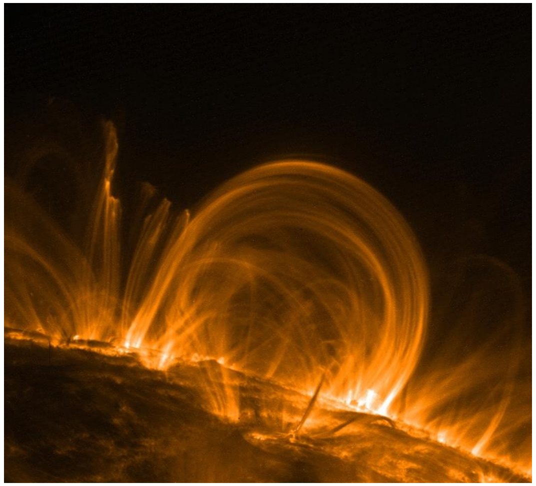

Heliophysics Summer School

Part 1

- **Motivation**: Why heliophysics?
- My view of plasma physics: kinetic, multi-fluid, and MHD approaches.
- Quick review of particle motion and adiabatic invariants.
- Shocks (basics) and why they are important (collisionless plasmas)
- Magnetic reconnection (basics) and why it is important (collisionless plasmas)

Prof. Robert Ergun
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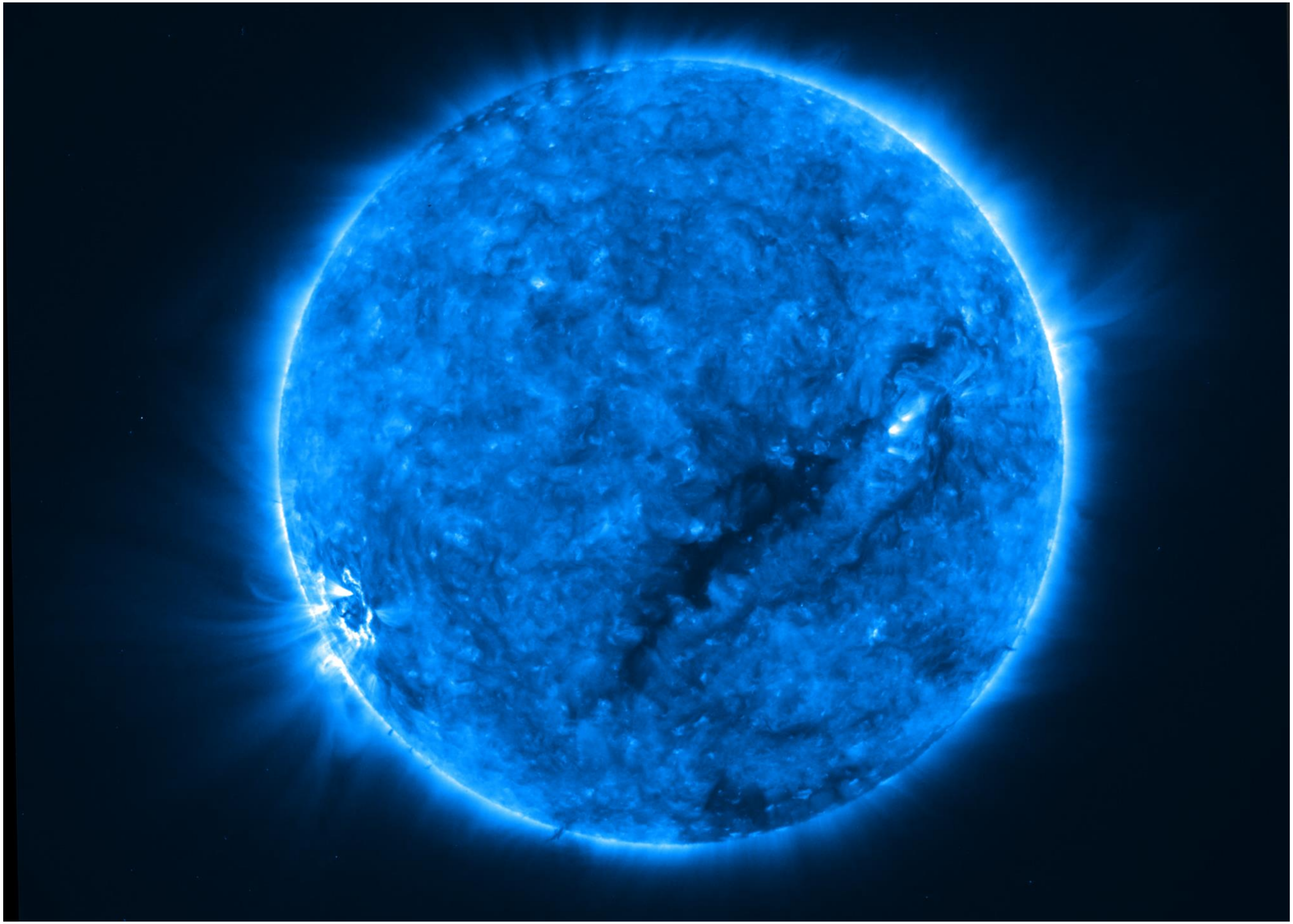
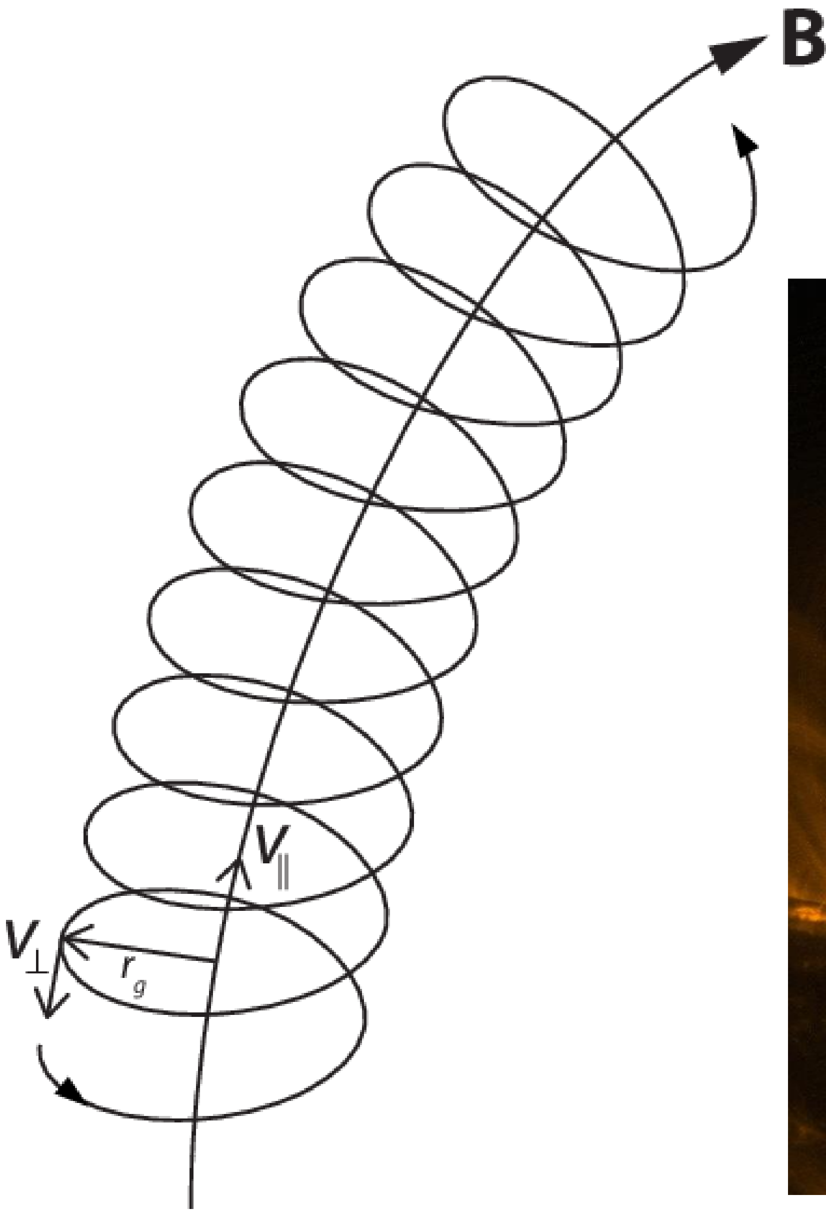
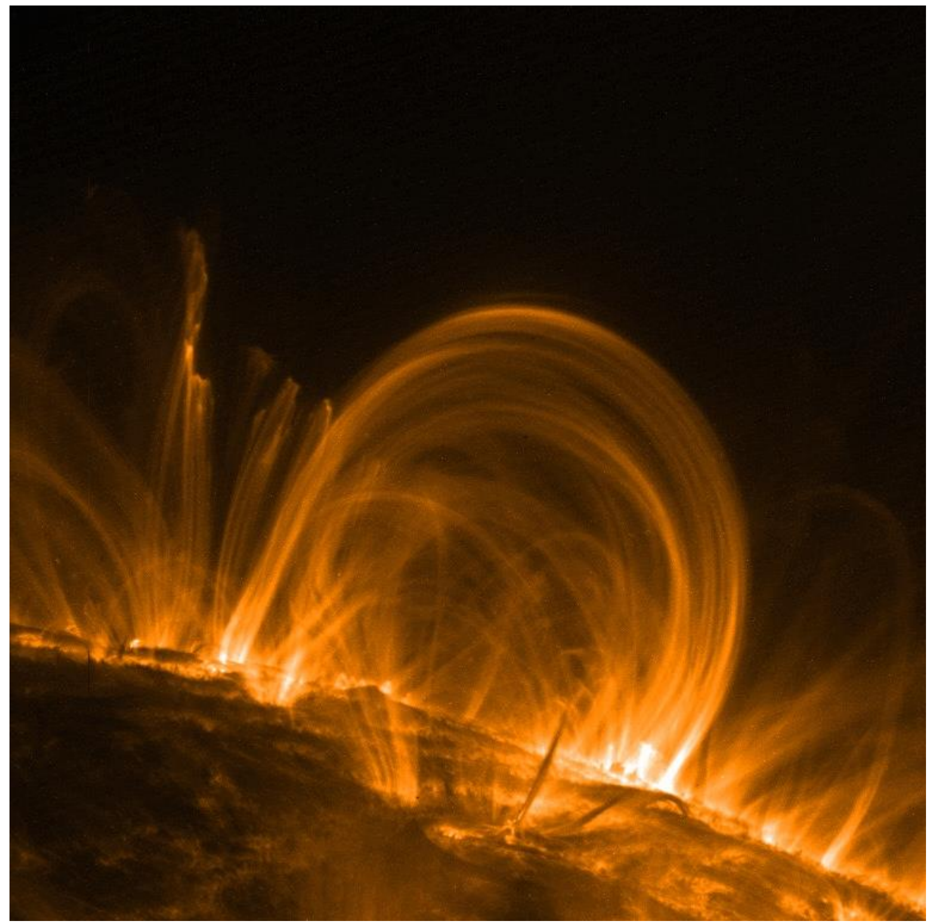
Why Heliophysics?



I Am Motivated by the "Physics" Part

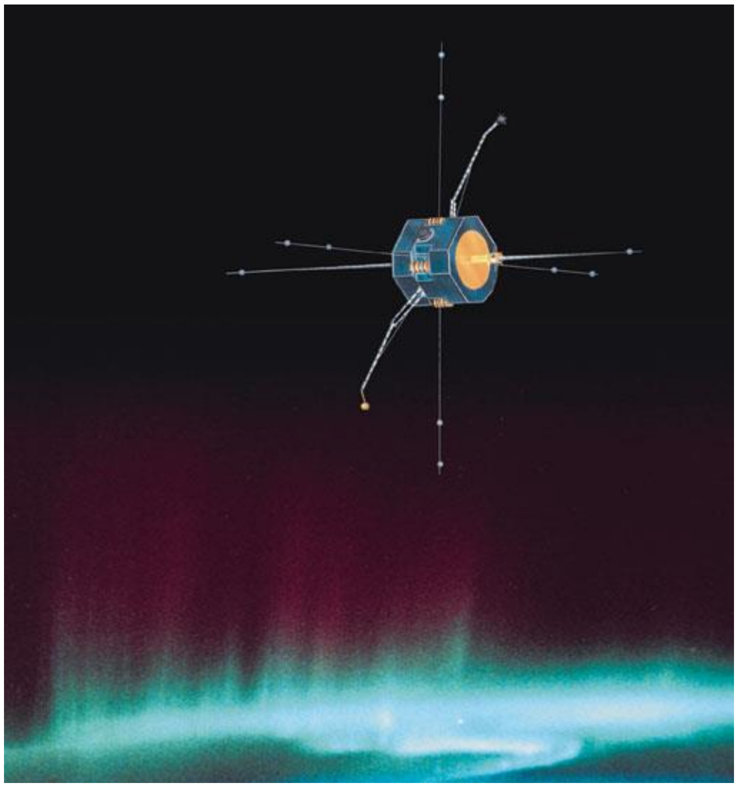


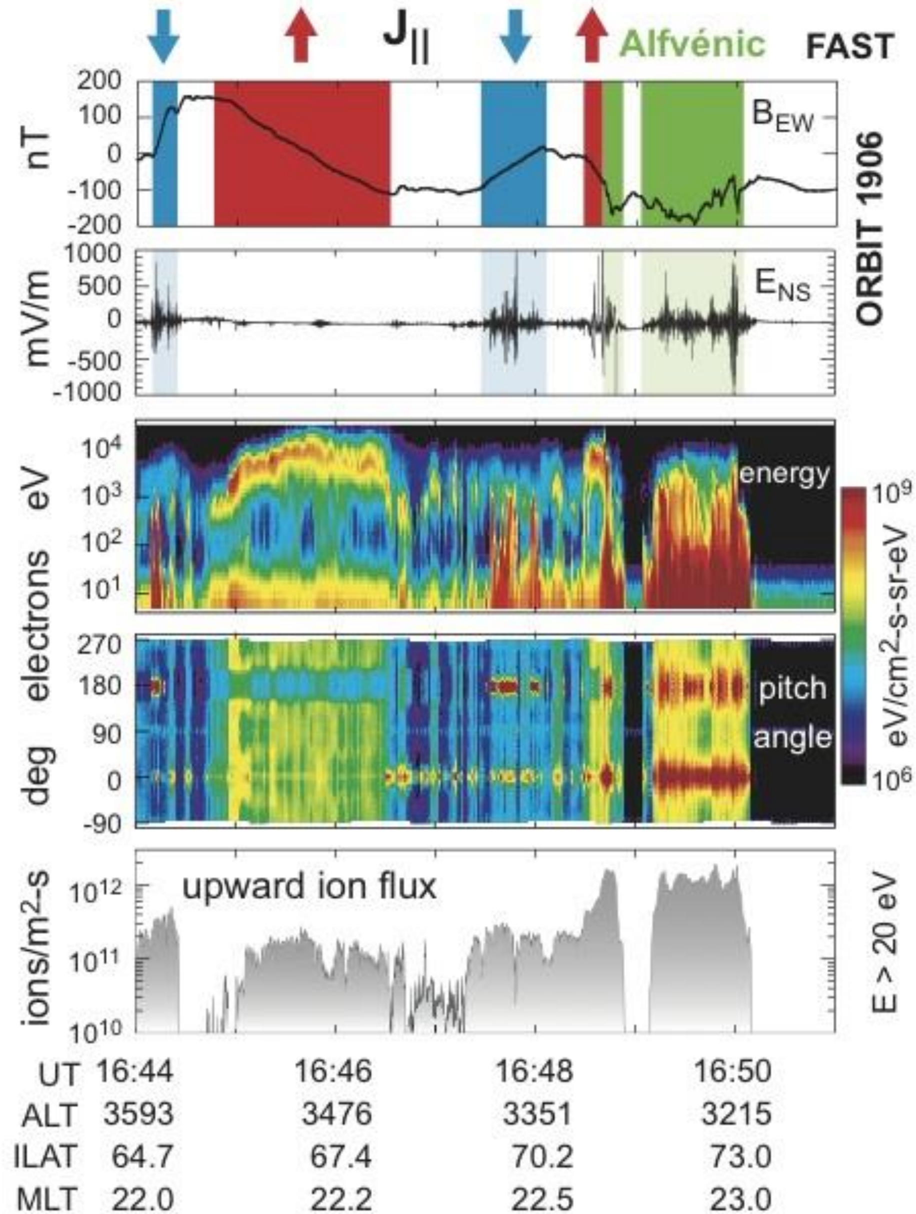
A motion of a charged particle is governed by a magnetic field, and vice-versa.



Early Mystery: Aurora and Particle Acceleration

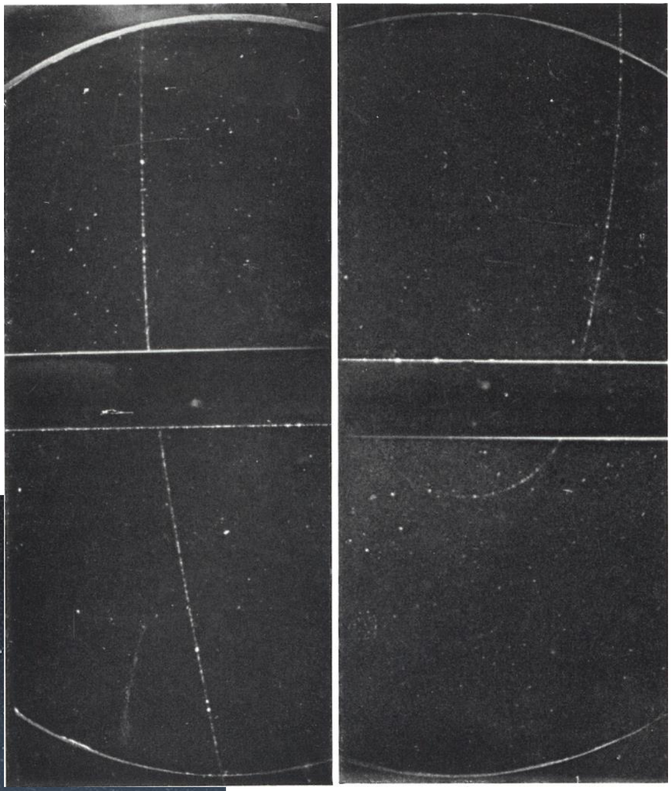
Later Discovery: Three Particle Acceleration Processes

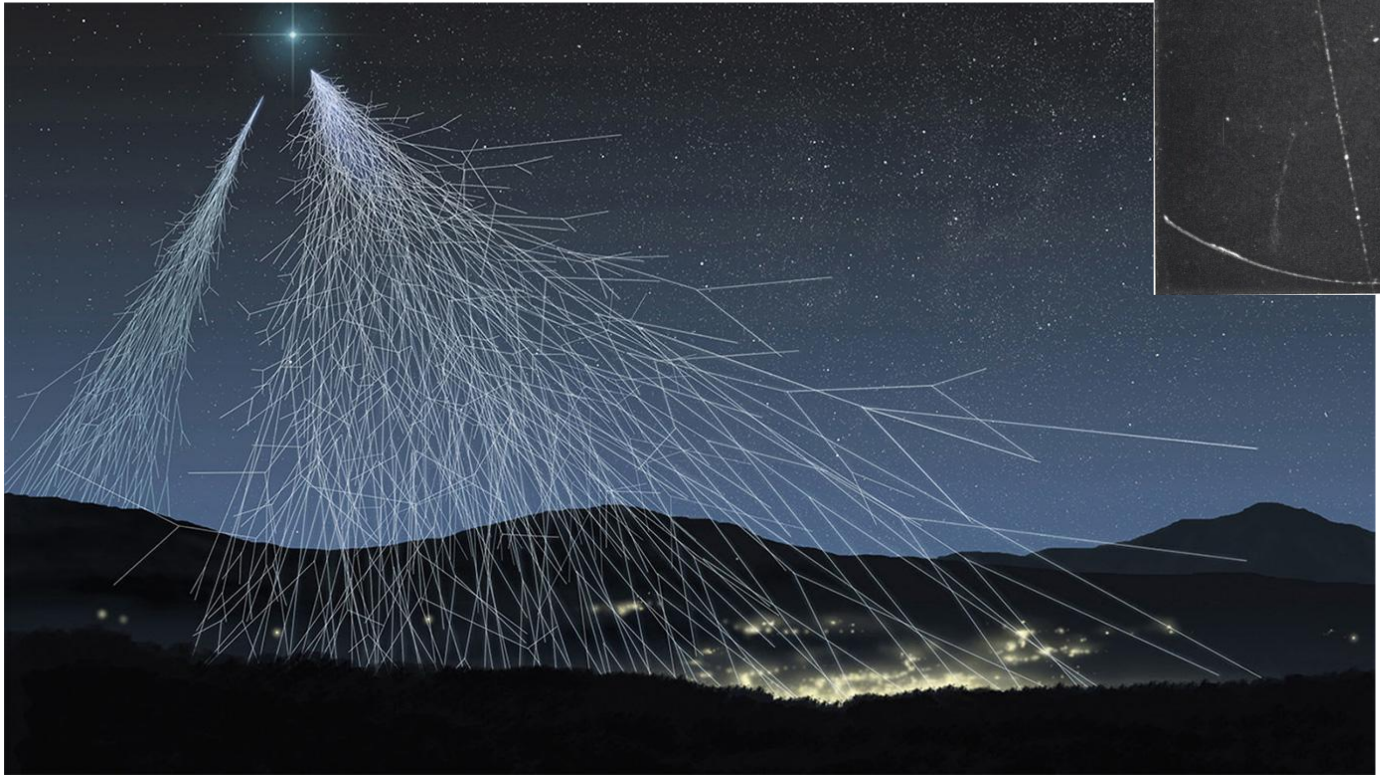




Early Mystery: Cosmic Rays

The discovery of cosmic rays by balloons and cloud chambers was the beginning of particle physics.

