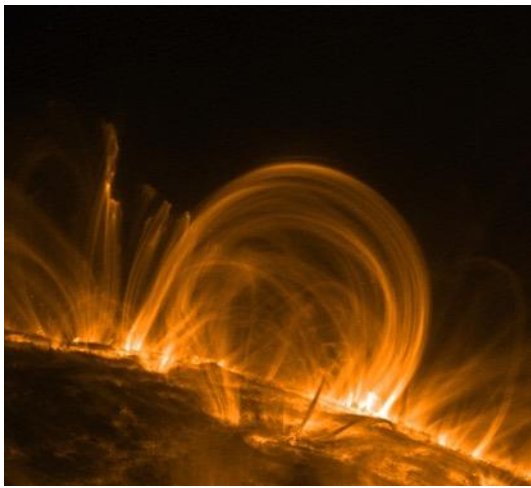




Heliophysics Summer School

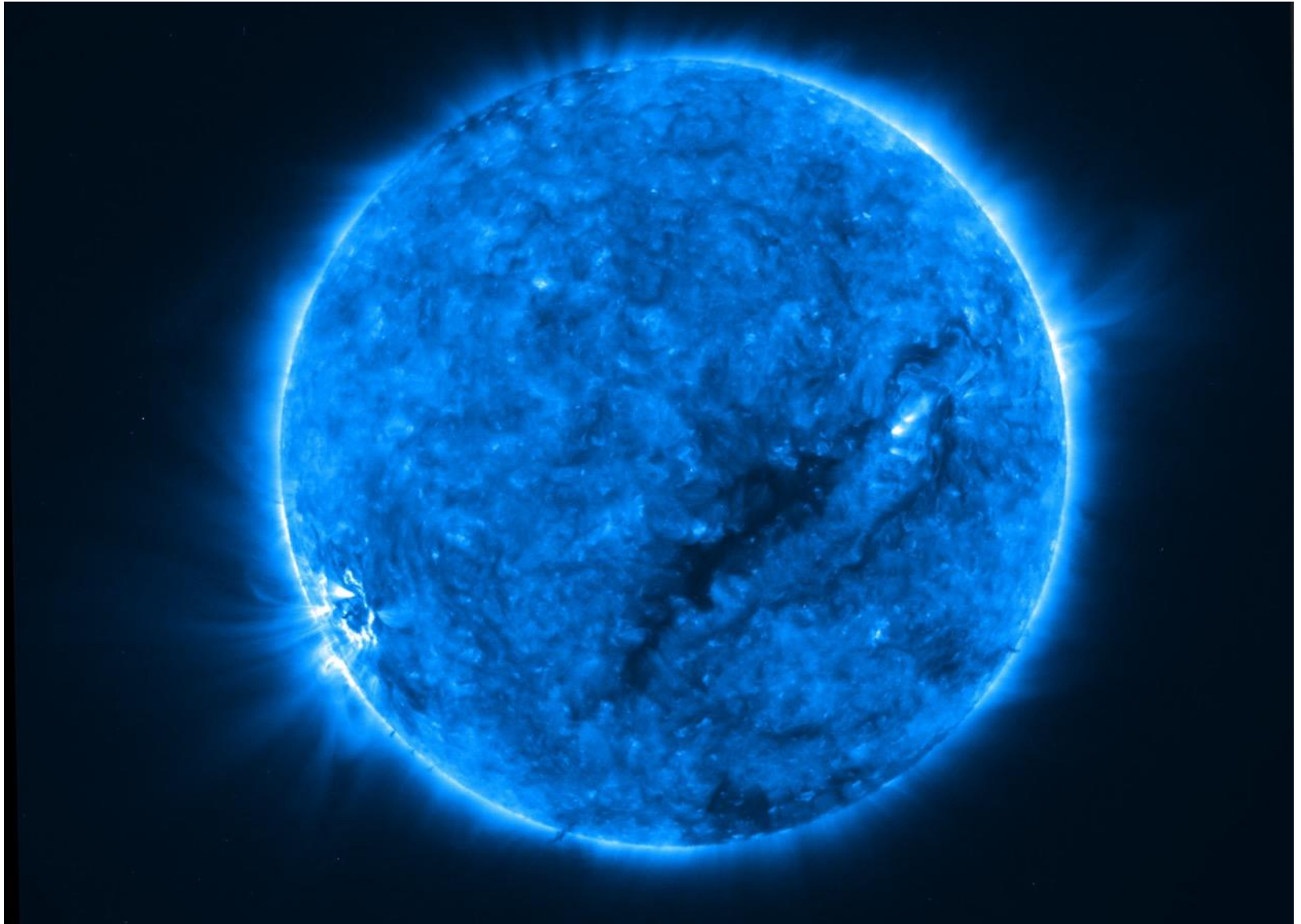


Foundations of Heliophysics II: Particle Orbits, Transport, Heating, and Acceleration

- Motivation: Why heliophysics? A physics point of view.
- 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)

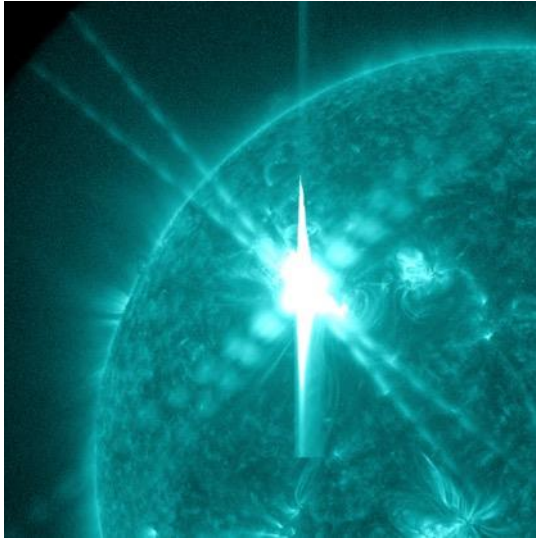
Prof. Robert Ergun
Email: ree@lasp.colorado.edu

Why Heliophysics?

