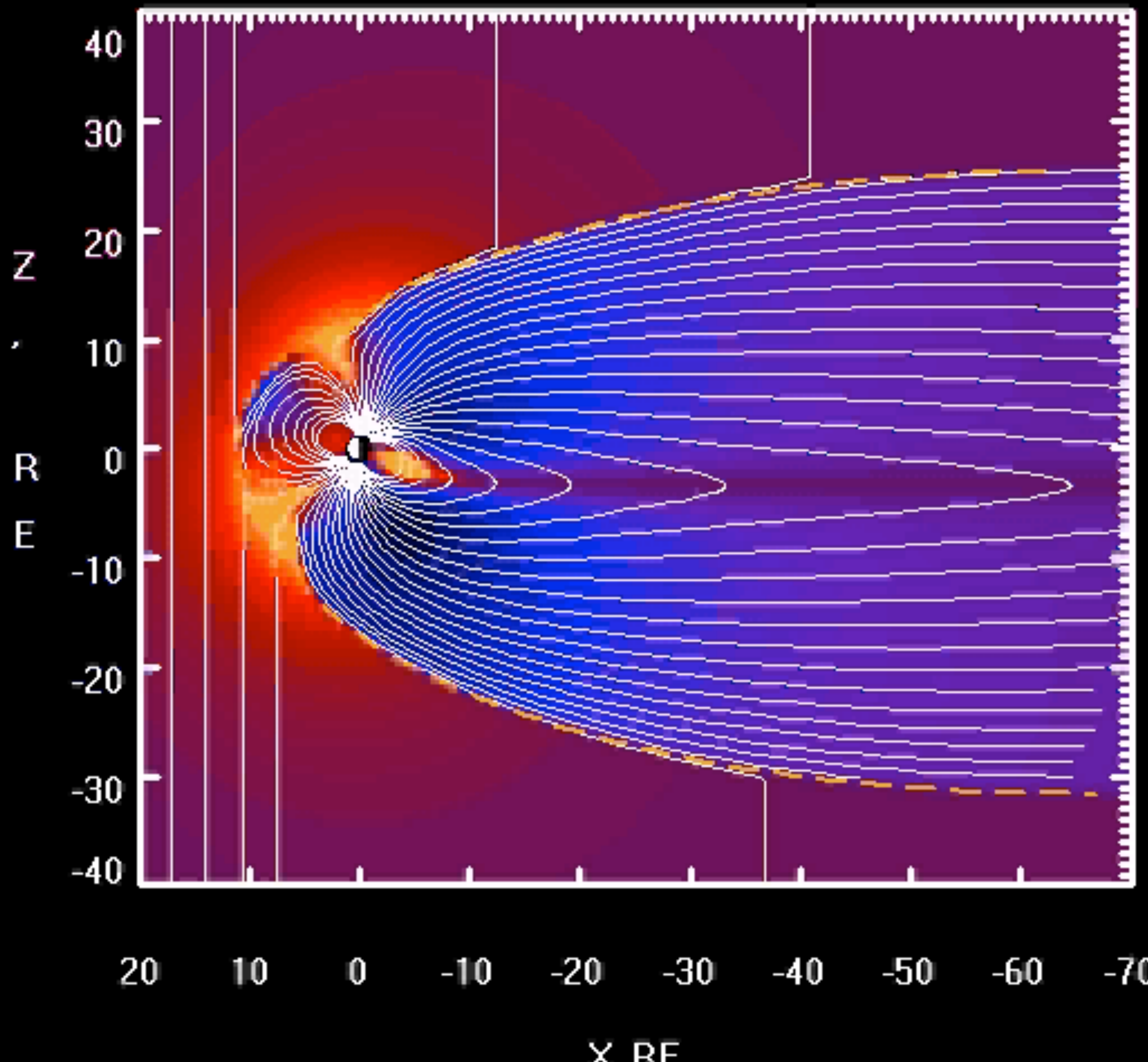


Solar Magnetic Field–Vertical Convected by Solar Wind

A.K.A. Interplanetary Magnetic Field, IMF **IMF+Solar Wind Frozen together**



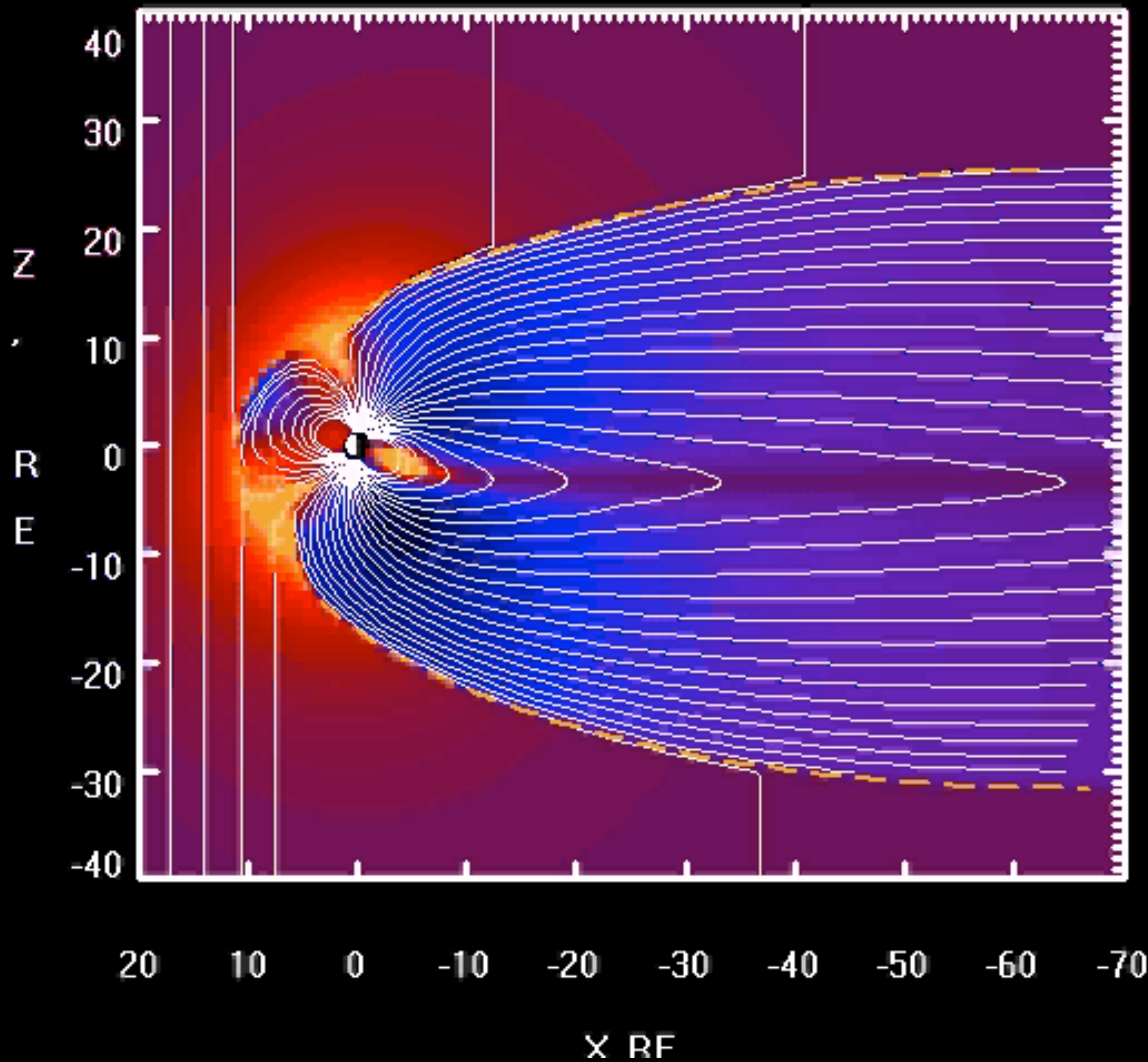
Solar Magnetic Field–Vertical

A.K.A. Interplanetary Magnetic Field, IMF

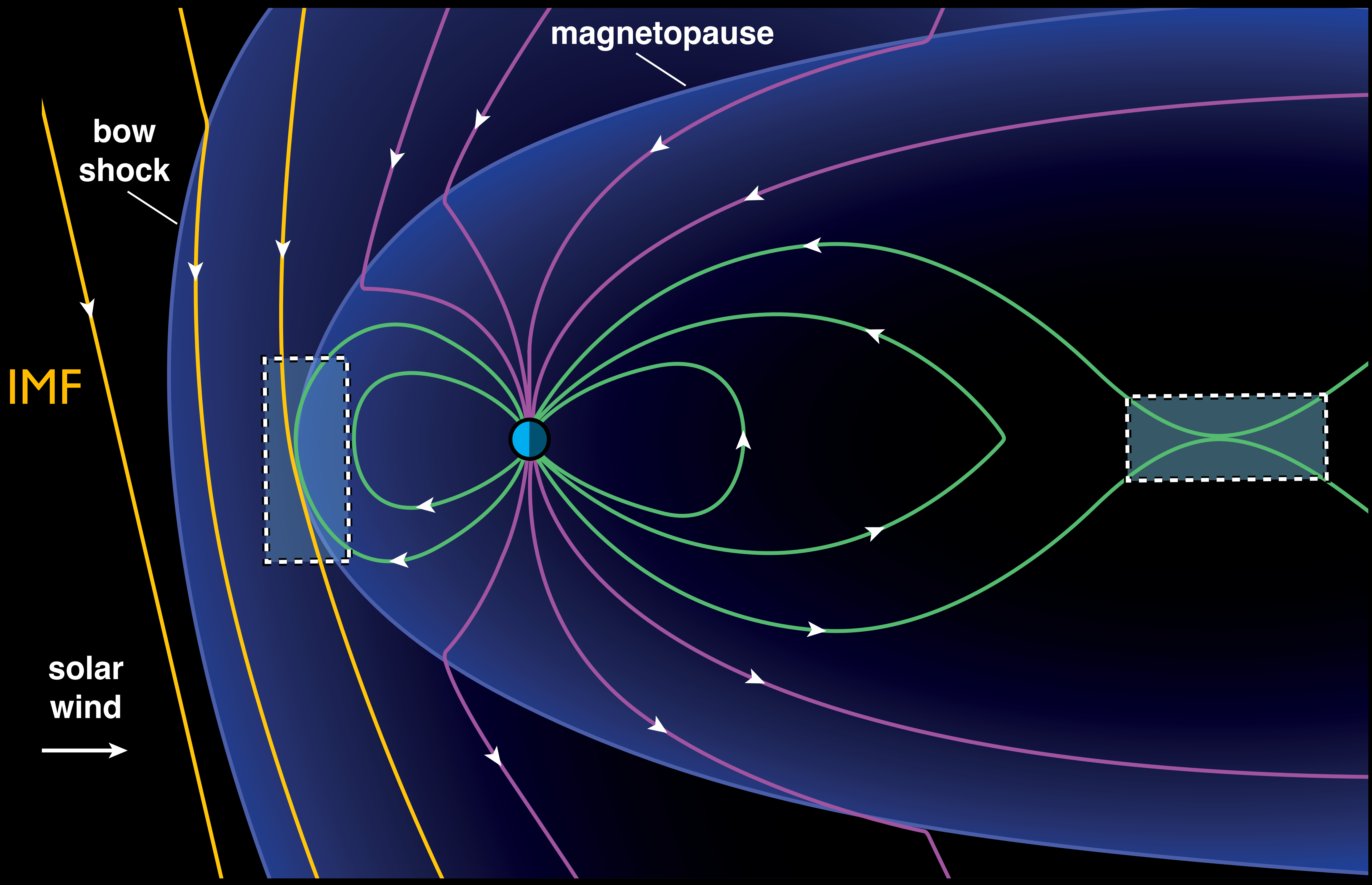
Convected by Solar Wind

IMF+Solar Wind Frozen together

Are they?



Magnetic Reconnection at the Earth's Magnetosphere



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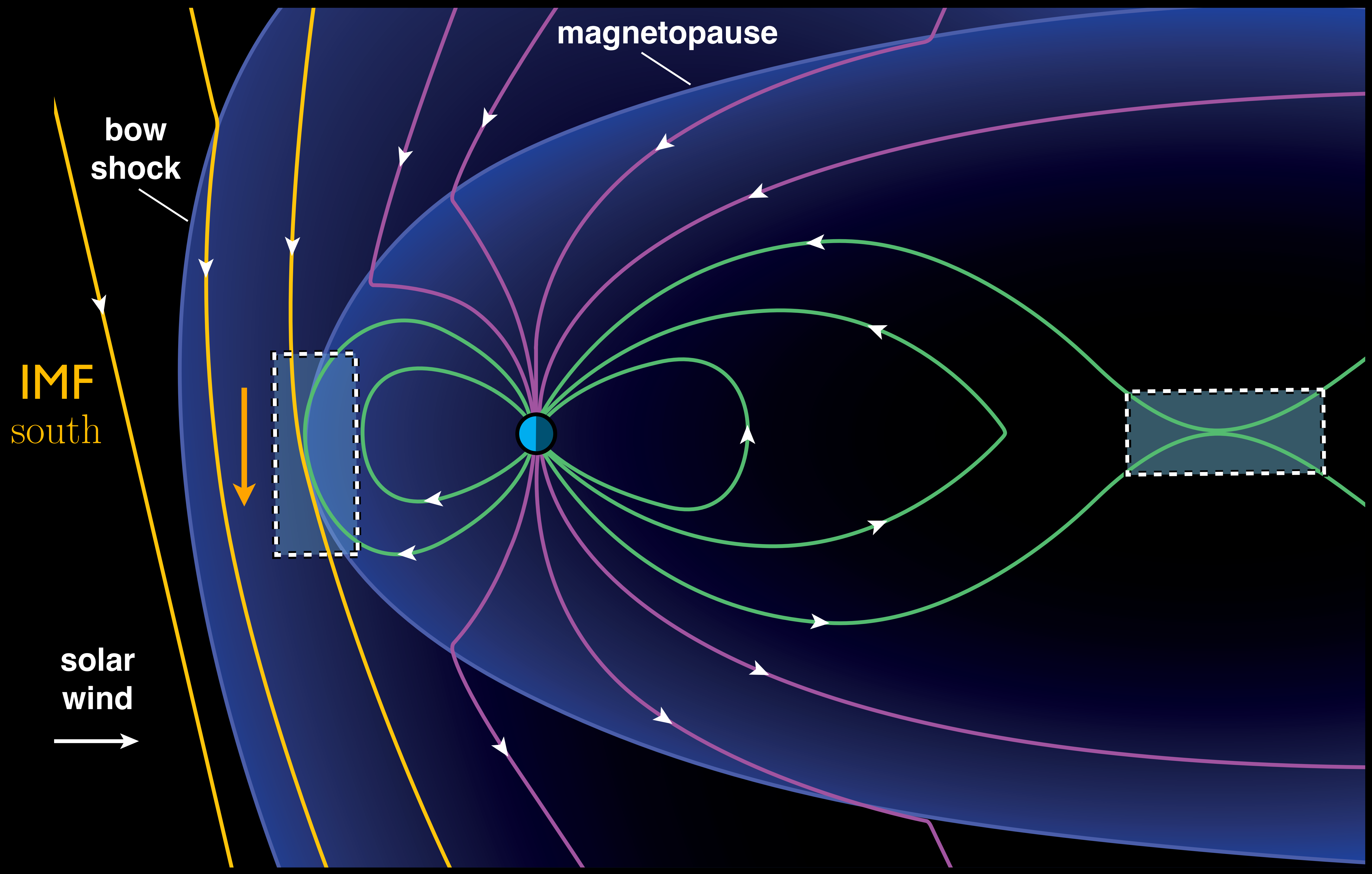

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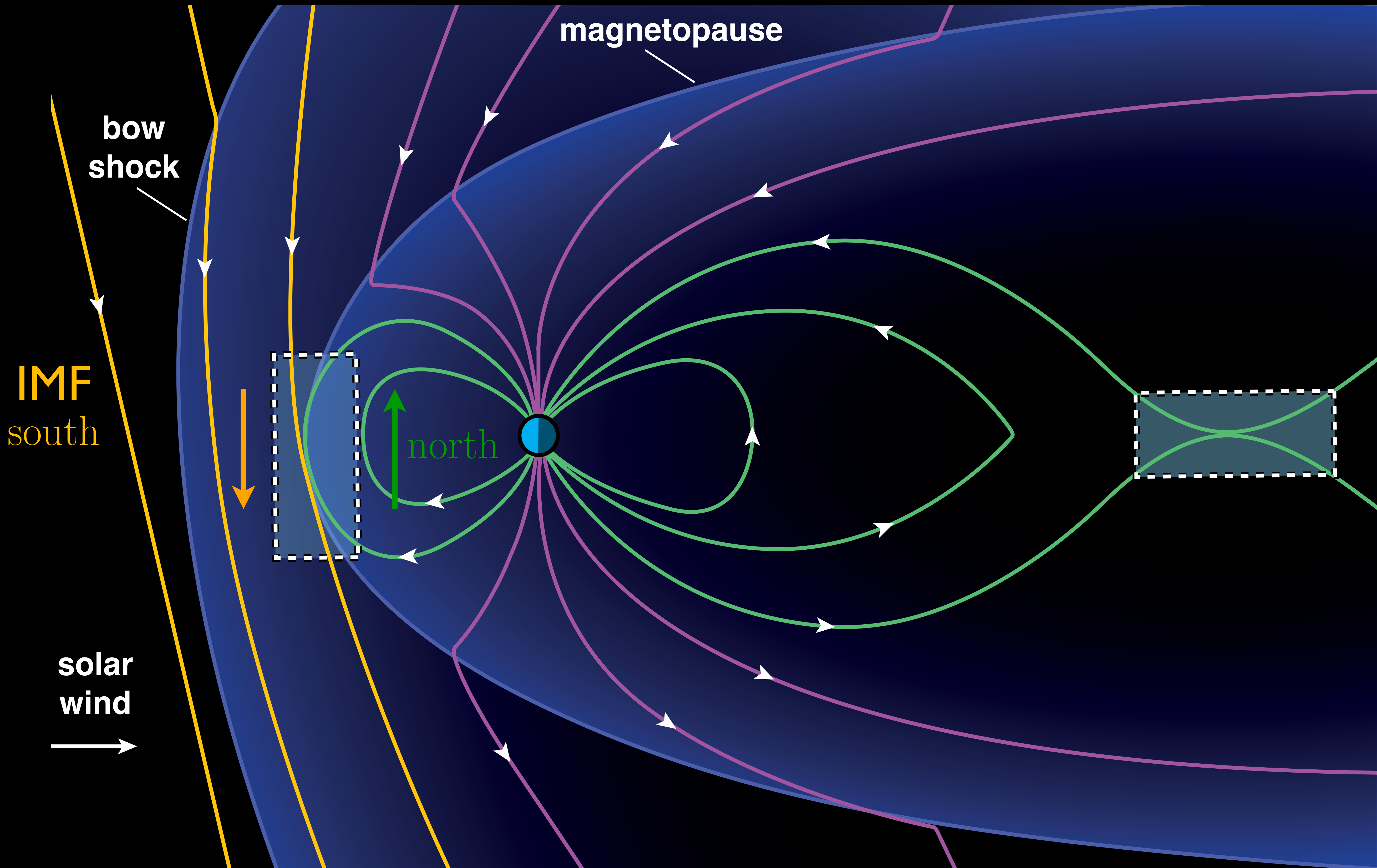