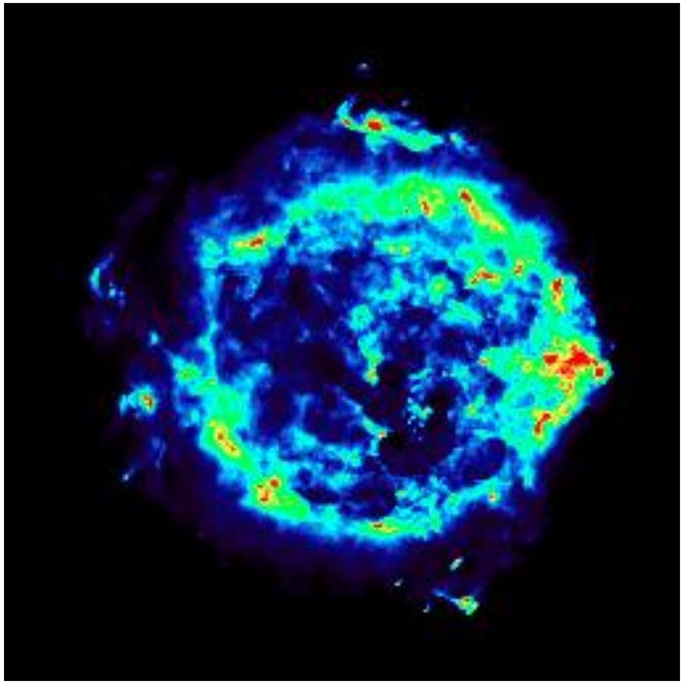


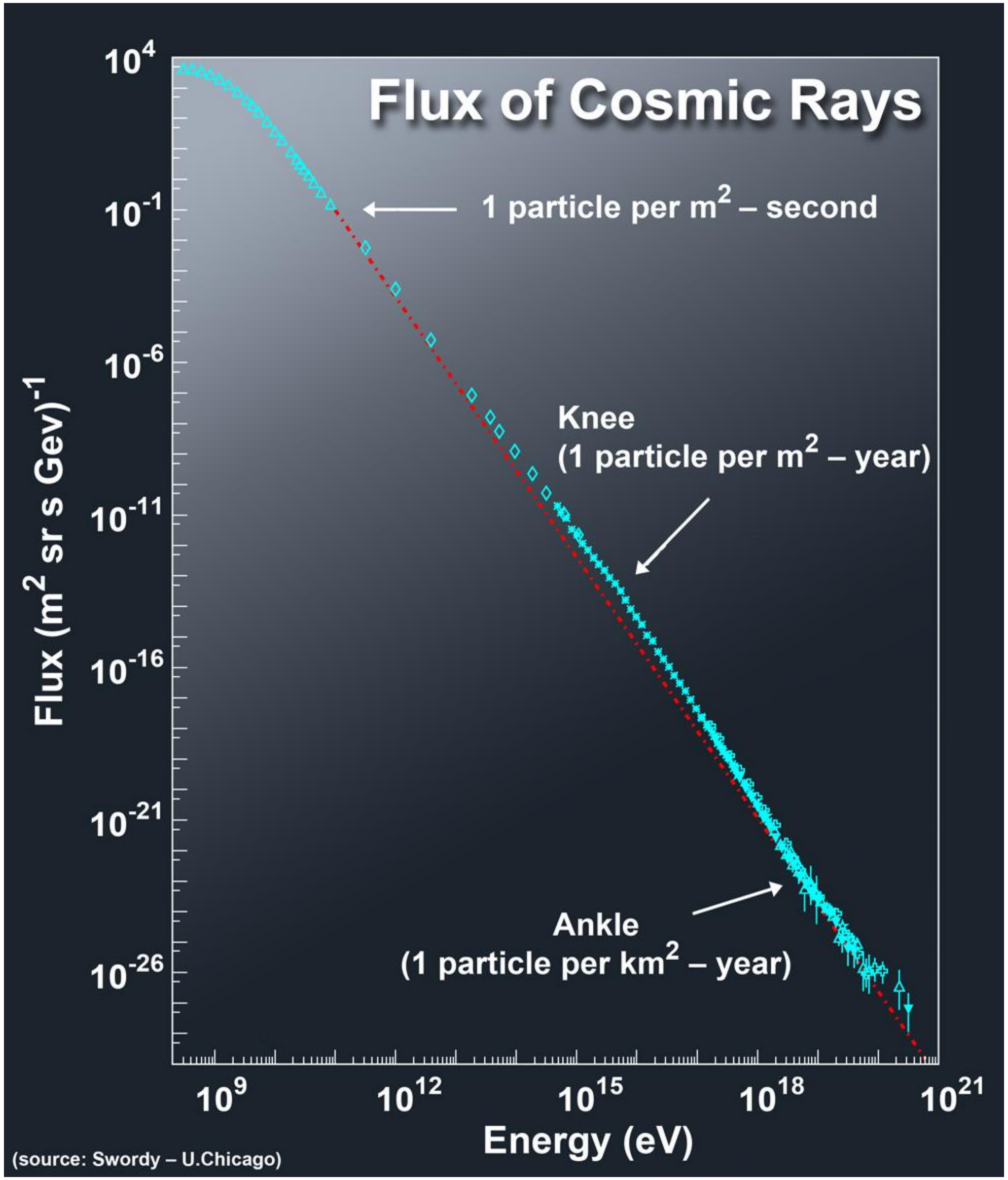


Later Discoveries: Cosmic Ray Accleration

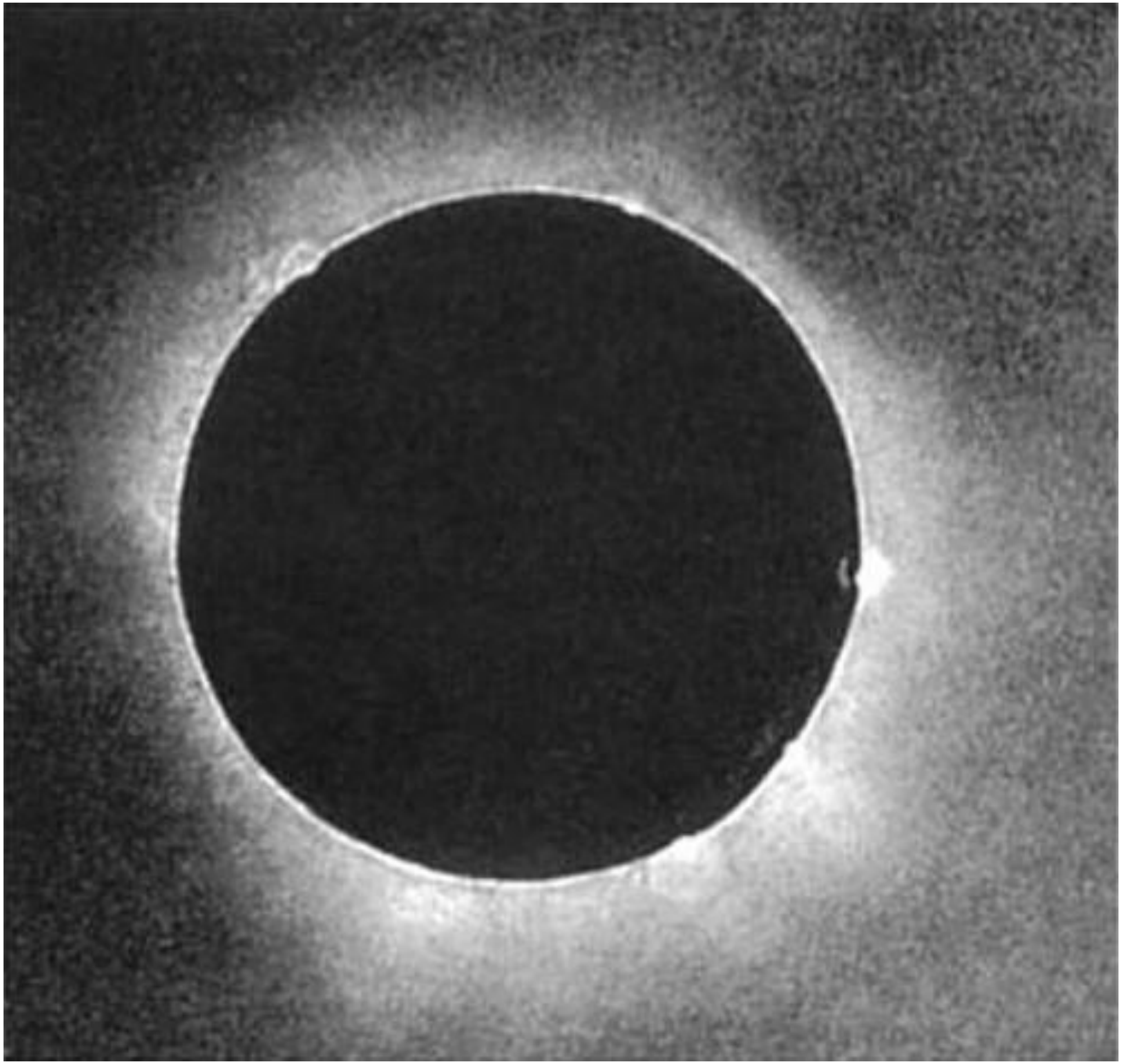
Cosmic rays are believed to be generated by collisionless shocks at supernova shells.

This work was based on heliophysics observations: the Earth's bow shock.

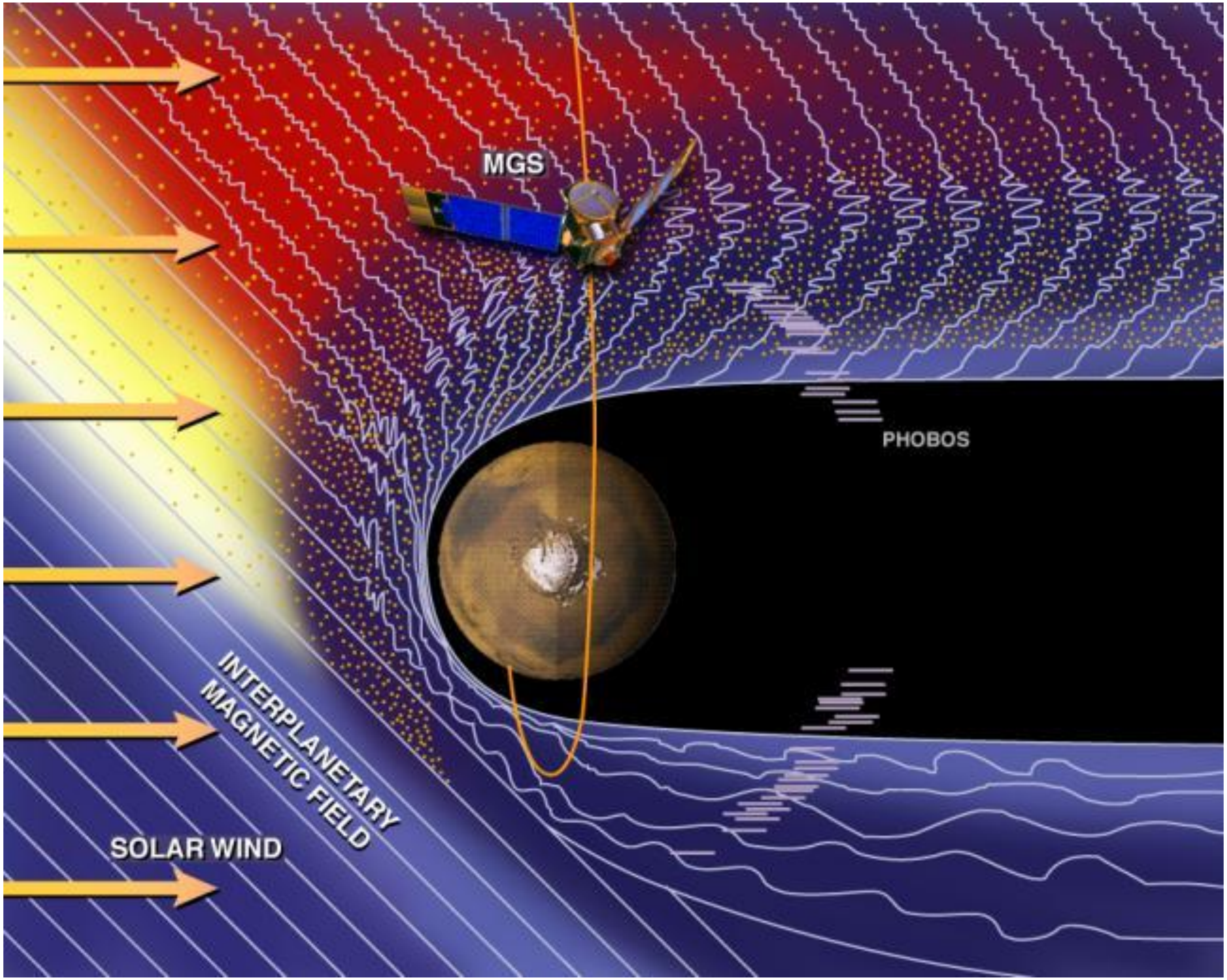




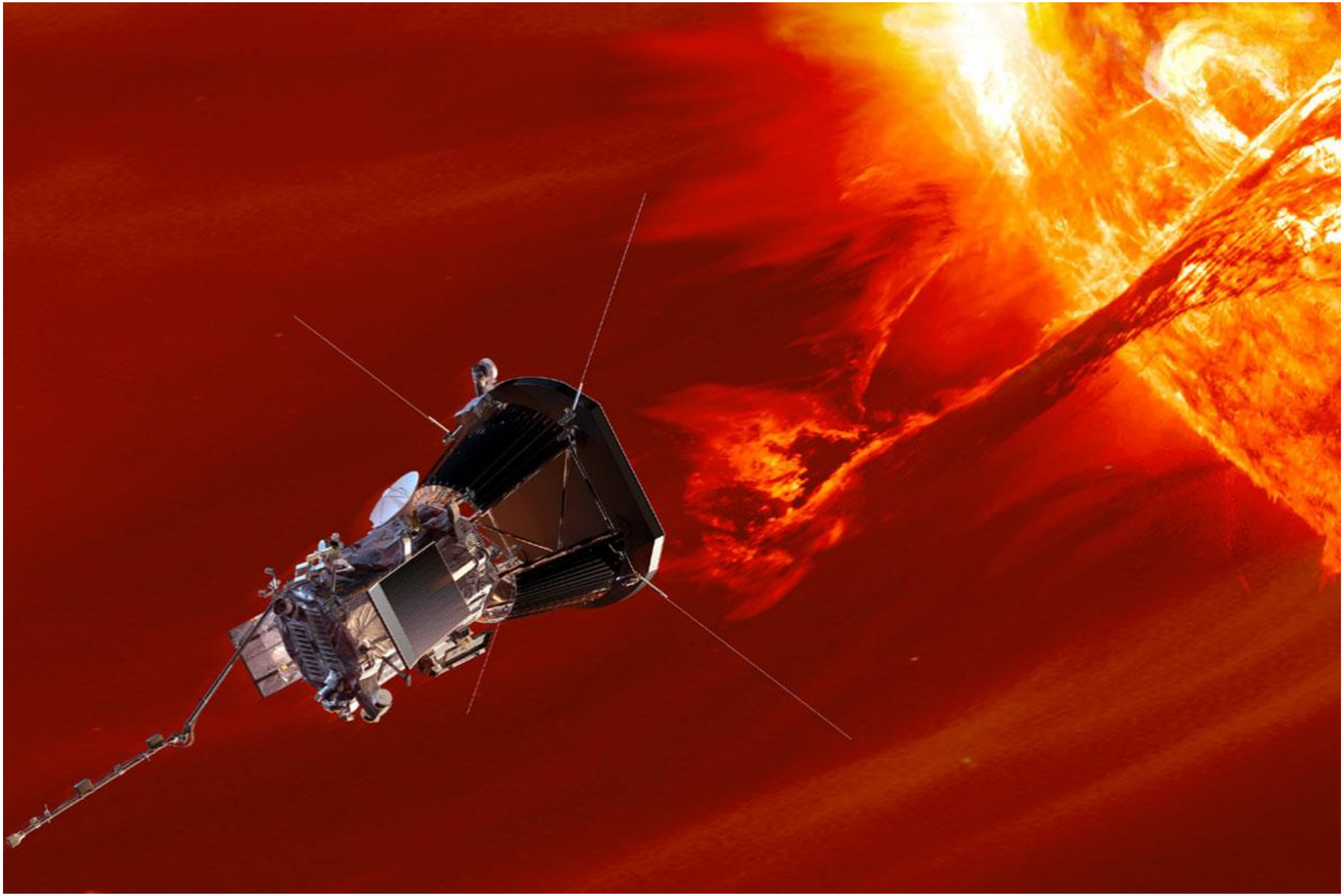
Early Mystery: Solar and Stellar Winds



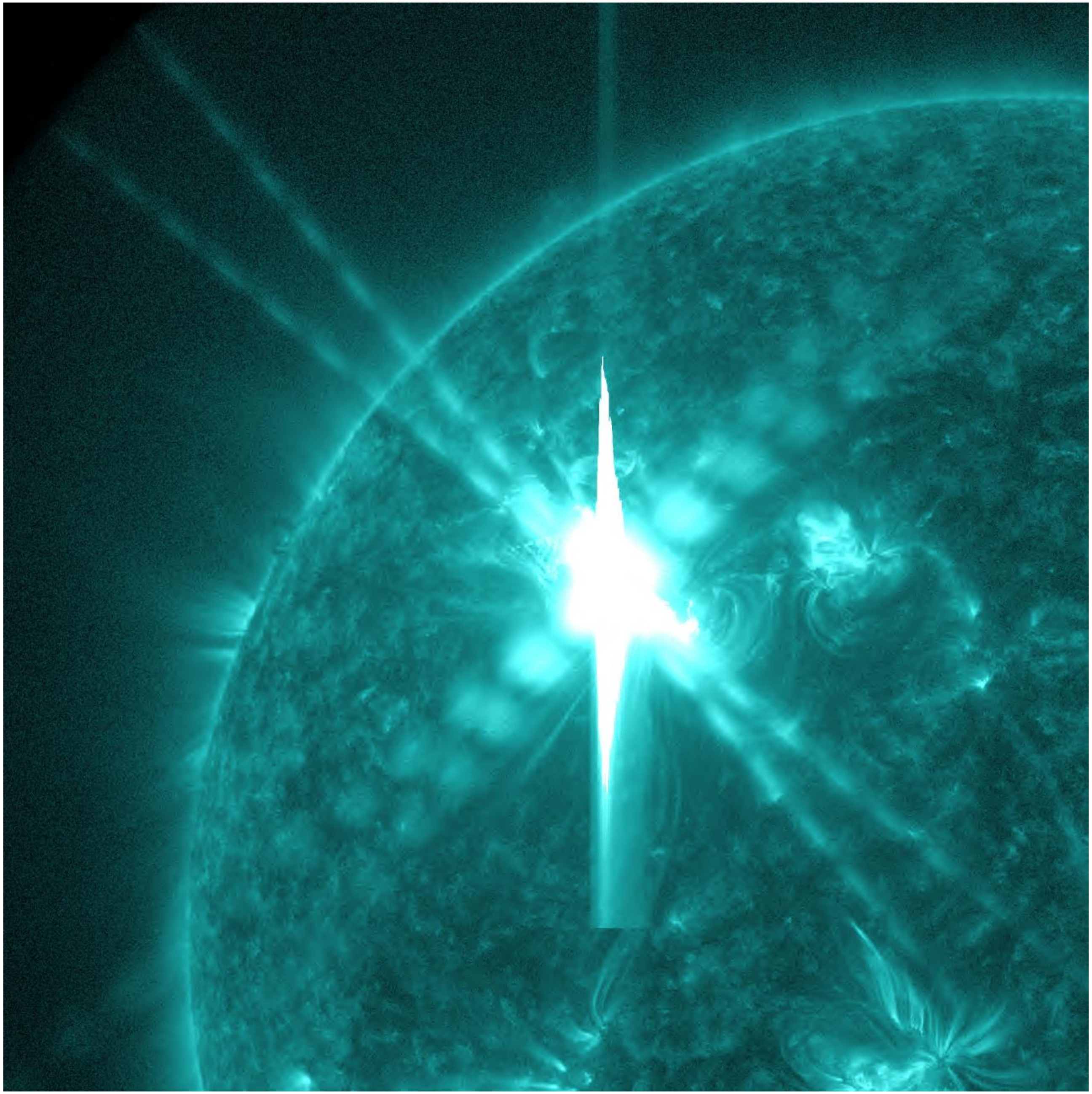
Heliophysics Discoveries: Solar and Stellar Winds



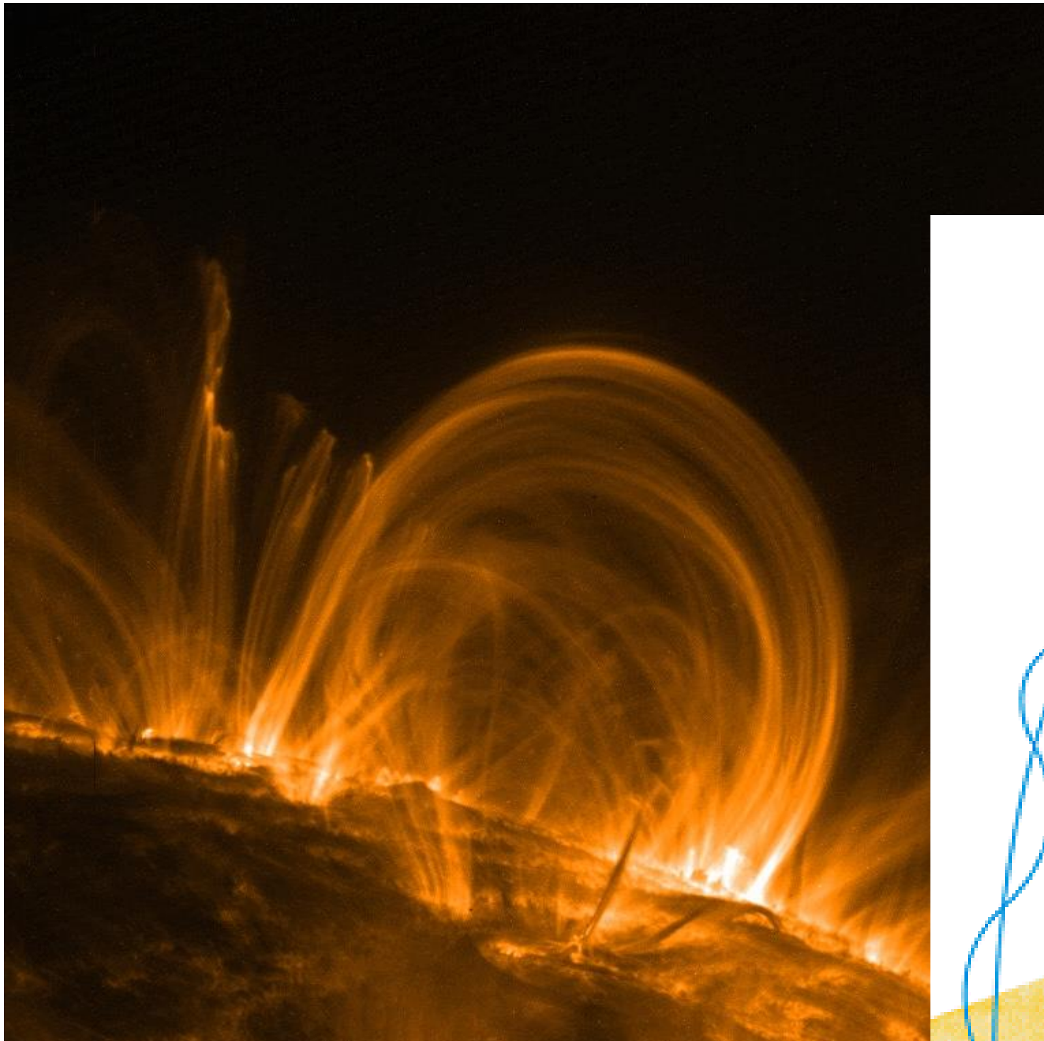
On-Going Heliophysics Work: Solar and Stellar Winds