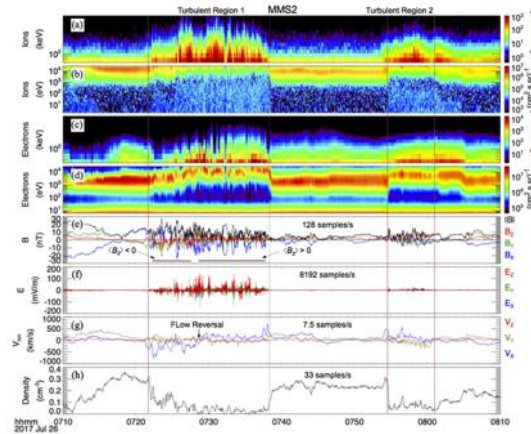


The Physics Part of Heliophysics

Magnetic Reconnection



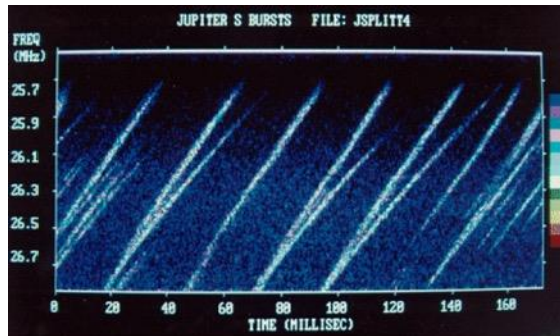
Turbulence



Particle Acceleration



Radio Emissions



Solar and Stellar Winds



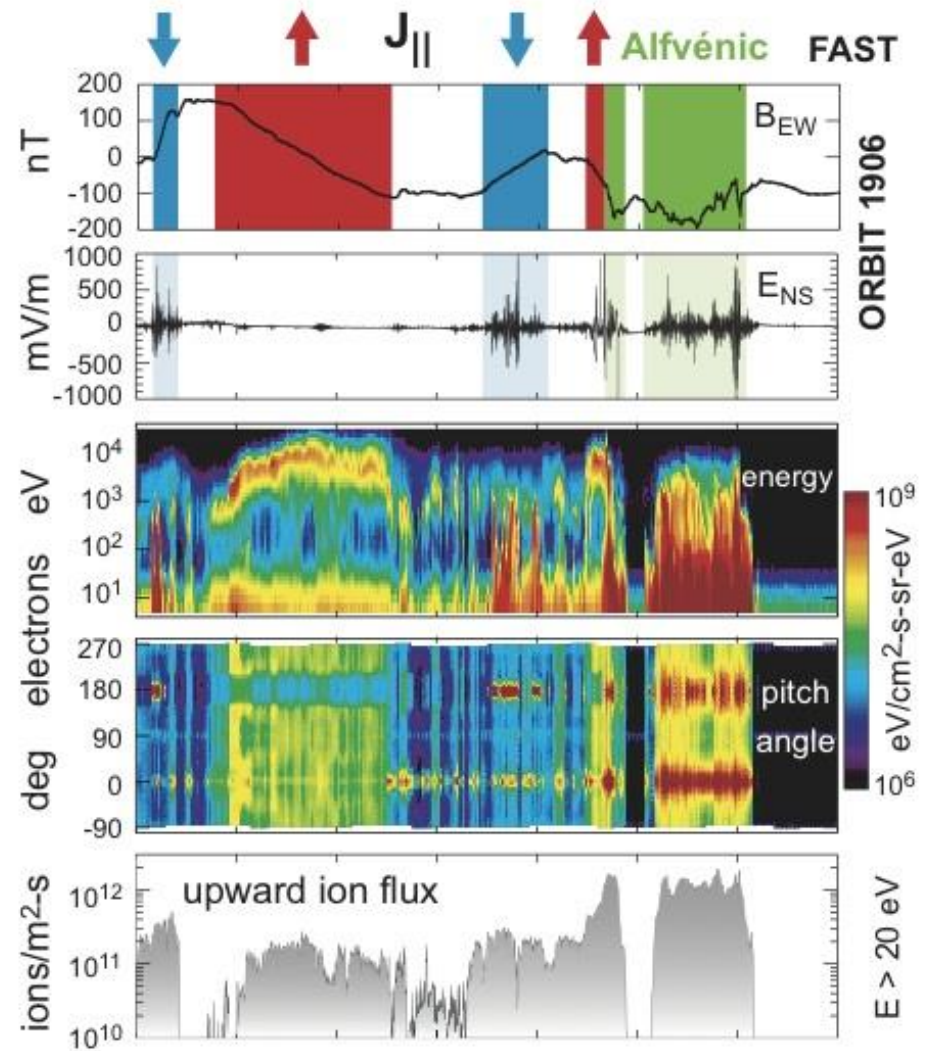
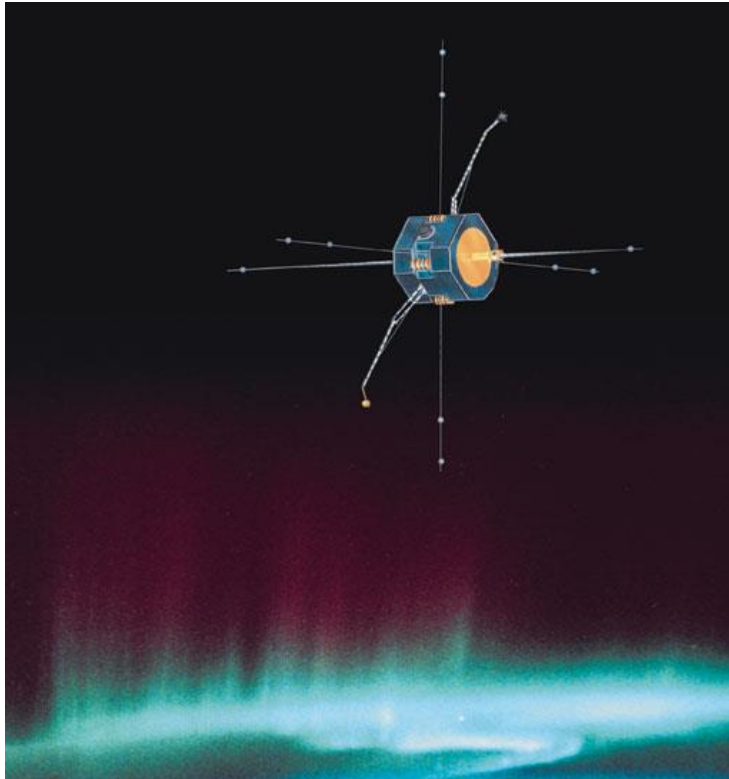
Shocks



Early Mystery: Aurora and Particle Acceleration



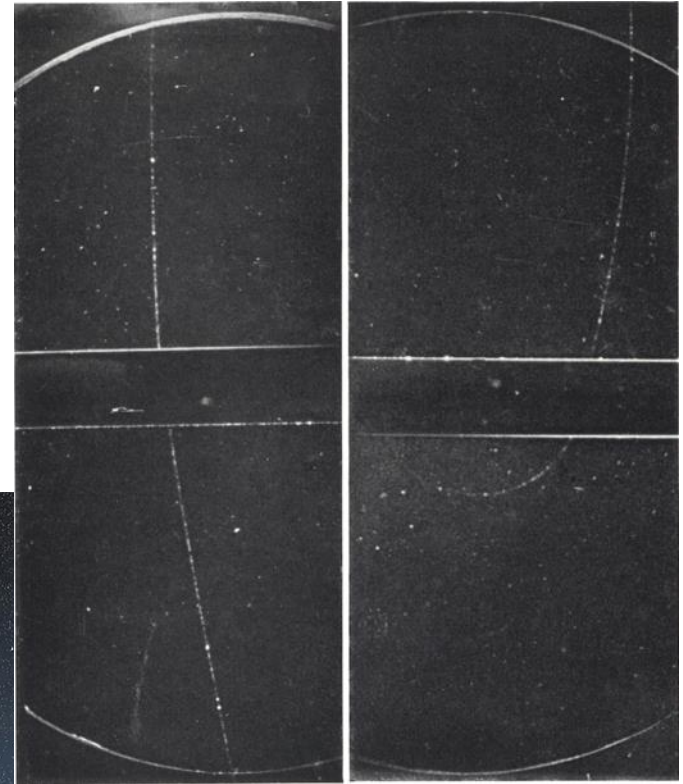
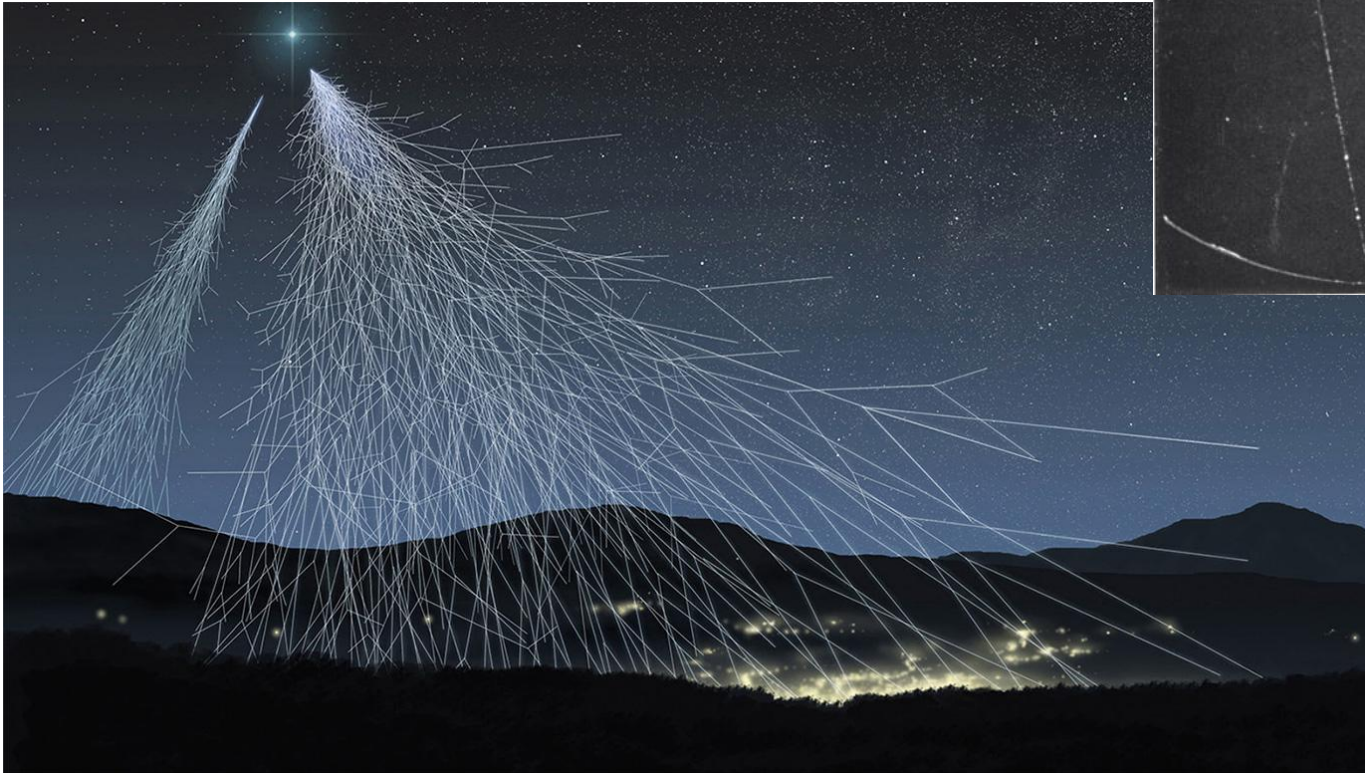
Later Discovery: Three Particle Acceleration Processes