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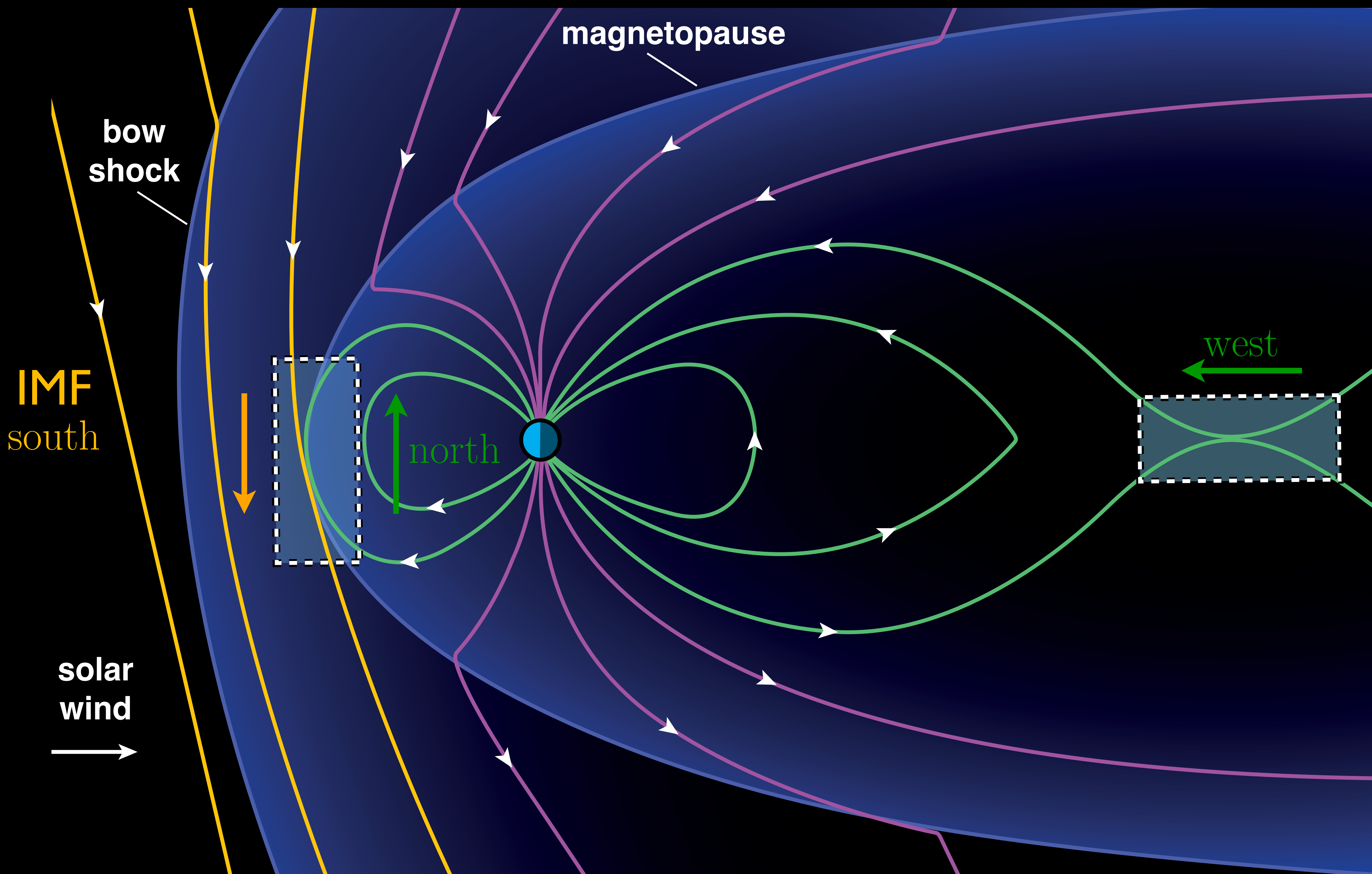

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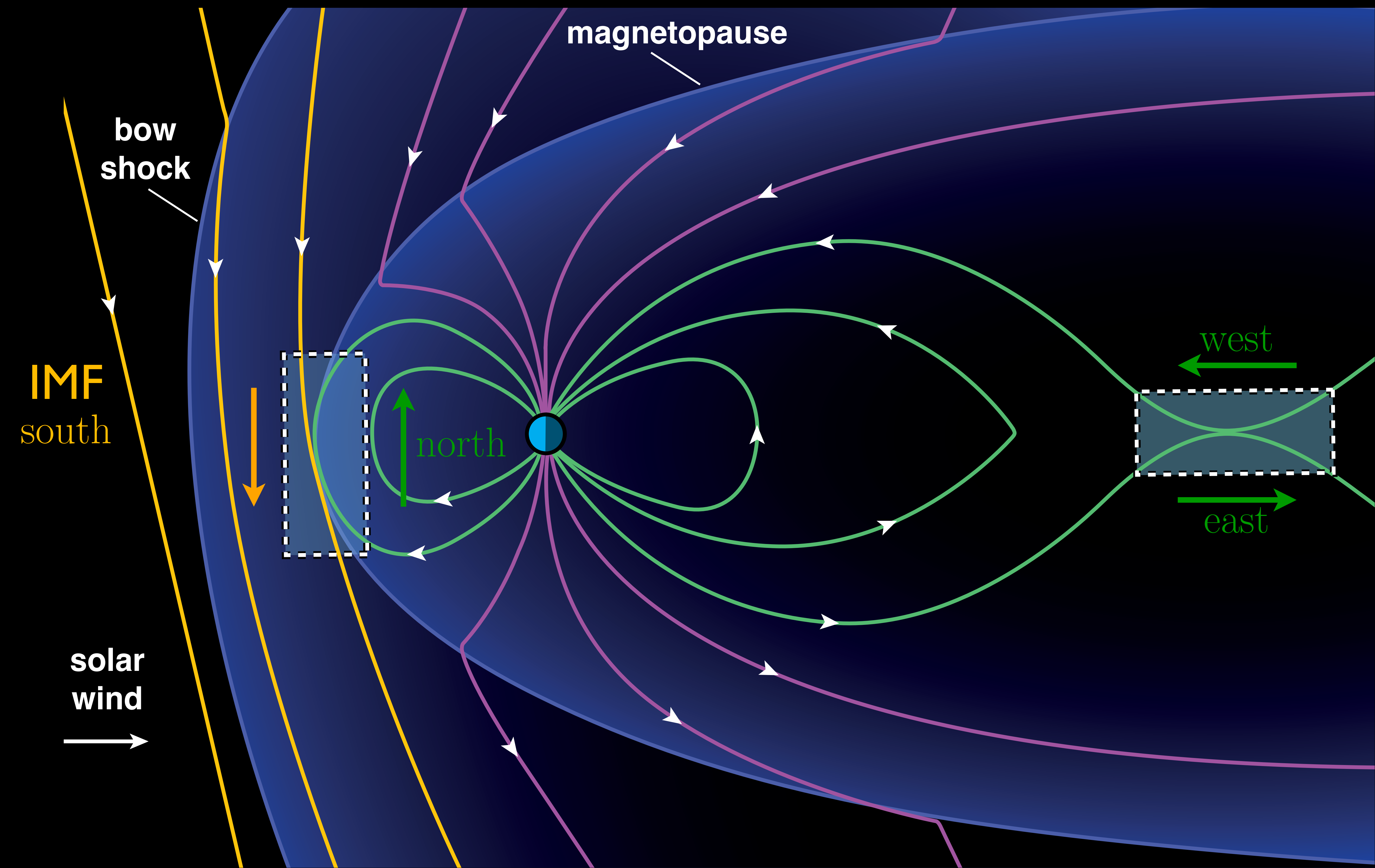
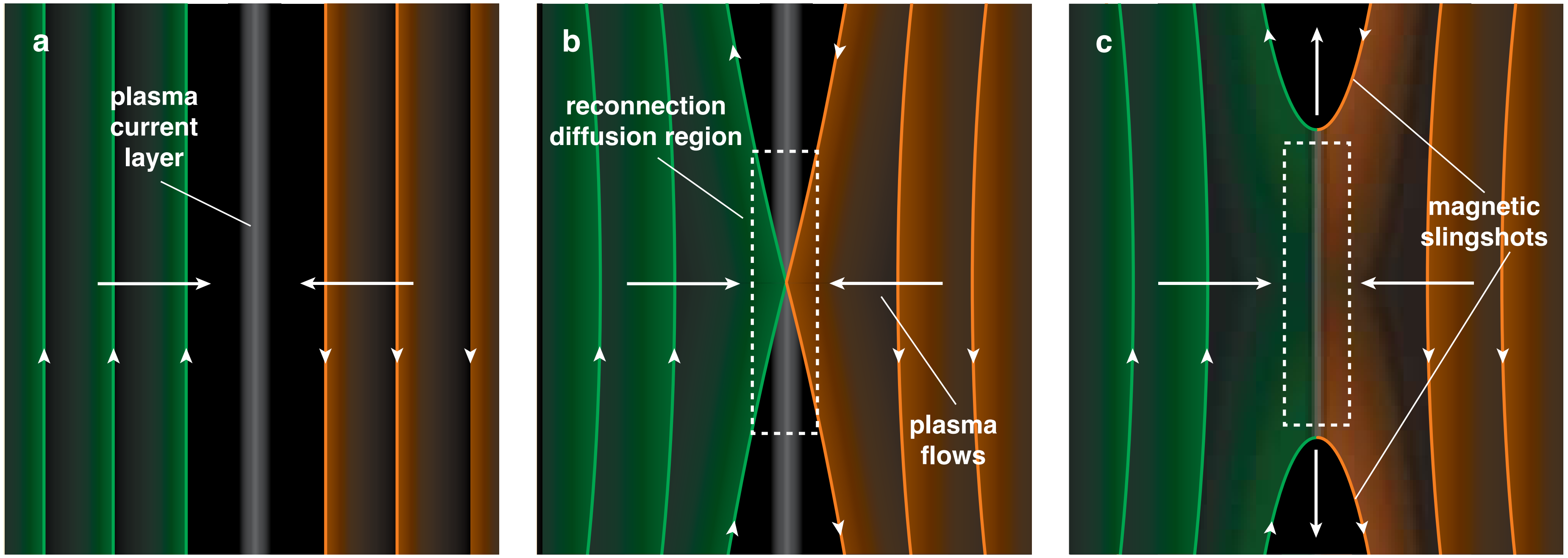


$$R_m = \mu_o \sigma V L$$

What happens when two plasmas with opposite magnetic fields ↑ ↓ approach each other ?

☆



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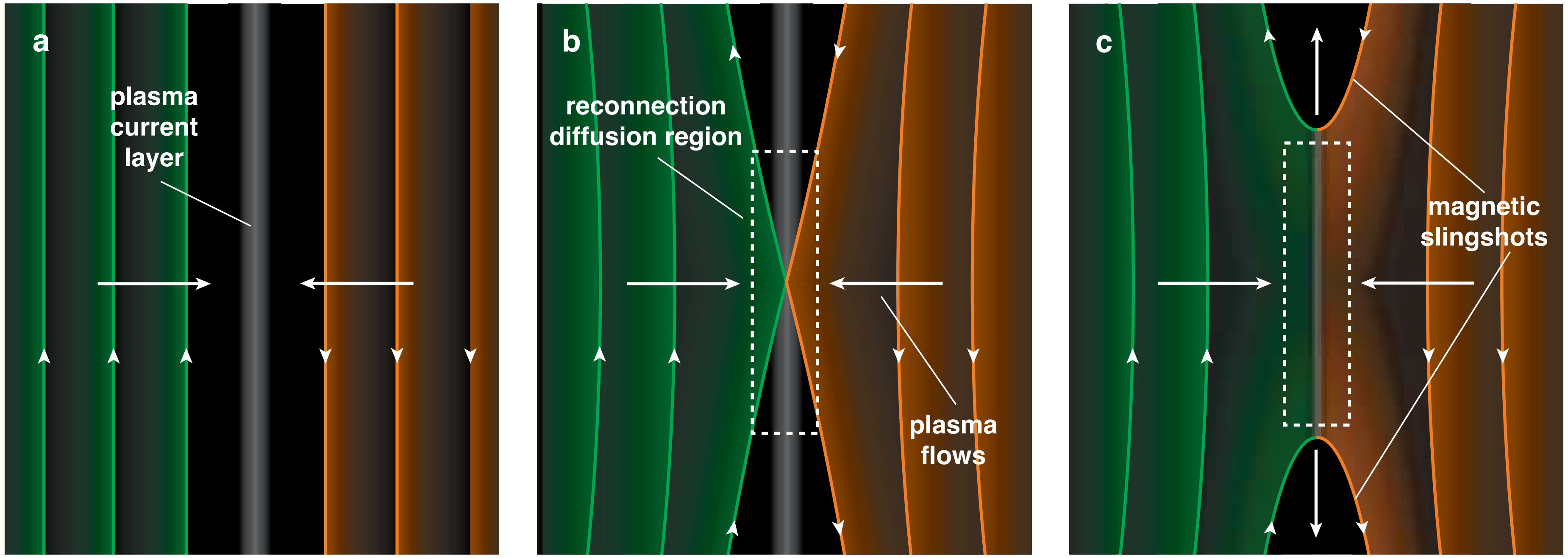
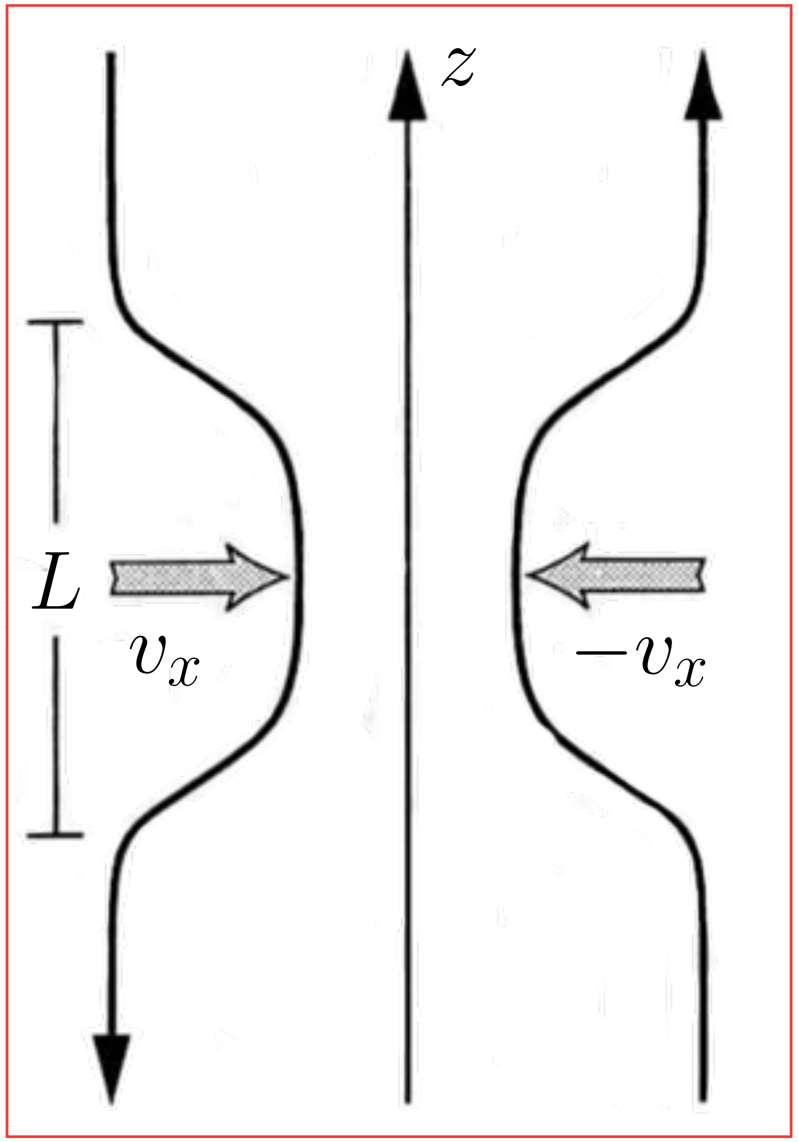


☆

$R_m \gg 1$ Frozen



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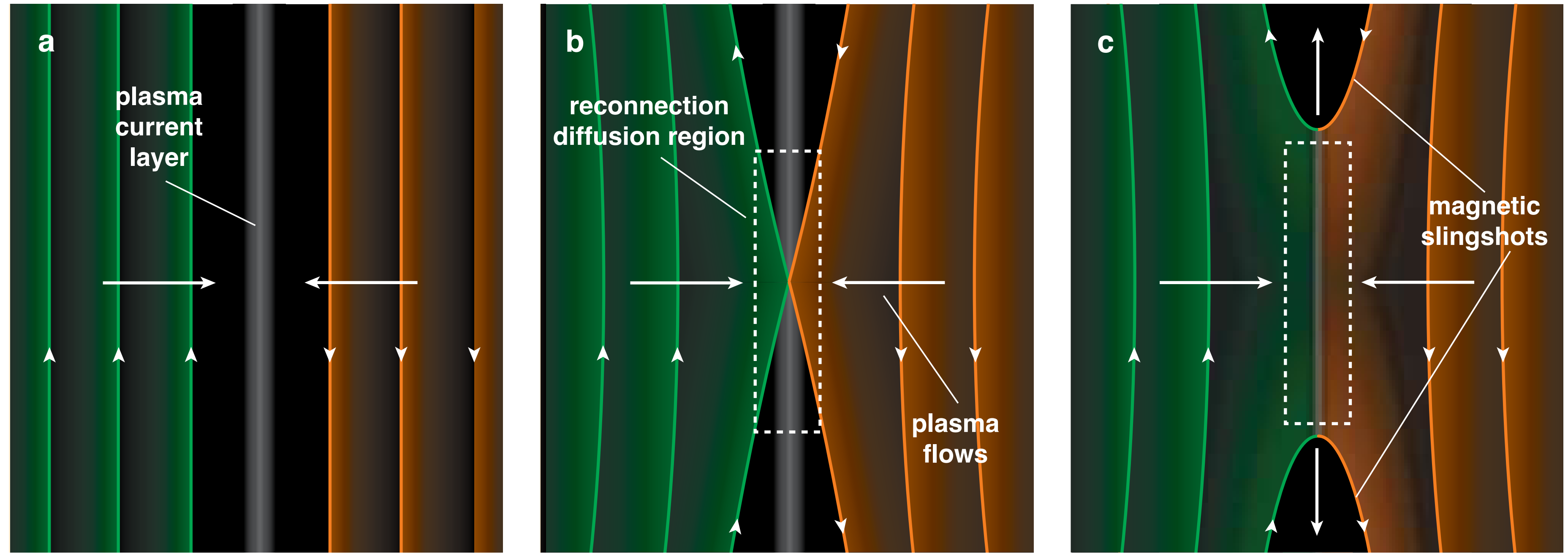