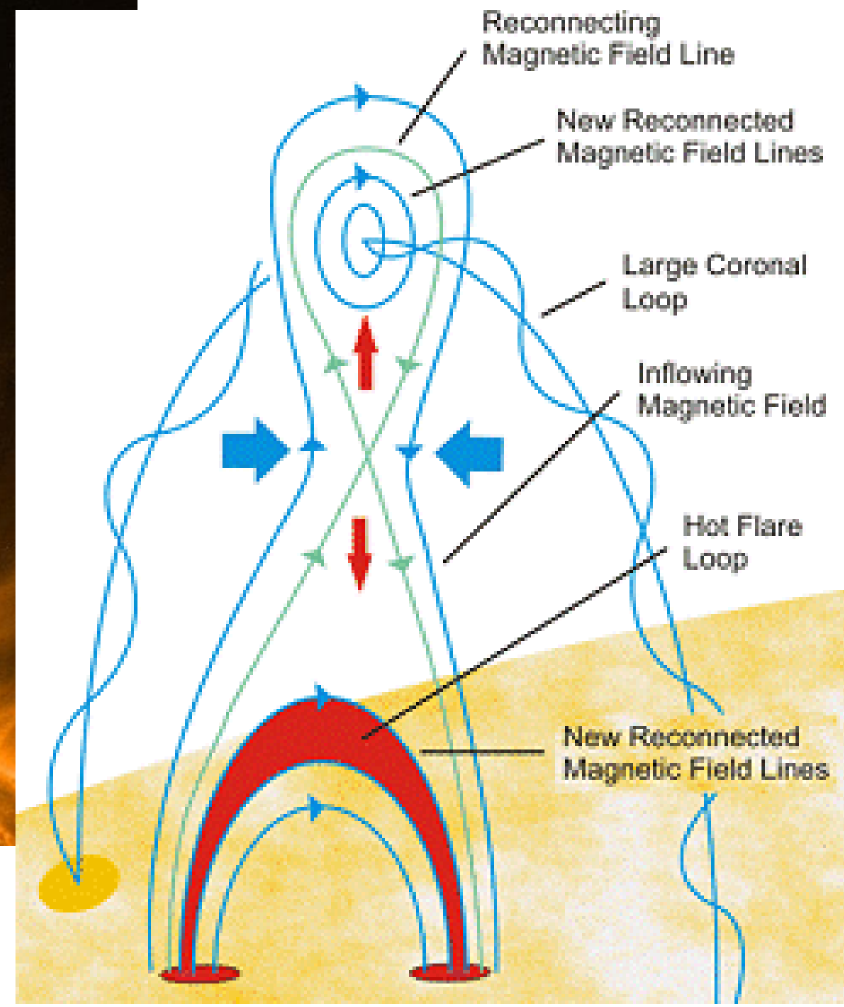


Early Mystery: Solar Flares

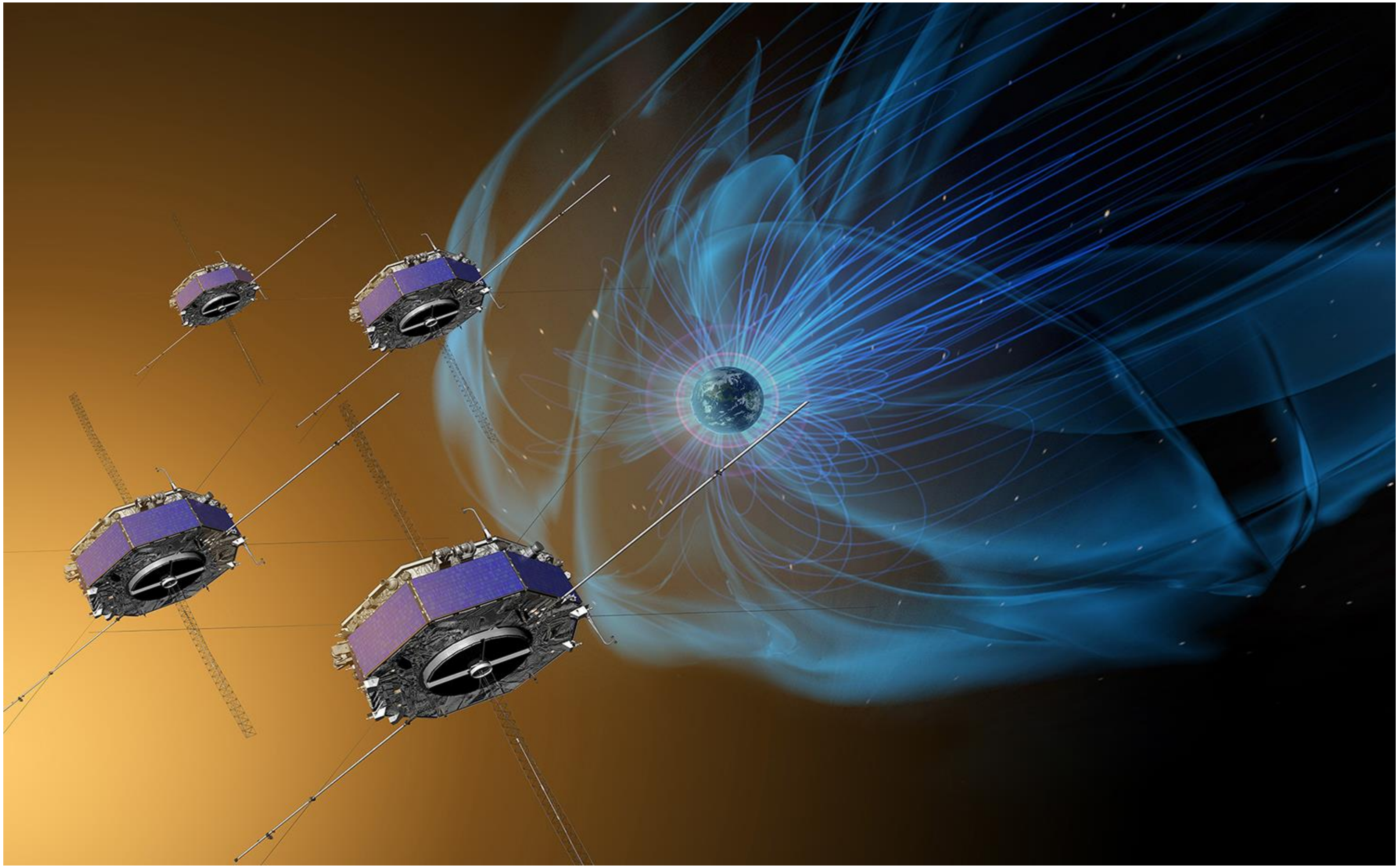


Heliophysics Discovery: Magnetic Reconnection

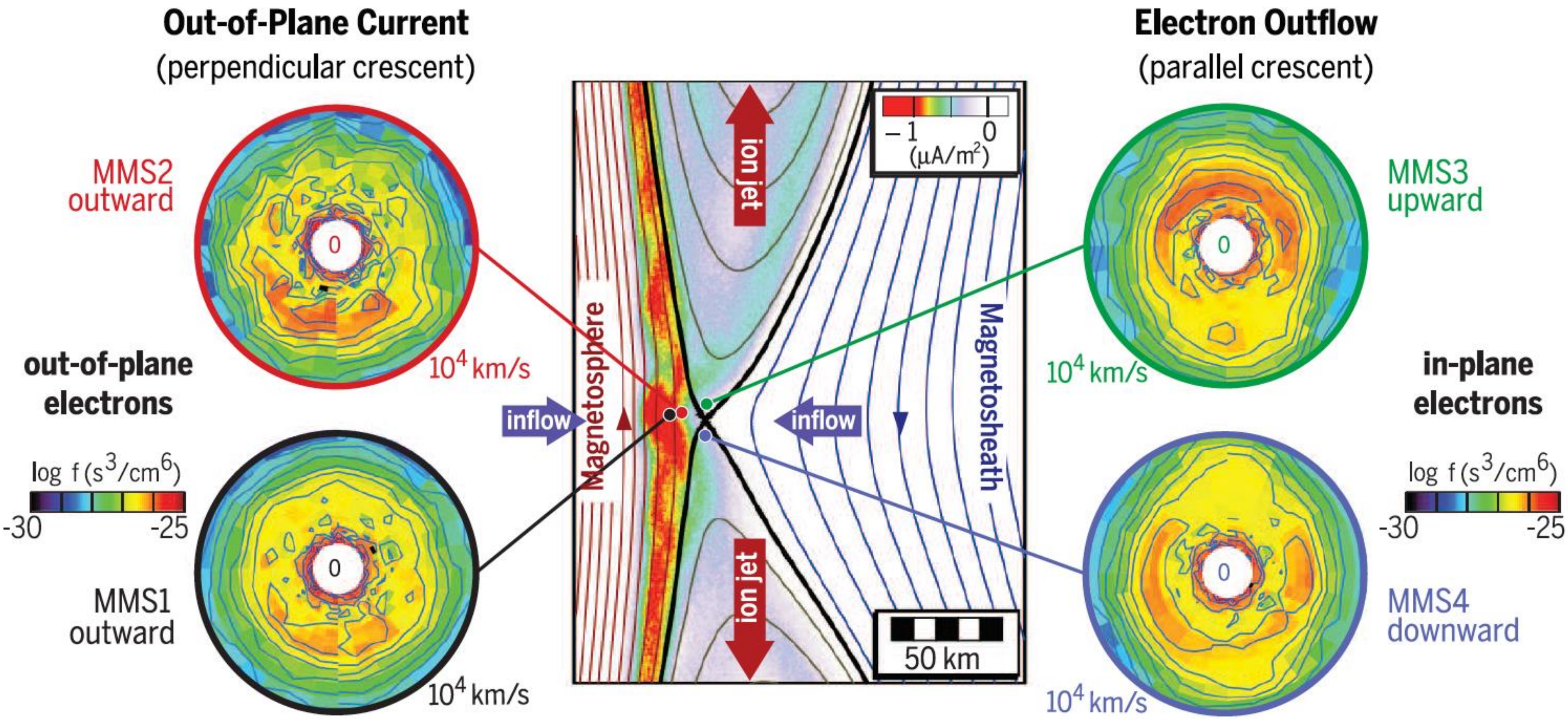




On-Going Heliophysics Work: Magnetic Reconnection

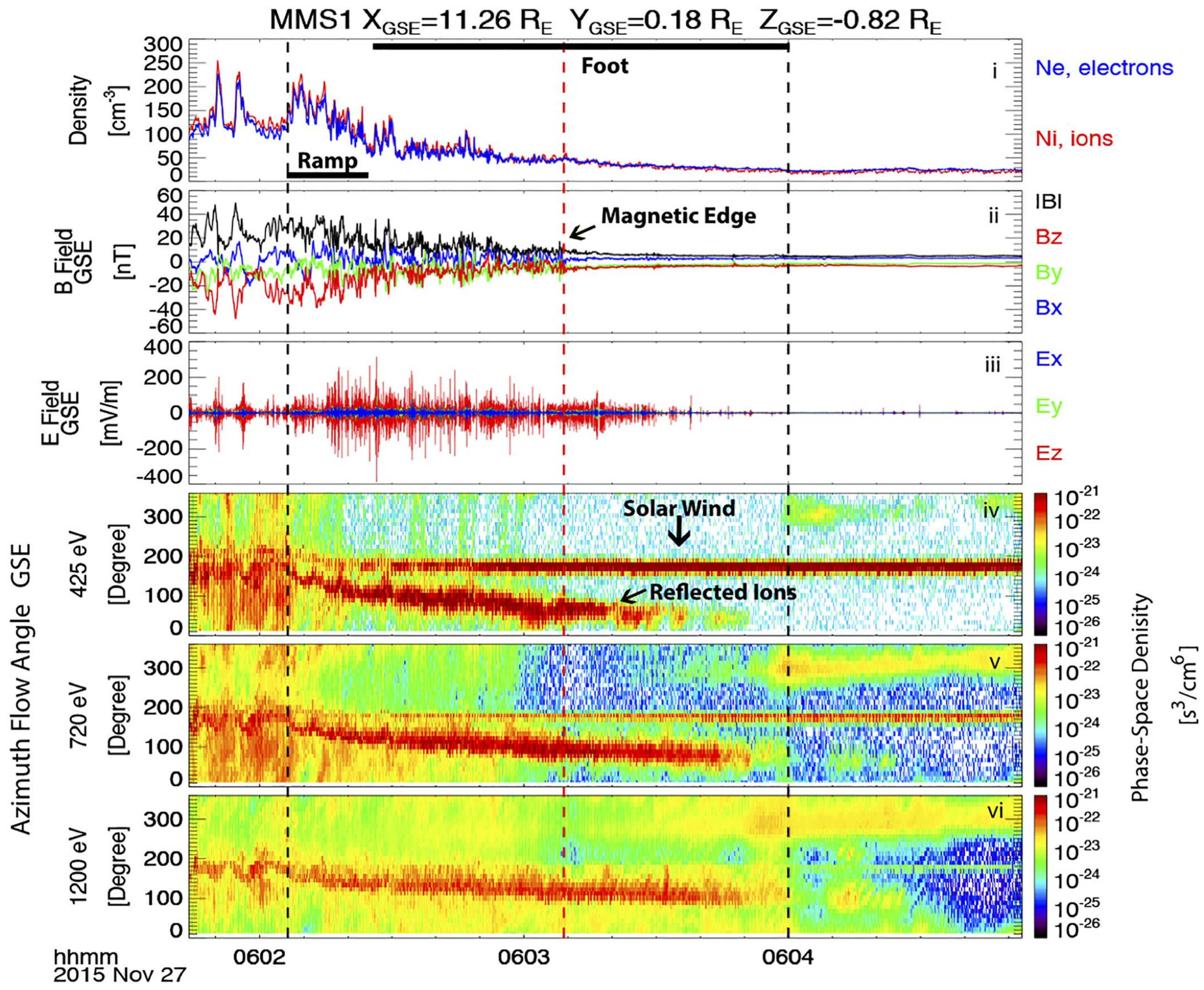


On-Going Heliophysics Work: Magnetic Reconnection

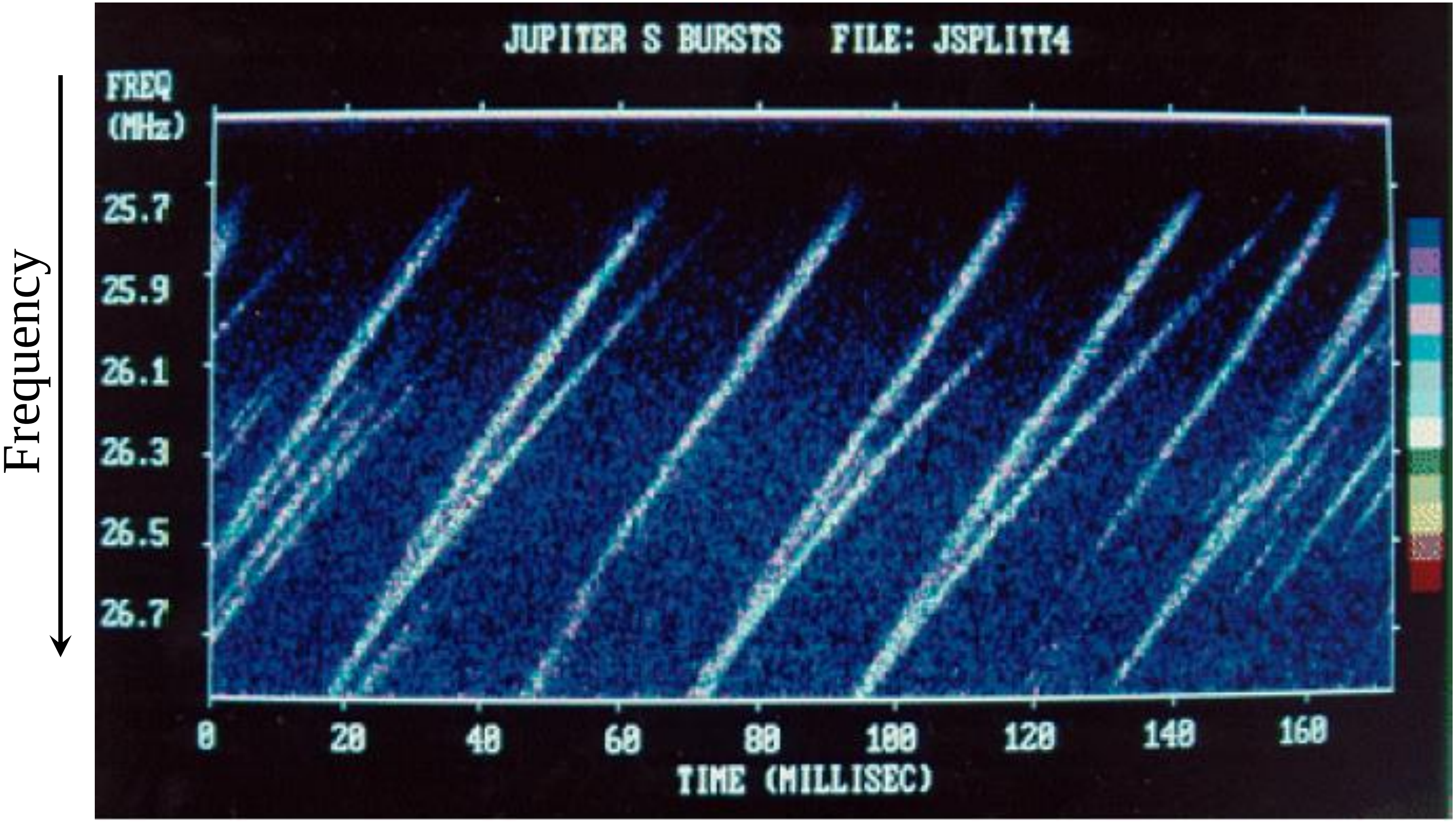


Early Mystery: Collisionless Shocks

Same Phenomenon Viewed from the Inside

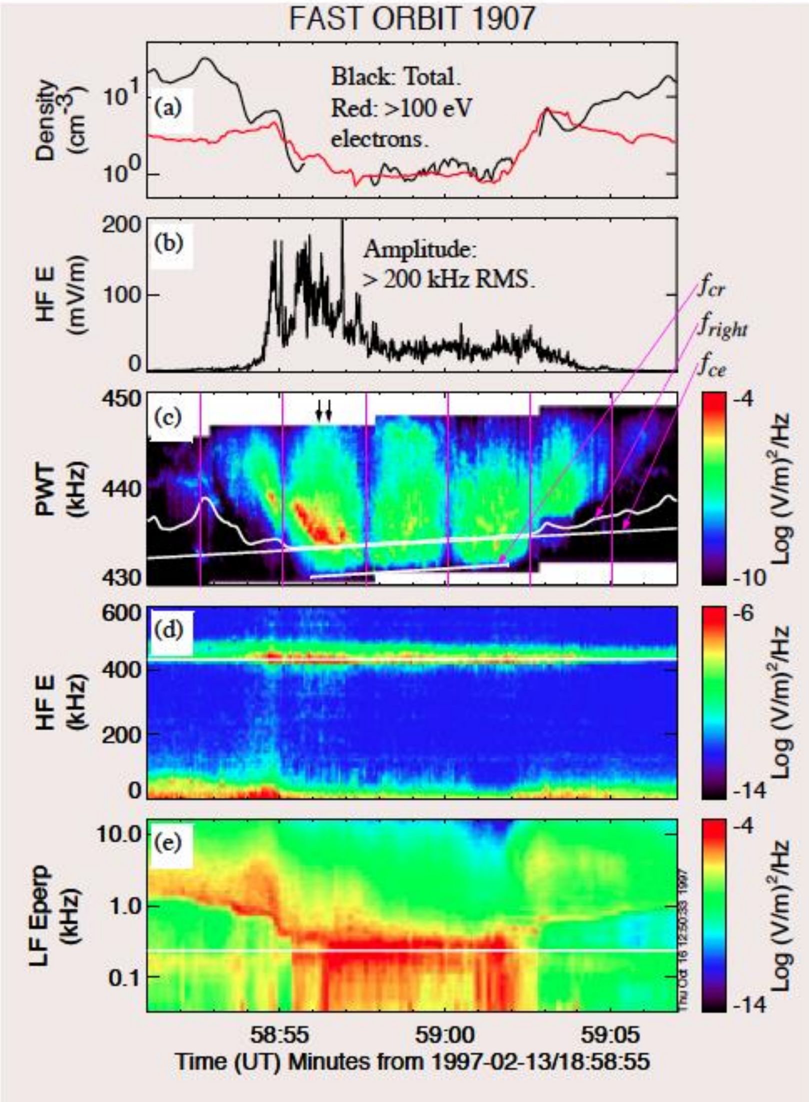


Early Mystery: Radio Emissions



Heliophysics Discovery: The Electron Cyclotron Maser

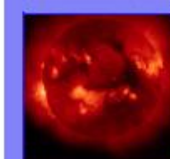
Radio emissions:



THE ELECTRON-CYCLOTRON MASER

Jupiter's Aurora

Saturn's Aurora



Solar Flares

Binary Systems

Dwarf M Stars

FAST Results

- The FAST observations within the source region have up to 1000 times better resolution than previous missions
- The energy source of auroral kilometric radiation is the electron-cyclotron maser powered by parallel electric fields, previously believed to come from a "loss-cone" instability.

Signature of the Electron-Cyclotron Maser

- Extremely high brightness temperature.
- Nearly 100% circularly polarized.
- Narrow frequency band.
- Strong variability.

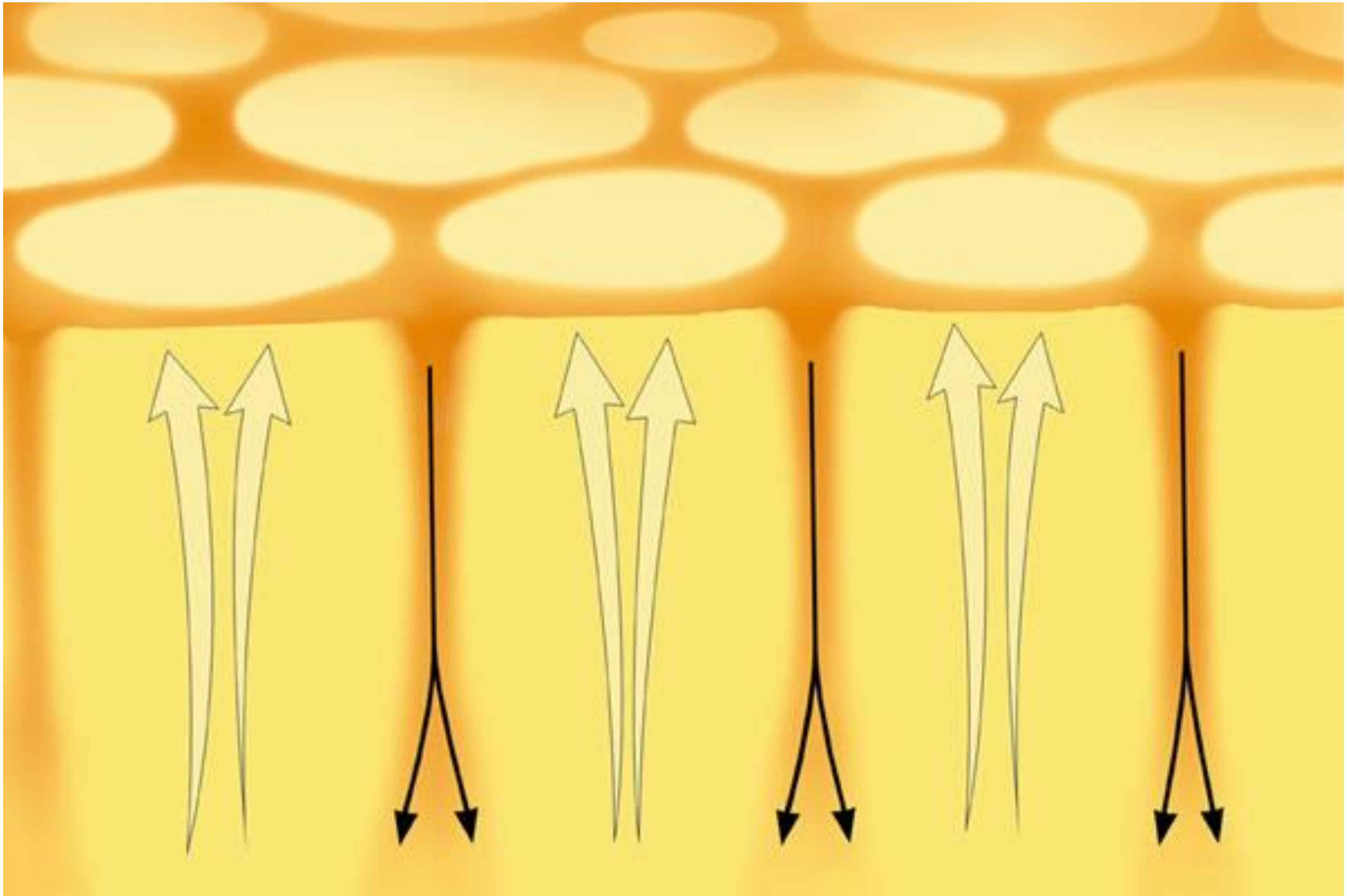
Electron-Cyclotron Maser Candidates in the Astrophysical Literature:

- Planetary radiation from all of the magnetized outer planets.
- Solar microwave spikes.
- Solar Type IV/V radio emissions.
- Radio emissions from RS CVn binaries.
- Radio emissions from AM Her binaries.
- Radio emissions from Dwarf M flare stars.

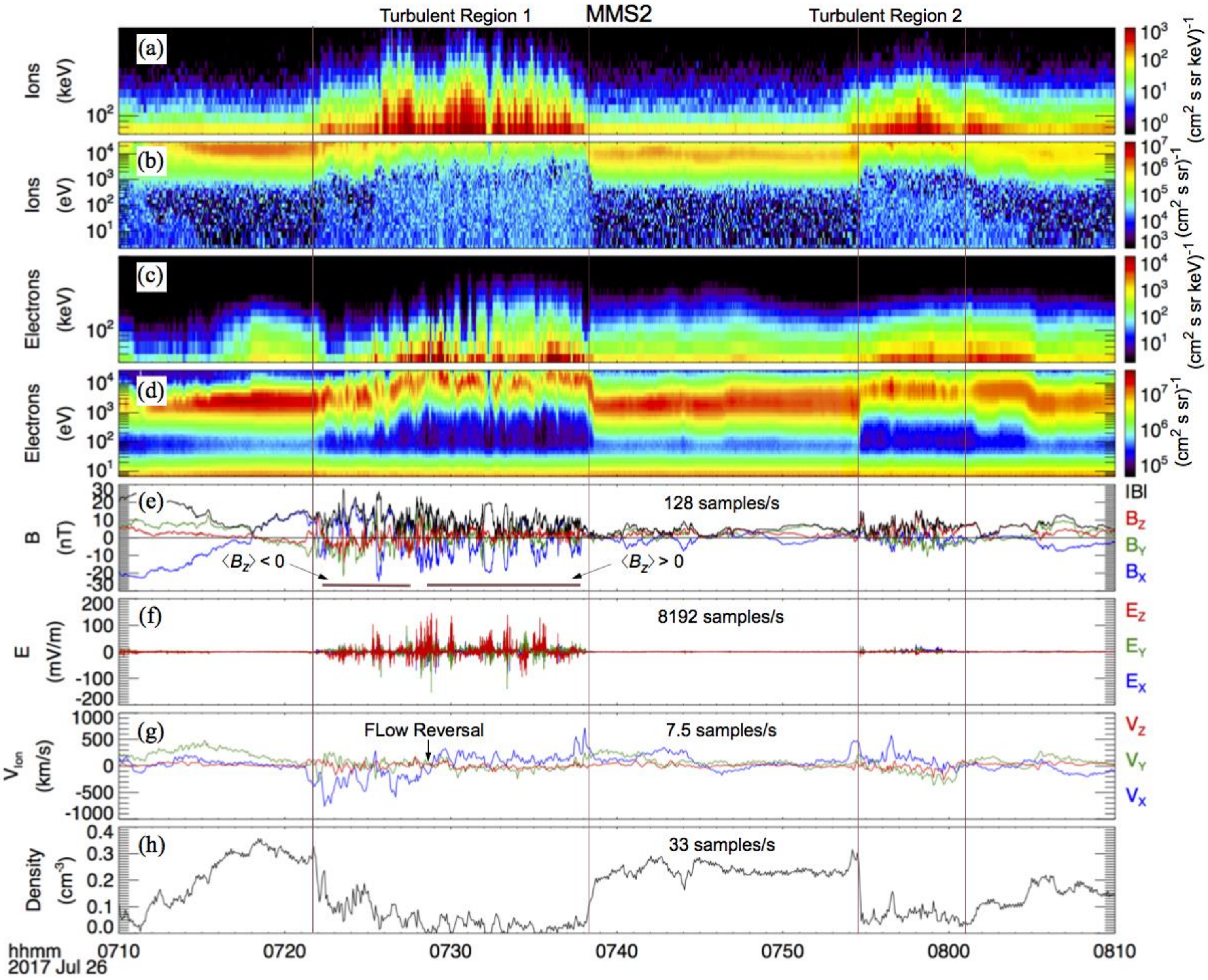
Implication of the FAST Results

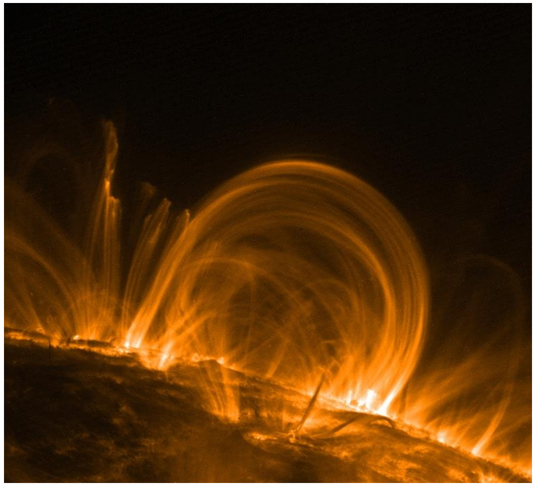
- These findings may call for re-analysis of some astrophysical radio sources.
- The FAST results suggest that parallel electric fields may be widespread in astrophysical plasmas, strongly supporting the idea proposed over 50 years by Nobel laureate, Hans Alfven of Sweden.