UT	16:44	16:46	16:48	16:50
ALT	3593	3476	3351	3215
ILAT	64.7	67.4	70.2	73.0
MLT	22.0	22.2	22.5	23.0

Early Mystery: Cosmic Rays

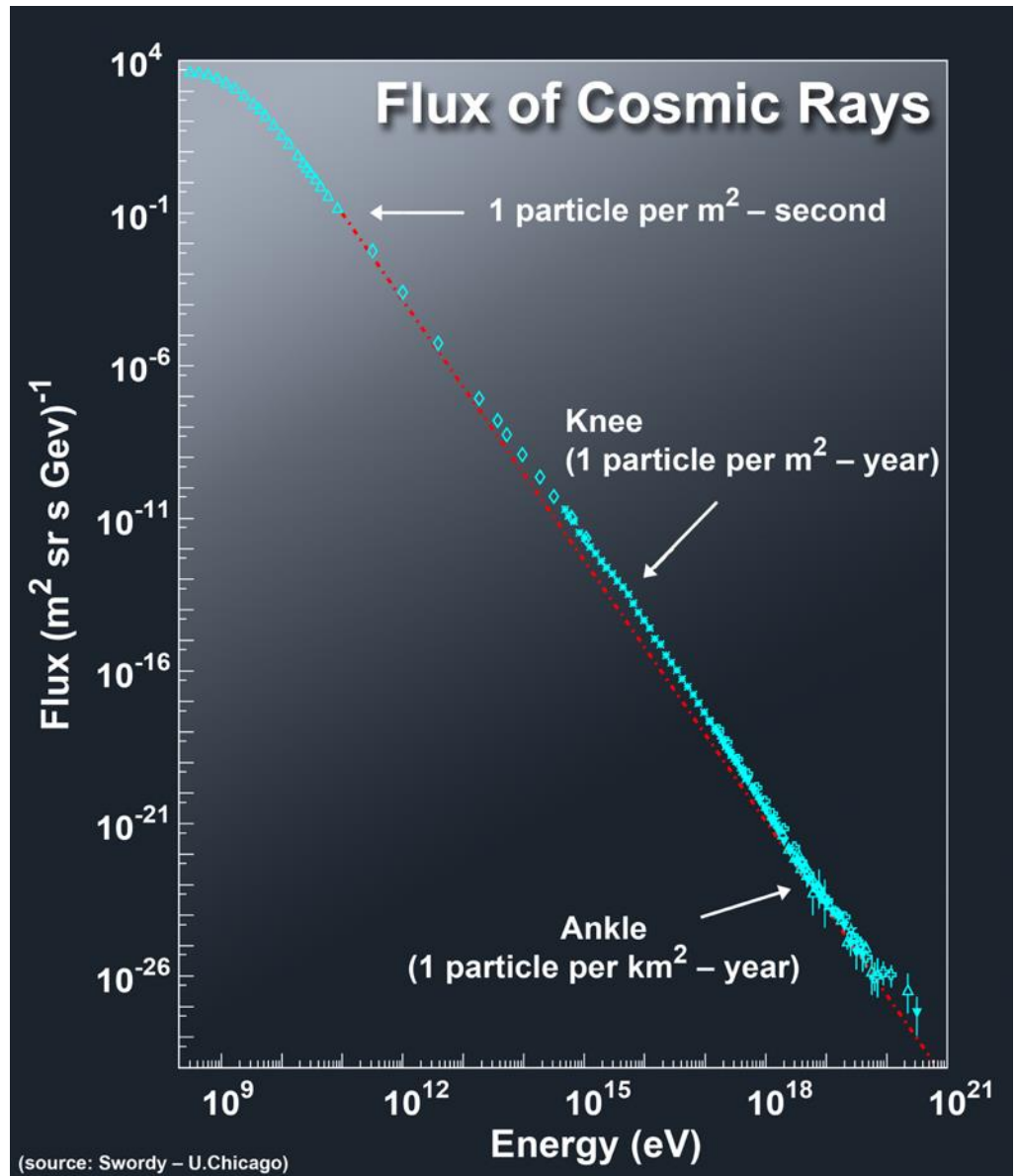
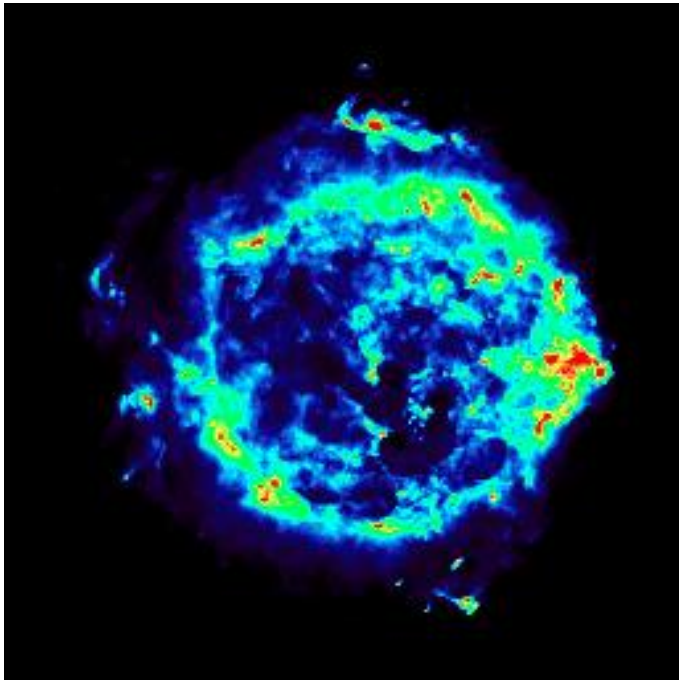
The discovery of cosmic rays by balloons and cloud chambers was the beginning of particle physics.



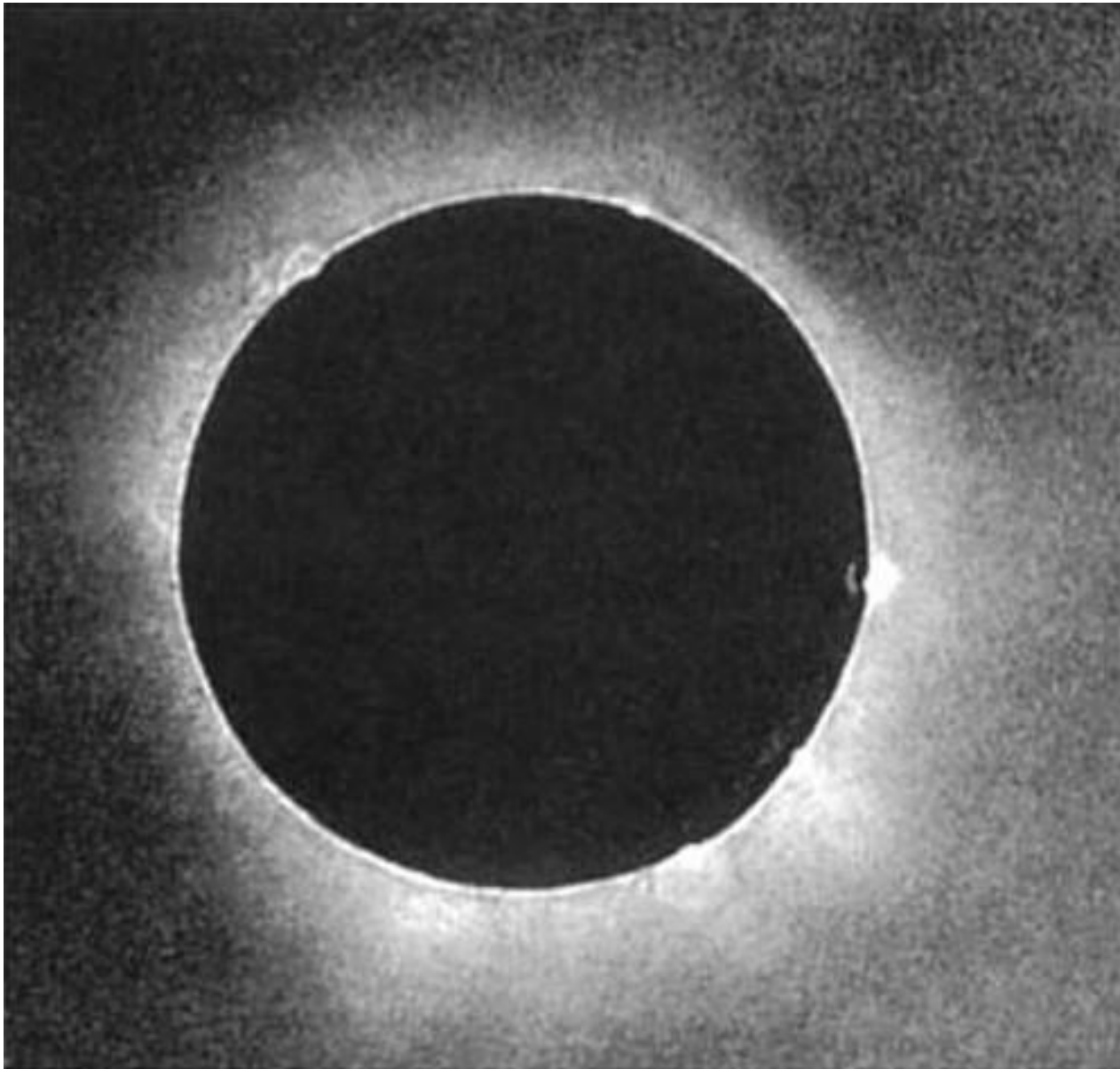
Later Discoveries: Cosmic Ray Acceleration