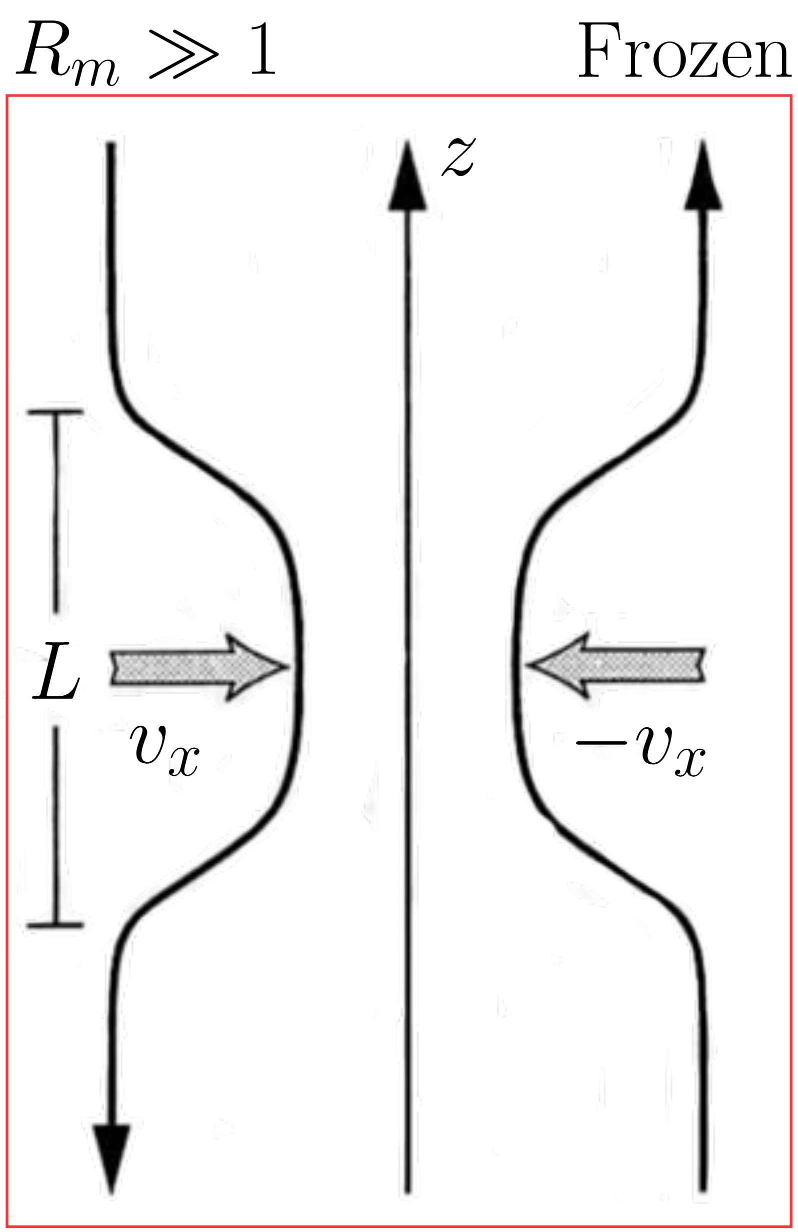

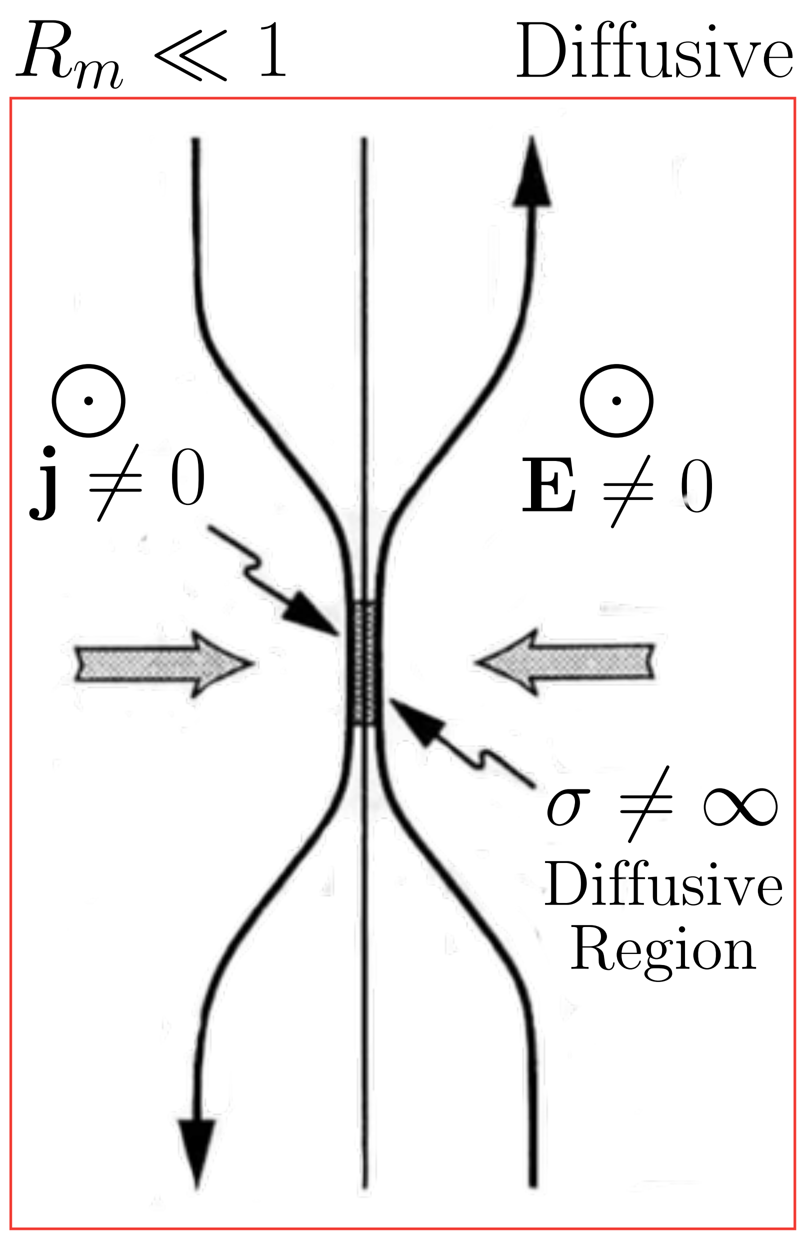

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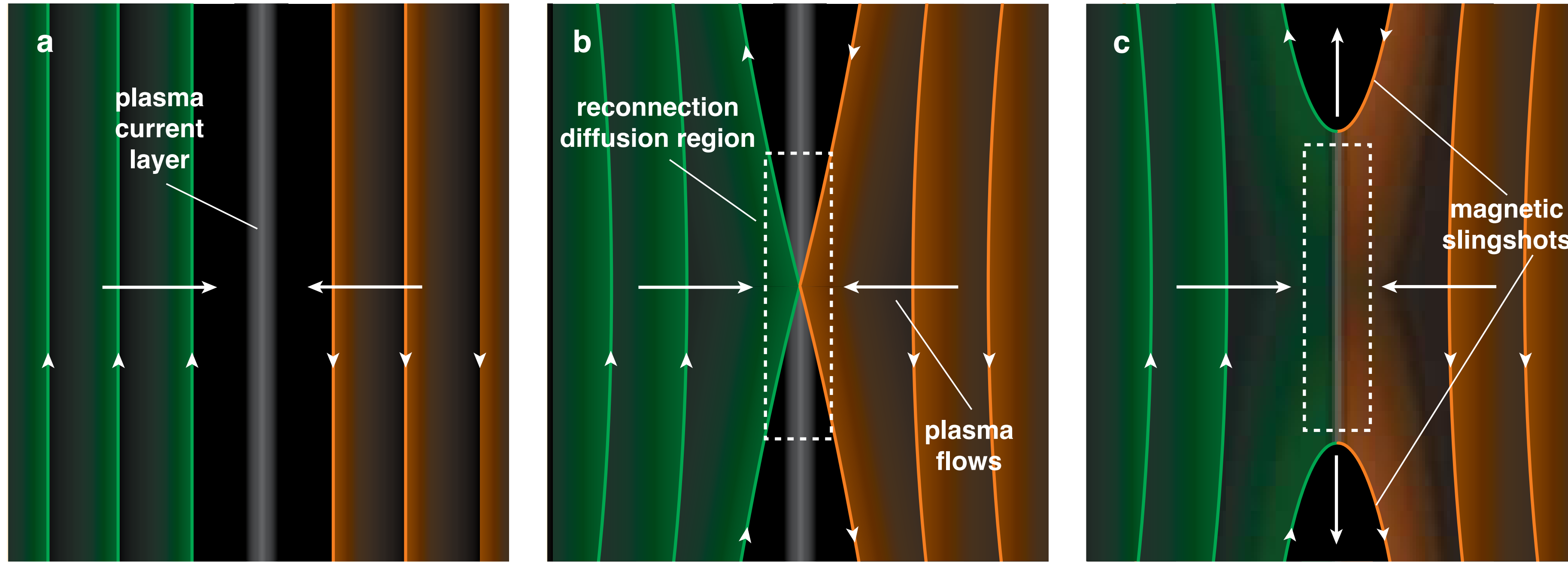

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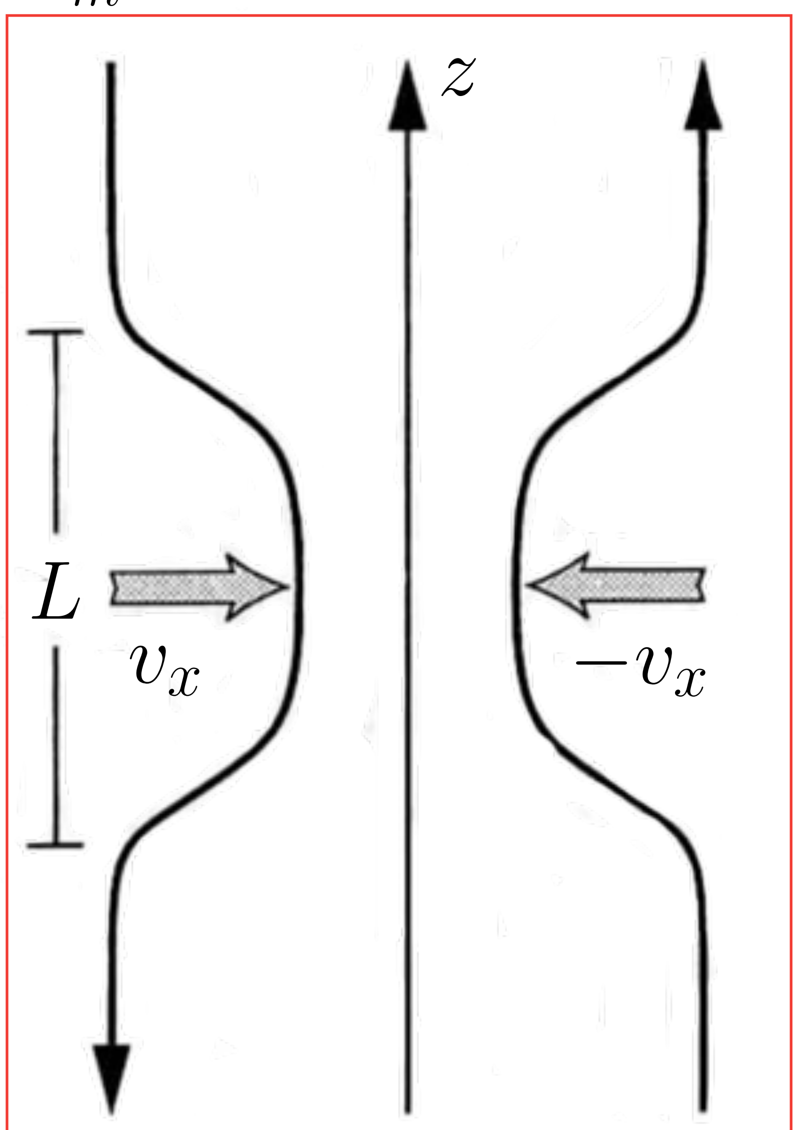
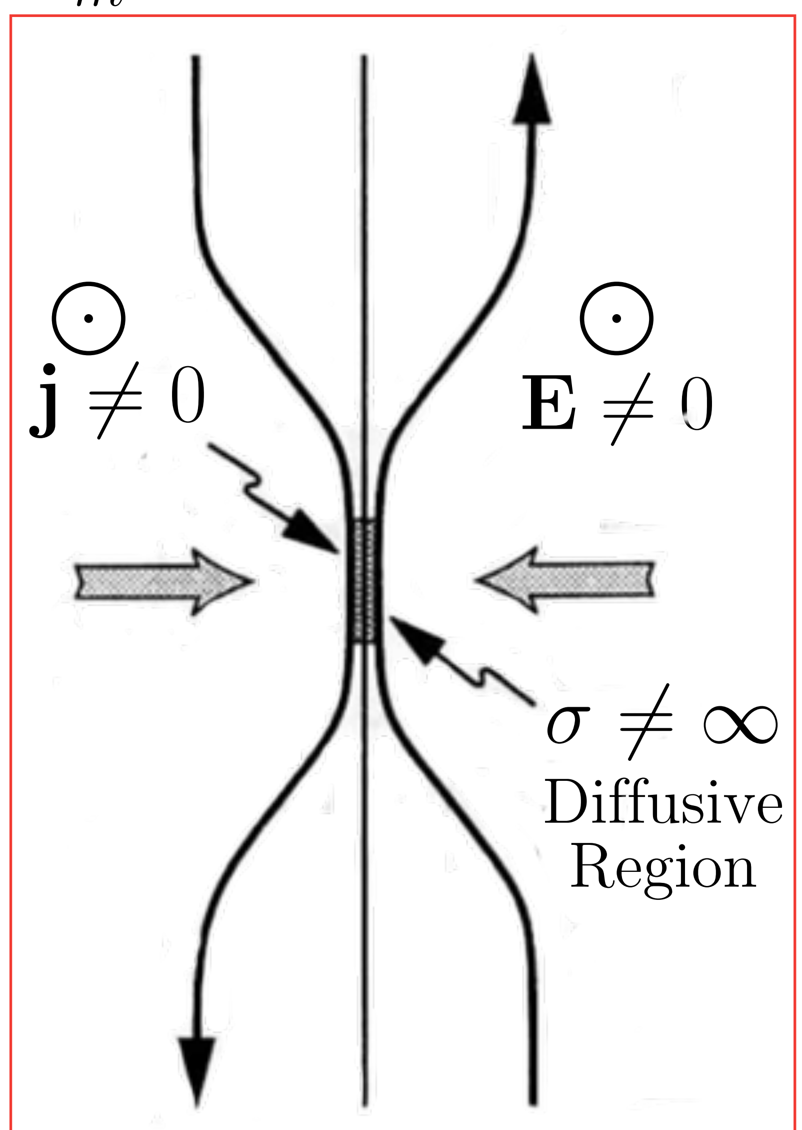
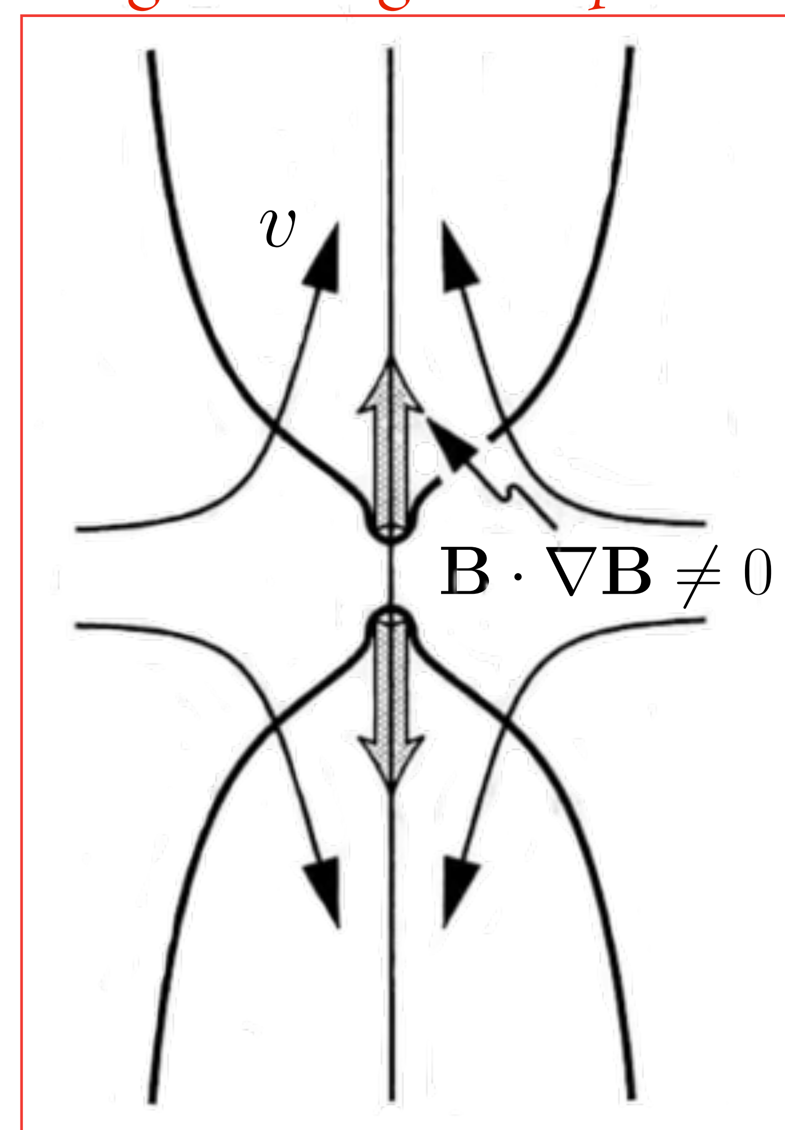