On-Going Heliophysics Work: Turbulence



On-Going Heliophysics Work: Turbulence





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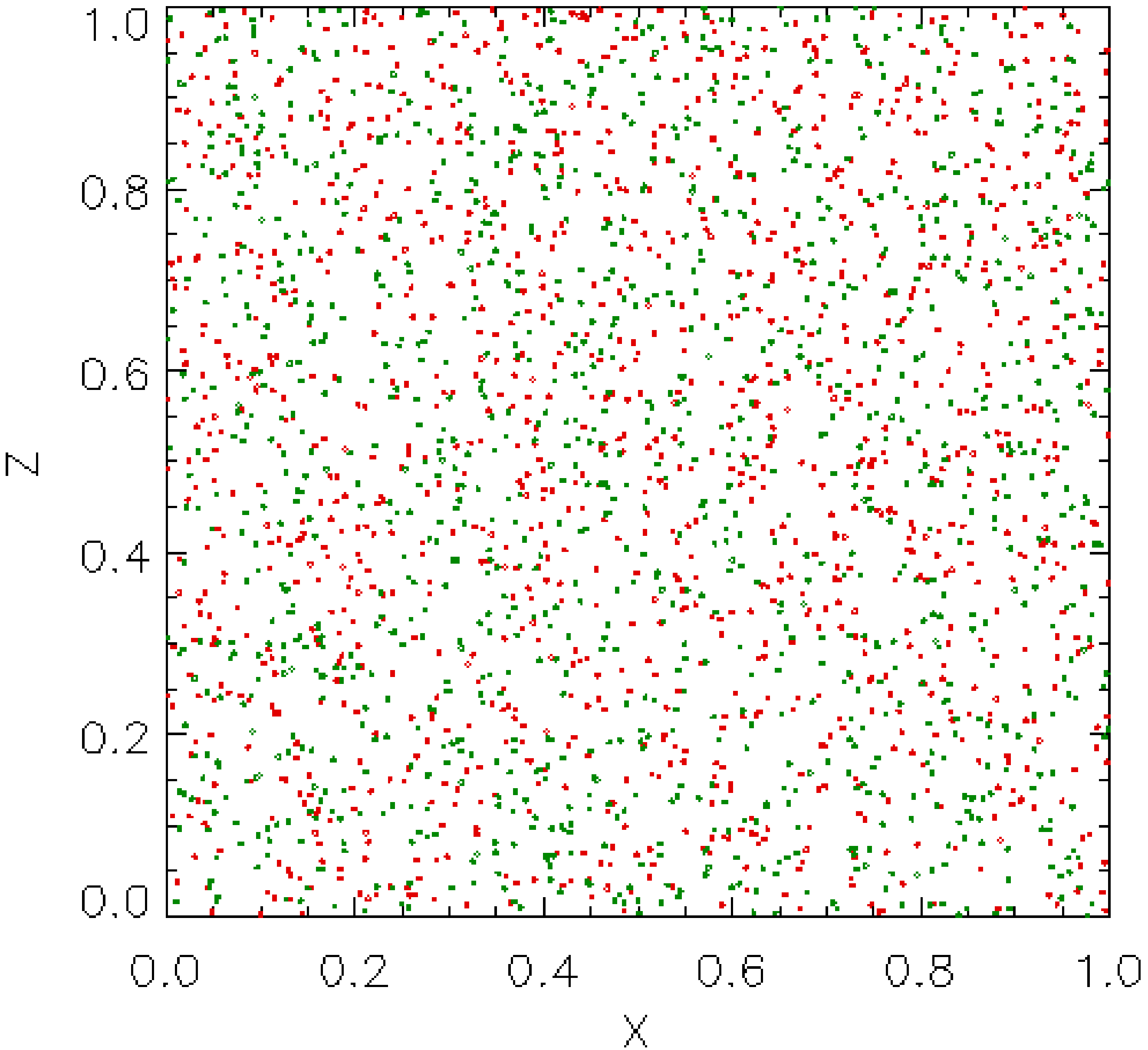
My View of a Plasma



Basic Approaches to Plasma Physics

Kinetic

(1) For each particle, calculate its motion given $\boldsymbol{B}$ and $\boldsymbol{E}$ using the Lorentz equation.

(2) At every particle location, calculate $\boldsymbol{B}$ and $\boldsymbol{E}$ from Maxwell's equations.

Most accurate method, but very unwieldy; basis of PIC simulations.

Multi-Fluid

(1) For each species (s, typically ions and electrons), calculate the density (n_s), velocity ($\boldsymbol{u}_s$), and temperature (T_s) using fluid equations for a given $\boldsymbol{B}$ and $\boldsymbol{E}$.

(2) Calculate $\boldsymbol{B}$ and $\boldsymbol{E}$ from Maxwell's equations.

MHD

Treat the plasma as a single fluid. Calculate the density (n), velocity ($\boldsymbol{u}$), and pressure (P) along with $\boldsymbol{B}$ and $\boldsymbol{E}$ using the MHD equations.

Least detailed but highly useful.

Kinetic Calculations

Kinetic

(1) For each particle, calculate its motion given ***B*** and ***E*** using the Lorentz equation.

(2) At every particle location, calculate ***B*** and ***E*** from Maxwell's equations.

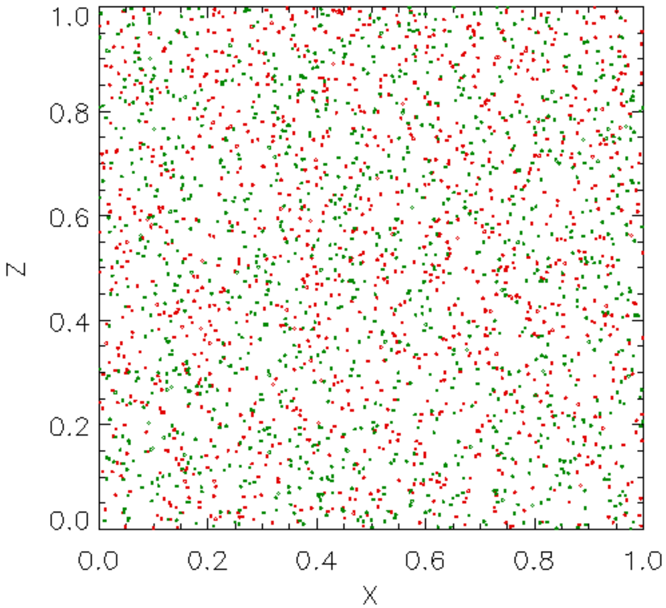
$$m\frac{d\boldsymbol{v}}{dt} = q(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})$$

$$\nabla \cdot \boldsymbol{E} = \frac{\rho_q}{\varepsilon_o}$$

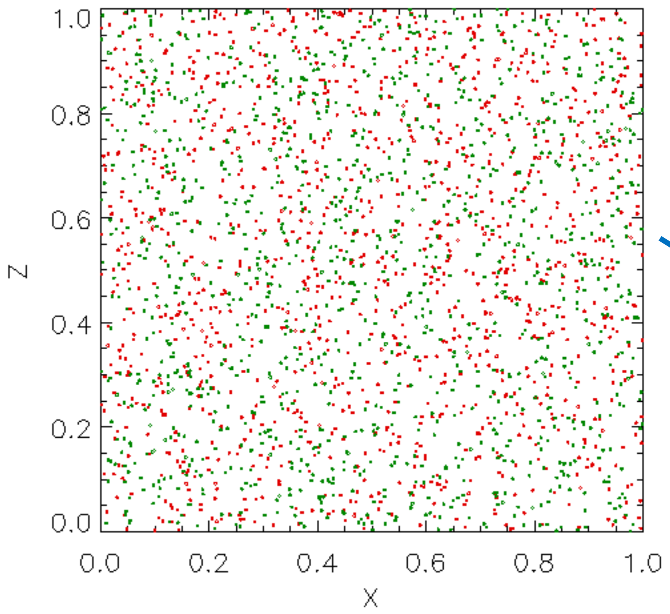
$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t}$$

$$\nabla \times \boldsymbol{B} = \frac{1}{c^2}\frac{\partial \boldsymbol{E}}{\partial t} + \mu_o \boldsymbol{J}$$

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

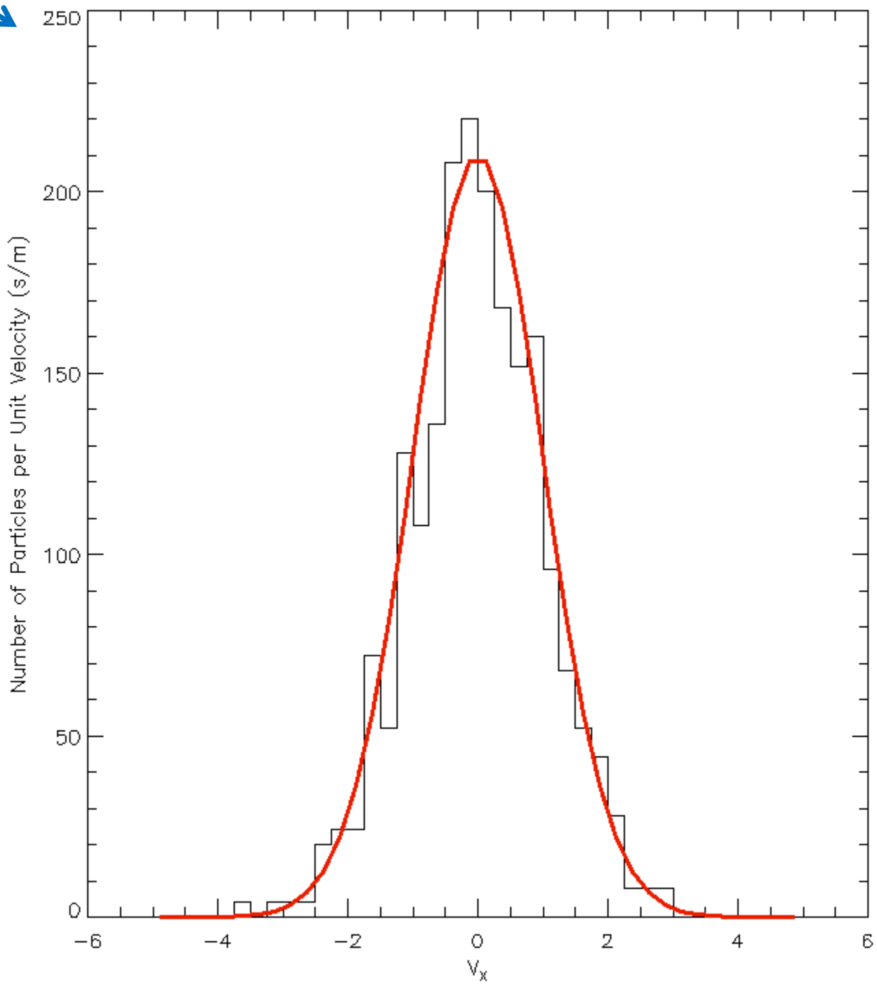


Distribution Functions



The most common type of distribution is a Maxwellian or Gaussian:

$$f = f_o e^{-\frac{1}{2}mv^2/k_B T}$$



The distribution function as a function of v_x is the number of particles per unit velocity.

In free-space the units are number of particles per unit velocity per m^3 (s/m^4). In three dimensions, the units of *f* are s^3/m^6.

Reducing Distribution Functions

For three dimensions of velocity space, the units of f are s^3/m^6.

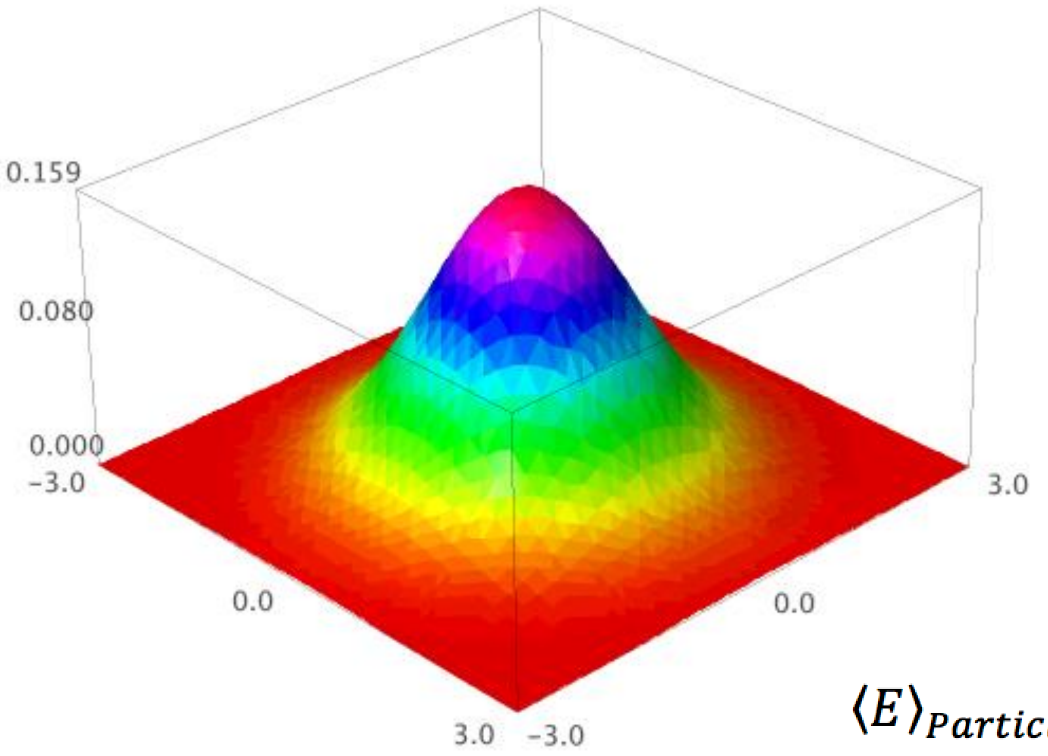
$$n(x,t) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f(\boldsymbol{x},\boldsymbol{v},t)\, dv_x dv_y dv_z$$

$$nu = \int_{-\infty}^{\infty} vf(x,v,t)\, dv$$

$$u \equiv \frac{\int_{-\infty}^{\infty} vf(x,v,t)\, dv}{n}$$

$$\langle E\rangle_{Particle} = \frac{3}{2} k_B T$$

$$\langle E\rangle_{Particle} \equiv \frac{1}{n}\iiint_{-\infty}^{\infty} \frac{1}{2} m(v_x^2 + v_y^2 + v_z^2) f\, d\boldsymbol{v}$$



Multi-Fluid Approach

Multi-Fluid

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$$\nabla \times \boldsymbol{B} = \frac{1}{c^2}\frac{\partial \boldsymbol{E}}{\partial t} + \mu_o \boldsymbol{J}$$

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

$$\frac{\partial n}{dt} + \nabla \cdot n\boldsymbol{u} = 0$$

$$m\,n\,\frac{\partial \boldsymbol{u}}{\partial t} + m\,n\,(\boldsymbol{u} \cdot \nabla)\boldsymbol{u} = -\nabla P + n\,q(\boldsymbol{E} + \boldsymbol{u} \times \boldsymbol{B}) + nmg$$

(Collisionless)

$$\nabla P = \gamma T\,\nabla n$$

Ideal MHD

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{u}) = 0$$

Continuity Equation:

$$\nabla P = \gamma T \, \nabla n$$

Equation of state.

Force Equation (Collisionless)

$$\rho \frac{\partial \boldsymbol{u}}{\partial t} + \rho(\boldsymbol{u} \cdot \nabla)\boldsymbol{u} = -\nabla P + \boldsymbol{J} \times \boldsymbol{B} + \rho \boldsymbol{g}$$

$$\boldsymbol{E}_\perp + \boldsymbol{u} \times \boldsymbol{B} = 0$$

Frozen-In Condition

$$\nabla \times \boldsymbol{B} = \mu_o \boldsymbol{J}$$

Ampere's Law

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

Faraday's Law

Define:

$$\rho \equiv m_i n_i + m_e n_e$$

$$\boldsymbol{u} \equiv \frac{m_i n_i \boldsymbol{u_i} + m_e n_e \boldsymbol{u_e}}{m_i n_i + m_e n_e}$$

$$P \equiv P_i + P_e$$

$$\boldsymbol{J} \equiv en(\boldsymbol{u}_i - \boldsymbol{u}_e)$$

Assumed: $n_i \approx n_e$

(1) "Principle of Quasi Neutrality"
(2) "Frozen-In"

Basic Approaches to Plasma Physics

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→

Multi-Fluid

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(2) Calculate ***B*** and ***E*** from Maxwell's equations.

↓

MHD

Treat the plasma as a single fluid. Calculate the density (*n*), velocity (***u***), and pressure (*P*) along with ***B*** and ***E*** using the MHD equations.

To solve problems, one often must start with MHD to obtain a large-scale solution, then use either multi-fluid or kinetic approach to understand the small-scale physics.

Collisional Versus Collisionless Plasmas

Collisional

(1) The interior of the Sun and planetary ionospheres examples of collisional plasmas; they have high densities

(2) Momentum and energy exchange between ions and electrons (and/or neutral particles) can be dominated by collisions.

(3) The force equation must include viscosity and collision terms related to momentum exchange.

(4) Collisions often lead to a Gaussian distribution as per the central limit theorem.

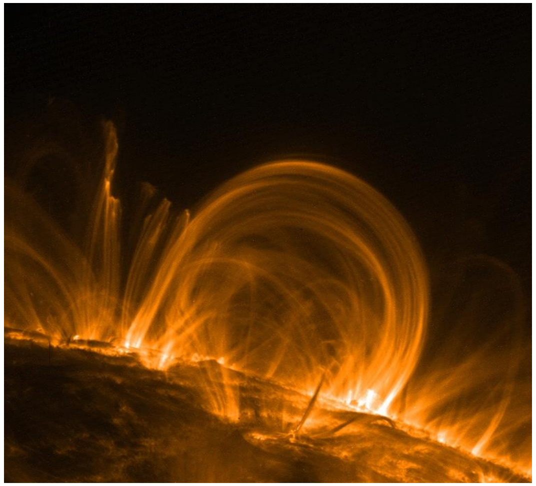
Collisionless

(1) The solar corona, solar wind, Earth's magnetosphere, and many astrophysical plasmas can be treated as "collisionless"**.**

(2) Momentum and energy exchange between ions and electrons is dominated by $\boldsymbol{B}$ and $\boldsymbol{E}$.

(3) Due to low damping, collisionless plasmas are often turbulent.

(4) Collisionless plasmas often do not have Gaussian distributions and may have energetic tails.



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Quick Review of Particle Motion and Adiabatic Invariants

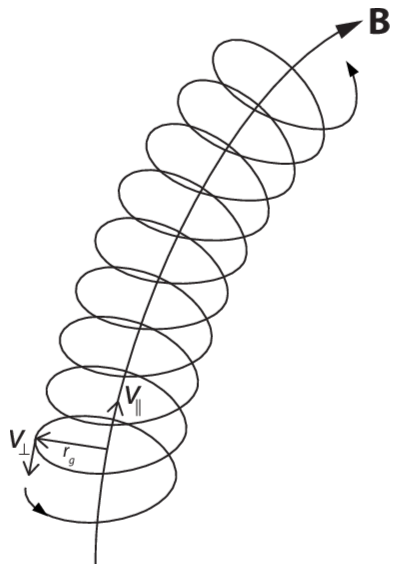
Examine the Lorentz force with a magnetic field (***B***). Let ***B*** be in the *z*-direction. Let's consider motion in the *x*-*y* plane.

$$\boldsymbol{F} = q(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})$$

Newton:

$$m\frac{d\boldsymbol{v}}{dt} = q(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})$$

Break the vector equation into components:



$$\frac{dv_x}{dt} = \frac{qE_x}{m} + \frac{qB_z}{m}v_y$$

$$\frac{dv_y}{dt} = \frac{qE_y}{m} - \frac{qB_z}{m}v_x$$

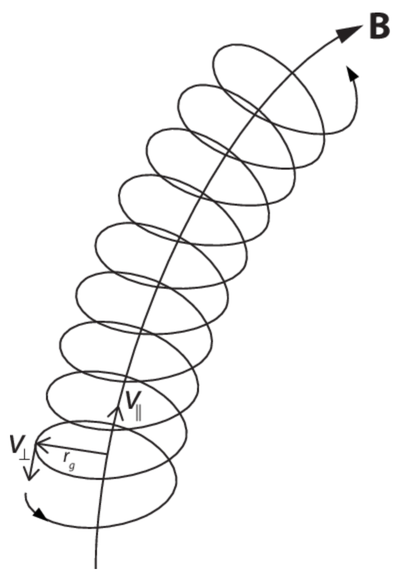
Particle Motion and Adiabatic Invariants

Let's start easy. Let $\boldsymbol{E} = 0$.

$$\frac{dv_x}{dt} = \frac{qB_z}{m} v_y \qquad \frac{dv_y}{dt} = -\frac{qB_z}{m} v_x$$

$$\frac{d^2 v_x}{dt^2} = -\Omega^2 v_x \qquad \Omega \equiv \left|\frac{qB_z}{m}\right|$$

This equation is that of a harmonic oscillator.



$$v_x = v_o \cos(\Omega t + \vartheta)$$

$$v_y = -\frac{q}{|q|} v_o \sin(\Omega t + \vartheta)$$

ϑ is an arbitrary angle (phase).

Particle Motion and Adiabatic Invariants

Let E_y be finite.

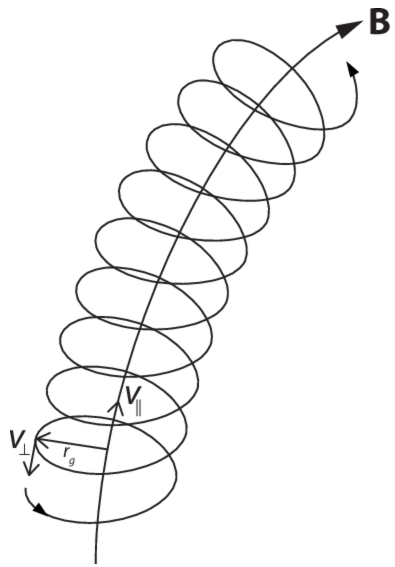
$$\frac{dv_x}{dt} = \frac{qB_z}{m} v_y \qquad \frac{dv_y}{dt} = \frac{qE_y}{m} - \frac{qB_z}{m} v_x$$

This equation is that of a harmonic oscillator **that moves at a constant speed**!

$$\frac{d^2 v_x}{dt^2} = \Omega^2 \frac{E_y}{B_z} - \Omega^2 v_x \qquad \Omega \equiv \left|\frac{qB_z}{m}\right|$$

$$v_x = v_o \cos(\Omega t + \vartheta) + \frac{E_y}{B_z}$$

$$v_y = -\frac{q}{|q|} v_o \sin(\Omega t + \vartheta)$$



ϑ is an arbitrary angle (phase).

Single Particle Motion

General Equation

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

$$\boldsymbol{v}_F = \frac{\boldsymbol{F} \times B}{qB^2}$$

Other drifts:

$$\boldsymbol{v}_{\nabla B} = \pm \frac{1}{2} \frac{v_{\perp}{}^2}{\Omega} \frac{\boldsymbol{B} \times \nabla_{\perp} \boldsymbol{B}}{B^2}$$

$$\boldsymbol{v}_{\mathrm{C}} = \pm \frac{v_{\parallel}{}^2}{\Omega R_C} \frac{\widehat{\boldsymbol{R}}_C \times \widehat{\boldsymbol{b}}}{B^2}$$

Adiabatic Invariants

If one can identify a conserved quantity (e.g. energy, momentum, etc.), problem solving becomes much easier. A few things one should realize:

(1) Since ***B*** can only impart a force normal to the particles motion (***v*** x ***B***), energy is conserved. (***E***, however, can change a particle's energy).

(2) We define:

$$W_\perp = \frac{1}{2} m {v_\perp}^2 \qquad\qquad W_\parallel = \frac{1}{2} m {v_\parallel}^2$$

(3) Therefore, $W_\parallel + W_\perp = W$, is constant.