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

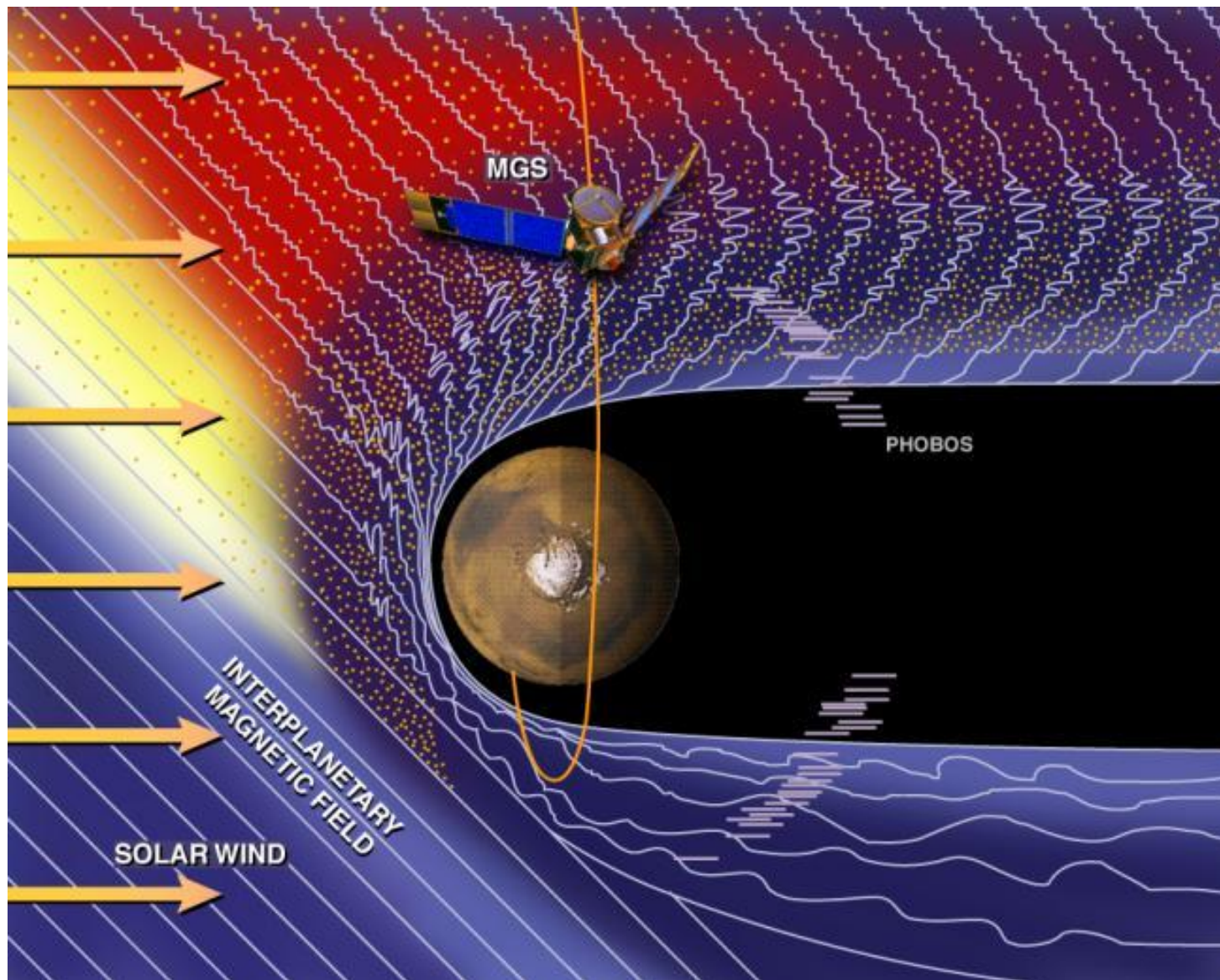
This work was based on heliophysics observations: the Earth's bow shock.



Early Mystery: Solar and Stellar Winds



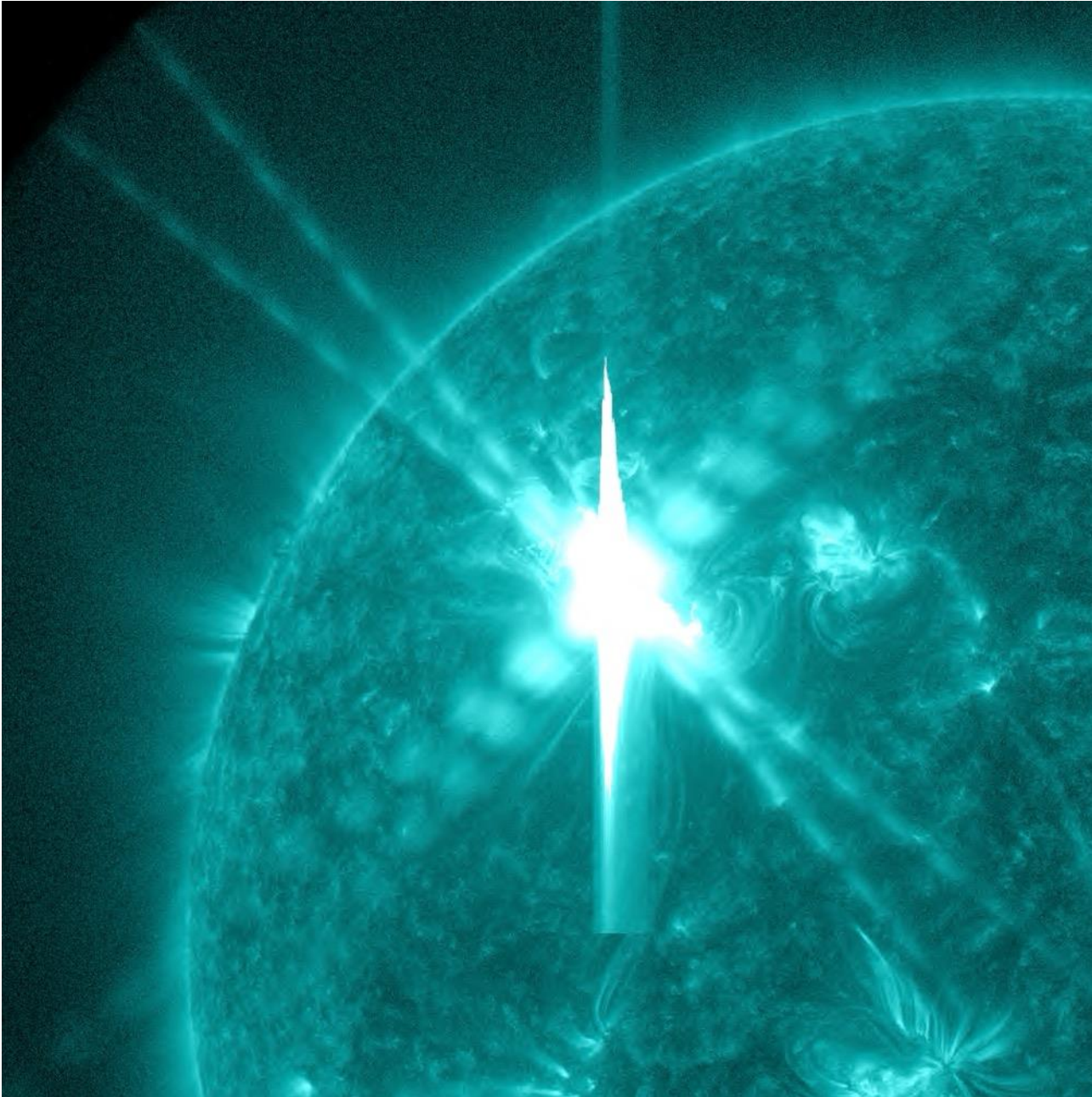
Heliophysics Discoveries: Solar and Stellar Winds