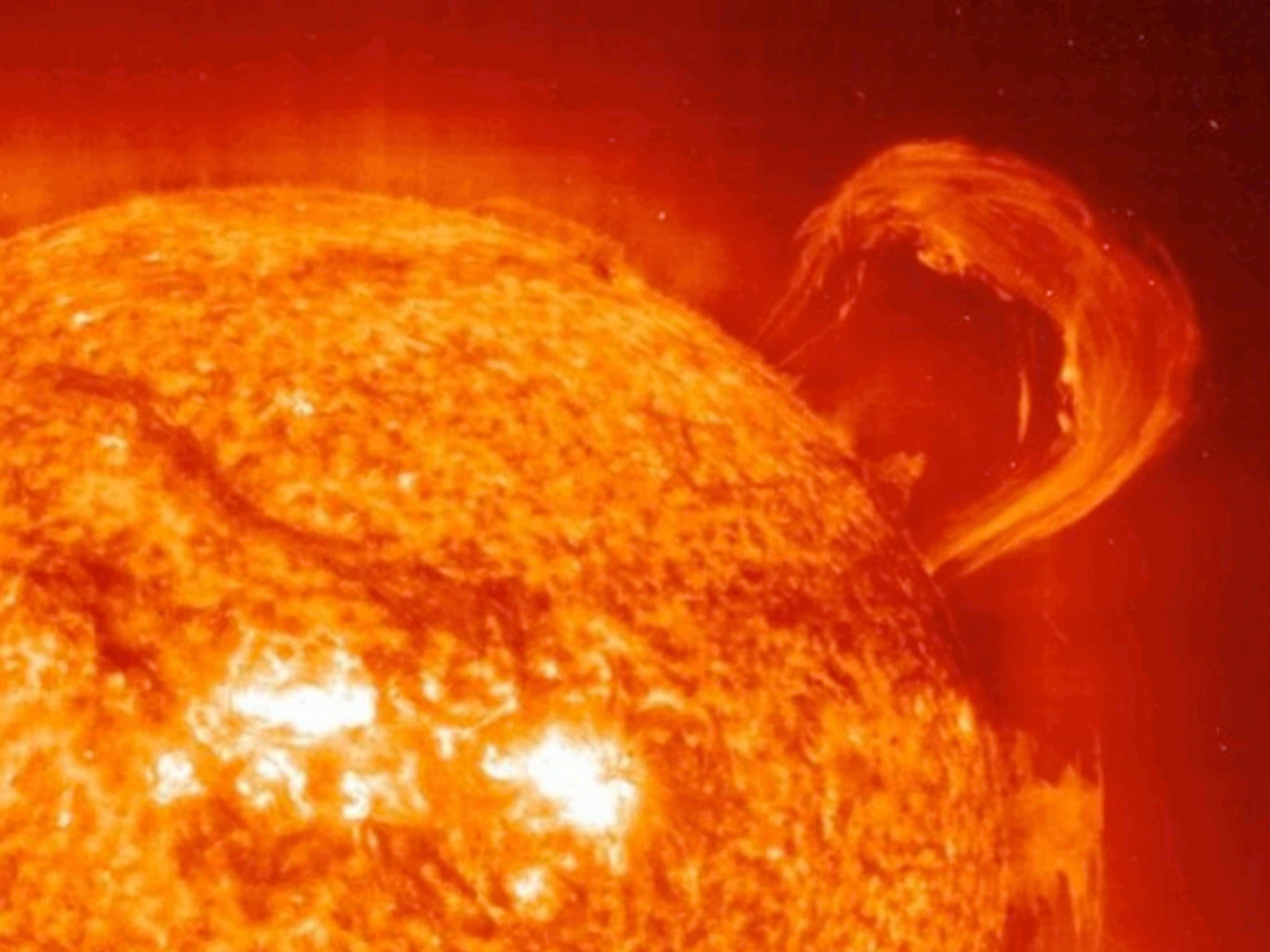
$R_m \ll 1$ Diffusive



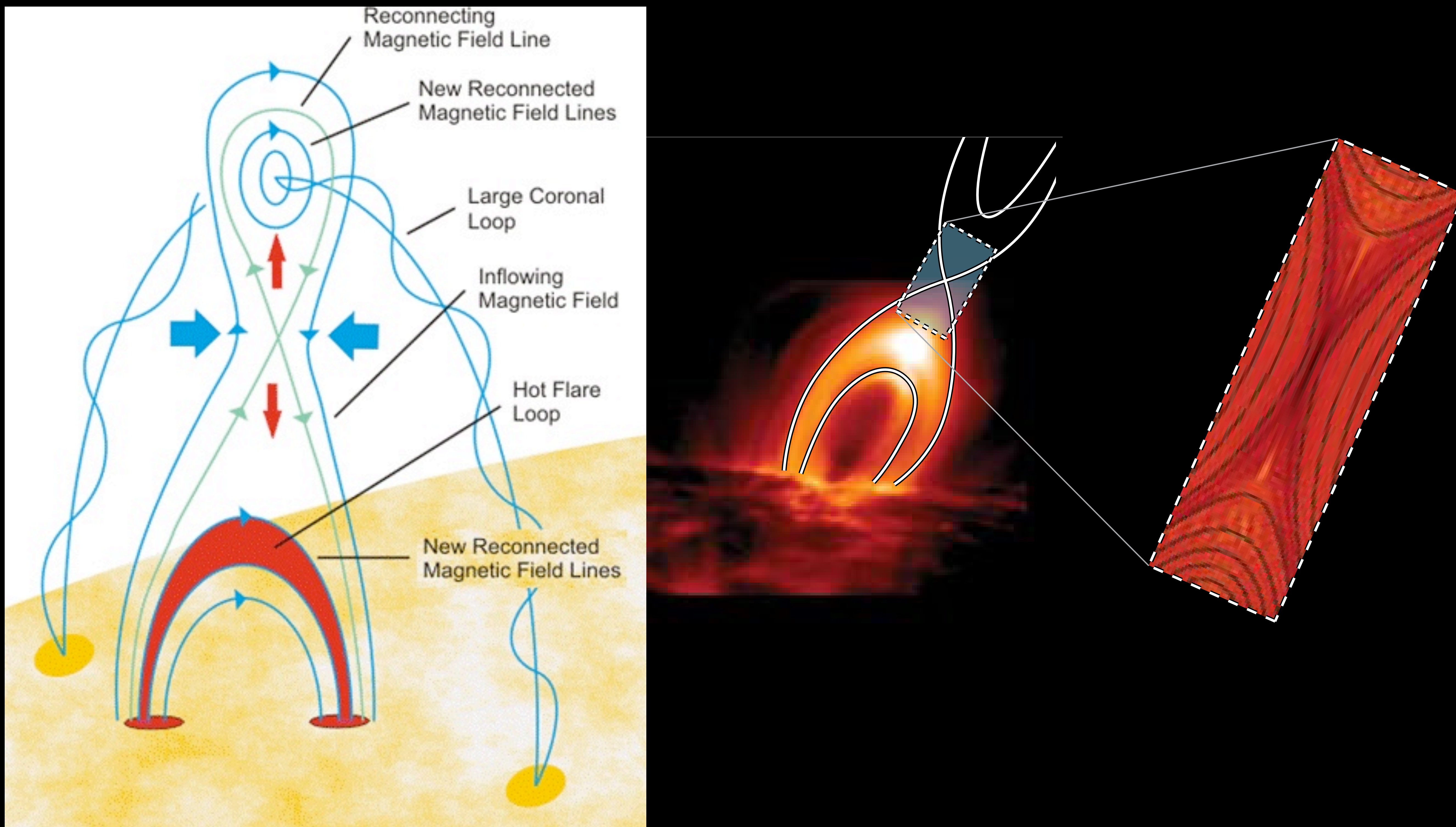
nozzle

magnetic slingshot explosion



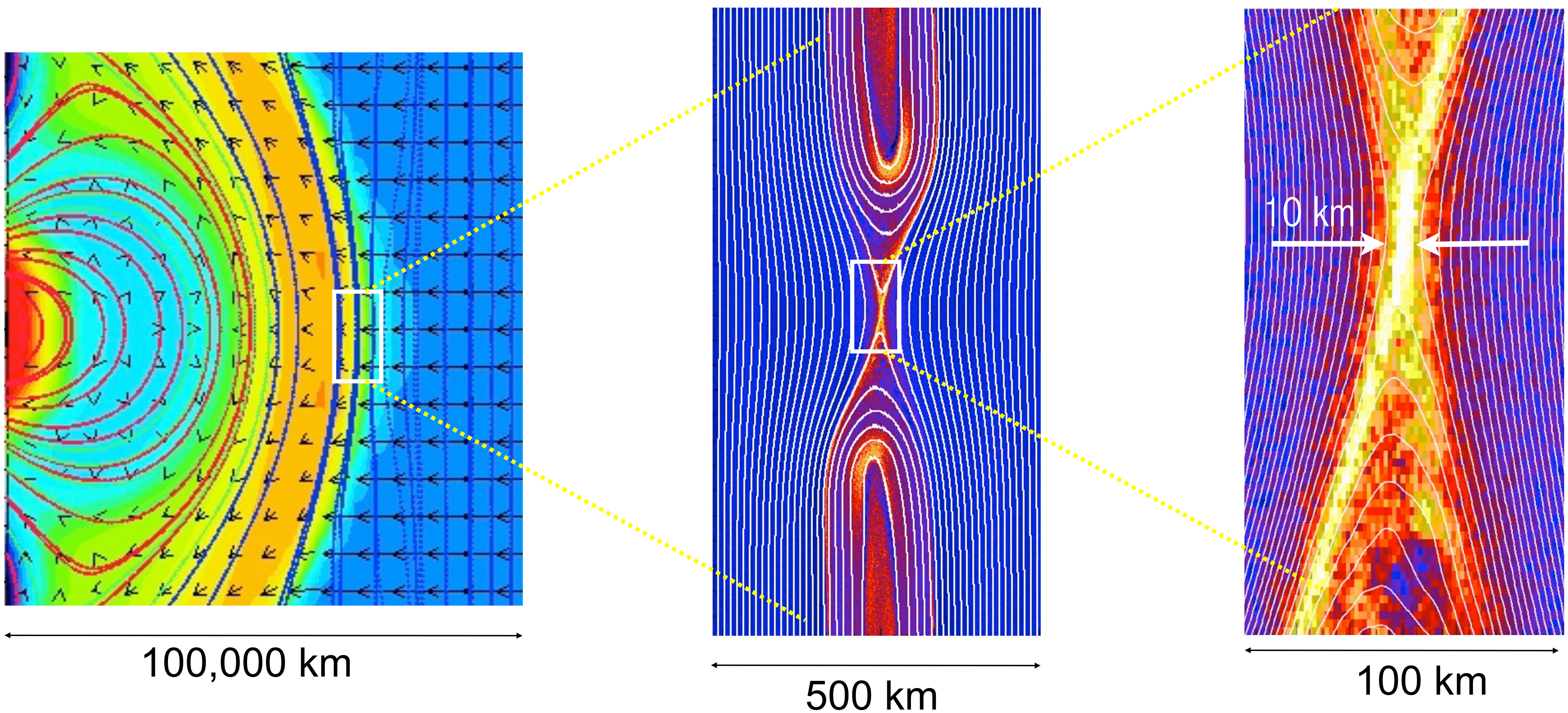


Solar Flare Reconnection Is Indisputable !



Important Scale Sizes

From simulations:



- Unstable, thin current sheets have thickness < 1000 km
- "Electron diffusion region" thickness is of order 10 km
- Current sheet motion is typically 10 to 100 km/s

$R_m \ll 1$
Diffusive

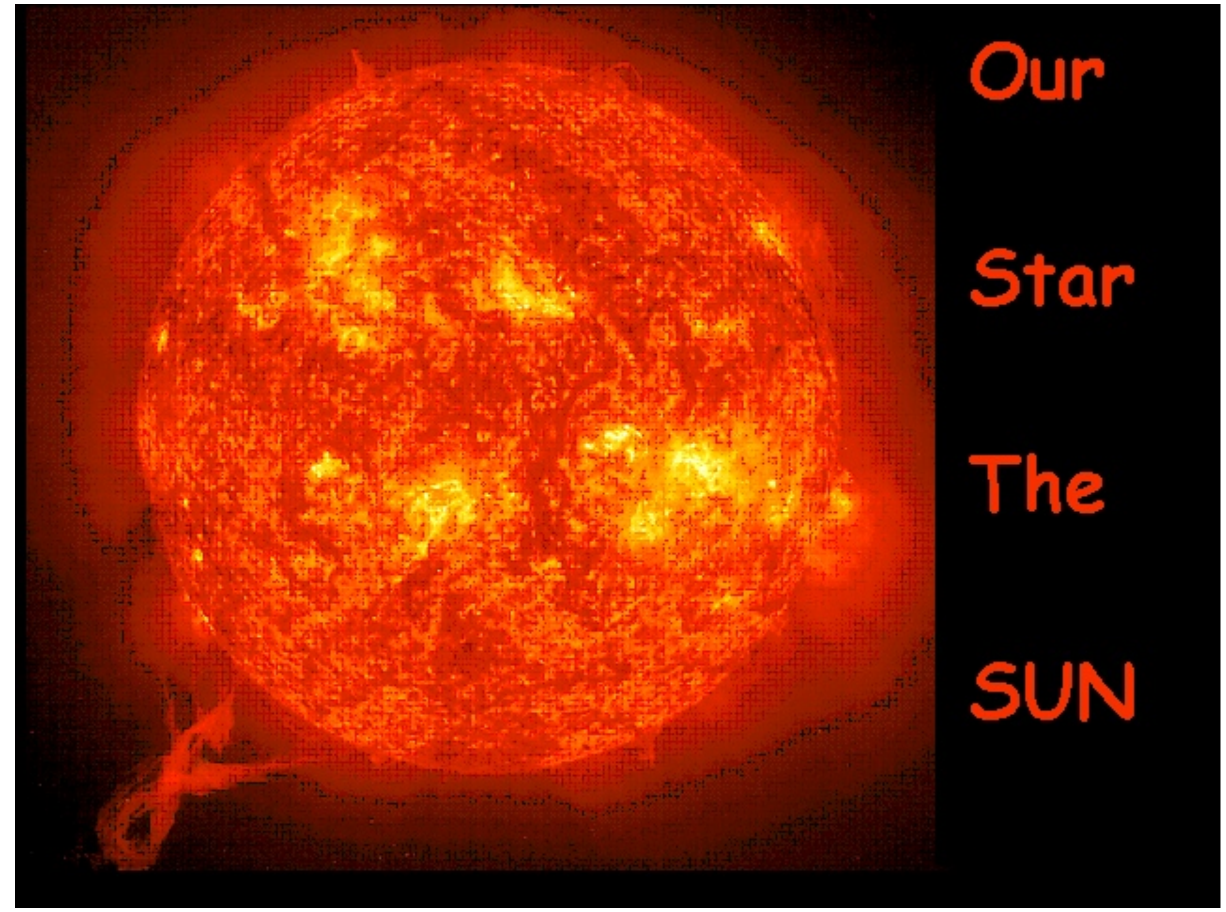
Jim Burch

It all starts at the SUN

Today we know that the auroral lights are the first clue we have that:

our planet is under attack!!

not by space aliens but by our very our own star: The Sun.



Loopy Flares!

What do the shapes you see in the movie remind you of?

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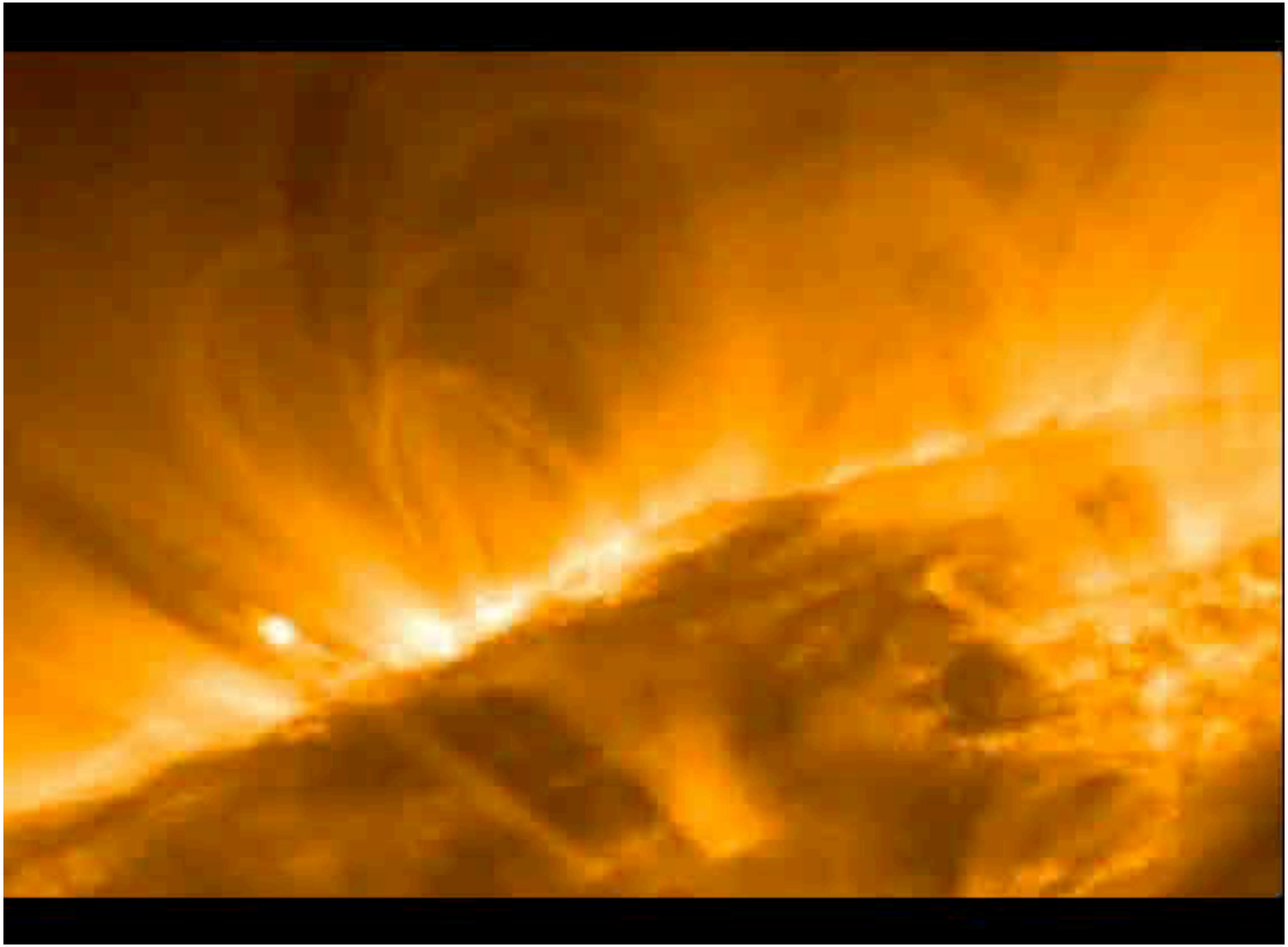

Aurora: Why does it happen at night?

When the solar wind passes Earth, it drags the magnetic tail far out into space and compresses it.

Stretched magnetic lines break and then (re) connect into a different shape.

When this happens, magnetic field lines snap towards Earth like stretched rubber-bands.

Gases guided by the magnetic field speed up towards Earth and hit the upper atmosphere at the North and South poles of Earth.

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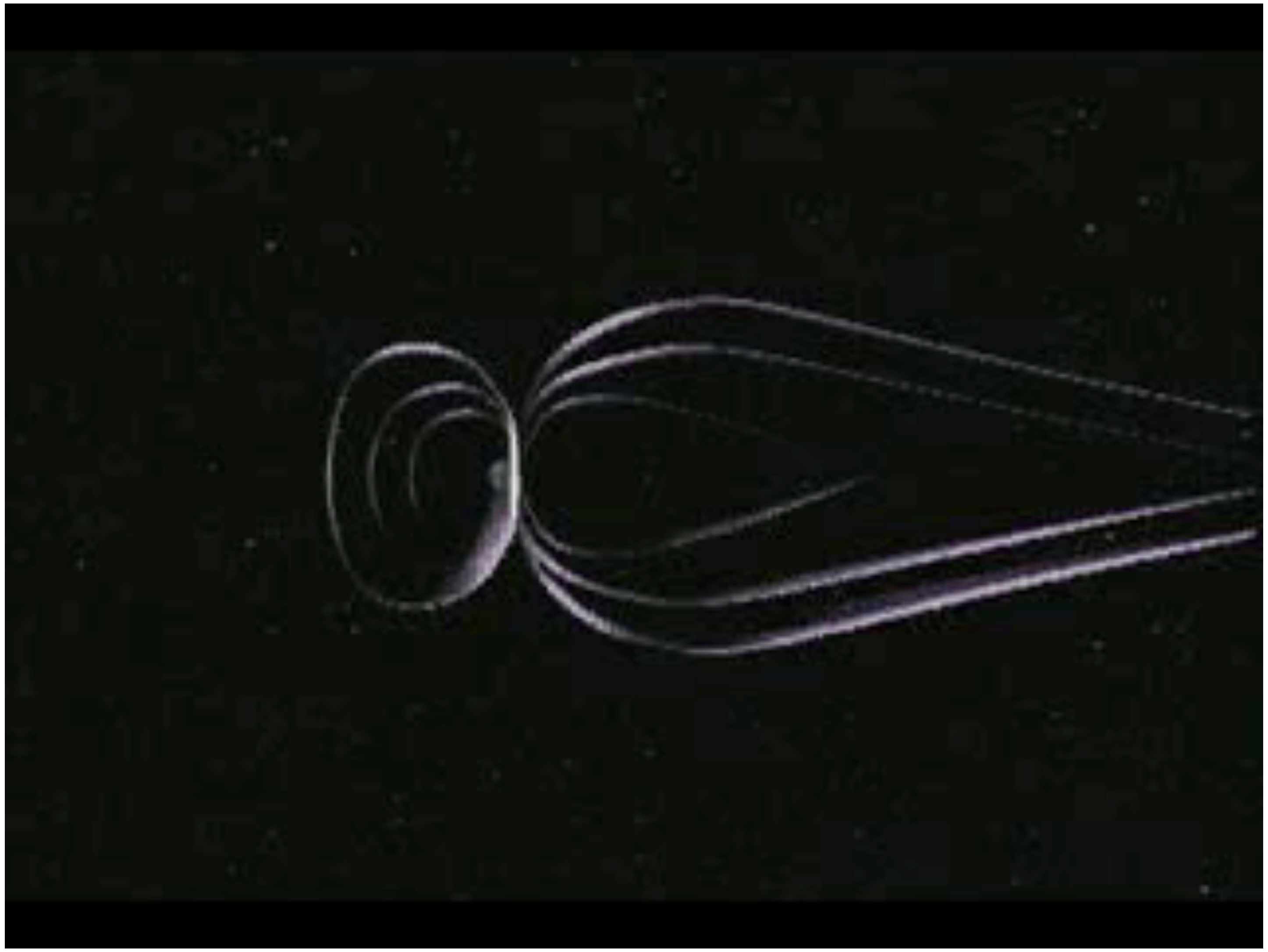