(4) Since a change in ***B*** can change $v_\parallel$, it must also change $v_\perp$ in a way that energy is conserved.

$$m \frac{dv_\parallel}{dt} = -\mu \frac{dB}{dz} \qquad\qquad \mu \equiv \frac{W_\perp}{B}$$

(5) Conservation of energy:

$$\frac{dW}{dt} = 0 \quad \rightarrow \quad \frac{d}{dt}(W_\parallel + W_\perp) = 0 \quad \rightarrow \quad \frac{d}{dt}(W_\parallel + \mu B) = 0$$

Adiabatic Invariants

So far: $W_\perp = \frac{1}{2} m v_\perp{}^2$ $\quad W_\parallel = \frac{1}{2} m v_\parallel{}^2$ $\quad m\frac{dv_\parallel}{dt} = -\mu \frac{dB}{dz}$ $\quad \mu \equiv \frac{W_\perp}{B}$

$$\frac{dW}{dt} = 0 \quad \rightarrow \quad \frac{d}{dt}(W_\parallel + W_\perp) = 0 \quad \rightarrow \quad \frac{d}{dt}(W_\parallel + \mu B) = 0$$

Chain rule and substitute $W_\parallel = \frac{1}{2} m v_\parallel{}^2$

$$m v_\parallel \frac{dv_\parallel}{dt} + B\frac{d\mu}{dt} + \mu\frac{dB}{dt} = 0$$

Use $m\frac{dv_\parallel}{dt} = -\mu \frac{dB}{dz}$

$$-v_\parallel \mu \frac{dB}{dz} + B\frac{d\mu}{dt} + \mu\frac{dB}{dt} = 0$$

Now use $v_\parallel = \frac{dz}{dt}$

$$-\mu \frac{dB}{dz}\frac{dz}{dt} + B\frac{d\mu}{dt} + \mu\frac{dB}{dt} = 0$$

$$B\frac{d\mu}{dt} = 0$$

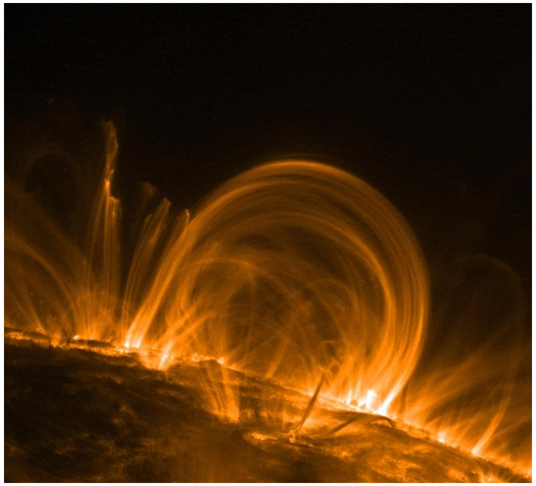
The first and third term cancel.

If B is not 0 then μ is conserved!

Adiabatic Invariant

We call μ an "adiabatic" invariant.

$$\mu \equiv \frac{W_\perp}{B}$$



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Ram Pressure/Shocks

Stellar winds travel 100's of AU then collide with the interstellar medium.

The collision causes as "shock", which appears as a curved structure.

The heliosphere's shock is toward α-Centauri.

Shocks

Shocks are hypothesized to be at the root of cosmic ray acceleration.

Shocks lead to strong turbulence in plasmas.

Shocks convert ram energy into magnetic and thermal energy.

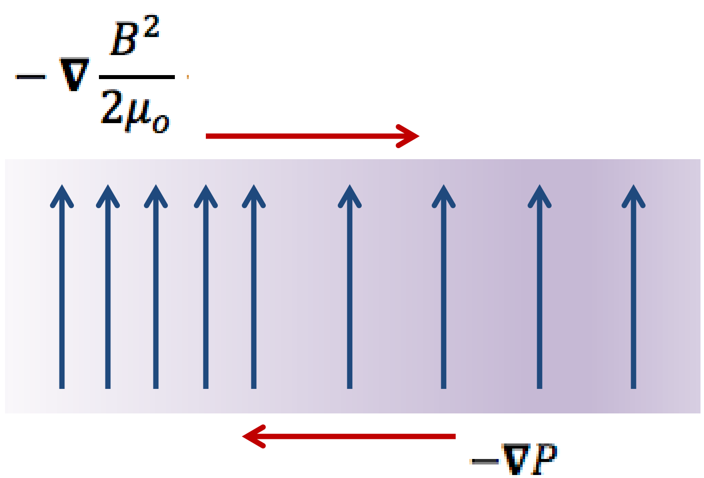
Magnetic Pressure

$$\rho\frac{\partial \boldsymbol{u}}{\partial t} + \rho(\boldsymbol{u}\cdot\boldsymbol{\nabla})\boldsymbol{u} = -\boldsymbol{\nabla}P - \boldsymbol{\nabla}\frac{B^2}{2\mu_o} + \frac{(\boldsymbol{B}\cdot\boldsymbol{\nabla})\boldsymbol{B}}{\mu_o} + \rho g$$

$$\boldsymbol{J}\times\boldsymbol{B} = \frac{\boldsymbol{\nabla}\times\boldsymbol{B}}{\mu_o}\times\boldsymbol{B} = -\boldsymbol{\nabla}\frac{B^2}{2\mu_o} + \frac{(\boldsymbol{B}\cdot\boldsymbol{\nabla})\boldsymbol{B}}{\mu_o}$$

Assume steady state, $\boldsymbol{u}$ = 0, $\boldsymbol{g}$ = 0,
and that $\boldsymbol{B}$ is straight.

$$0 = -\boldsymbol{\nabla}P - \boldsymbol{\nabla}\frac{B^2}{2\mu_o} \quad\rightarrow\quad \boldsymbol{\nabla}\left(P + \frac{B^2}{2\mu_o}\right) = 0 \quad\rightarrow\quad P + \frac{B^2}{2\mu_o} = C$$



Ram Pressure / Shocks

Suppose a plasmas impinges on a object, which compresses the plasma as slows the flow. Steady state, no curvature in ***B***, and not gravity.

Ram Pressure

$$\rho(\boldsymbol{u}\cdot\nabla)\boldsymbol{u}$$

Continuity Equation:

$$\frac{\partial\rho}{\partial t}+\nabla\cdot(\rho\boldsymbol{u})=0$$

Compressible & 1D
(plasma shock)

$$\nabla\cdot(\rho\boldsymbol{u})=0$$

Constant

$$\rho(\boldsymbol{u}\cdot\nabla)\boldsymbol{u}=\nabla(\rho u^2)$$

$$\boxed{\rho(\boldsymbol{u}\cdot\nabla)\boldsymbol{u}=\nabla(\rho u^2)}$$

Incompressible
(water pipe)

$$\nabla\cdot(\rho\boldsymbol{u})=0$$

Constant

$$\rho(\boldsymbol{u}\cdot\nabla)\boldsymbol{u}=\frac{1}{2}\nabla(\rho u^2)$$

~~$$\rho(\boldsymbol{u}\cdot\nabla)\boldsymbol{u}=\frac{1}{2}\nabla(\rho u^2)$$~~

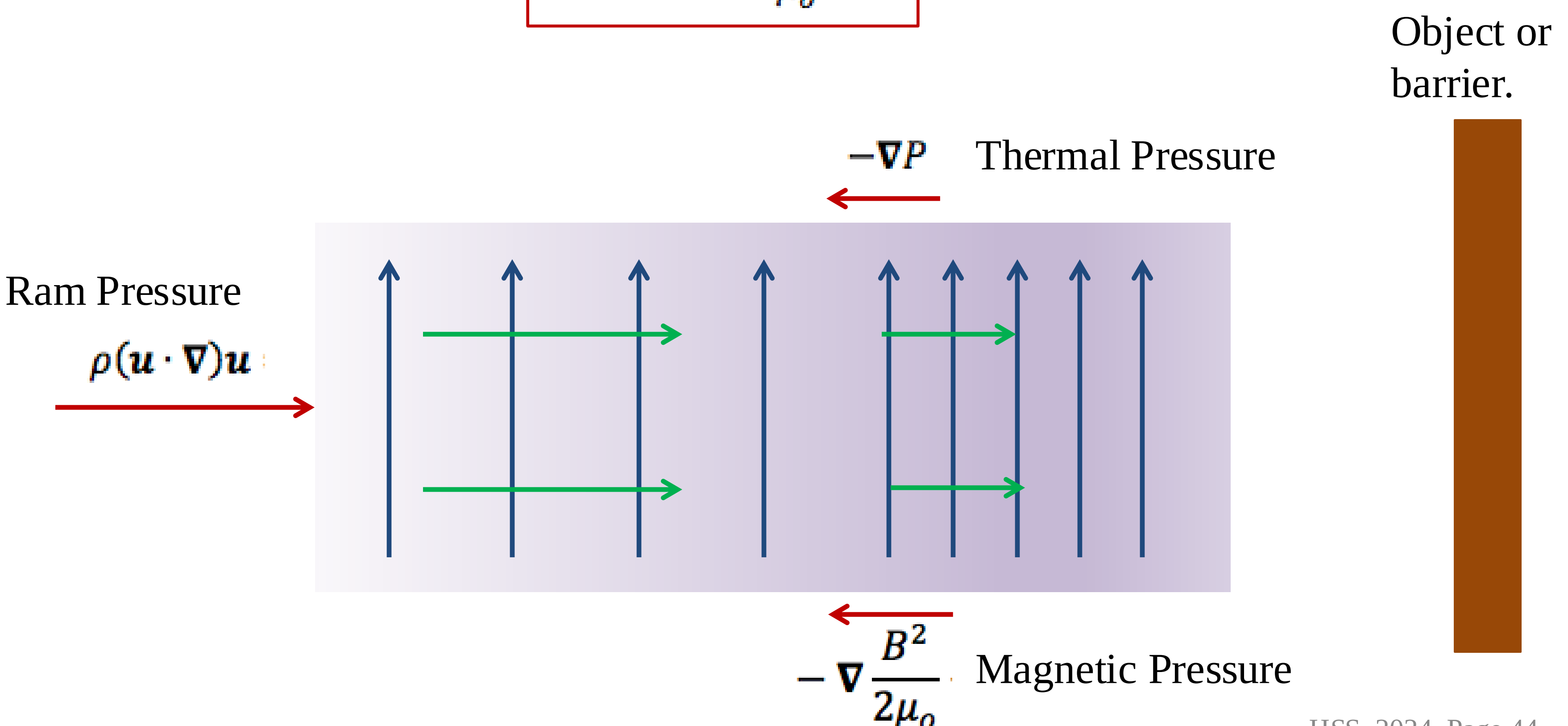
(We don't do water.)

Ram Pressure / Shocks

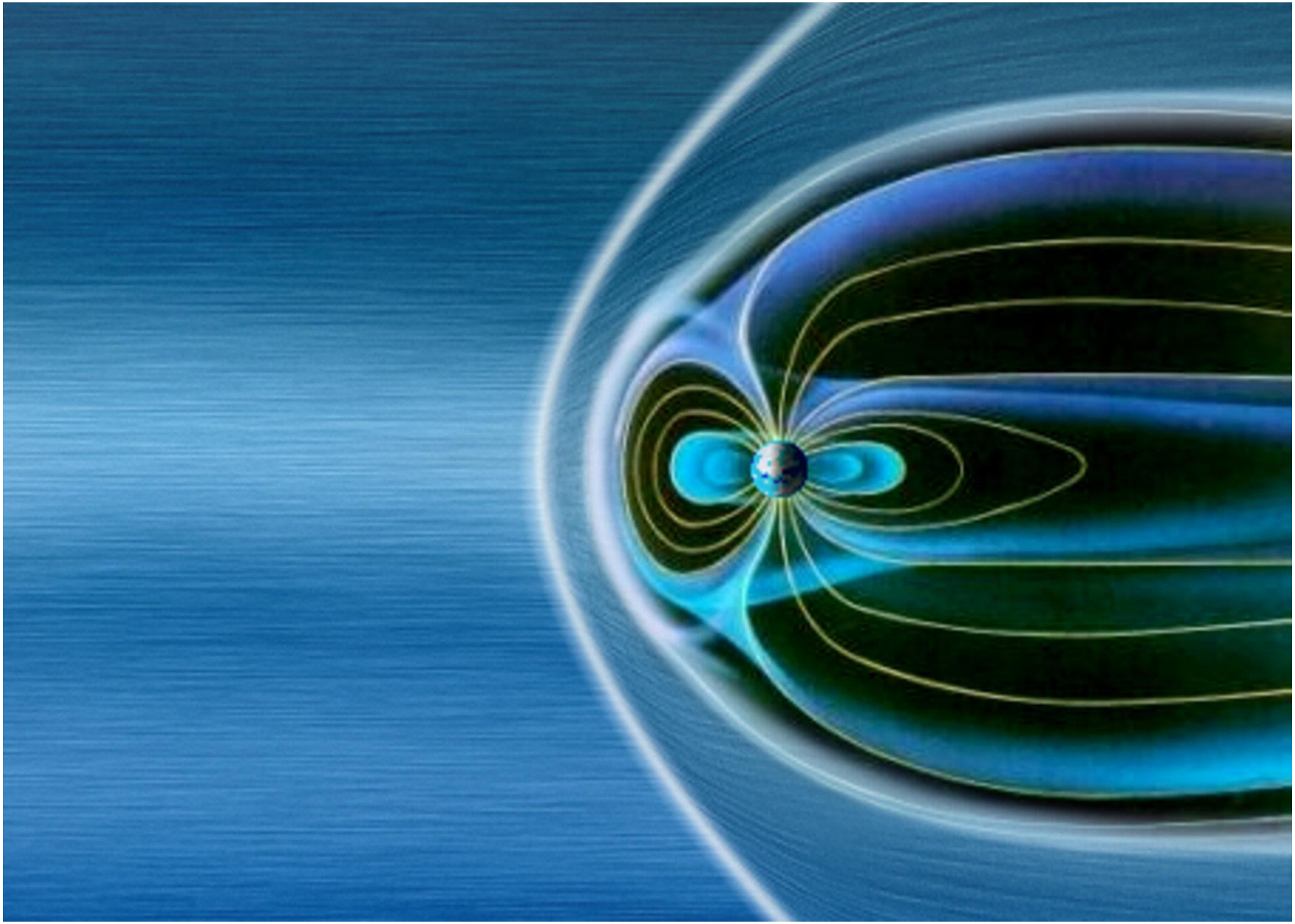
$$\nabla(\rho u^2) = -\nabla P - \nabla \frac{B^2}{2\mu_o}$$

Suppose a plasmas impinges on a object, which compresses the plasma as slows the flow. Steady state, no curvature in $\boldsymbol{B}$, and not gravity.

$$\rho u^2 + P + \frac{B^2}{2\mu_o} = C$$

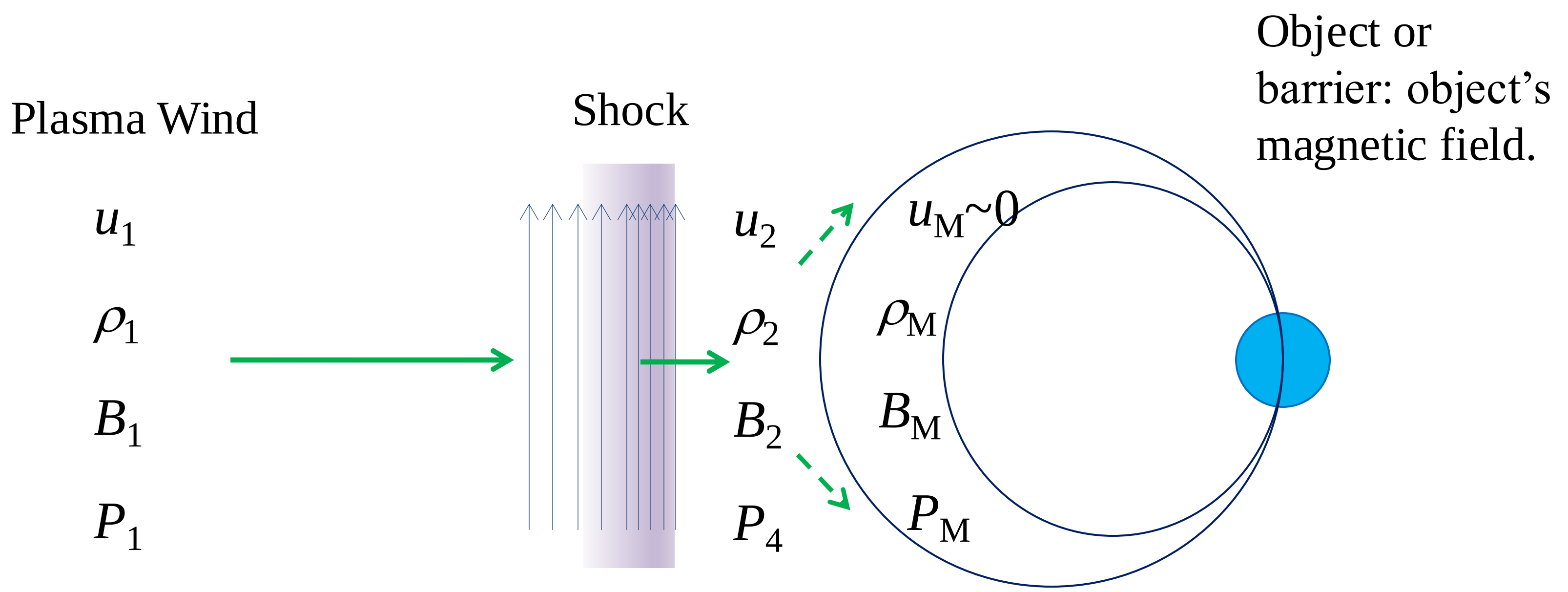


Earth's Bow Shock



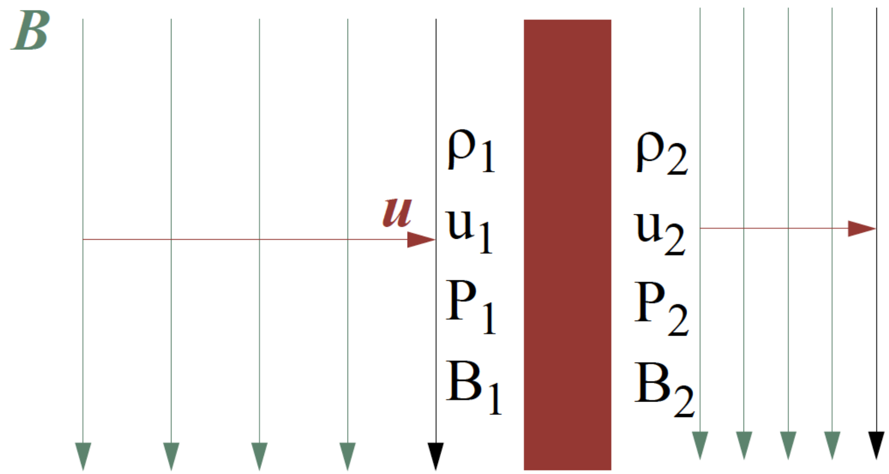
Ram Pressure / Shocks

$$\rho_2 u_2^2 + P_2 + \frac{B_2^2}{2\mu_o}$$



$$\rho_1 u_1^2 + P_1 + \frac{B_1^2}{2\mu_o} = \rho_2 u_2^2 + P_2 + \frac{B_2^2}{2\mu_o} = P_M + \frac{B_M^2}{2\mu_o}$$

Shocks



Rankine-Hugoniot Jump Conditions

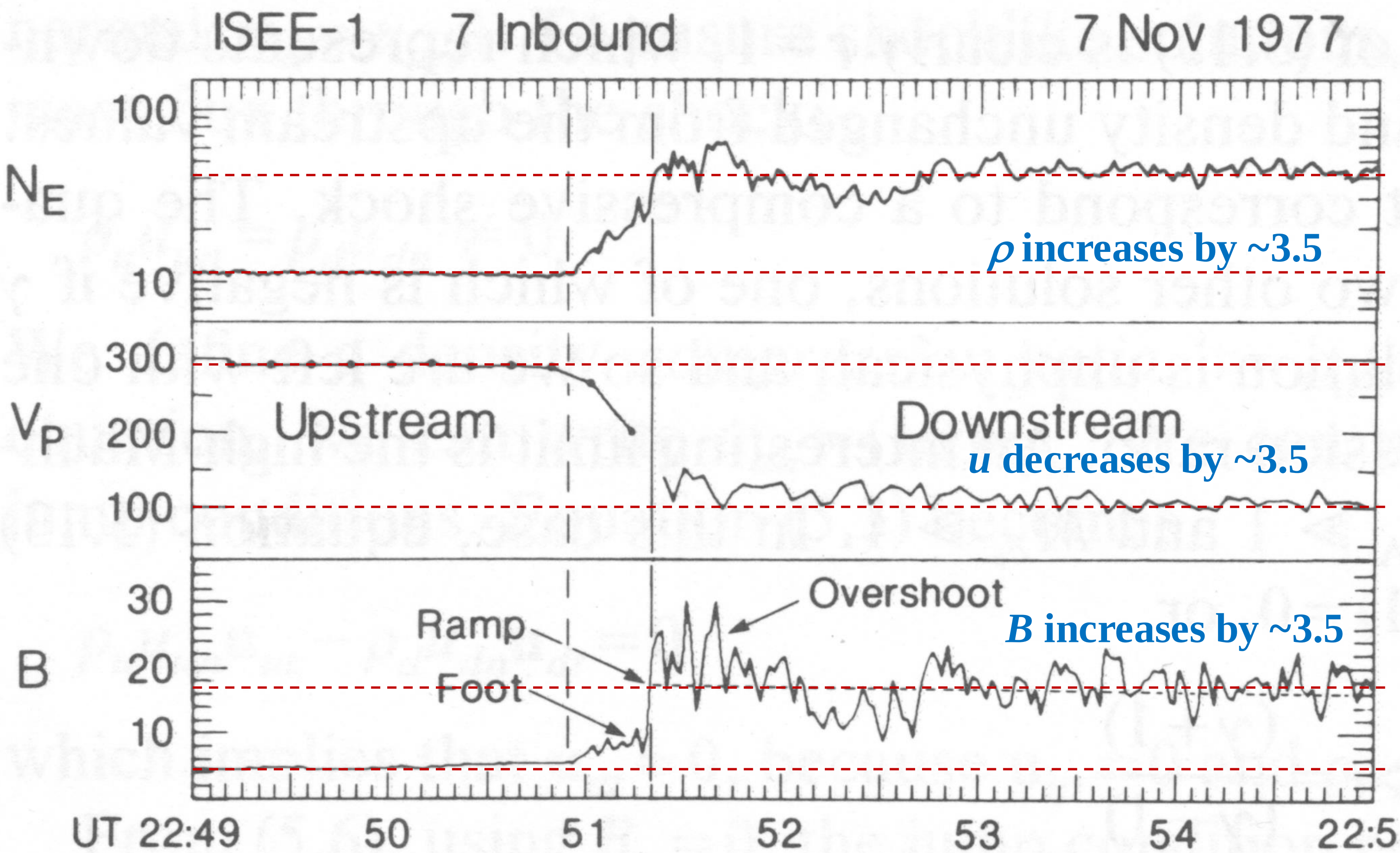
$$\rho_1 u_1 = \rho_2 u_2$$

$$B_1 u_1 = B_2 u_2$$

$$\rho_1 u_1{}^2 + P_1 + B_1{}^2/2\mu_o = \rho_2 u_2{}^2 + P_2 + B_2{}^2/2\mu_o$$

$$u_1(1/2\ \rho_1 u_1{}^2 + \gamma/(\gamma-1)\ P_1 + B_1{}^2/\mu_o) = u_2(1/2\ \rho_2 u_2{}^2 + \gamma/(\gamma-1)\ P_2 + B_2{}^2/\mu_o)$$