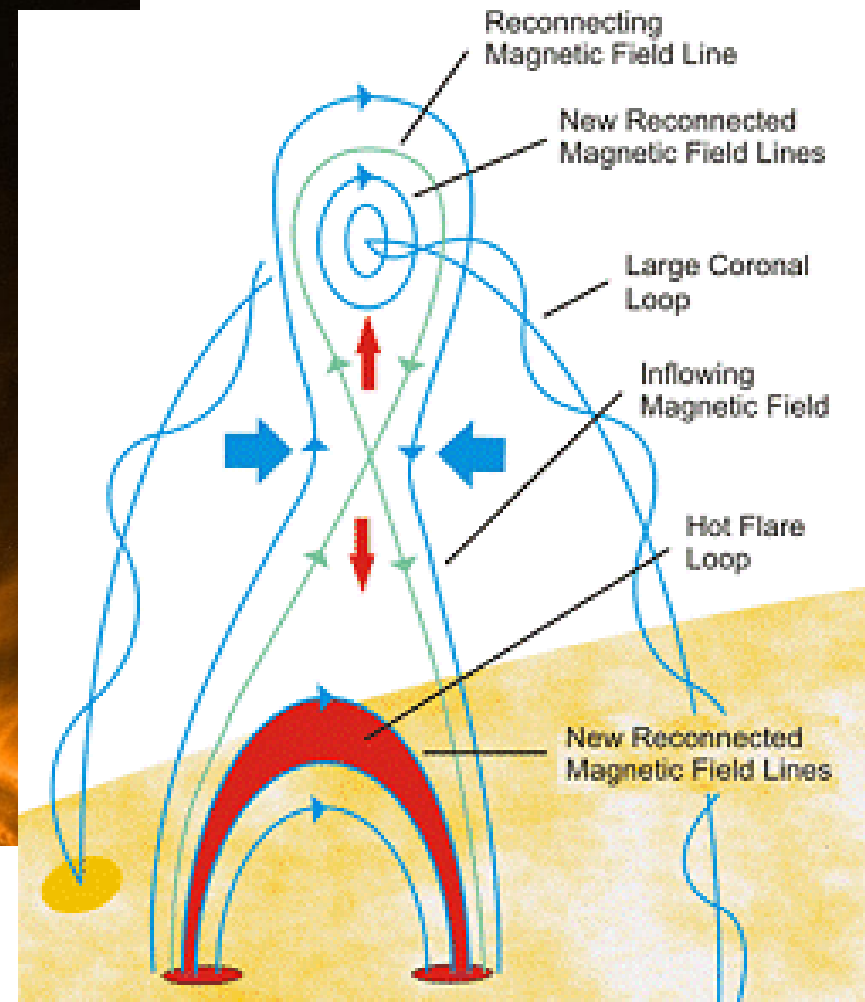
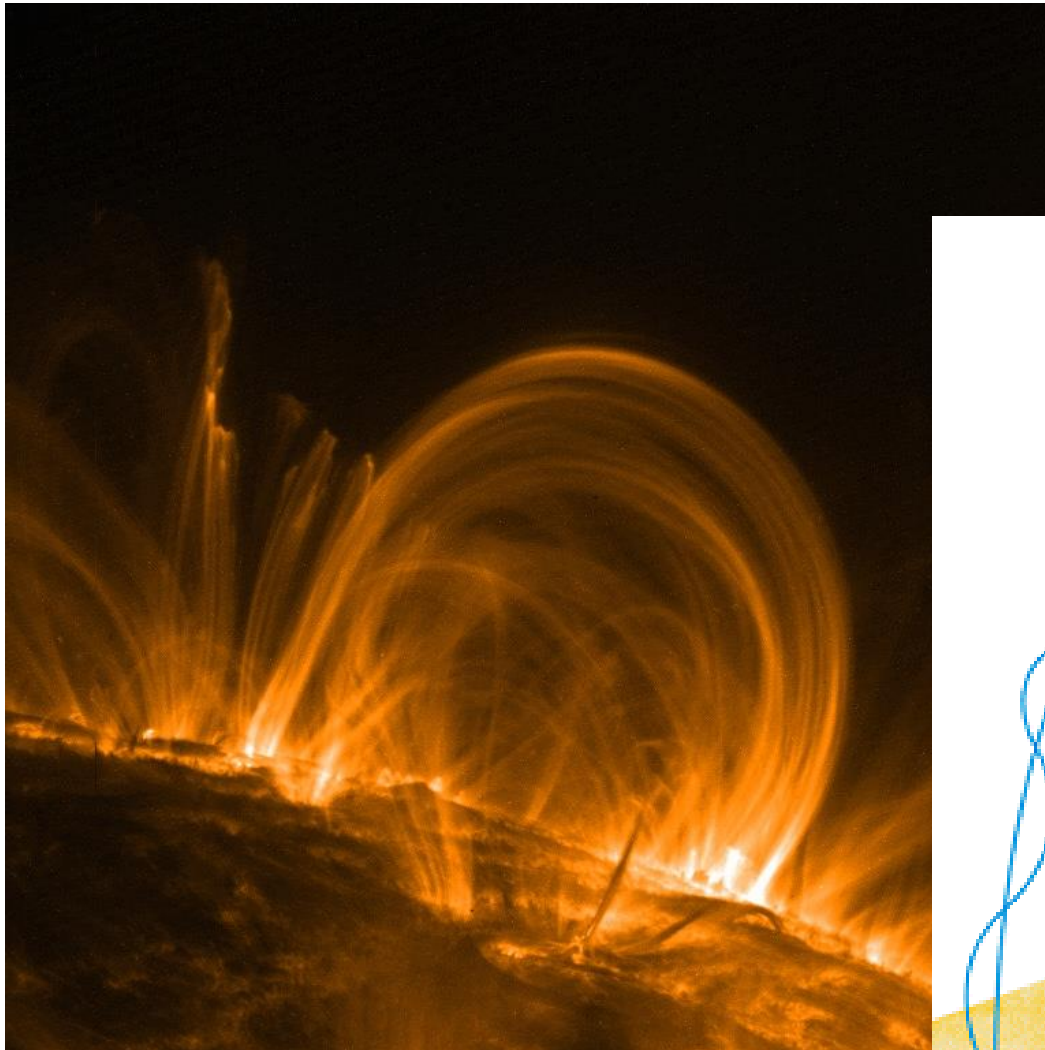
On-Going Heliophysics Work: Solar and Stellar Winds