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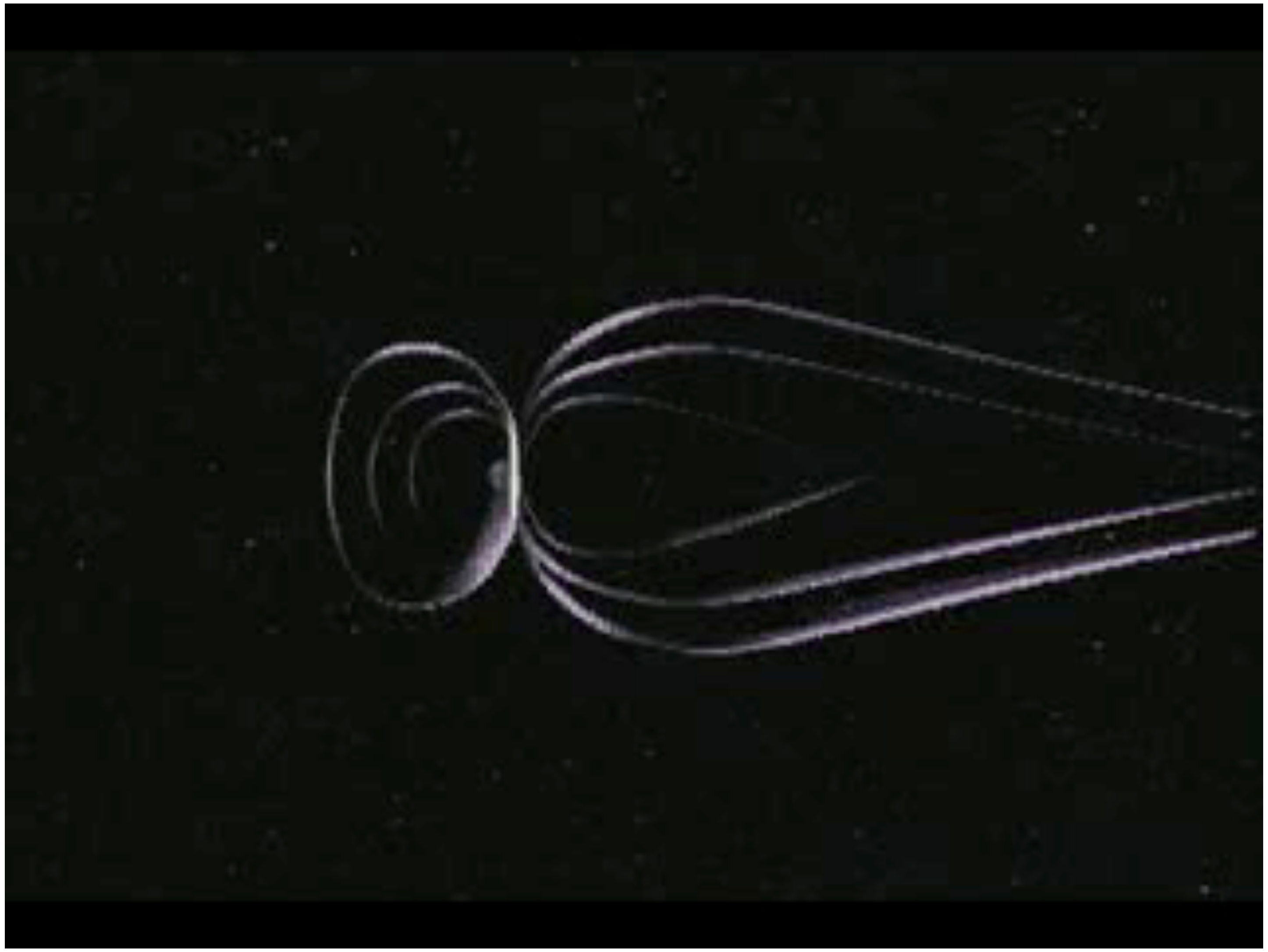
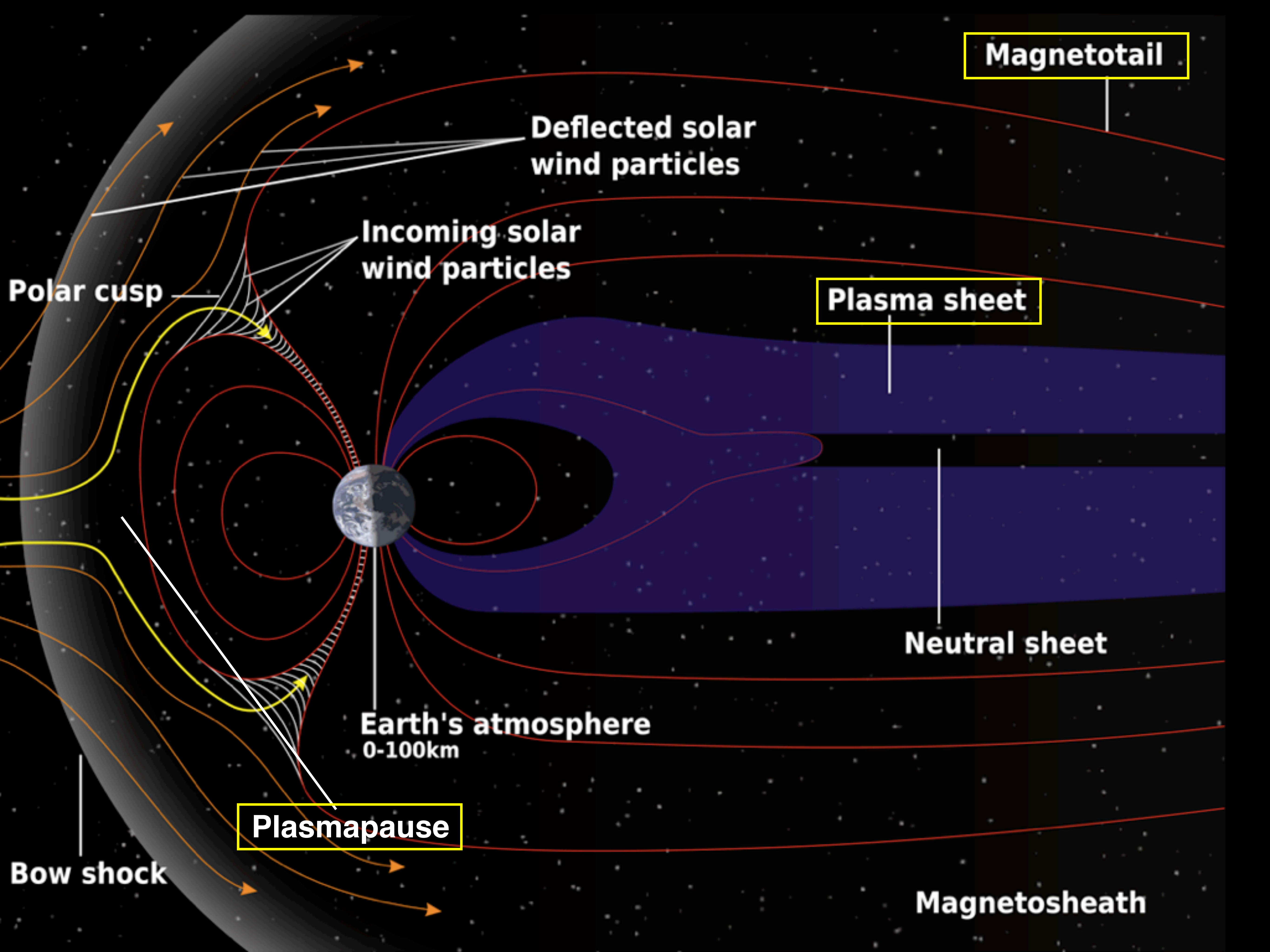




Magnetotail
Deflected solar wind particles
Incoming solar wind particles
Polar cusp
Plasma sheet
Neutral sheet
Earth's atmosphere 0-100km
Plasmapause
Bow shock
Magnetosheath

The Geomagnetic Substorm

A substorm, magnetospheric substorm, or **auroral substorm**, is a brief disturbance in the Earth's magnetosphere causing an almost explosive release of energy from the magnetotail and injected into the high latitude ionosphere. Visually, a substorm is seen as a sudden brightening and increased movement of auroral arcs. Substorms were first described by the Norwegian scientist Kristian Birkeland. The morphology of a substorm was first described by Japanese geophysicist Syun-Ichi Akasofu in 1964 using data collected during the International Geophysical Year.

Substorm Phases

- Growth
- Expansion
- Recovery

Near-Earth-Neutral-Line Model

Growth phase

X-line forms in middle plasma sheet

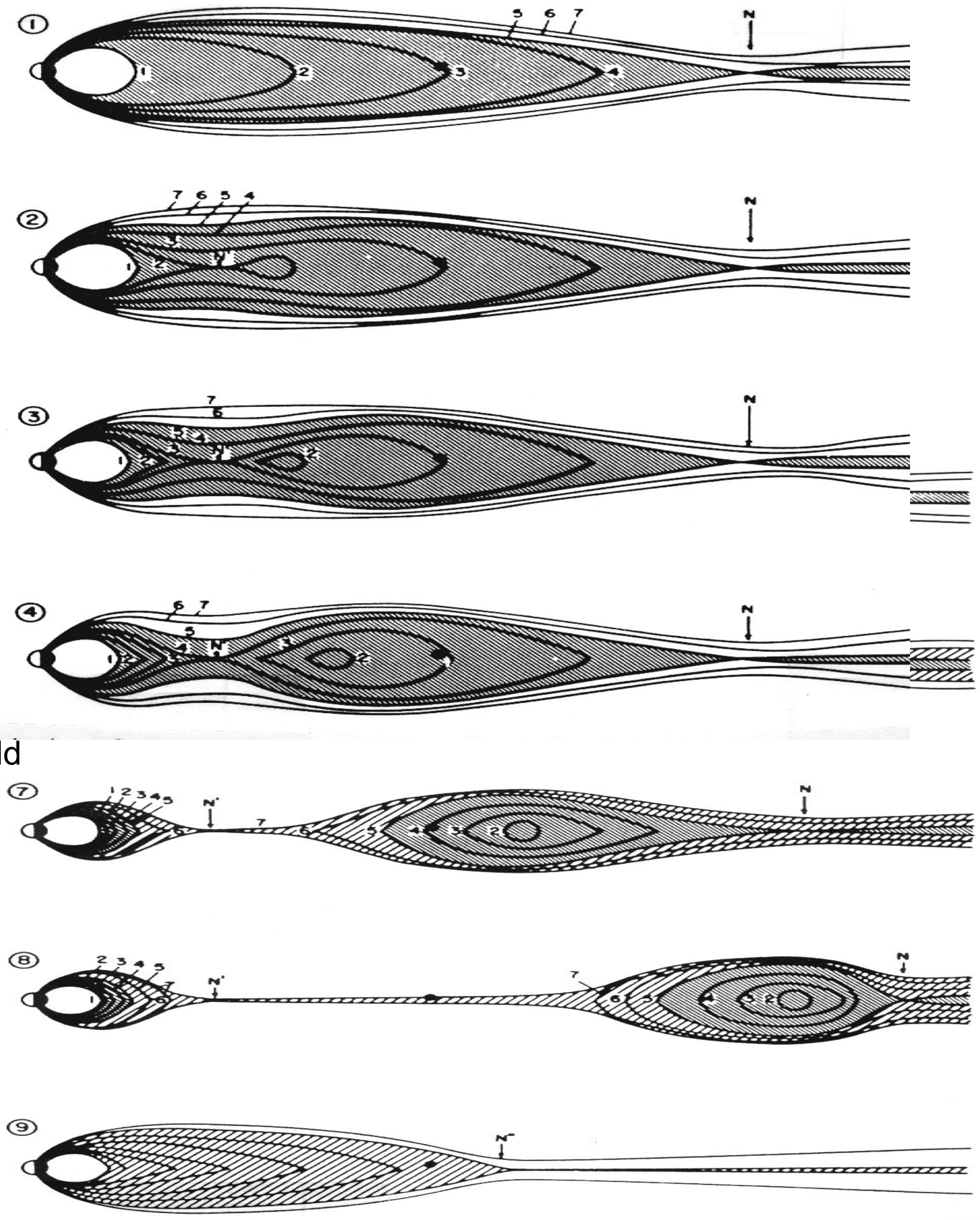
Expansion phase

Reconnection proceeds and plasmoid grows

X-line eats it way through all closed field

Plasmoid moves antisunward

Recovery phase:
Plasma sheet refills

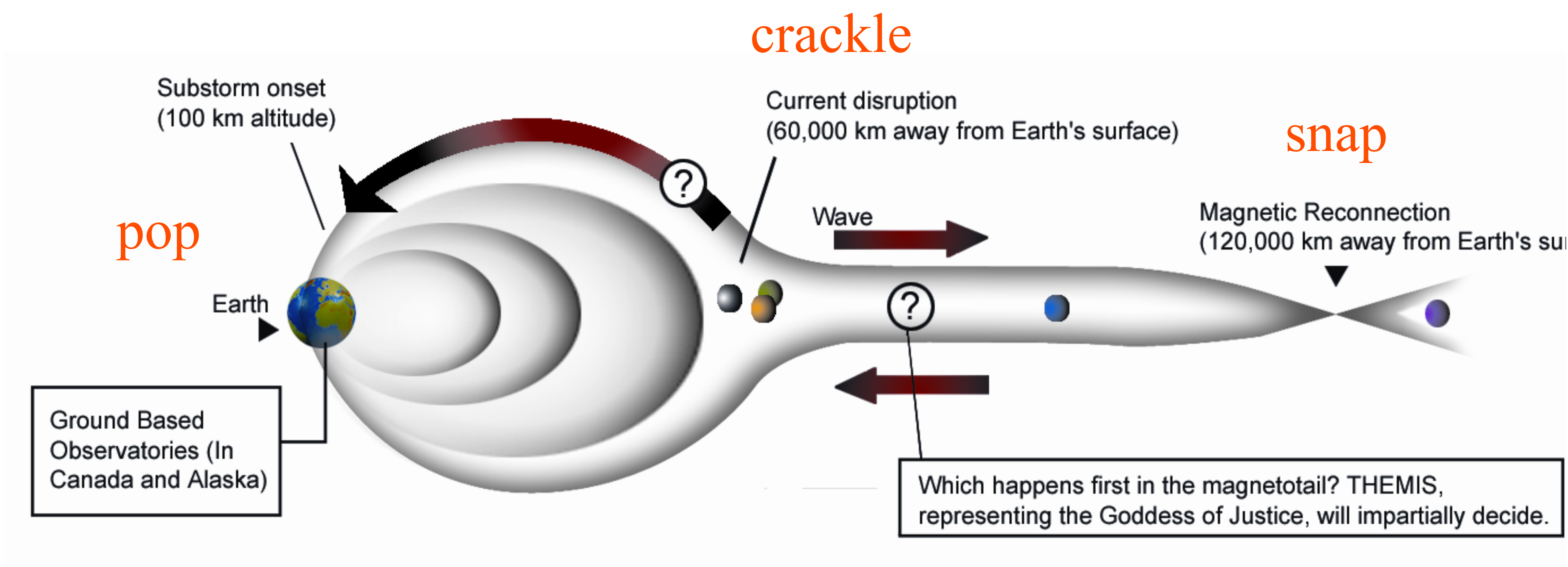


NENL model, from Hones (*JGR*, *92*, 5633, 1977)

Substorm Phases

- During the GROWTH PHASE of the classical substorm, the tail magnetic-field configuration gets very stretched, and the peak current density in the cross-tail current becomes very large.
  - Energy seems to be stored in the tail during the growth phase.
- An energy release begins suddenly at the onset of the EXPANSION PHASE. Field lines near local midnight, which had been very stretched and tail-like at the end of the growth phase, collapse to a more dipolar shape.
  - The aurora suddenly brighten, and the ionospheric conduction currents -- particularly the westward electrojet -- intensify greatly, usually in a limited region of the auroral zone near local midnight.
  - As the expansion phase proceeds, the region of dipolarization, bright aurora and intense currents expands.
  - A large substorm eventually affects nearly all of the nightside auroral zone.
- In the RECOVERY PHASE, the intense ionospheric currents and auroral activity gradually die out.
  - The post-substorm plasma sheet is hotter than it was before the substorm. One or more large substorms normally occur in the main phase of a magnetic storm.

Where in the Magnetotail does the magnetosphere snap and then pop with Aurora? (snap-crackle-pop? or crackle-pop-snap?)



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Aurora: Why does it happen at night?

When the solar wind passes Earth, it drags the magnetic tail far out into space and compresses it.

Stretched magnetic lines break and then (re) connect into a different shape.

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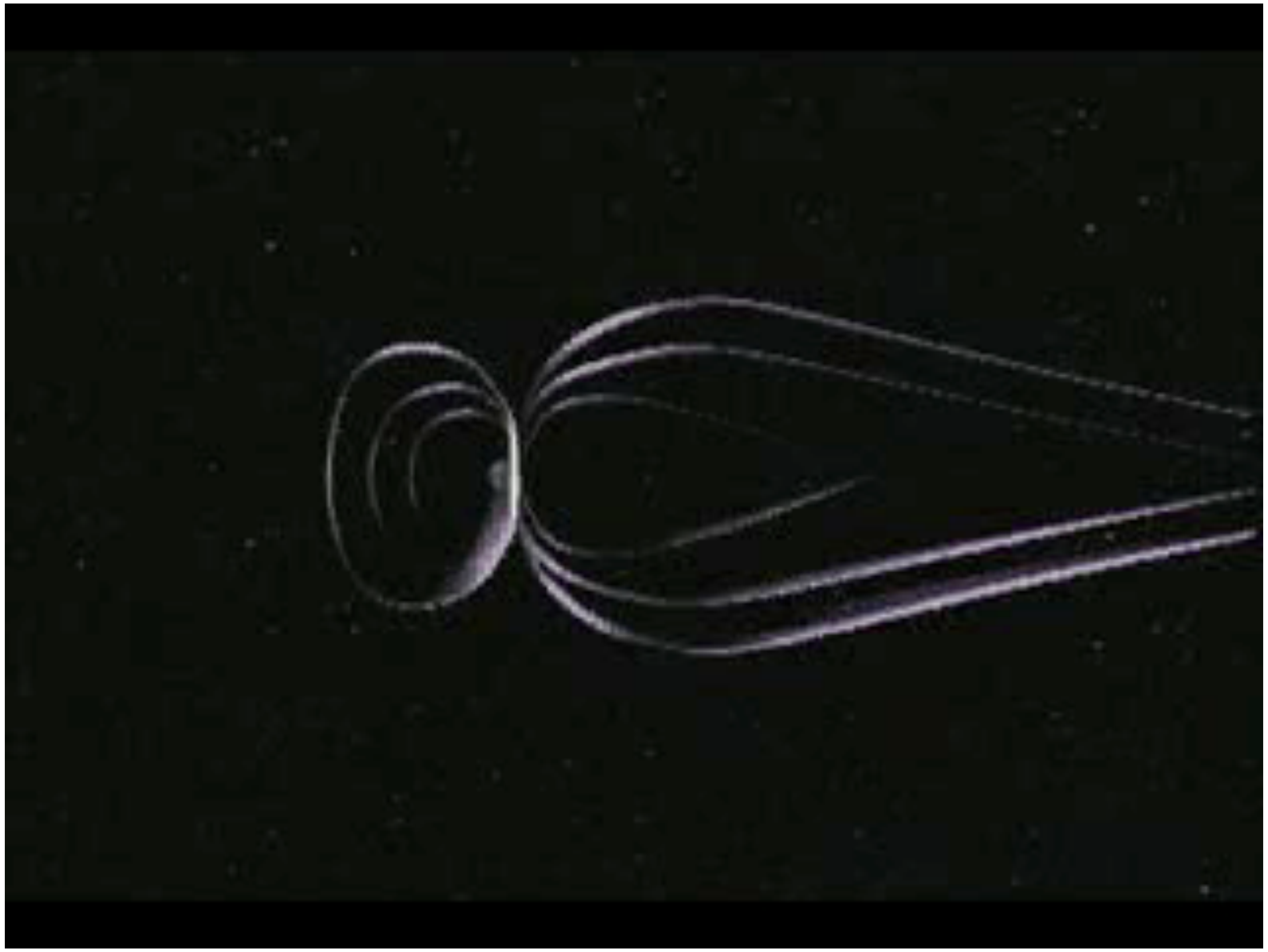