Example: Shocks

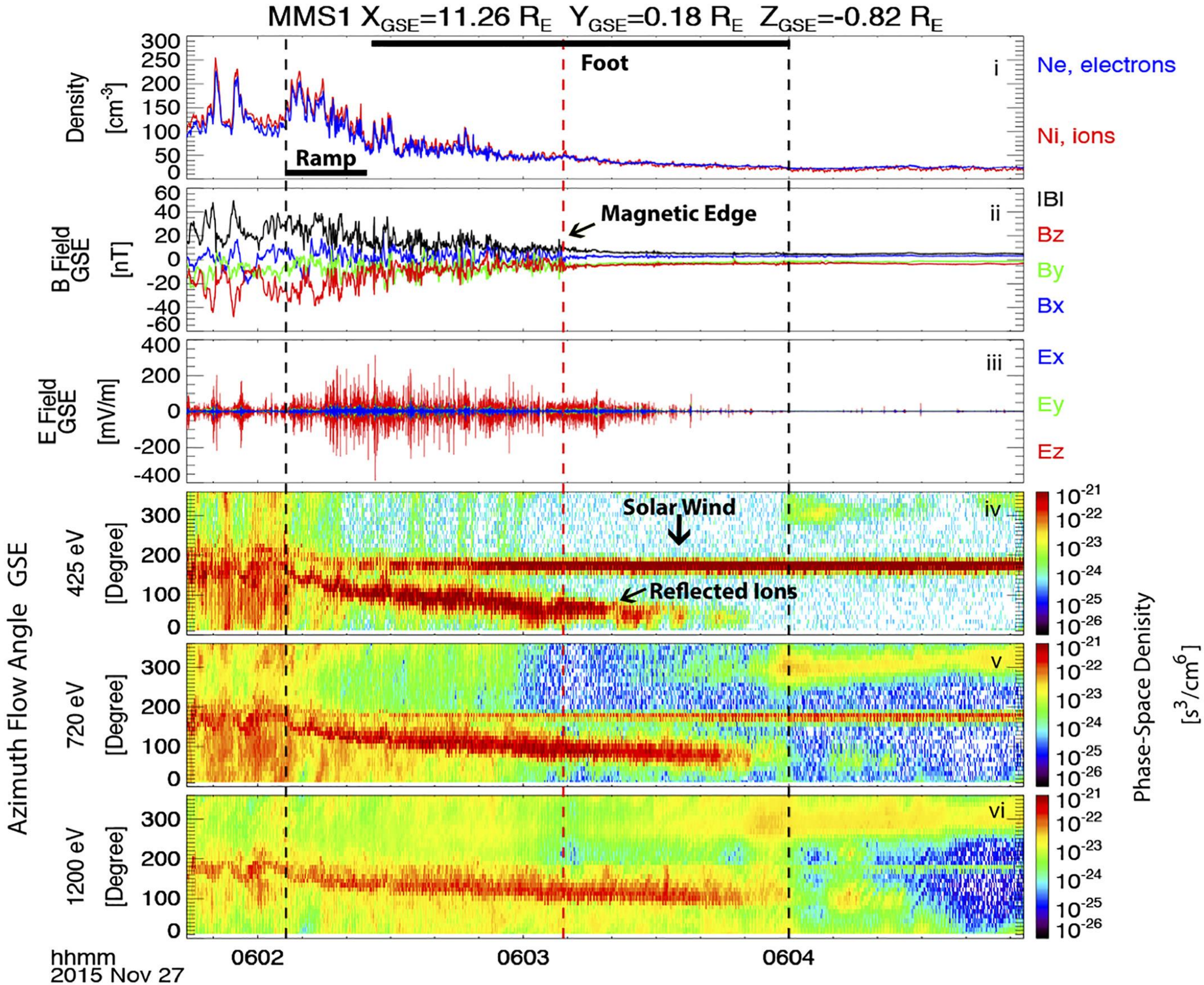


ρ **increases by ~3.5**

u **decreases by ~3.5**

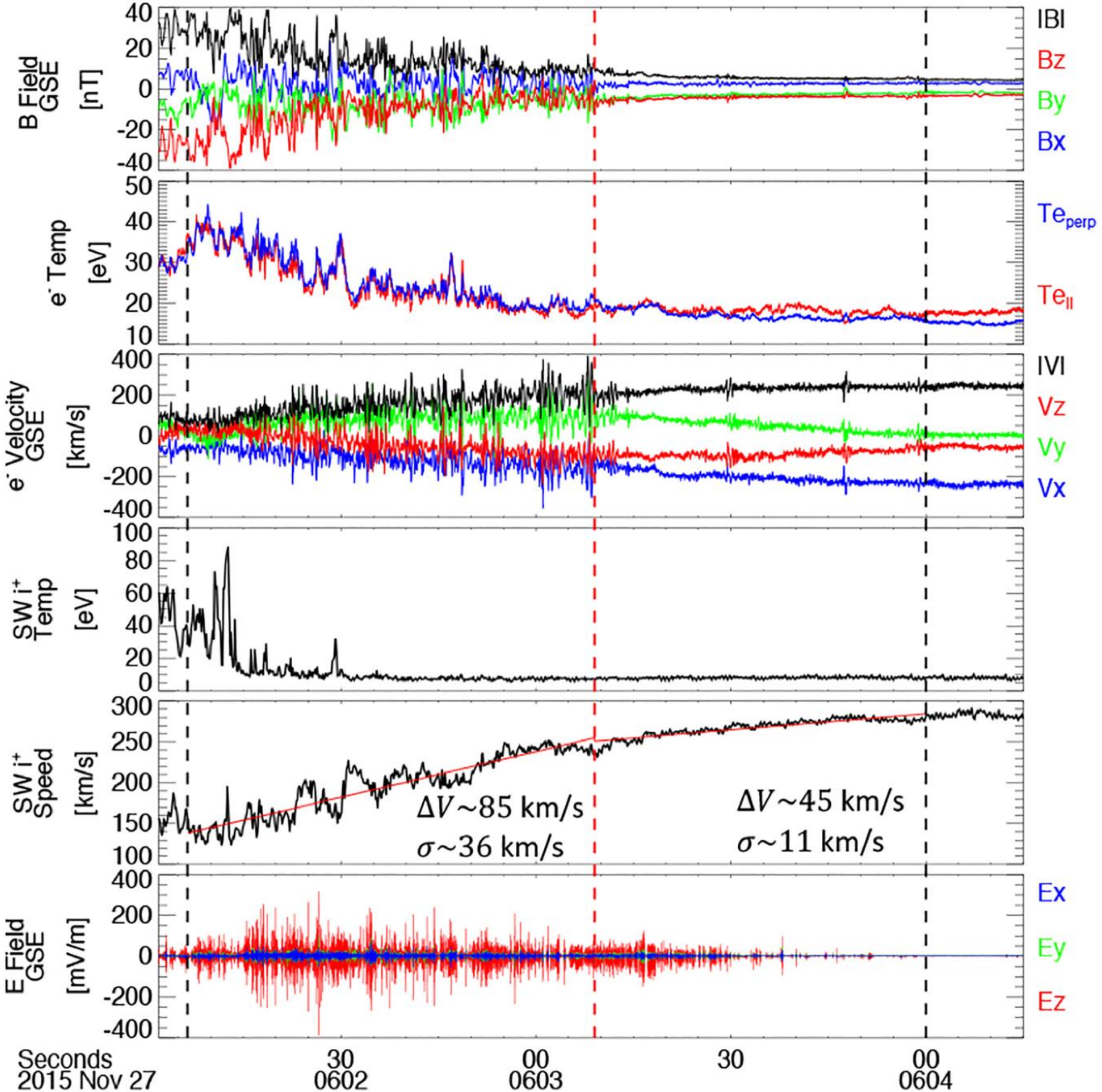
B **increases by ~3.5**

Shocks



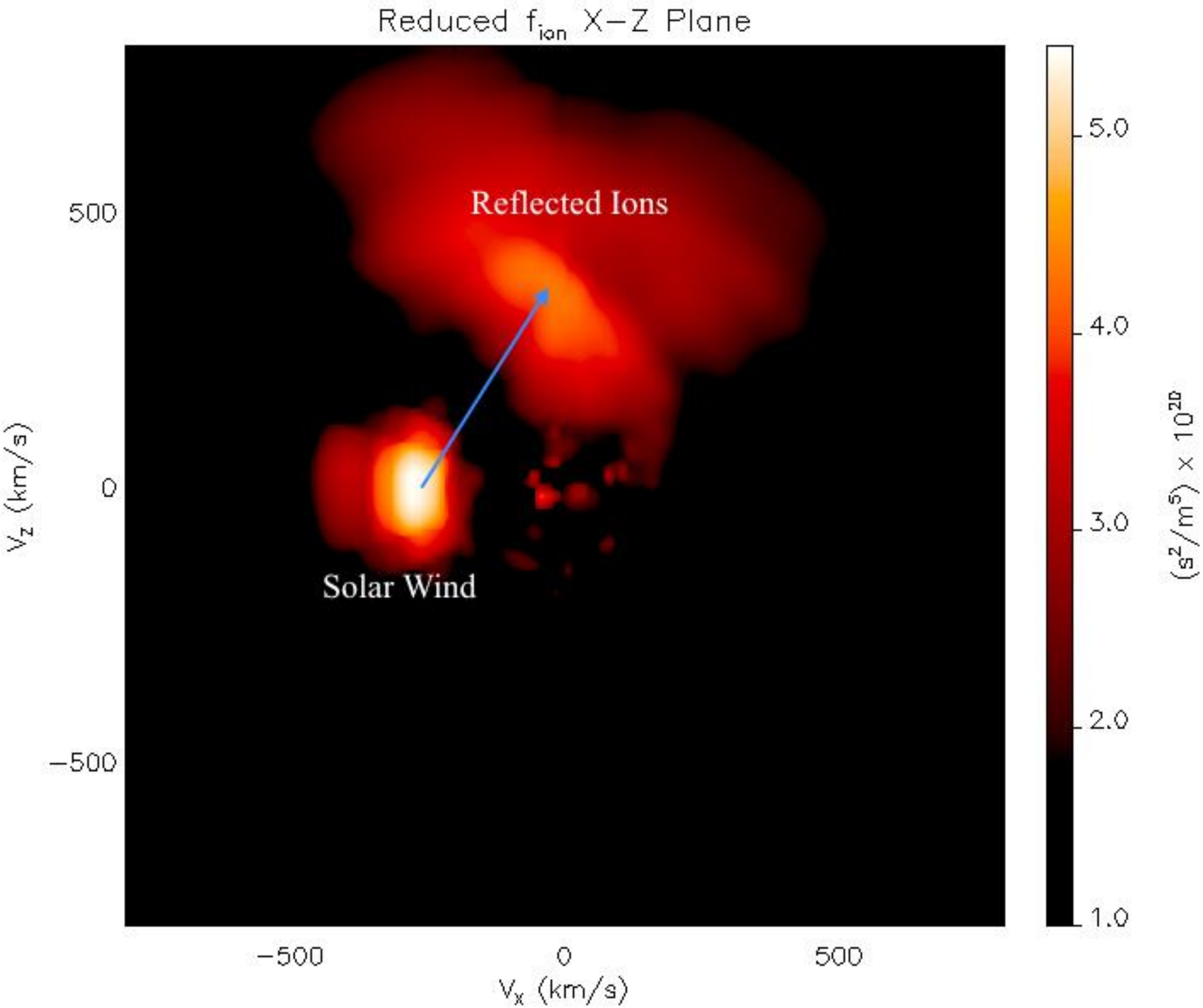
MMS1 X_{GSE}=11.26 R_E Y_{GSE}=0.18 R_E Z_{GSE}=-0.82 R_E
Density [cm^{-3}]
Foot
Ramp
i
Ne, electrons
Ni, ions
B Field GSE [nT]
Magnetic Edge
ii
|B|
Bz
By
Bx
E Field GSE [mV/m]
iii
Ex
Ey
Ez
Azimuth Flow Angle GSE
425 eV [Degree]
720 eV [Degree]
1200 eV [Degree]
Solar Wind
Reflected Ions
iv
v
vi
Phase-Space Denisity [s^3/cm^6]
hhmm
2015 Nov 27
0602
0603
0604

Shocks

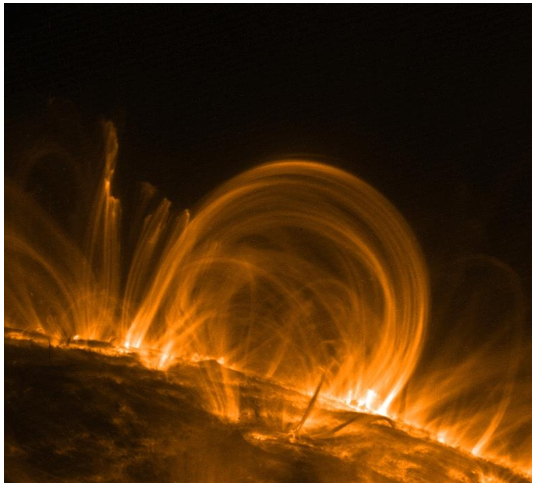


B Field GSE [nT]
IBI
Bz
By
Bx
e⁻ Temp [eV]
Te_perp
Te_II
e⁻ Velocity GSE [km/s]
IVI
Vz
Vy
Vx
SW i⁺ Temp [eV]
SW i⁺ Speed [km/s]
ΔV~85 km/s
σ~36 km/s
ΔV~45 km/s
σ~11 km/s
E Field GSE [mV/m]
Ex
Ey
Ez
Seconds
2015 Nov 27
30
0602
00
0603
30
00
0604

Shocks



Reduced f_{ion} X–Z Plane
Reflected Ions
Solar Wind
500
0
−500
V_z (km/s)
−500
0
500
V_x (km/s)
5.0
4.0
3.0
2.0
1.0
$(s^2/m^5) \times 10^{20}$



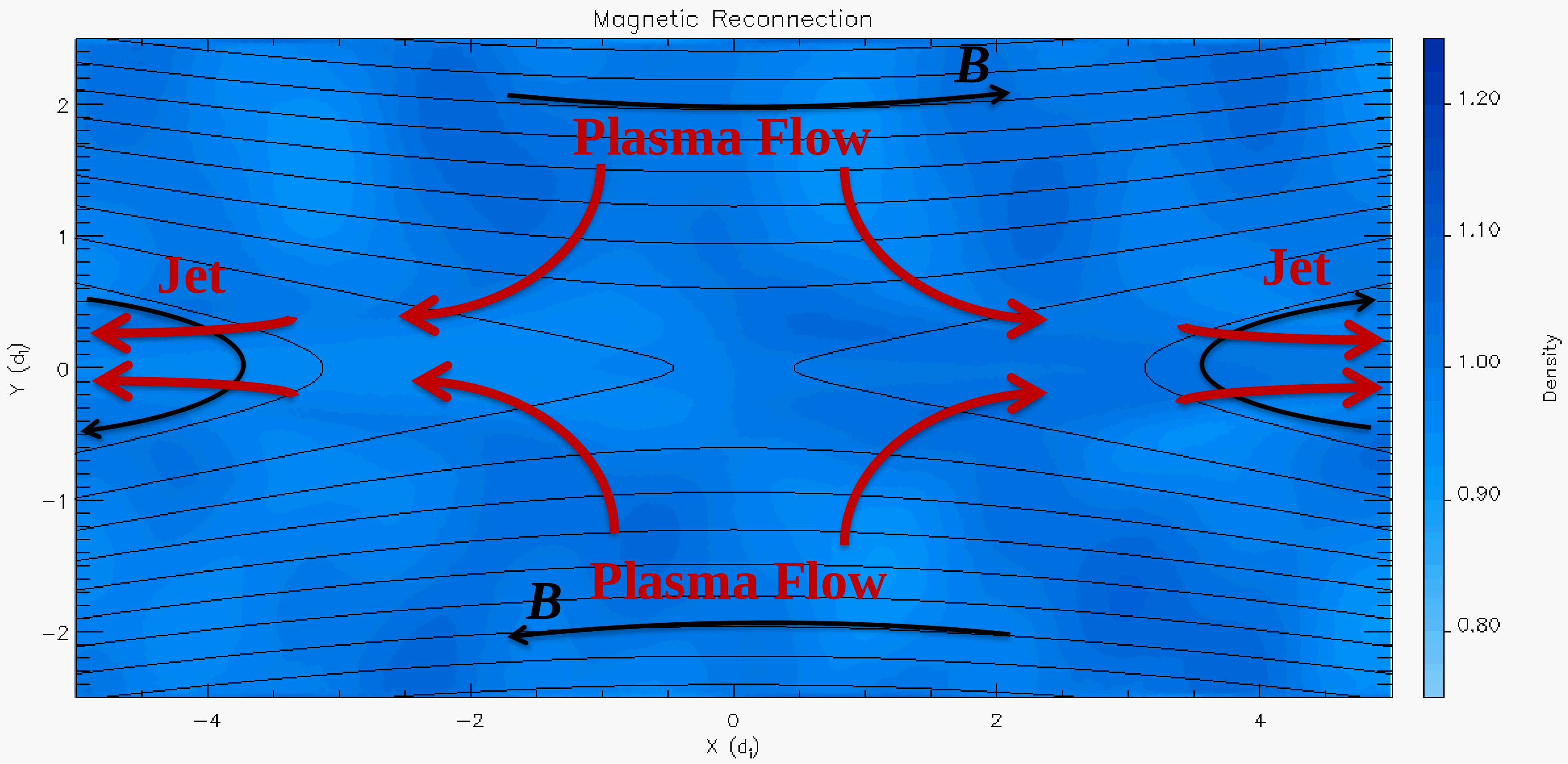
Heliophysics Summer School

Part 1

- Motivation: Why heliophysics?
- My view of plasma physics: kinetic, multi-fluid, and MHD approaches.
- Quick review of particle motion and adiabatic invariants.
- Shocks (basics) and why they are important (collisionless plasmas)
- **Magnetic reconnection (basics) and why it is important (collisionless plasmas)**

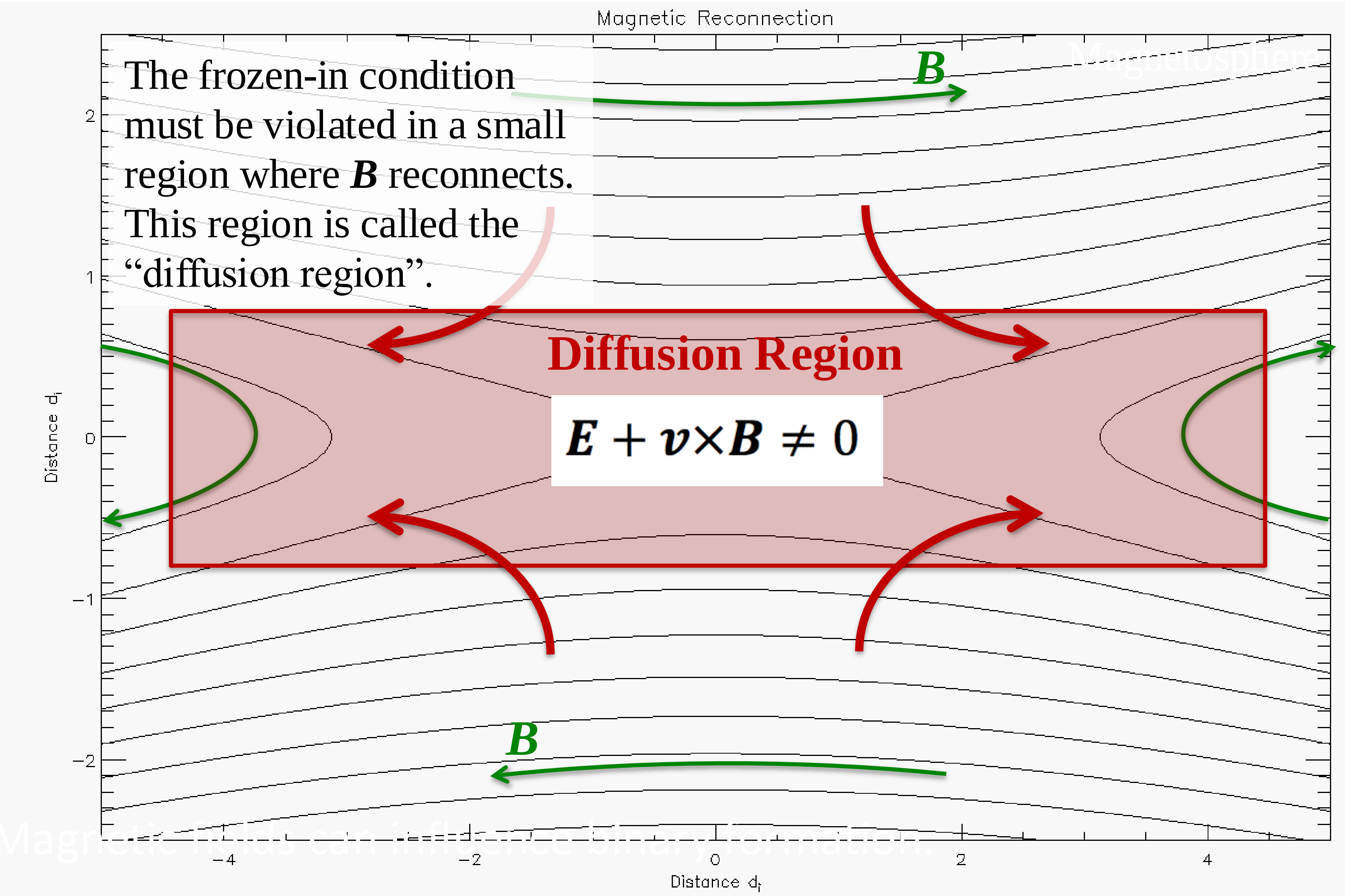
Prof. Robert Ergun
Email: ree@lasp.colorado.edu

Anti-Parallel Magnetic Reconnection



Magnetic Reconnection

The frozen-in condition must be violated in a small region where ***B*** reconnects. This region is called the “diffusion region”.

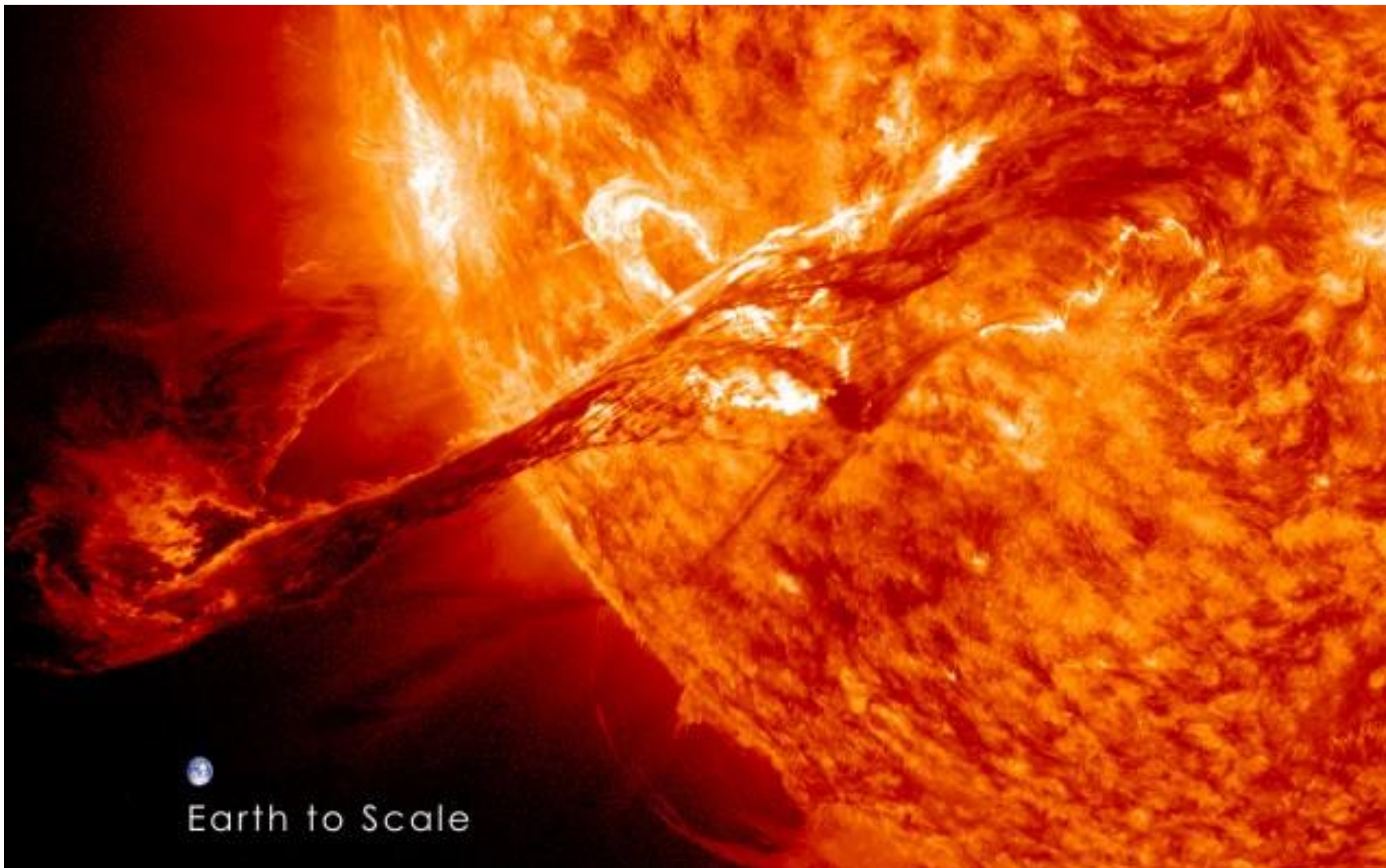


The Solar Flare Puzzle

The puzzle (1950's):

Solar flares erupt in minutes (~10^2 s).

Magnetic diffusion time across 10 Mm is on the order of 10^{16} s using simple magnetic diffusion.