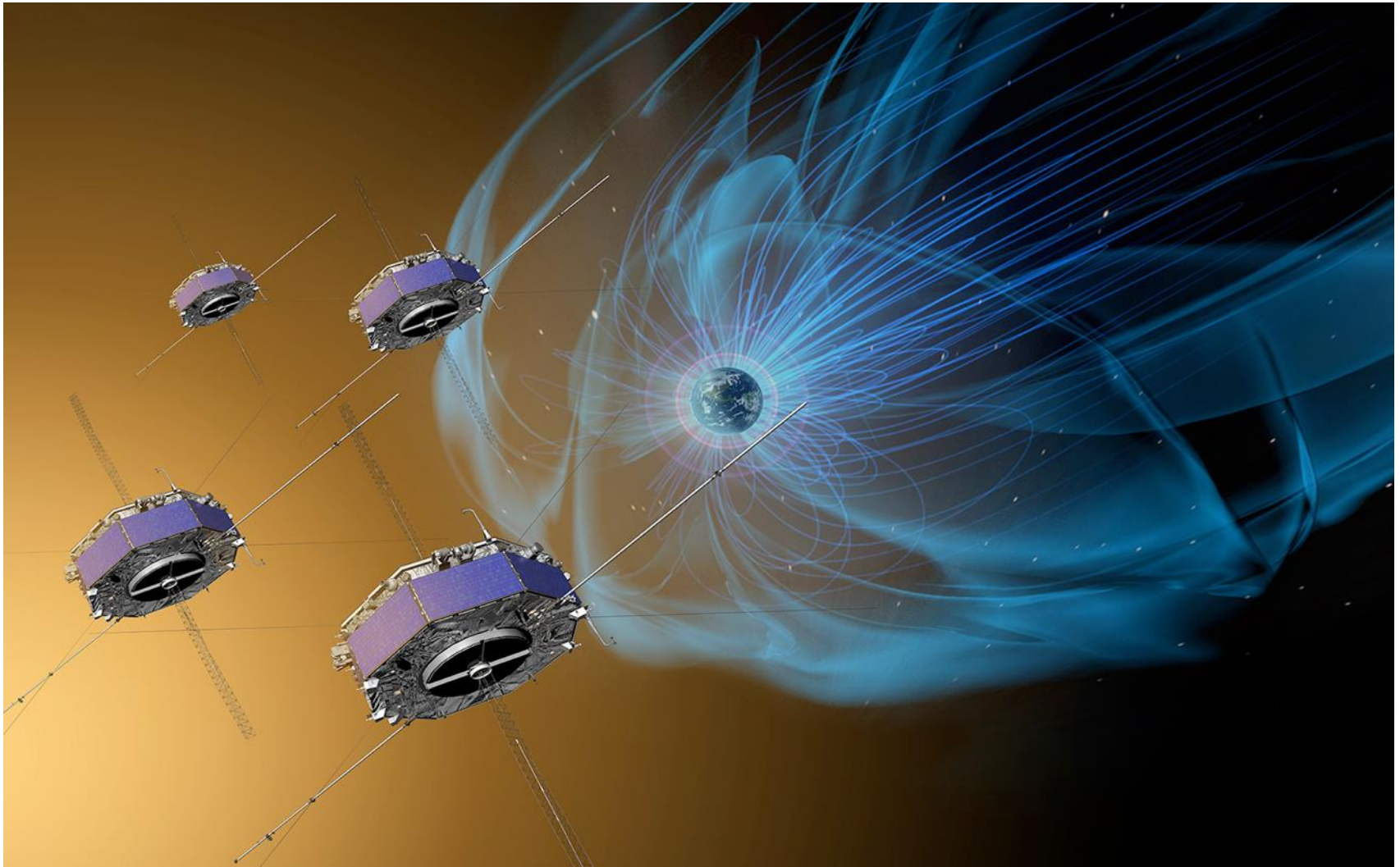
Early Mystery: Solar Flares



Heliophysics Discovery: Magnetic Reconnection



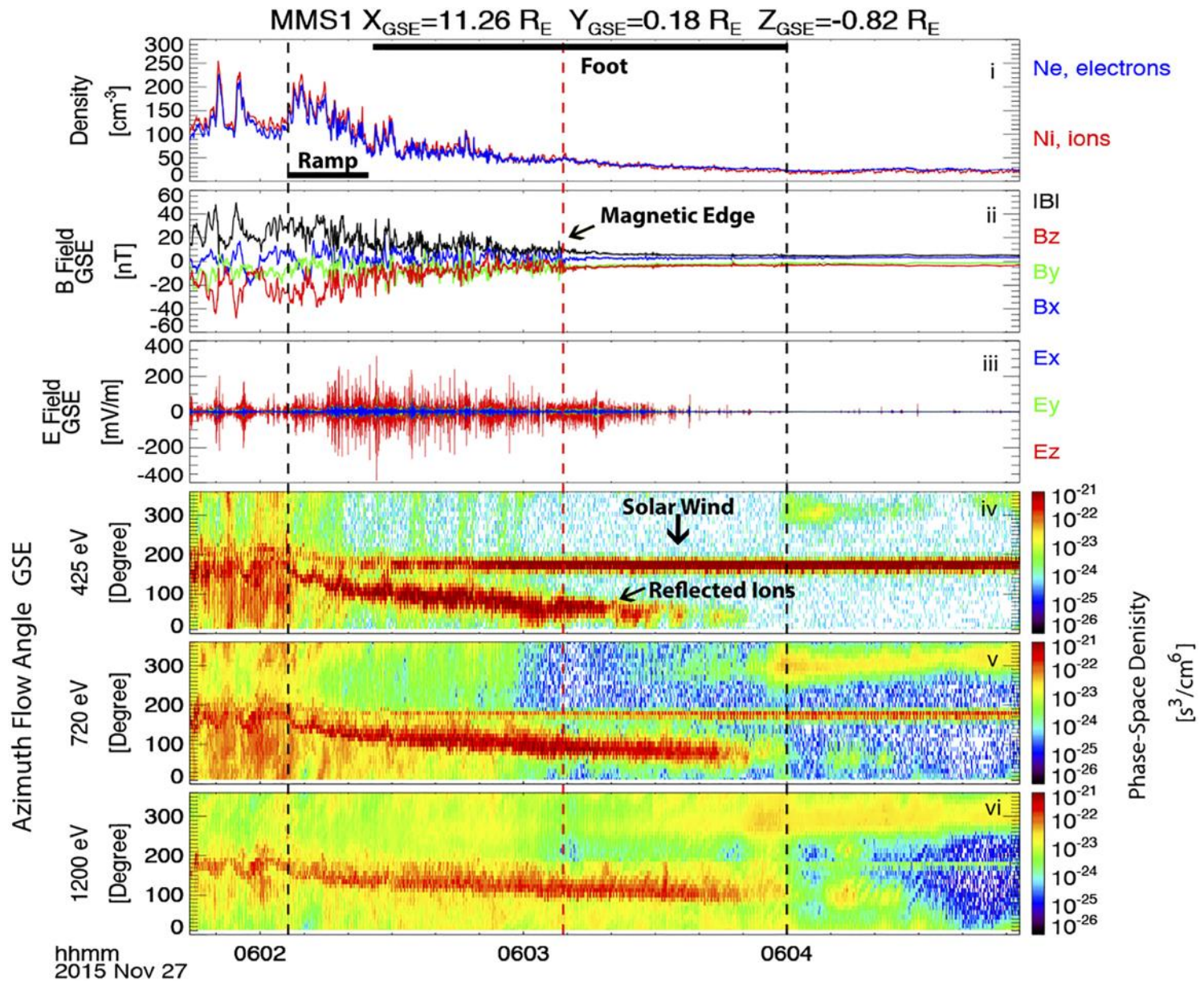
On-Going Heliophysics Work: Magnetic Reconnection