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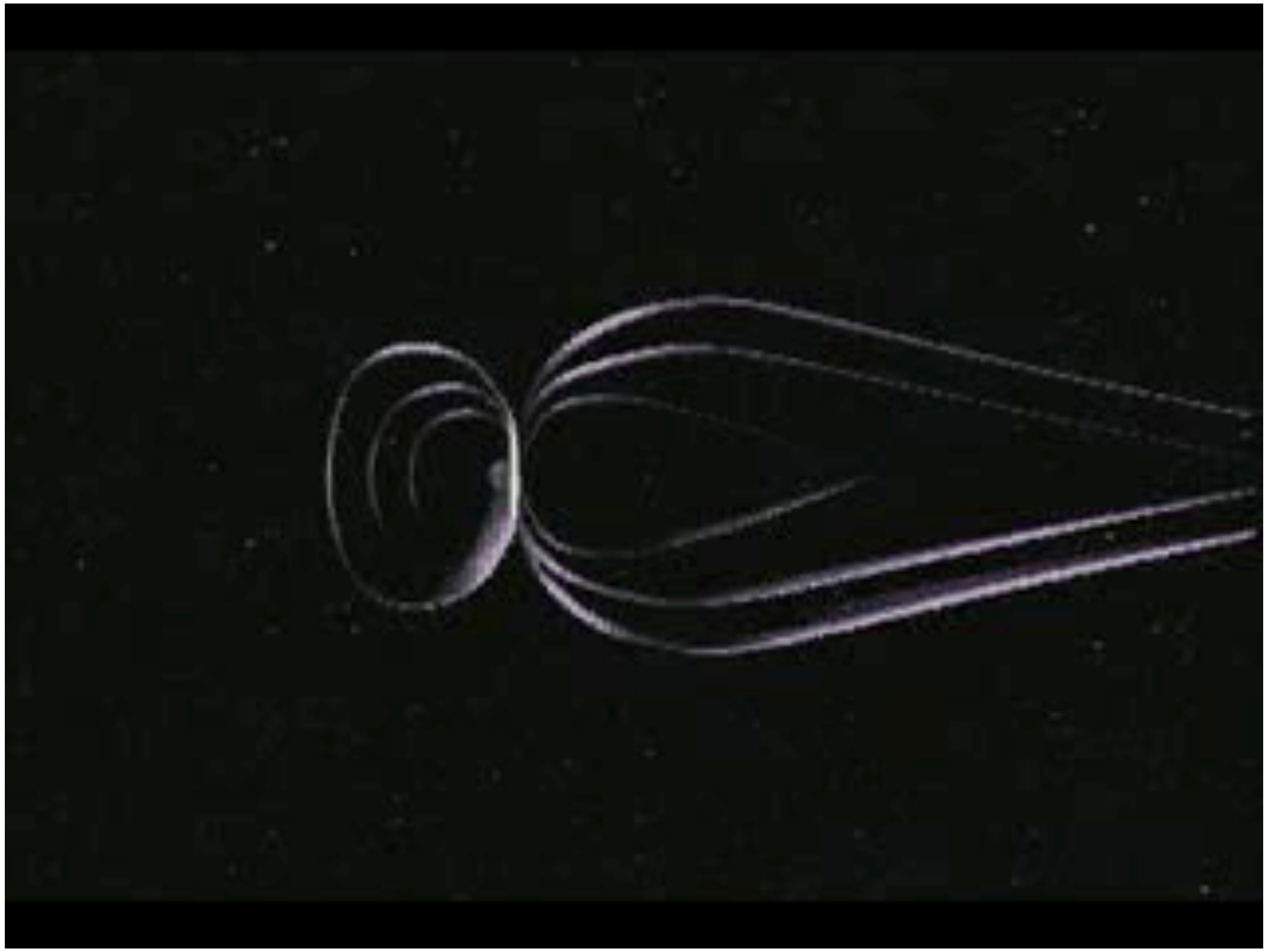
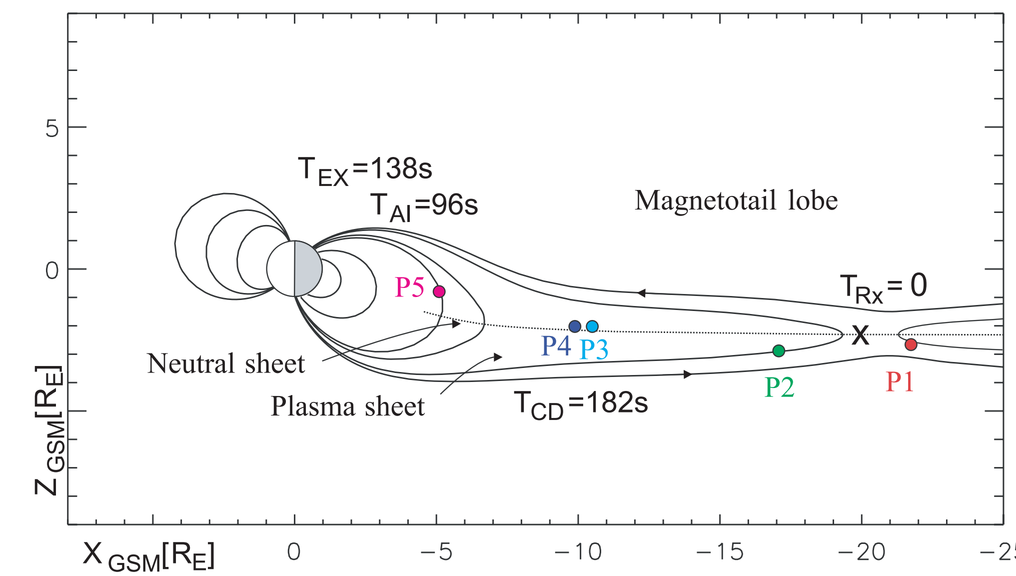


THEMIS Satellite Constellation



Satellite	Color
THEMIS-A (P5)	
THEMIS-B (P1)	
THEMIS-C (P2)	
THEMIS-D (P3)	
THEMIS-E (P4)	

Science AAAS

Tail Reconnection Triggering Substorm Onset
Vassilis Angelopoulos, *et al.*
Science **321**, 931 (2008);
DOI: 10.1126/science.1160495

Tail Reconnectio Triggering Substorm Onset

Vassilis Angelopoulos,[1*] James P. McFadden,[2] Davin Larson,[2] Charles W. Carlson,[2] Stephen B. Mende,[2] Harald Frey,[2] Tai Phan,[2] David G. Sibeck,[3] Karl-Heinz Glassmeier,[4] Uli Auster,[4] Eric Donovan,[5] Ian R. Mann,[6] I. Jonathan Rae,[6] Christopher T. Russell,[1] Andrei Runov,[1] Xu-Zhi Zhou,[1] Larry Kepko[7]

Magnetospheric substorms explosively release solar wind energy previously store Earth's magnetotail, encompassing the entire magnetosphere and producing spectacular auroral displays. It has been unclear whether a substorm is triggered by a disruption of the electrical current flowing across the near-Earth magnetotail, at ~10R_E (R_E Earth radius, or 6374 kilometers), or by the process of magnetic reconnection typically seen farther out in the magnetotail, at ~20 to 30 R_E at the time of substorm onset. Reconnection was observed at 20R_E at least 1.5 minutes before auroral intensification, at least 2 minutes before substorm expansion, and about 3 minutes before near-Earth current disruption. These results demonstrate that substorms are likely initiated by tail reconnection.

Reconnection Accounts for of most Space Weather
The Largest Variations
Low Probability High Risk Events

Magnetic Reconnection is almost certainly the energy release mechanism in:

- Solar flares and Coronal Mass Ejections (CME's)
- Geomagnetic storms and substorms

Without Reconnection Space Weather would be duller

Sweet–Parker Model

Ampere $\Rightarrow$ $\nabla \times \mathbf{B} = \mu_o \mathbf{J} \Rightarrow$ $J_{dy} \approx B_{oz}/\mu_o d$

Magnetic tension $\Rightarrow$ $(\mathbf{J}_{dy} \times \mathbf{B}_{dx}) \cdot \hat{\mathbf{e}}_z \approx J_{dy} B_{dx} \approx B_{oz} B_{dx}/\mu_o d$

Balanced by kinetic pressure $\Rightarrow$ $\rho_i (\mathbf{v} \cdot \nabla) v_{dz} \approx \rho_i v_{dz}^2/L \approx B_{oz} B_{dx}/\mu_o d$

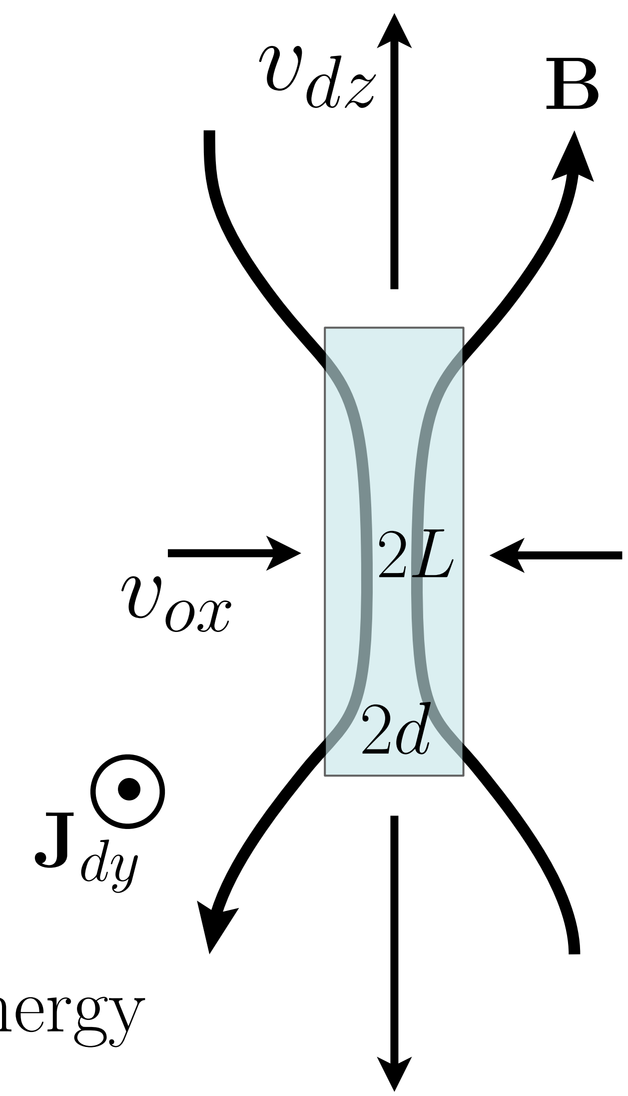
$\nabla \cdot \mathbf{B} = 0 \Rightarrow$ $B_{oz}/L = B_{dx}/d$

Outflow velocity $\Rightarrow$ $v_{dz}^2 \approx B_{oz}^2/\mu_o \rho_i = v_{A0}^2$ $\Leftarrow$ Alfven speed

Reconnection rate $\Rightarrow$ $\mathcal{R} = v_{dz}/v_{ox} = M_{A0}$ $\Leftarrow$ Mach number

Exercise $\Rightarrow$ $\mathcal{R}_{SP} = M_{A0} = R_m^{-1/2}$ $\quad R_m = \mu_o \sigma v_{A0} L$

Exercise $\Rightarrow$ Half of the magnetic energy becomes mechanical energy



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Balanced by kine ... $_z B_{dx}/\mu_o d$

A Solar flare lasts 1000 sec
Sweet-Parker predicts 10^7 sec.

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

Outflow velocity ...

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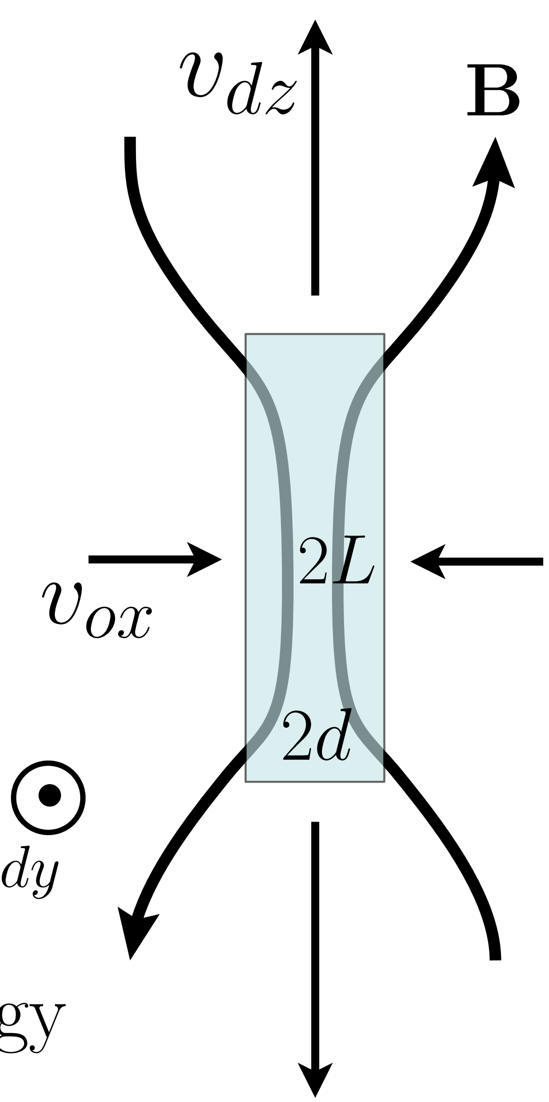

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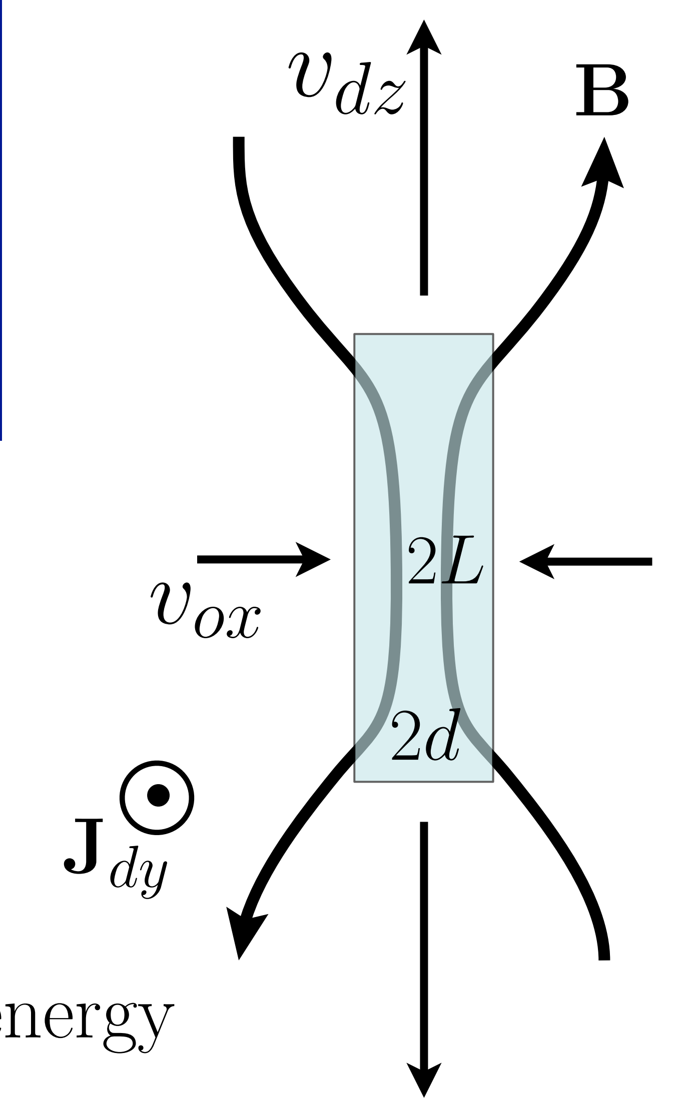
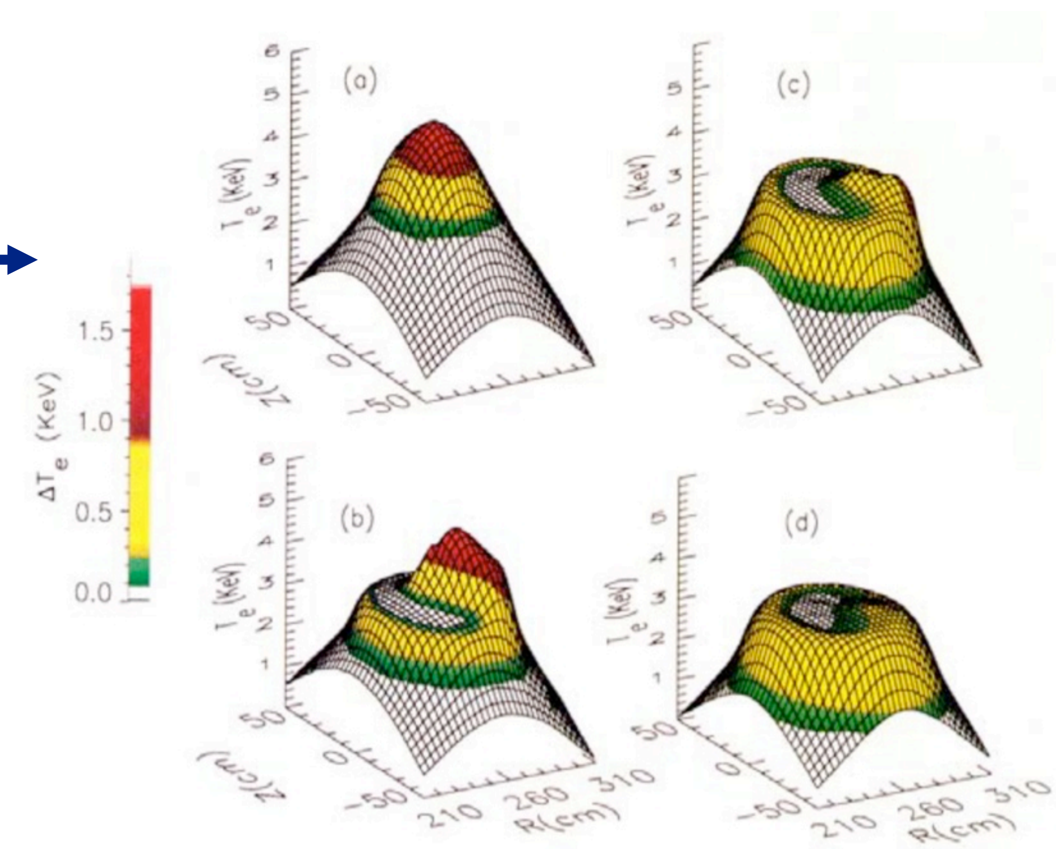


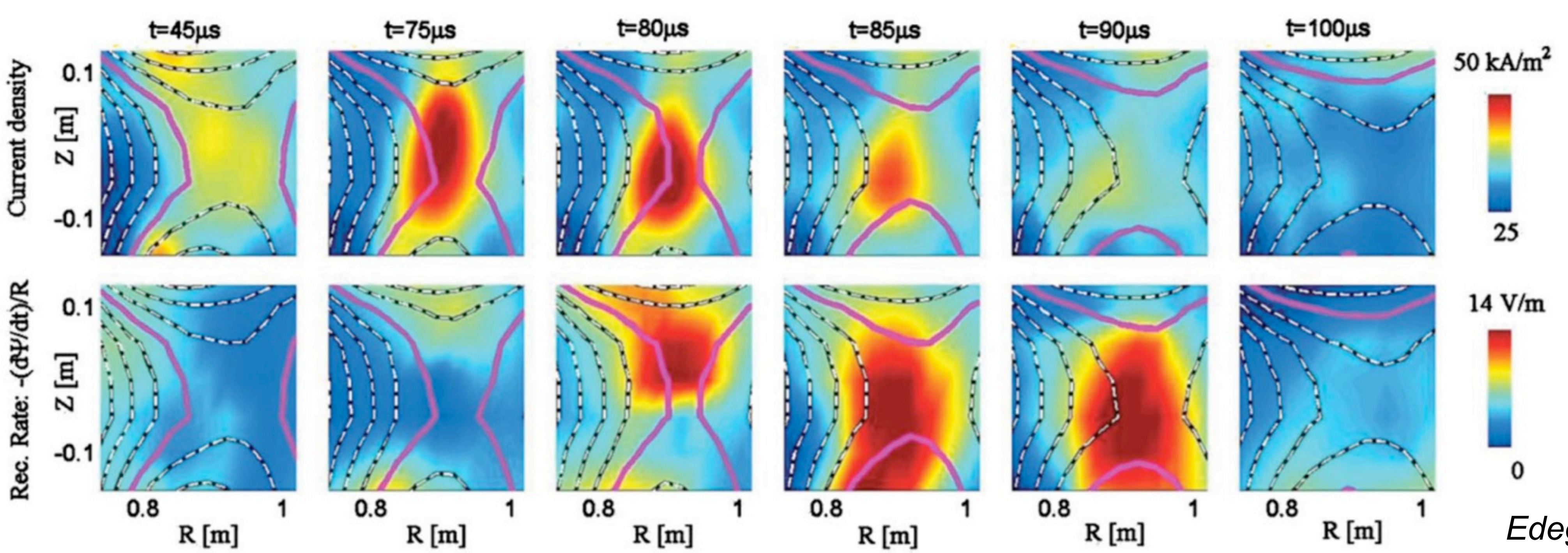
Reconnection in Tokamaks: Sawtooth Crashes

Sudden flattening (or crashes) of the electron temperature profile limit plasma heating within Tokamaks, thereby defeating their purpose.

These crashes are explained by reconnection with a strong guide field within the device as shown in laboratory experiments.