Breaking the Frozen-In Condition

The first thought (1950's) was that collisions are the primary process that break the frozen-in condition resulting in resistance and diffusion:

$$\boldsymbol{E} + \boldsymbol{v}\times\boldsymbol{B} = \eta\boldsymbol{J}$$

Generalized Ohm's Law

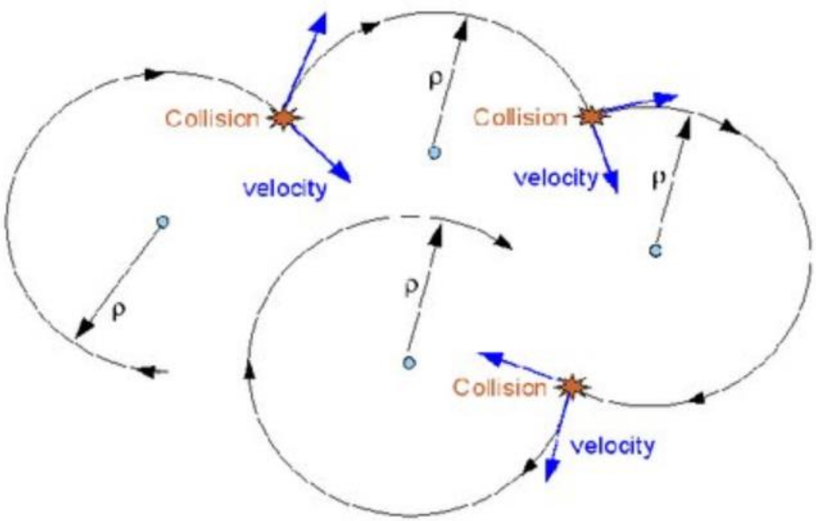
Resistance results in magnetic diffusion:

$$\nabla\times(\boldsymbol{E} + \boldsymbol{v}\times\boldsymbol{B} = \eta\boldsymbol{J})$$

Use $\nabla\times\boldsymbol{B} = \mu_o\boldsymbol{J}$

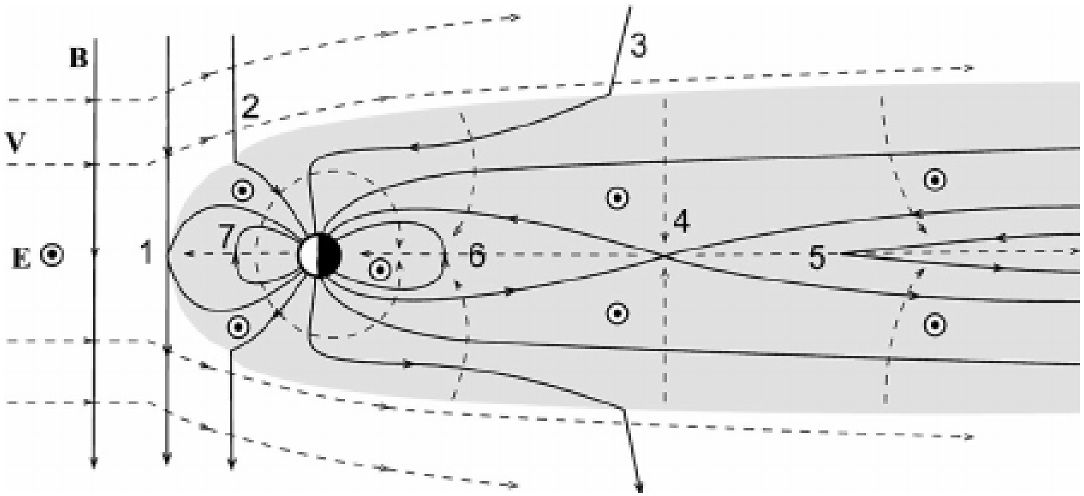
If $\boldsymbol{v} = 0$: $\frac{\partial\boldsymbol{B}}{\partial t} = \frac{\eta}{\mu_o}\nabla^2\boldsymbol{B}$

$$t_D \approx \frac{\mu_o}{\eta}\mathrm{L}^2\boldsymbol{B}$$



Magnetic Reconnection at Earth

Dungy (1961) realized that magnetic reconnection could “open” the Earth’s magnetosphere allowing solar wind and its energy to enter. He correctly inferred that magnetic reconnection is part of the energy transfer from the solar wind that power aurorae.



Dungy’s model was not well accepted. At the time (1960’s), controversy raged. The plasma resistance is near zero, so magnetic reconnection could not occur.

$$\boldsymbol{E} + \boldsymbol{v}\times\boldsymbol{B} = \eta \boldsymbol{J} = 0$$

However, as research went forward (1970’s) the first satellite observations showed evidence supporting the Dungy model.

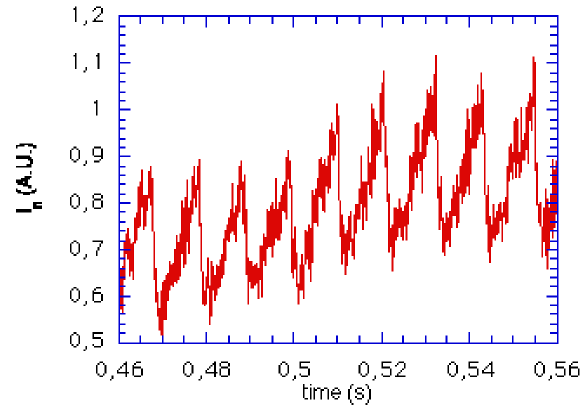
Now we have a bigger mystery! Collisionless magnetic reconnection?

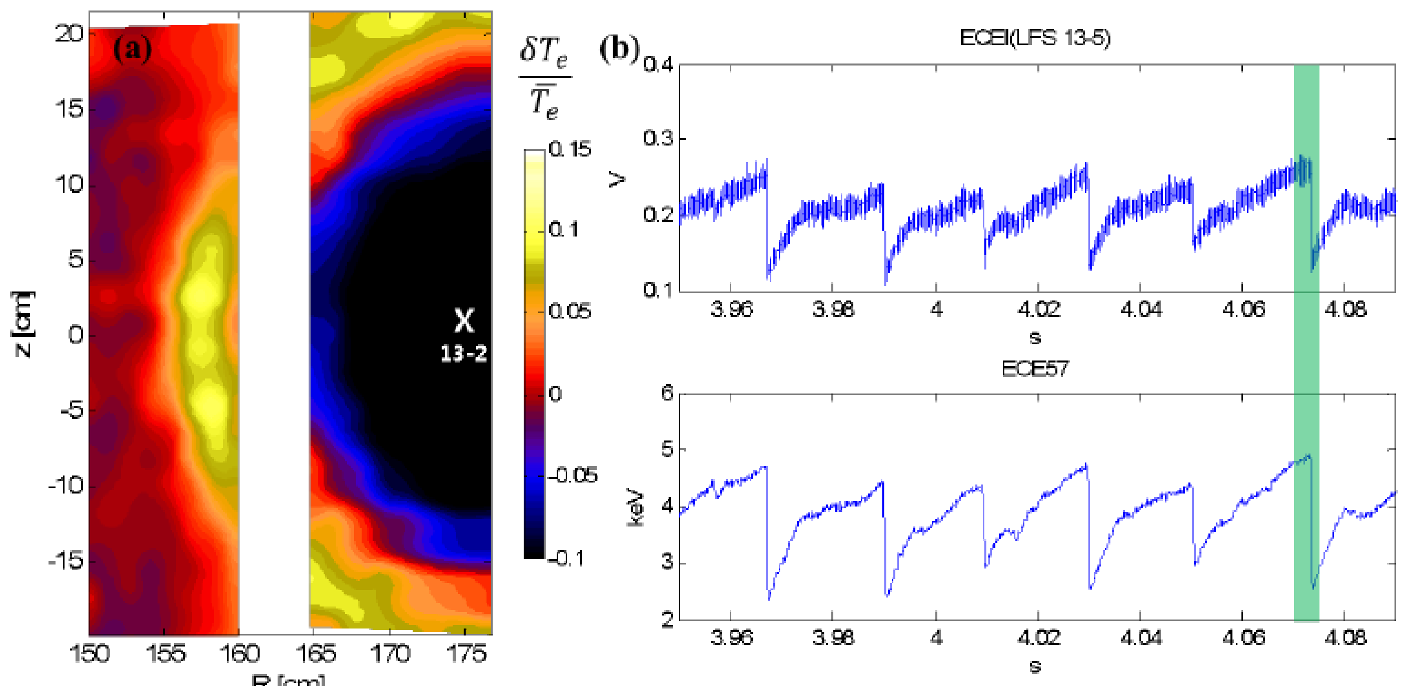
The Tokamak Problem

First reported in 1974, magnetic fields in tokamaks would suddenly disrupt resulting in a loss of confinement. These events were named “sawtooth crashes” due to the nonlinear shape of the signals.

Ultimately, the root cause of sawtooth crashes has been determined to be magnetic reconnection.

Once again, the magnetic reconnection rate is much higher than expected.



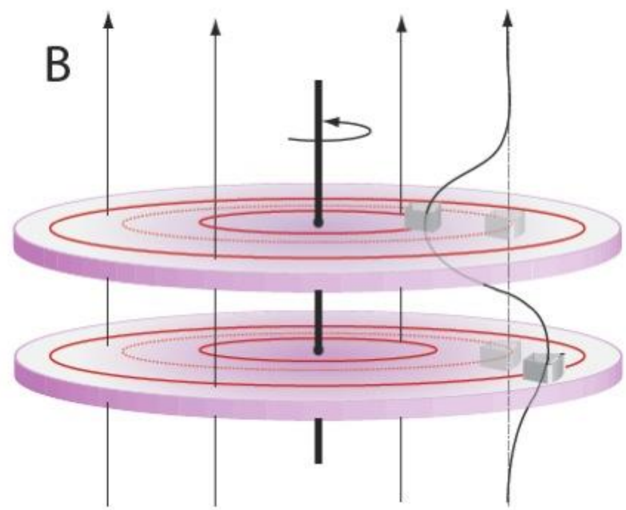


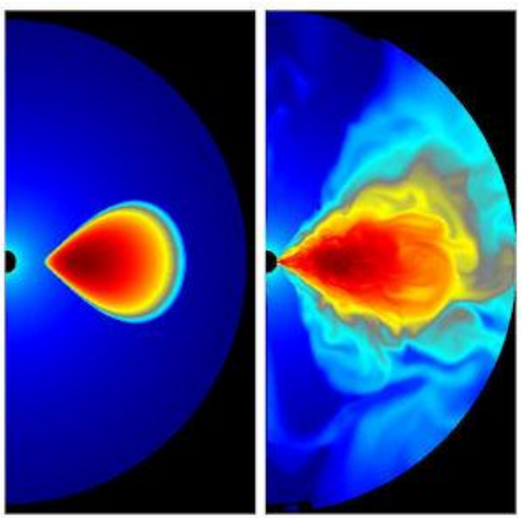
Magntorotational Instability – Accretion Disks

The magnetorotational instability in accretion disks (*Velikov*, 1959; *Chandrasekhar* , 1960) is thought to be primarily driven by the Rayleigh-Taylor instability.

Recent work now includes magnetic reconnection and turbulence to describe the nonlinear evolution.

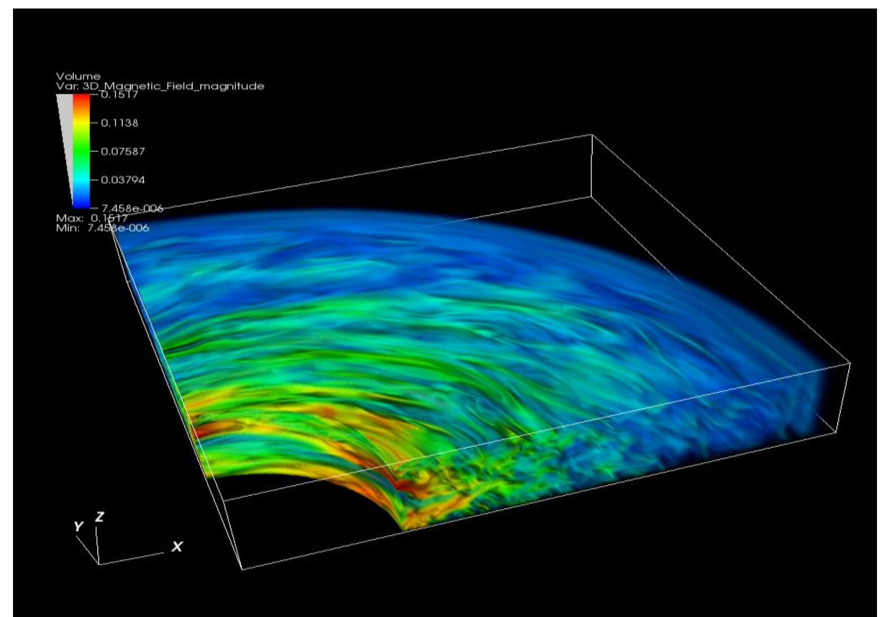
"*If you don't understand it, invoke magnetic reconnection or turbulence*!"





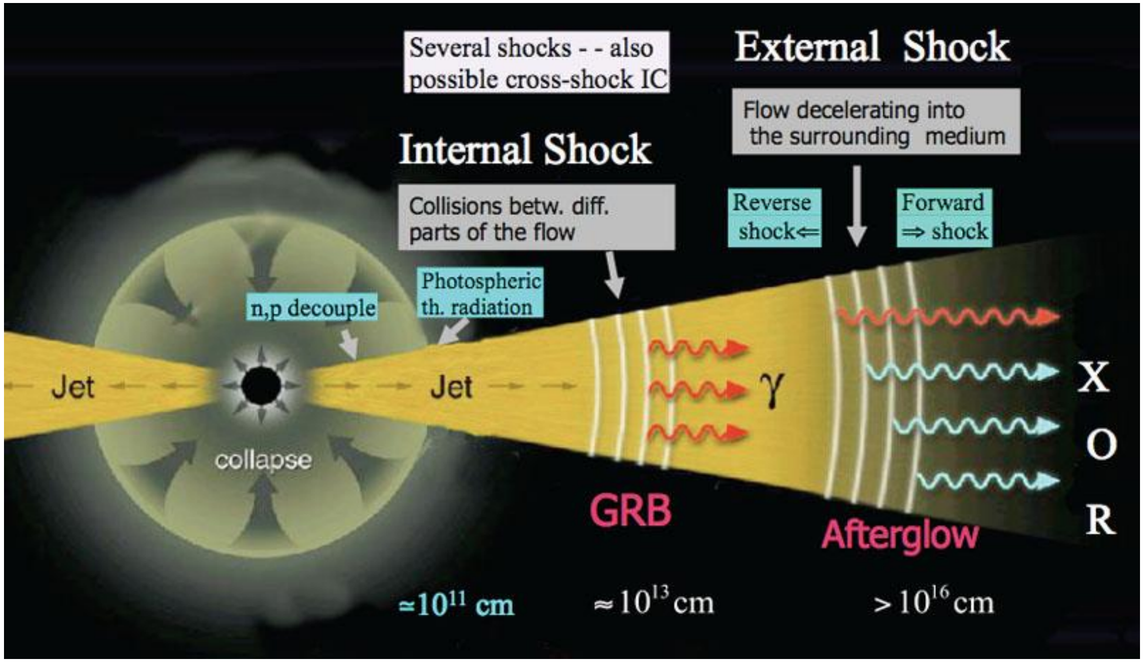
MRI simulation near a Kerr black hole.

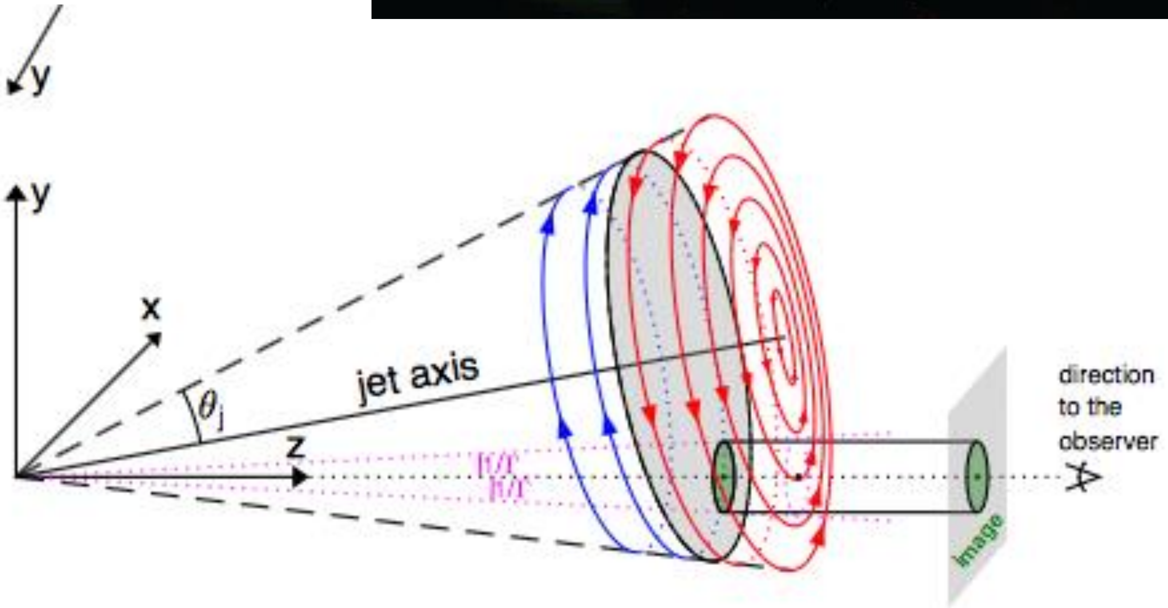
MRI in an accretion disk.



γ-Ray Bursts

In high-σ (magnetic field energy to kinetic energy) outflows, magnetic reconnection can be more efficient than the internal shock (*Thompson* 1994; *Spruit et al*. 2001; *Lyutikov & Blandford 2002;* 2003).

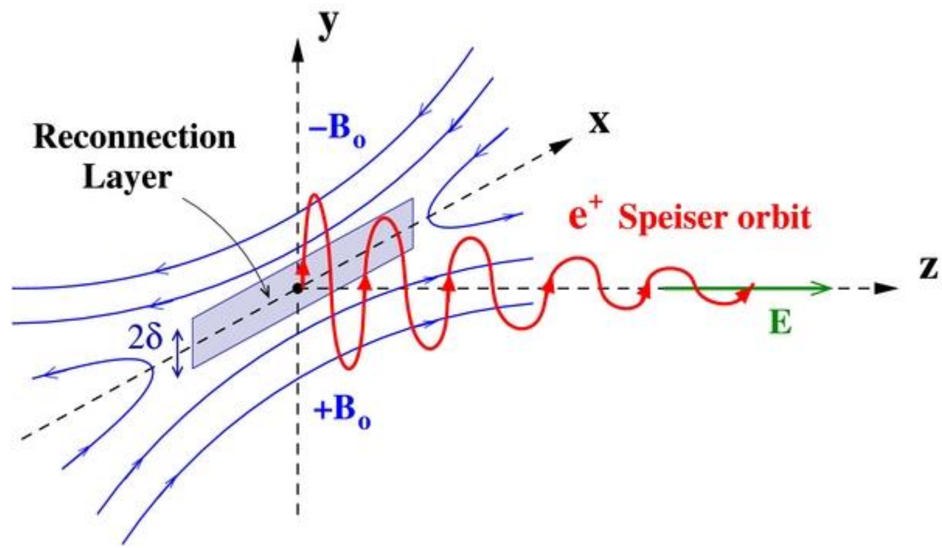


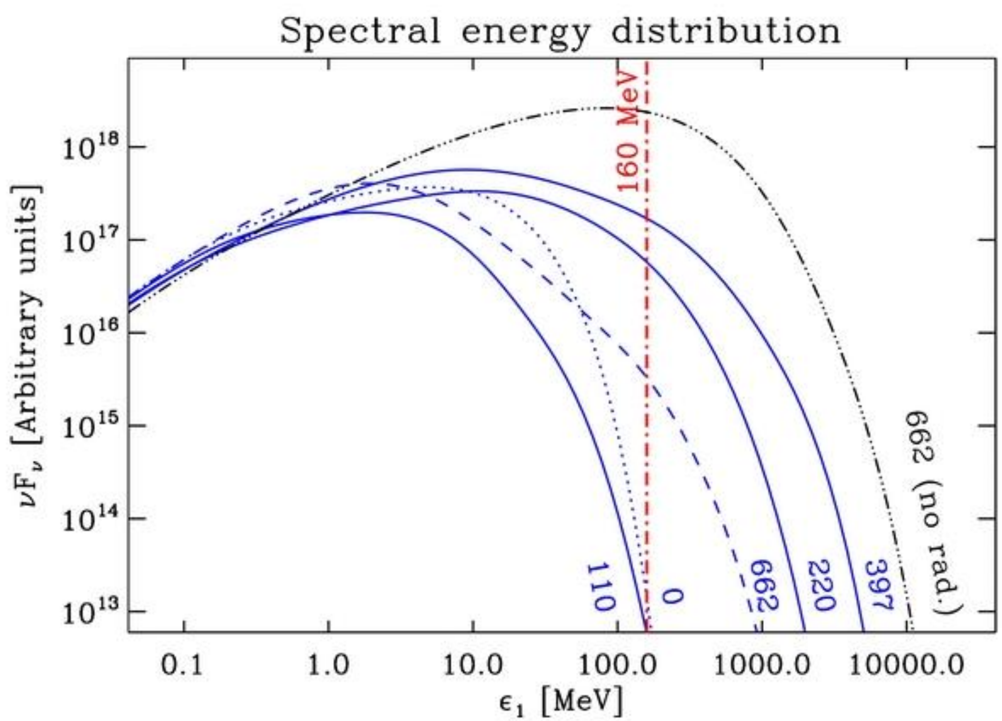


Pulsar Nebulae

Extreme particle acceleration (beyond the radiation reaction limit) in pulsar nebulae has been inferred from synchortron radiation. It has been postulated that particles can be accelerated well above the classical radiation reaction limit (160 MeV), by a relativistic Speiser mechanism inside of a magnetic reconnection layer (*Uzdensky, Cerutti, & Begelman*, 2011).

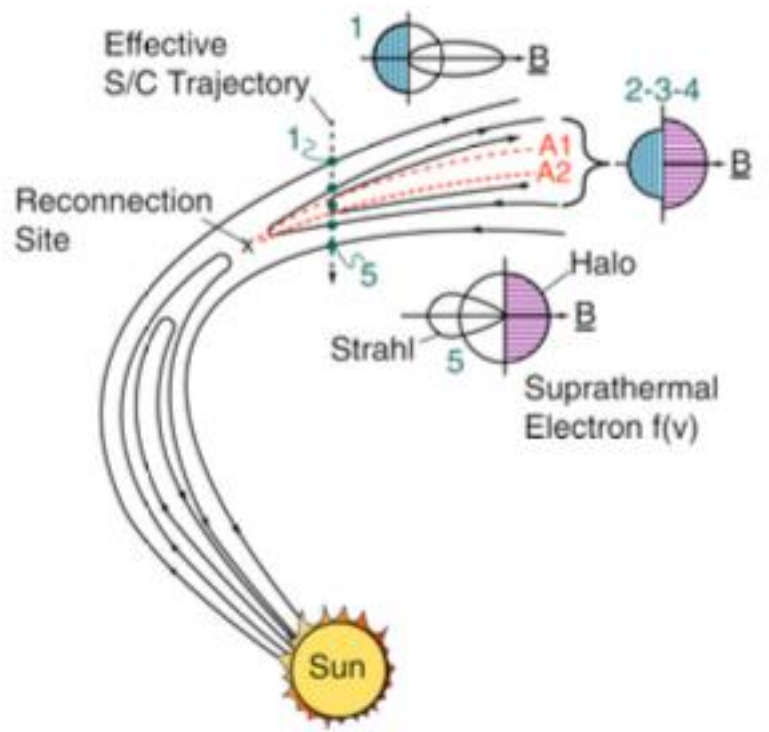
Simulations of particle acceleration beyond the classical synchrotron burnoff limit in magnetic reconnection: an explanation of the crab flares (*Cerutti et al*., 2013).