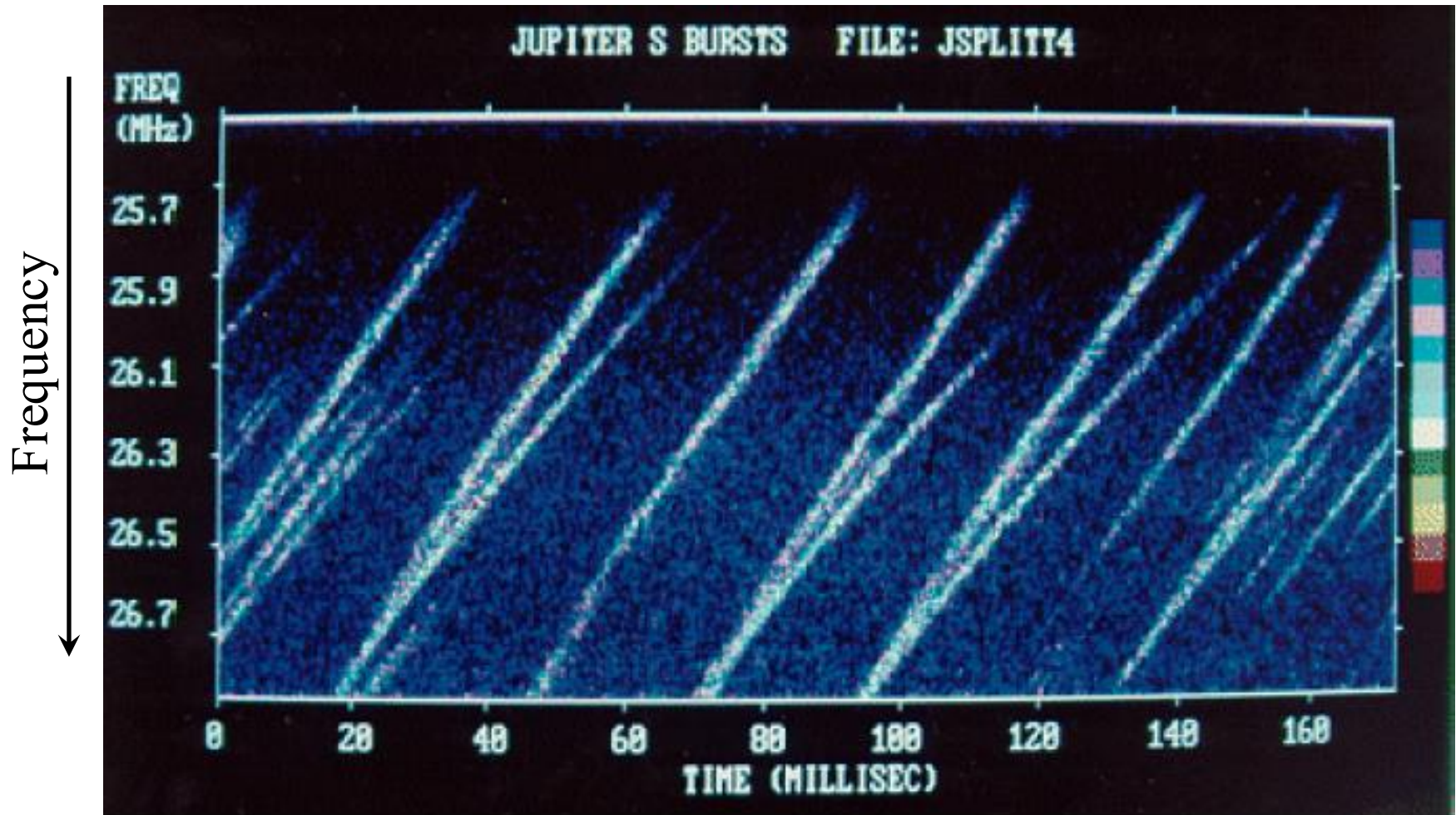
Early Mystery: Collisionless Shocks



Same Phenomenon Viewed from the Inside

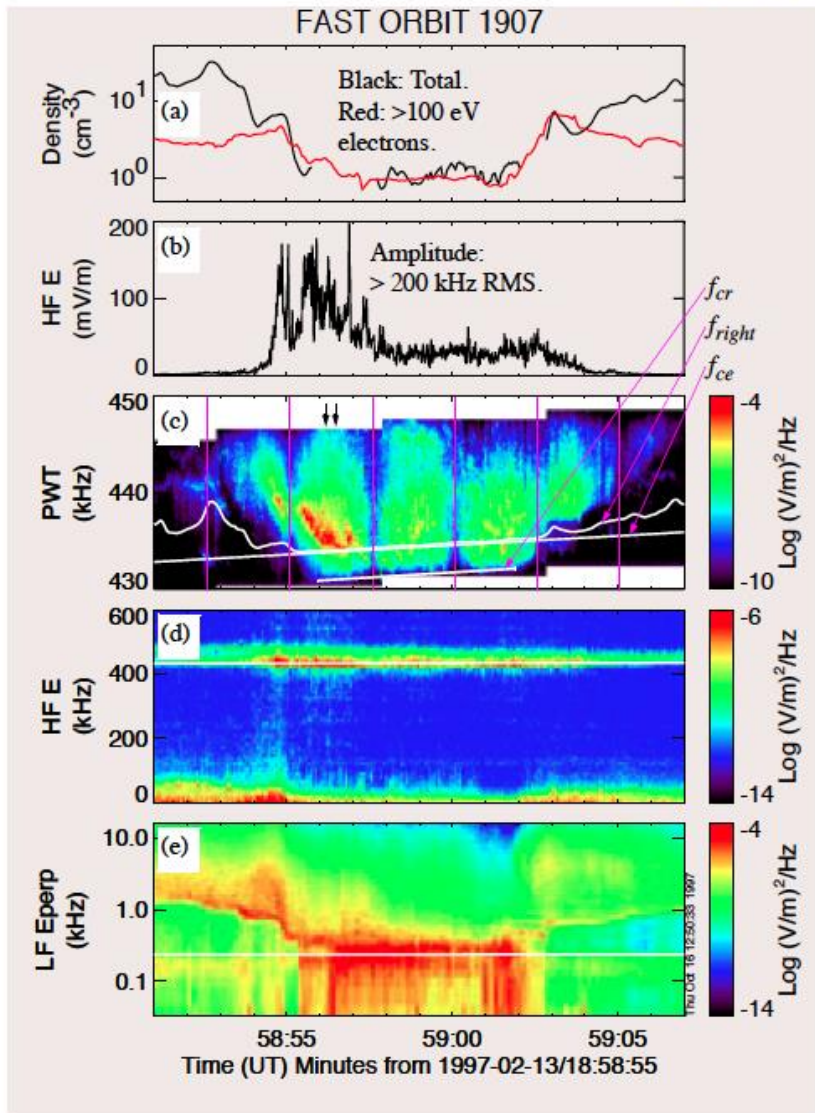


Early Mystery: Radio Emissions



Heliophysics Discovery: The Electron Cyclotron Maser

Radio emissions:



THE ELECTRON-CYCLOTRON MASER



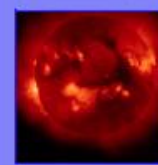
Jupiter's
Aurora



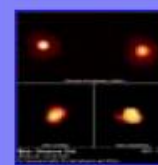
Saturn's
Aurora



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.

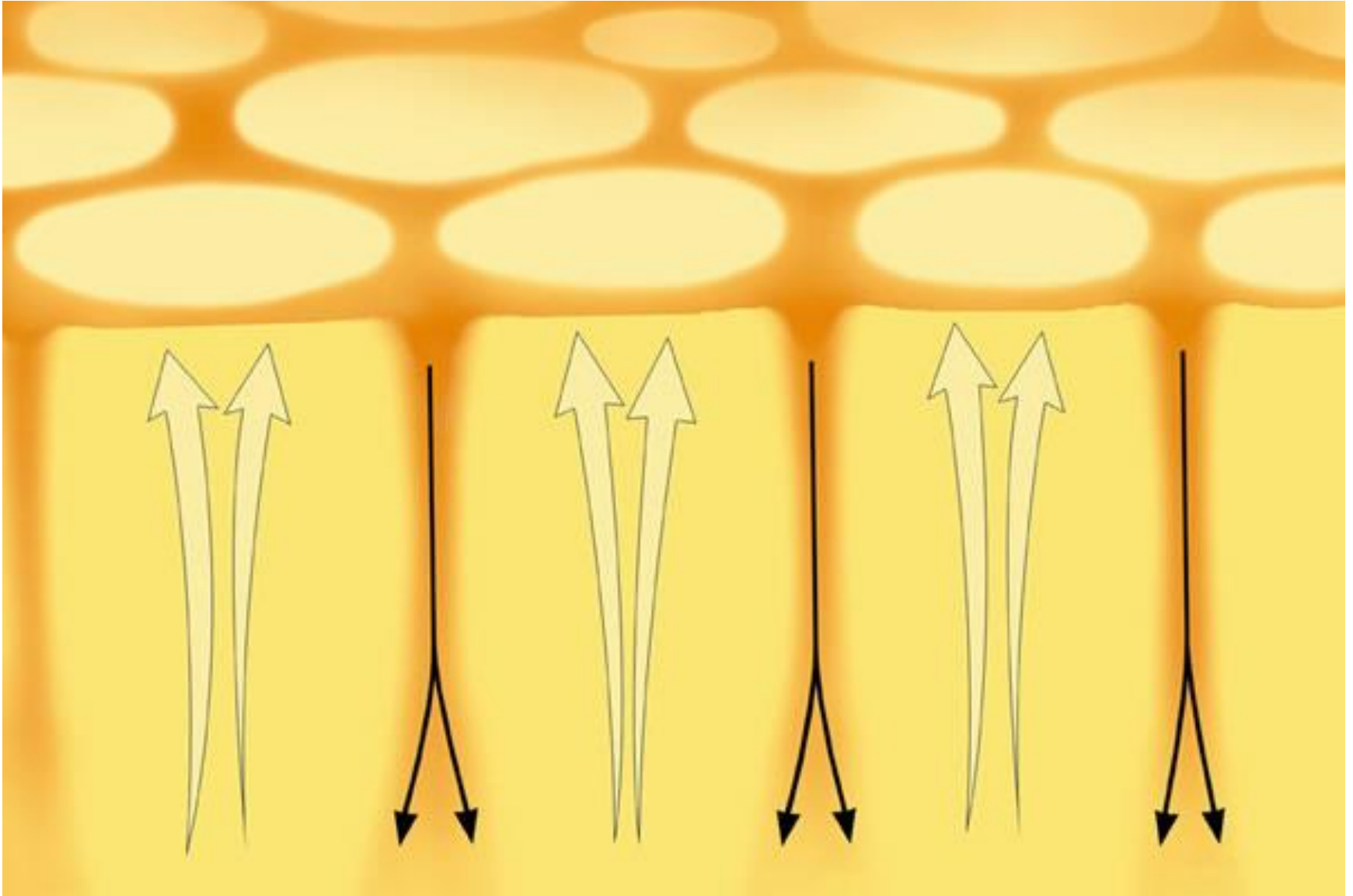
Electron-Cyclotron Maser Candidates in the Astrophysical Literature:

- 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.