Yamada et al. [1994]



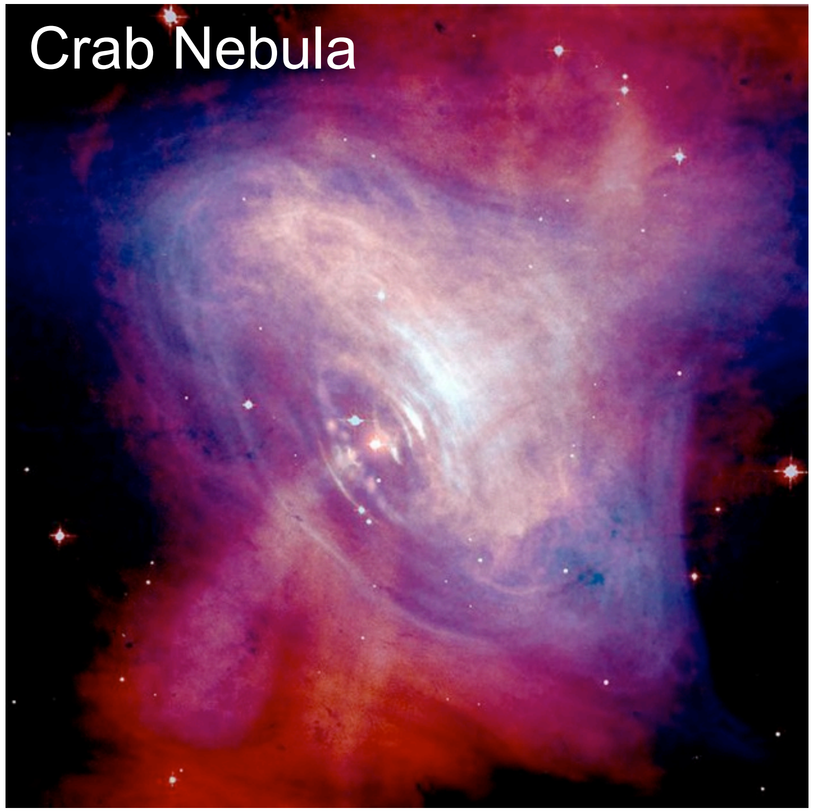
Current Density

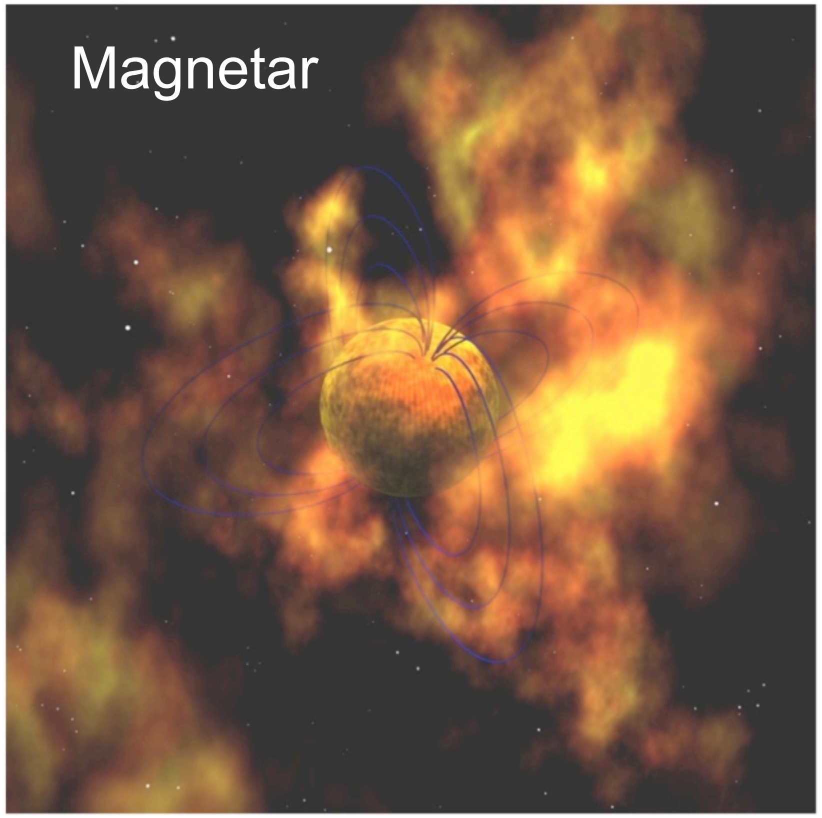
Reconnection Rate >> S-P

Edegal et al. [2007]

Astrophysical Contexts

- Some of the most energetic phenomena in the universe result from supernova explosions.
- After the explosion the star collapses into a neutron star and often into a black hole.
- Later any nearby stars can be distorted and drawn into the black hole trough an accretion disk that is magnetically connected through **reconnection** to the black hole and neutron star.
- The transfer of angular momentum by the magnetic field to the neutron star results in the ejection of jets of material from the star.
- The neutron star can evolve into a pulsar or, in extreme cases, into a magnetar, which exhibits very energetic flare-type emissions that, by analogy with the solar corona, are likely produced by **magnetic reconnection**.





Magnetic Reconnection in a Nutshell

Two magnetic fields with antiparallel components; annihilate each other on contact

Some mechanism exists in the region of contact that decouples the plasma from the field — Frozen-field violation

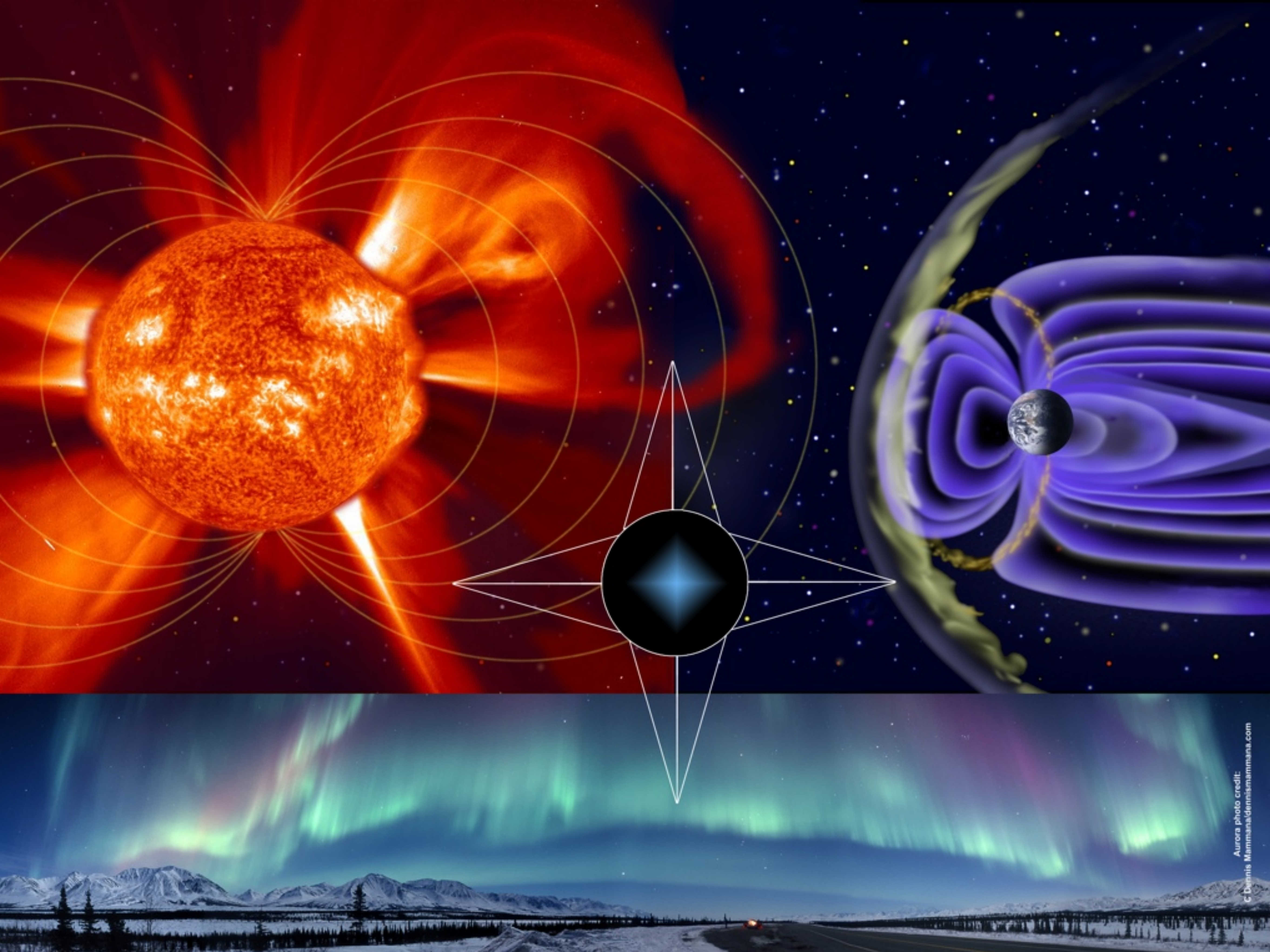
The Four Mysteries of Reconnection

What produces the dissipation? — Plasmas are collisionless

What is the relation between the aspect ratio of the diffusion region and the rate of reconnection?

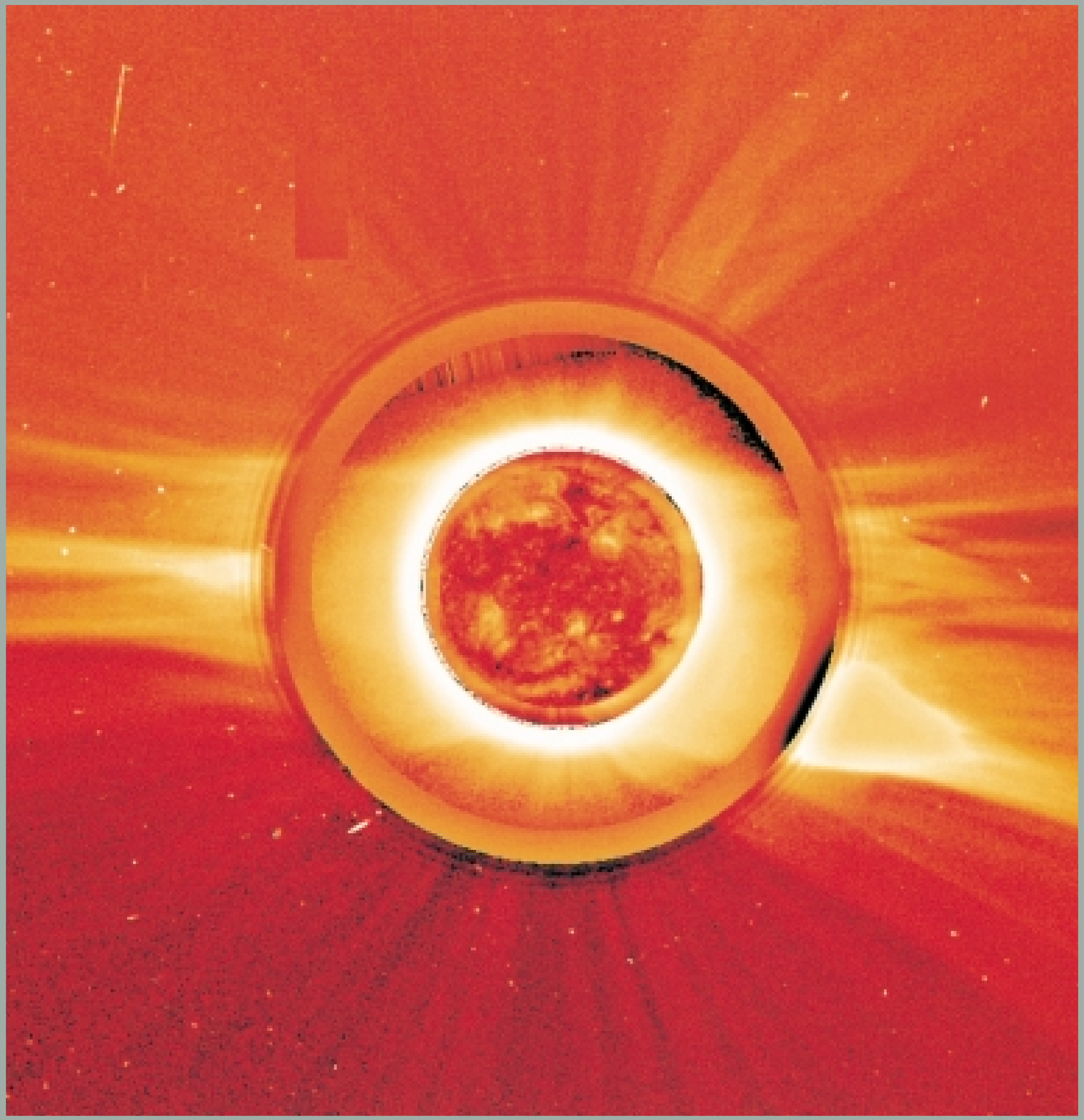
What triggers explosive reconnection? — Could be in steady state

What is the mechanism to convert magnetic energy to kinetic and heat energy?


Aurora photo credit:
© Dennis Mammana/dennismammana.com

Swiss Re

Space weather
Hazard to the Earth?



Space weather
Hazard to the Earth?

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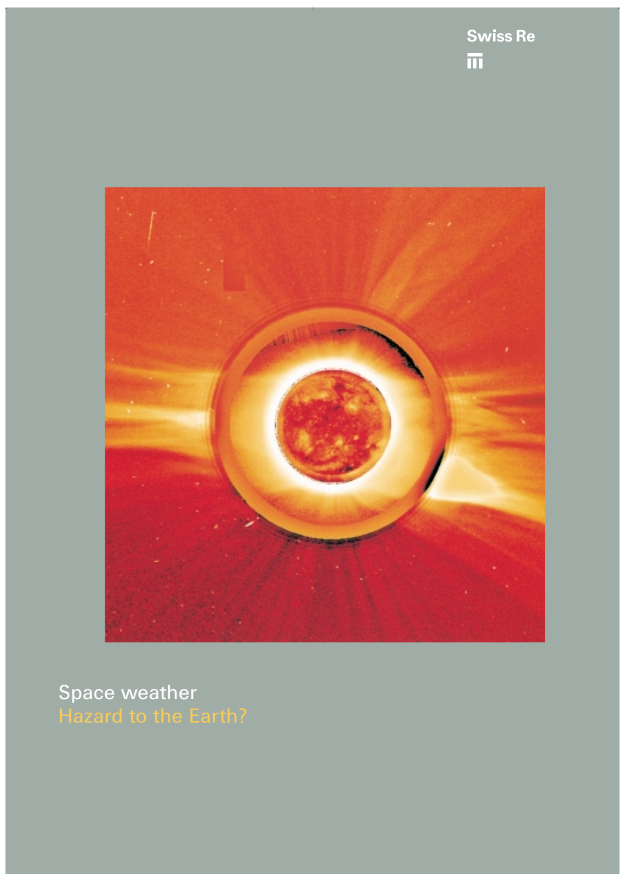
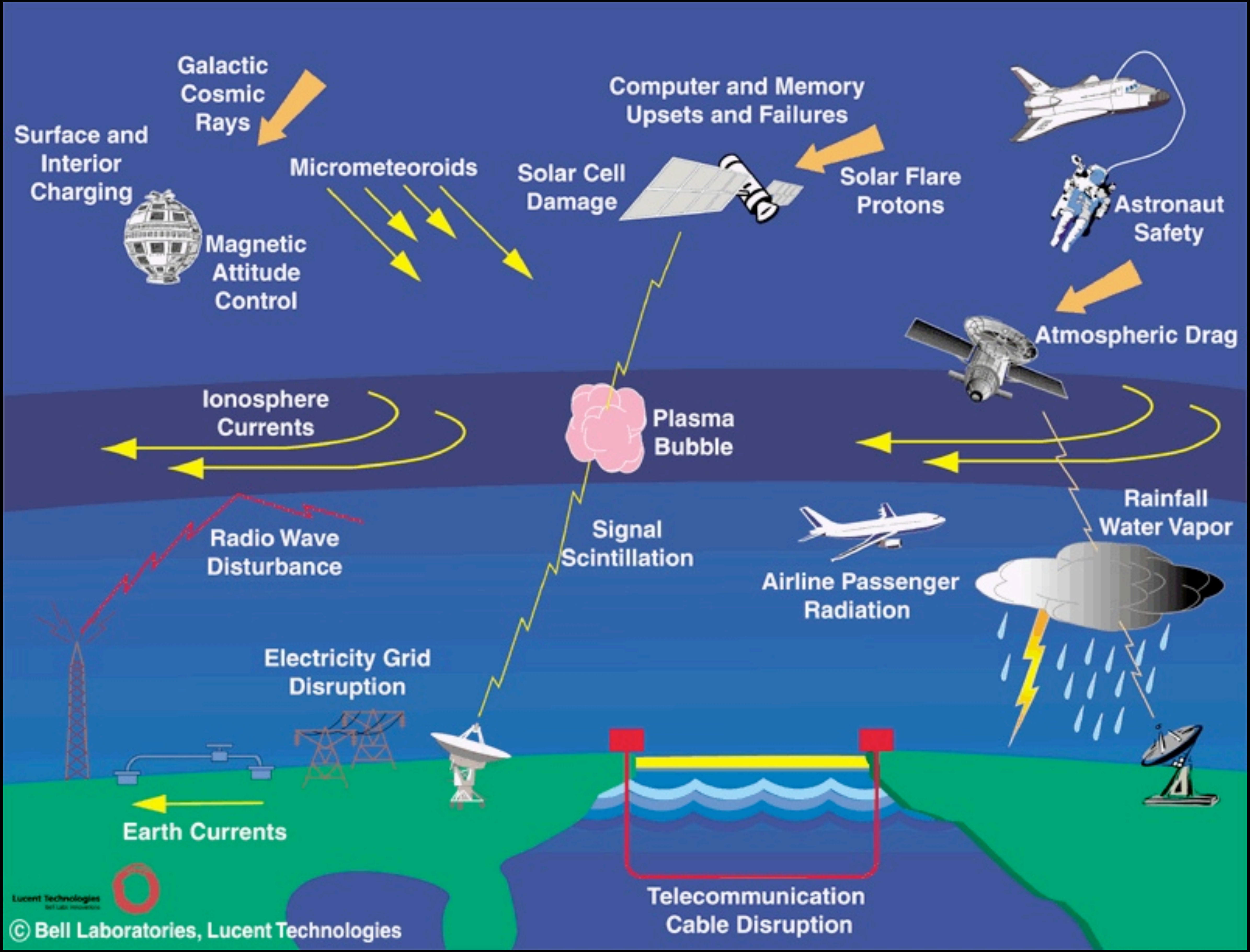
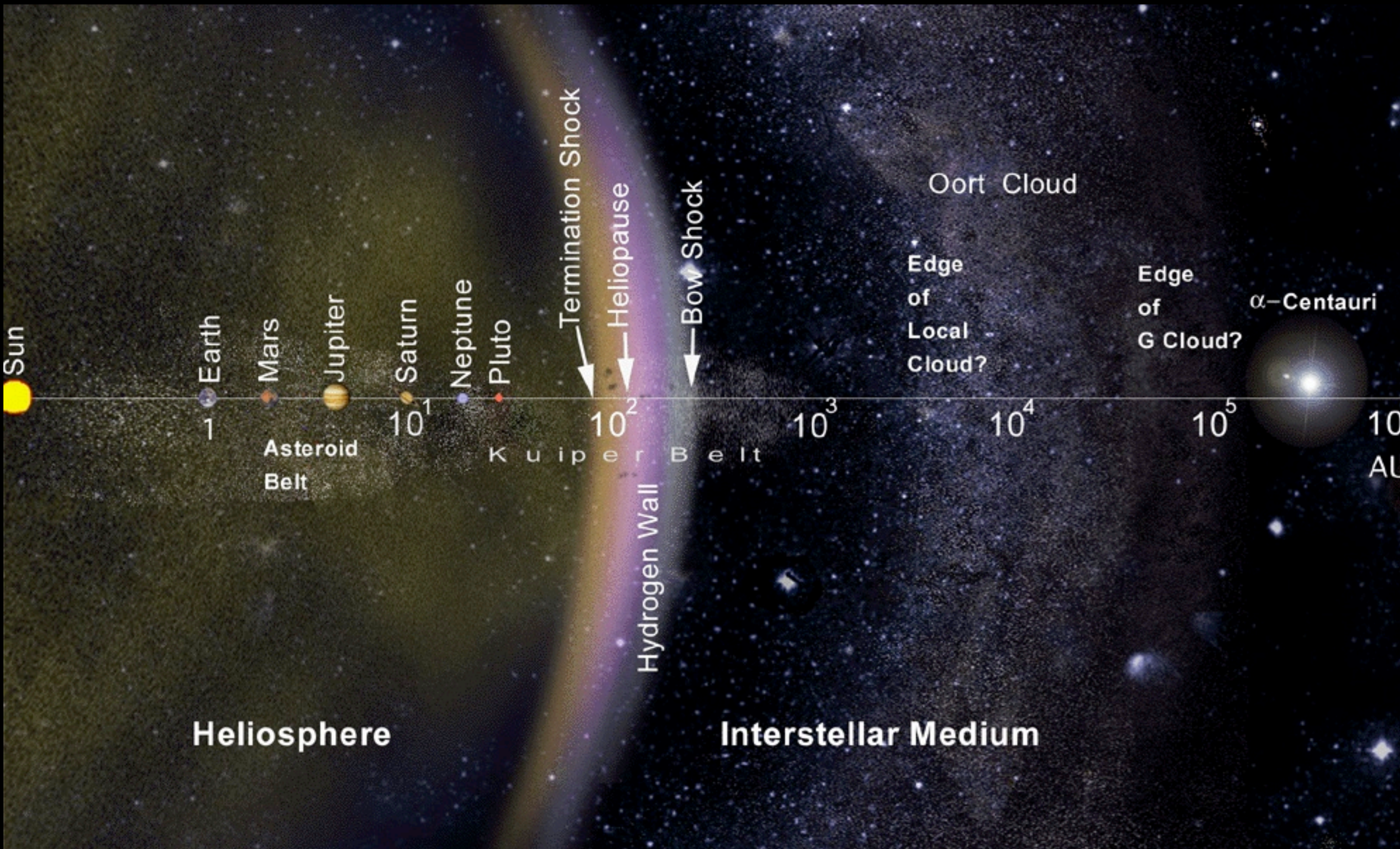