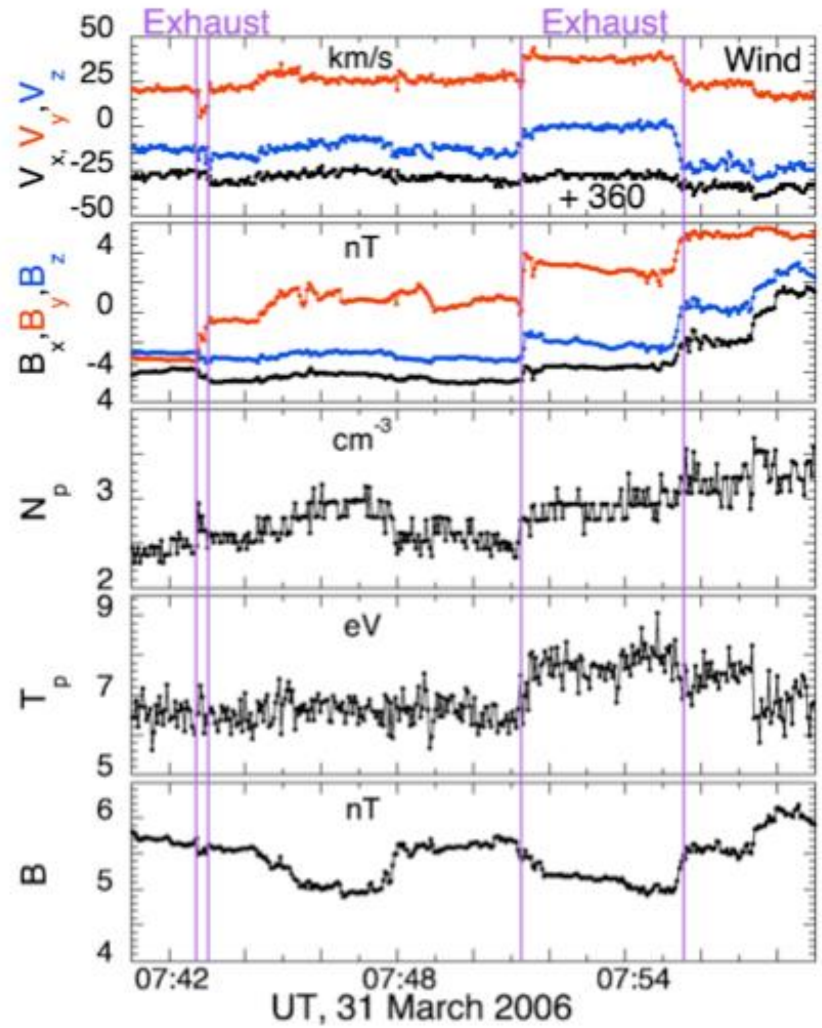




Magnetic Reconnection in the Solar Wind

Collisionless magnetic reconnection has also been observed in the solar wind (*Gosling et al.*, 2005; 2007)



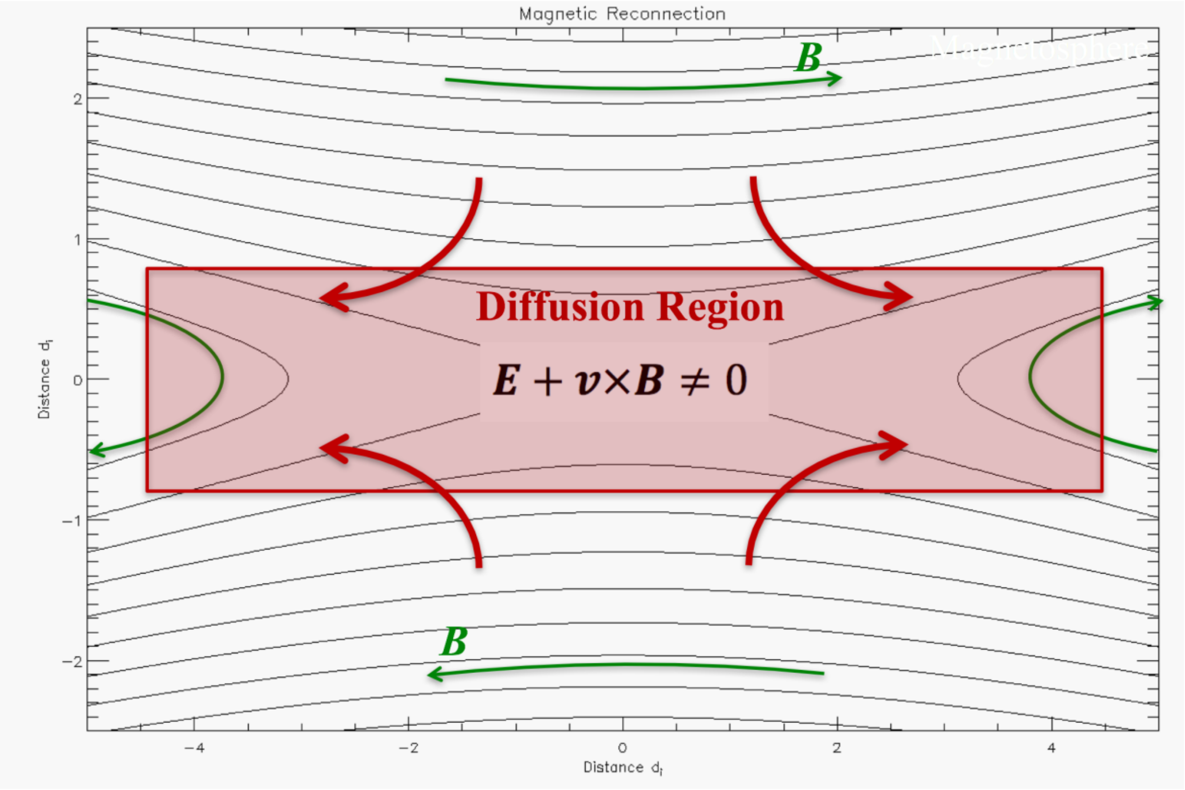


Magnetic Reconnection, a Universal Process

Magnetic reconnection has been observed/postulated in vastly differing plasma environments, from tokamaks to neutron stars to pulsar nebulae, with scale sizes ranging from cm to Mm, with plasma densities scaling over 12 orders of magnitude, and magnetic field strengths from nT to >kT. It is associated with turbulence and particle acceleration. Yet, the physics of the diffusion region was not understood!

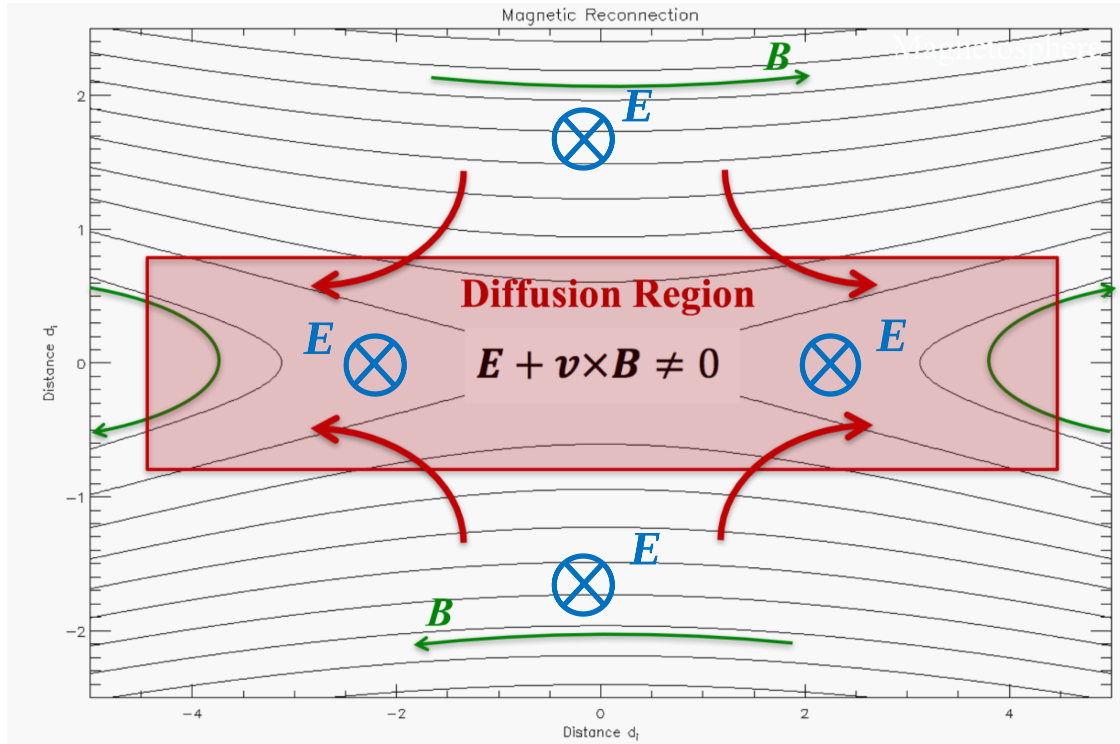
Major questions:

- How does collisionless magnetic reconnection occur?
- What physical process breaks the frozen in condition in fast magnetic reconnection?
- What supports the reconnection electric field?
- How is the magnetic field energy dissipated?



Magnetic Reconnection Research

20-30 years ago, it was recognized that fast reconnection and collisionless reconnection required examination of the full Generalized Ohm's Law.



Several types of MHD simulations are used to balance ***E*** + ***v***x***B***:

- Ideal MHD: 0
- Resistive MHD: η***J***.
- Hall MHD: ***J***x***B***/*en*

Generalized Ohm's Law:

Resistive — Hall — Electron Pressure — Electron Inertia

$$\boldsymbol{E} + \boldsymbol{v}\times\boldsymbol{B} = \eta\boldsymbol{J} + \frac{\boldsymbol{J}\times\boldsymbol{B}}{en} - \frac{\nabla\cdot\overline{\overline{\boldsymbol{P}_e}}}{en} + \frac{m_e}{e^2 n}\frac{D\boldsymbol{J}}{Dt}$$

Adding electron pressure or inertia required one to abandon MHD.

Hall Reconnection

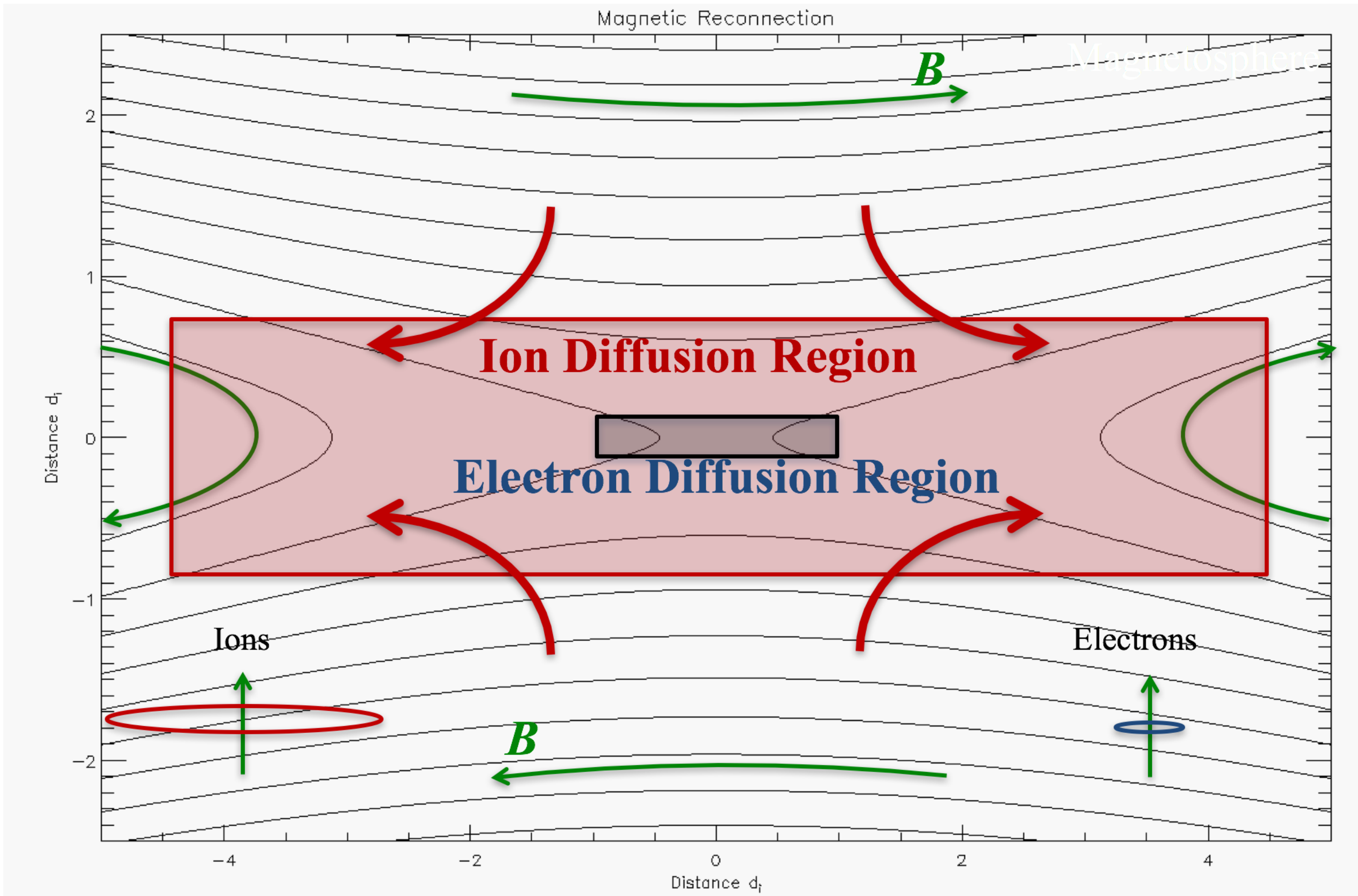
Ions, which have much larger skin depth (c/ω_{pi}) and gyroradii, decouple from $\boldsymbol{B}$ (via Hall term) resulting in two diffusion regions named the “ion diffusion region” and the “electron diffusion region”.

Hall MHD was a large step forward. However, electrons do not decouple via the Hall term.

And since:

$$\boldsymbol{J} \times \boldsymbol{B} \cdot \boldsymbol{J} = 0$$

Hall MHD cannot account for magnetic energy conversion.



PIC Simulations

A number of advances came from PIC (Particle-In-Cell; kinetic) simulations:

Primarily in 2D.

(1) Energy dissipation into electrons was quantified.

(2) Island formation (tearing mode) was verified.

(3) Particle acceleration methods were postulated.

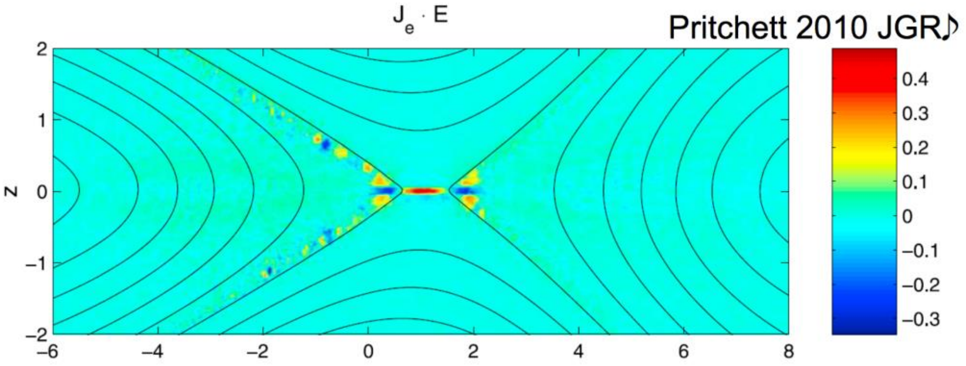
(4) Asymmetric magnetic reconnection (reconnection between differing plasmas) was studied.

(5) In 3D, turbulence emerges.

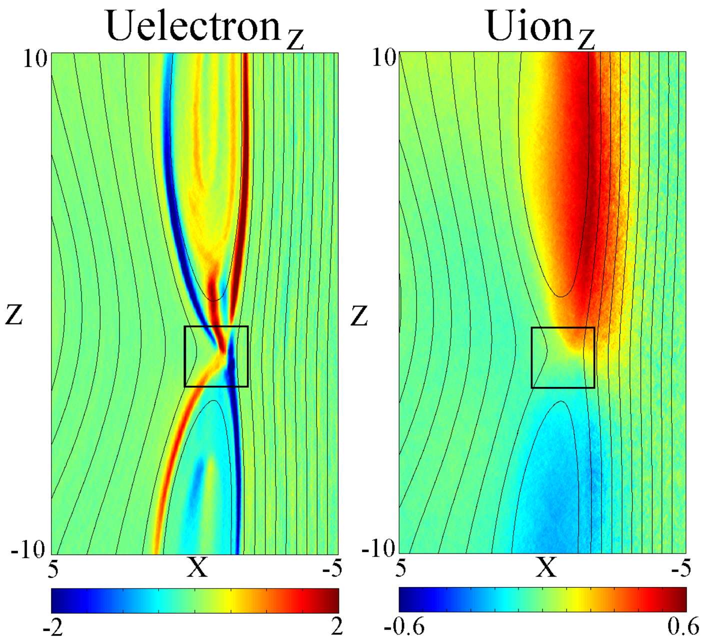
(6) Magnetic reconnection with a finite guide field differs for anti-parallel magnetic reconnection.

(7) Electron jets can emerge from magnetic reconnection.

(8) Much more…

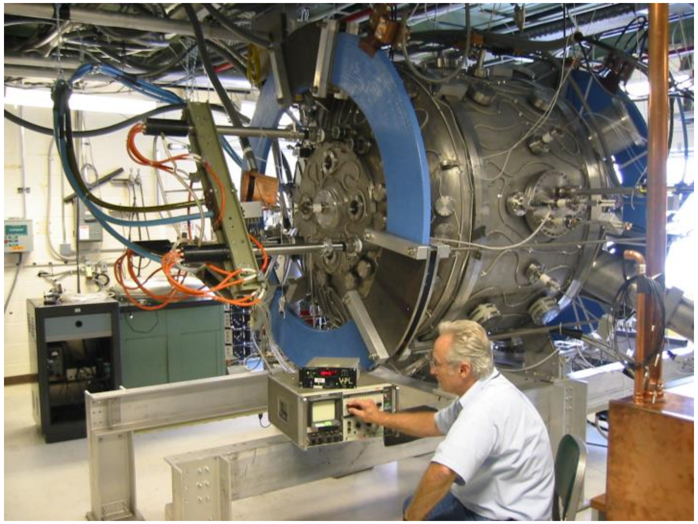


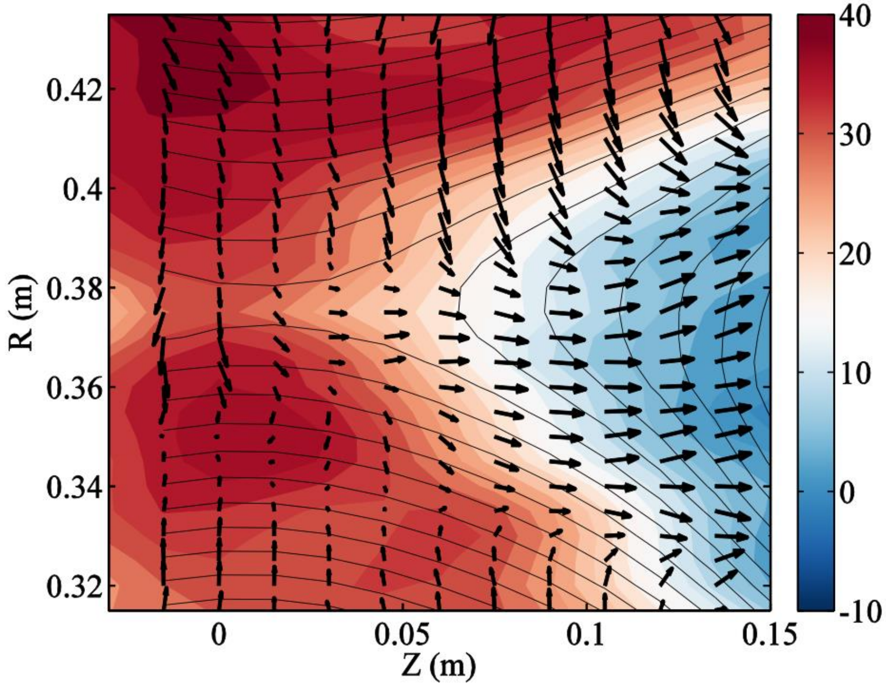
Ion and electron outflows.

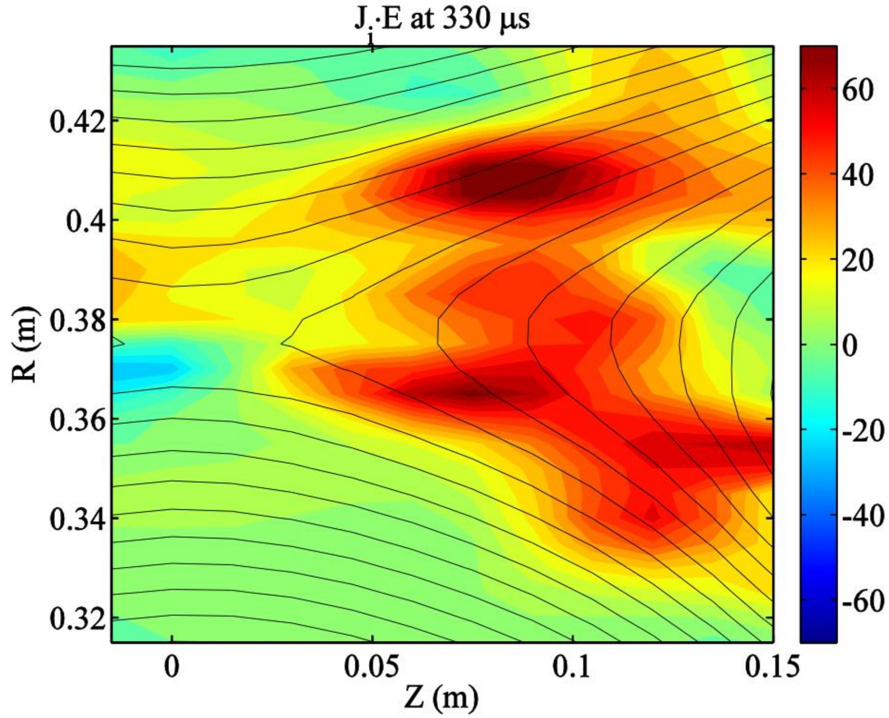


Laboratory Experiments

Laboratory experiments were able to verify or disprove a number of the theories of magnetic reconnection.





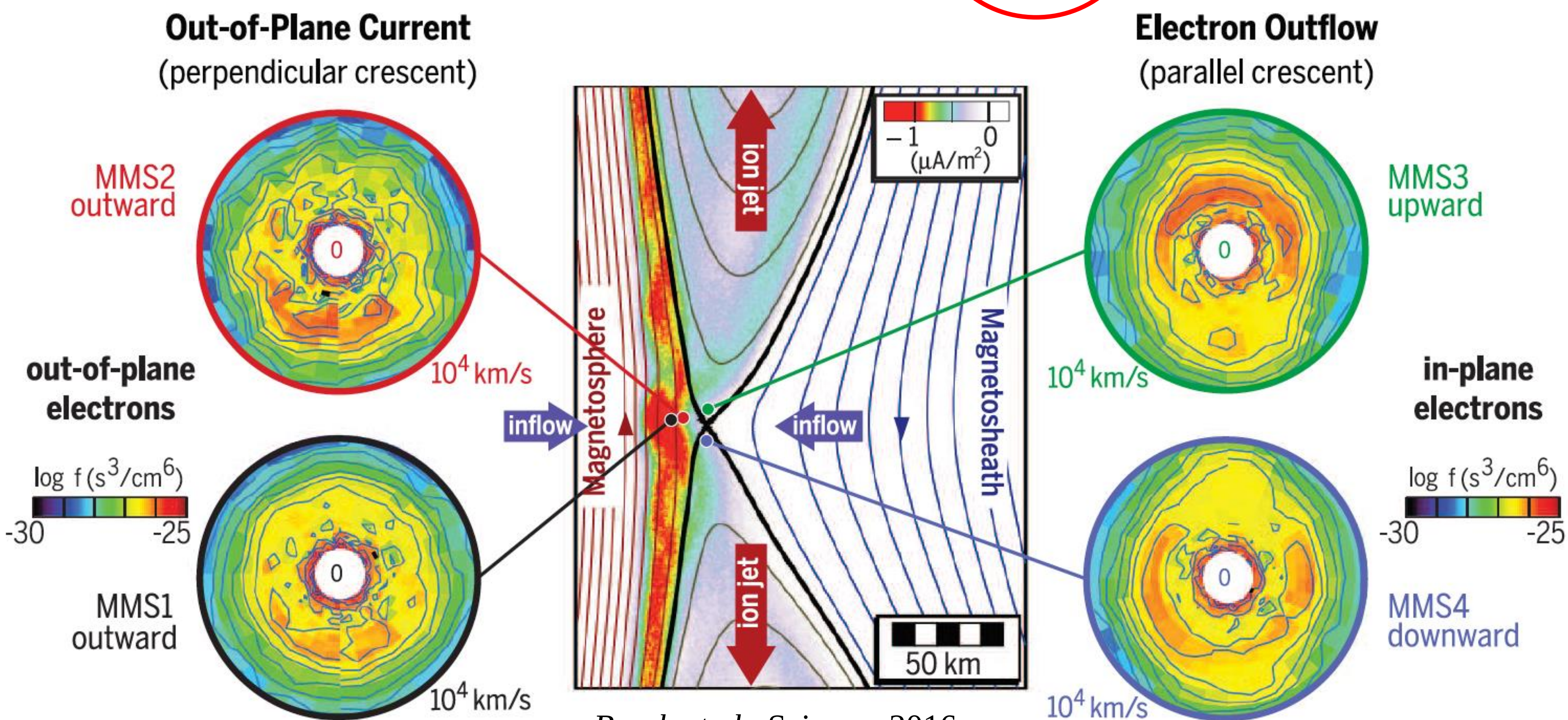


Space Measurements of the EDR

Generalized Ohm's Law:

Resistive — Hall — Electron Pressure — Electron Inertia

$$\boldsymbol{E} + \boldsymbol{v}\times\boldsymbol{B} = \eta\boldsymbol{J} + \frac{\boldsymbol{J}\times\boldsymbol{B}}{en} - \frac{\nabla\cdot\overline{\overline{\boldsymbol{P}_e}}}{en} + \frac{m_e}{e^2 n}\frac{D\boldsymbol{J}}{Dt}$$



Burch et al., Science, 2016

Space Measurements of Magnetic Reconnection

Generalized Ohm's Law:

Resistive — Hall — Electron Pressure — Electron Inertia

$$\boldsymbol{E} + \boldsymbol{v}\times\boldsymbol{B} = \eta\boldsymbol{J} + \frac{\boldsymbol{J}\times\boldsymbol{B}}{en} - \frac{\nabla\cdot\overline{\overline{\boldsymbol{P}_e}}}{en} + \frac{m_e}{e^2 n}\frac{D\boldsymbol{J}}{Dt}$$

What MMS observed in the electron diffusion region of anti-parallel magnetic reconnection:

(a) The Hall term breaks ion coupling (predicted).

(b) Electrons de-couple ***kinetically*** forming "crescent distributions". The reconnection electric field is supported by an ***off-diagonal term in the electron pressure gradient*** (predicted by some, e. g. *Hesse et al.*, 2014, but a major controversy prior to MMS).

(c) Electron heating: $T_{||} > T_{\perp}$ (partly predicted by some).

(d) Strong, localized energy conversion $\boldsymbol{J}\cdot\boldsymbol{E} > 0$ (predicted, except MMS observes much higher values and much more structure.)

Burch et al., Science, 2016

The Frozen-In Condition