Space Weather Hazards

Lou Lanzerotti

Bell Labs

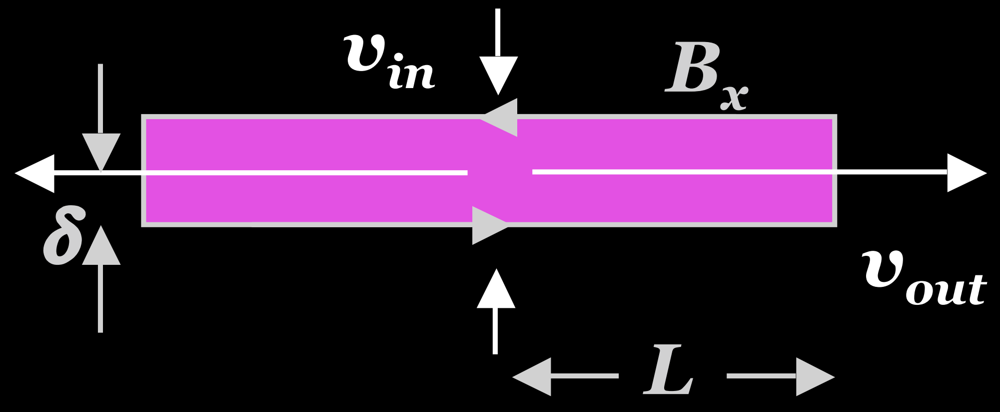



Sun
Earth
Mars
Jupiter
Saturn
Neptune
Pluto
Termination Shock
Heliopause
Bow Shock
Oort Cloud
Edge of Local Cloud?
Edge of G Cloud?
α−Centauri
1
10^1
10^2
10^3
10^4
10^5
10^6
AU
Asteroid Belt
Kuiper Belt
Hydrogen Wall
Heliosphere
Interstellar Medium

Sun's Power Output	300×10^{24}	W
Sun's Power Flux	20×10^{6}	W $m^{-2}sr^{-1}$
At 1AU	1361	W m^{-1}
	174×10^{15}	W
Sun Energy absorbed by Earth	3.85×10^{24}	Joule/yr
Solar Flare Energy	$\leq 60 \times 10^{24}$	Joule
Magnetospheric Substorm	10^{16}	Joule
ETEC (2008)	474×10^{18}	Joule
	15×10^{12}	W
USA EC (2008)	10×10^{18}	Joule
Norway EC (2008)	0.4×10^{18}	Joule
1 kW-hr	3.6×10^{6}	Joule
1 Megaton	4.184×10^{9}	Joule
Large H-bomb (25 Megaton)	104×10^{9}	Joule
Javelin World Record (98.5 m)	386	joule

Sweet–Parker Model

- **A steady-state is reached when field lines convect into the collisional layer at the same rate that they are annihilated**



$$v_{in} \sim \frac{\eta c^2}{4\pi\delta}$$

- **"The pressure available for squeezing the fluid out …" is magnetic ($B^2/8\pi$), so "from energy considerations," the outflow speed is** $v_{out} \sim \frac{B_x}{\sqrt{4\pi\rho}} \sim c_A$
- **Combine with continuity "based on geometrical considerations,"** $v_{in} \sim \frac{\delta}{L} v_{out}$

- **The result** (Parker, JGR, 1957)

$$\frac{\delta}{L} \sim \frac{v_{in}}{v_{out}} \sim \frac{cE}{B_x c_A} \sim \sqrt{\frac{\eta c^2}{4\pi c_A L}} \sim S^{-1/2}$$

  - **It is fully nonlinear and (almost) entirely self-consistent**
    - **Based on conservation laws (mass, energy, magnetic flux)**
  - **It has been confirmed by simulations** (Biskamp, Phys. Fluids, 1986) **and experiments** (Ji et al., PRL, 1998) **in certain regimes**

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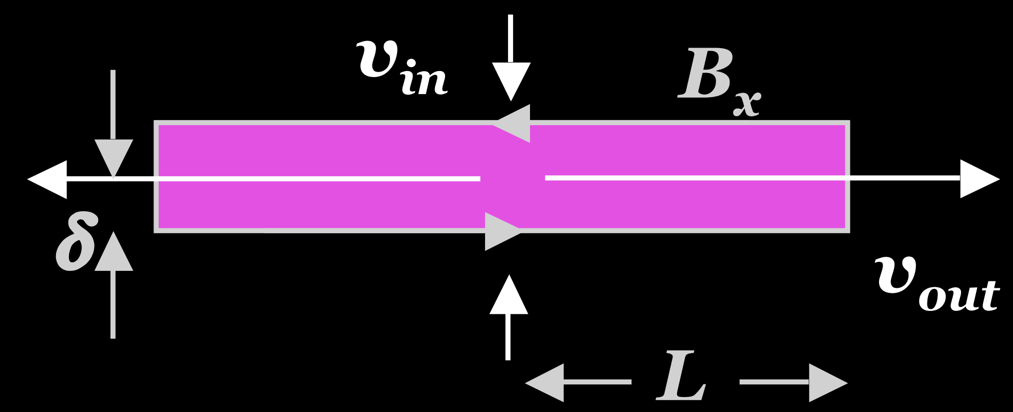

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  the fluid out ..
  "from energy
- **Combine with**
  on geometrica

$$\frac{B_x}{\sqrt{4\pi\rho}} \sim c_A$$

A Solar flare lasts 1000 sec

Sweet-Parker predicts 10^7 sec.

- **The result** (Par

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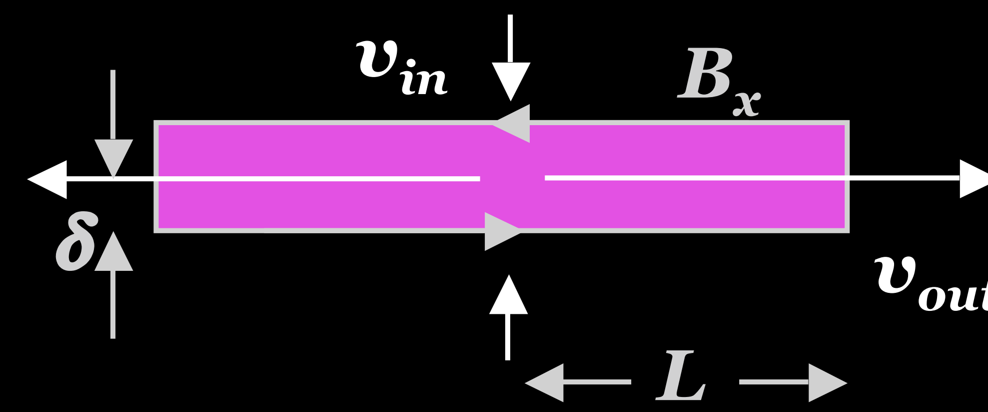

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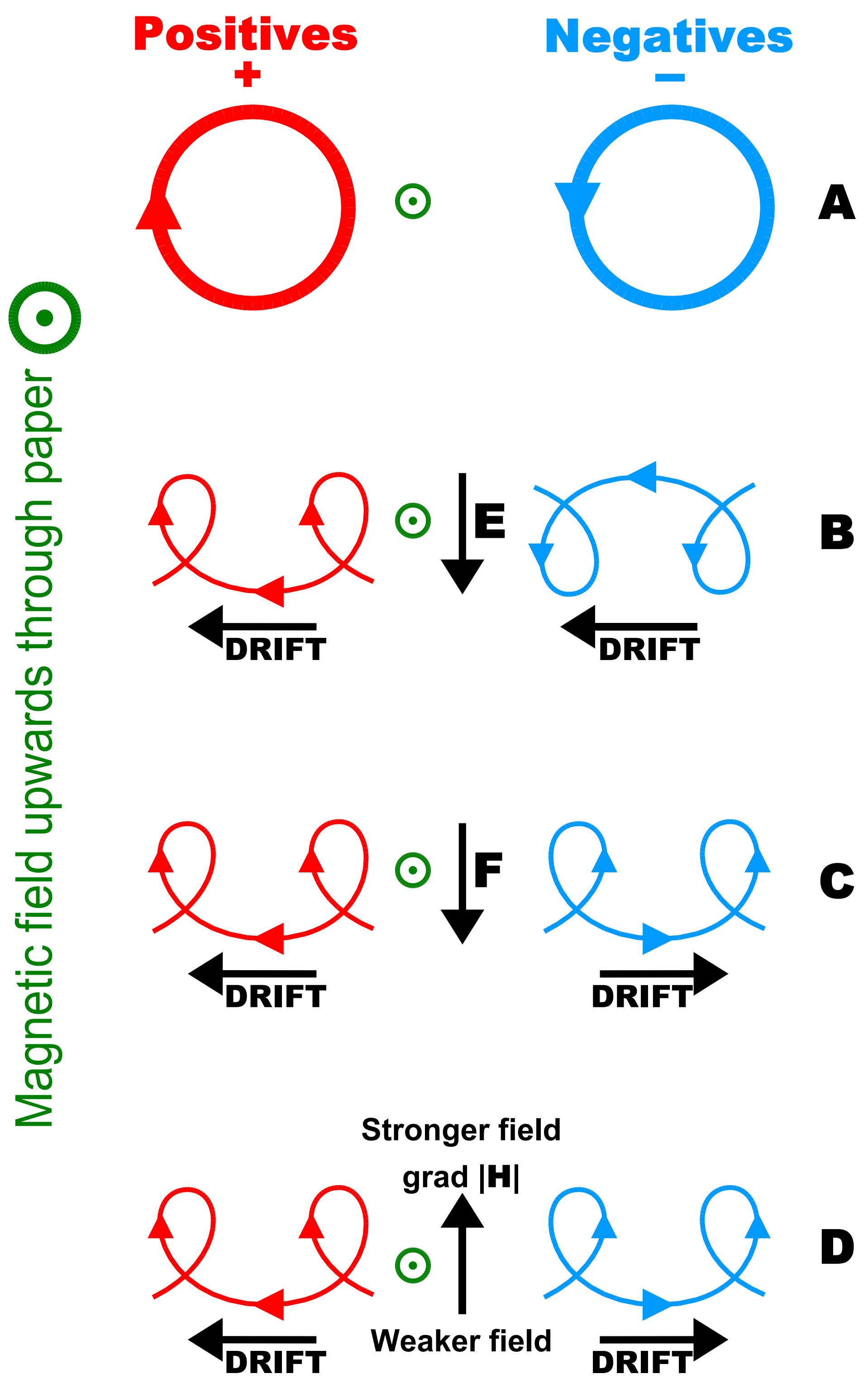

Positives
+
Negatives
−
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E
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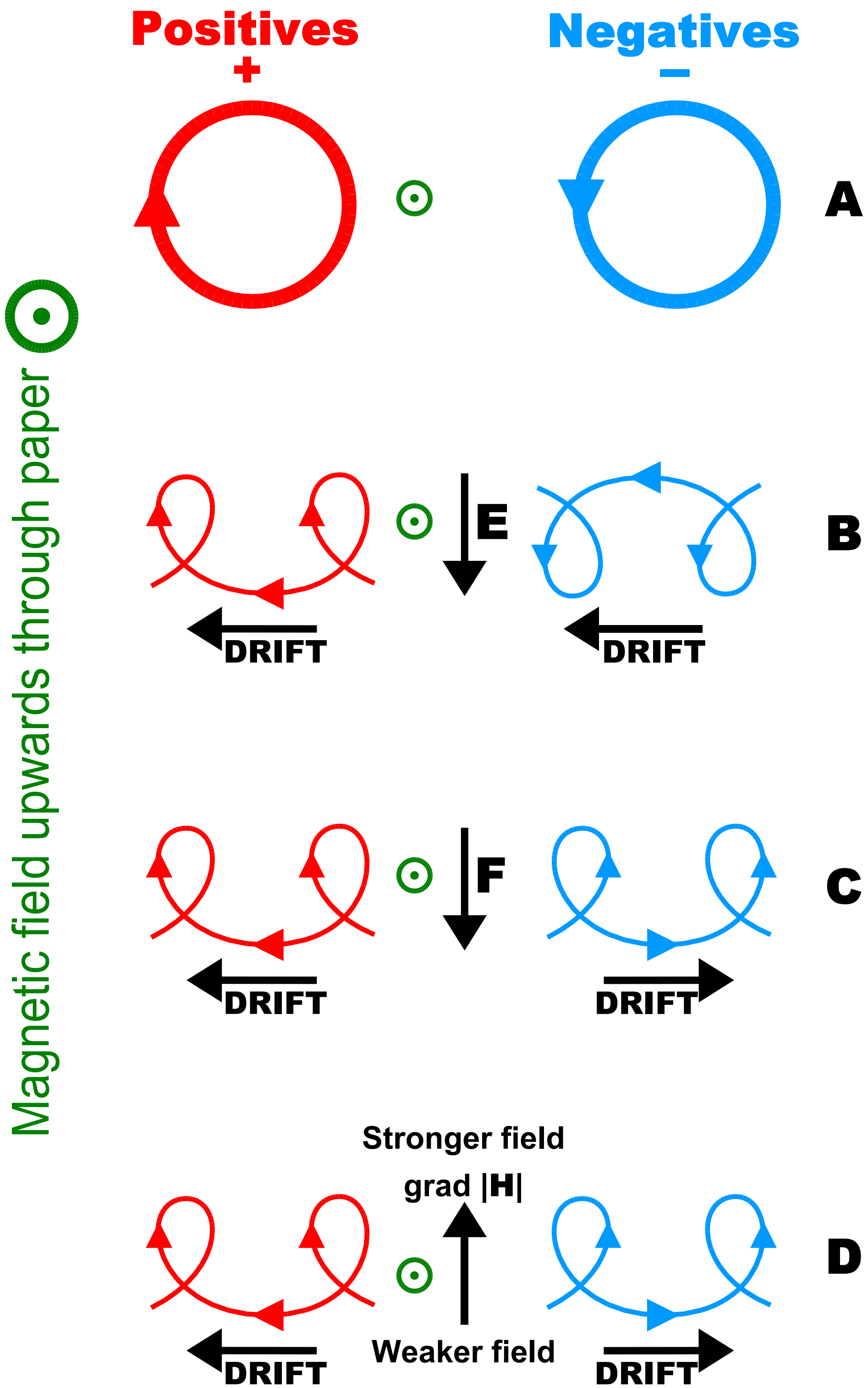
DRIFT
F
C
DRIFT
DRIFT
Stronger field
grad |H|
Weaker field
D
DRIFT
DRIFT
Magnetic field upwards through paper


Magnetic field upwards through paper
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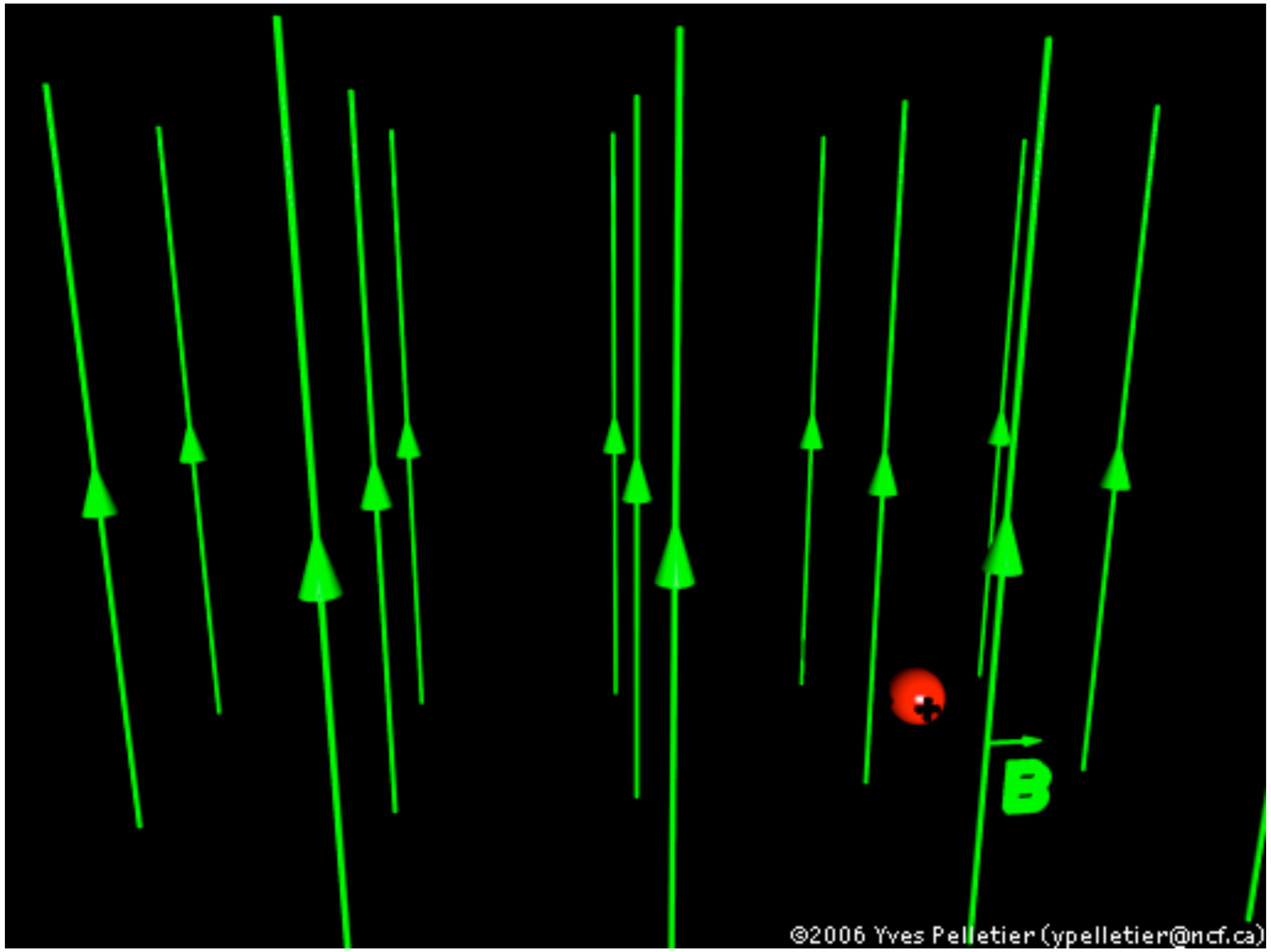
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