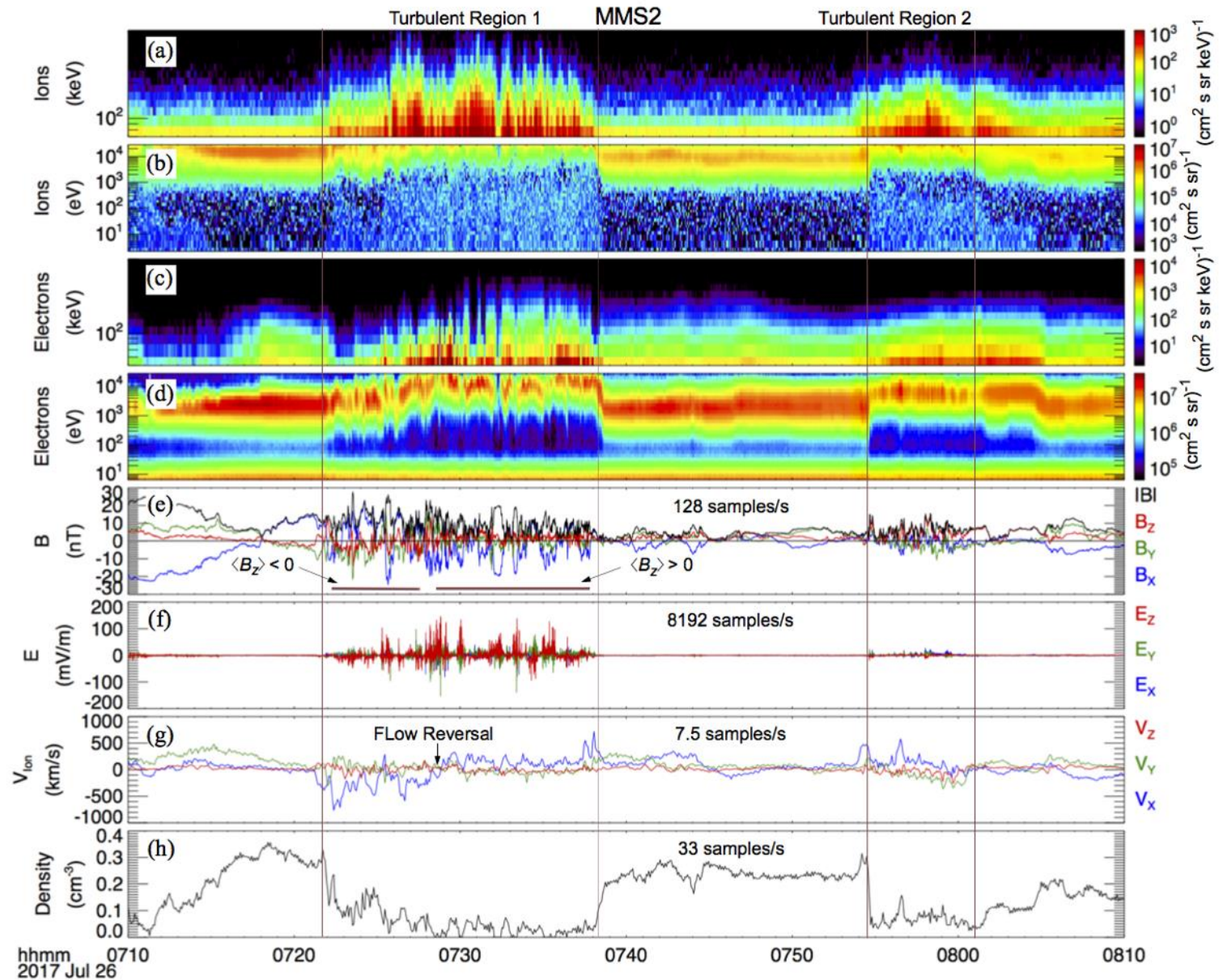
Implication of the FAST Results

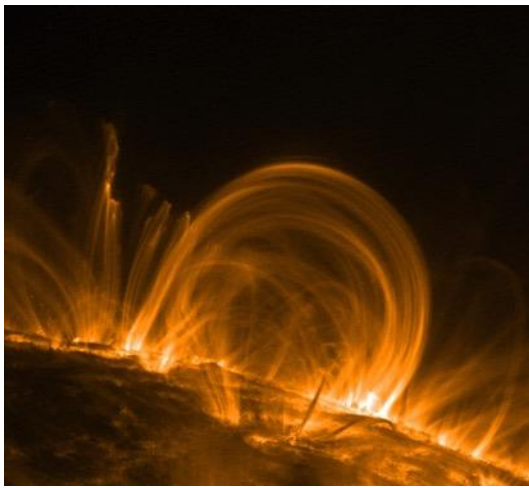
- These findings may call for re-analysis of some astrophysical radio sources.
- The FAST results suggest that parallel electric fields may be widespread in astrophysical plasmas, strongly supporting the idea proposed over 50 years by Nobel laureate, Hans Alfvén of Sweden.

On-Going Heliophysics Work: Turbulence



On-Going Heliophysics Work: Turbulence





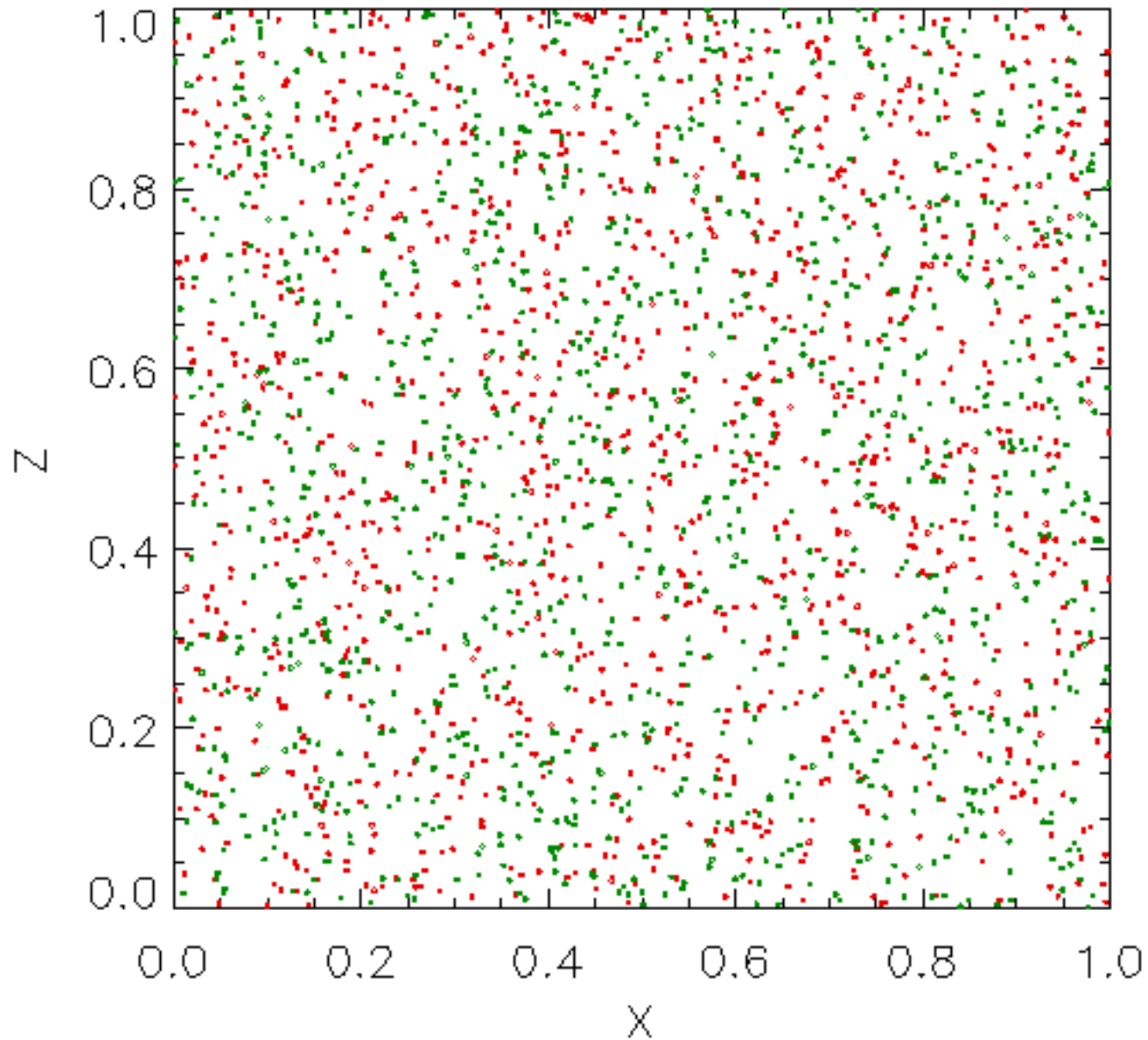
Heliophysics Summer School



- Motivation: Why heliophysics? A physics point of view.
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Prof. Robert Ergun
Email: ree@lasp.colorado.edu

My View of a Plasma



Basic Approaches to Plasma Physics

Kinetic

- (1) For each particle, calculate its motion given $\mathbf{B}$ and $\mathbf{E}$ using the Lorentz equation.
- (2) At every particle location, calculate $\mathbf{B}$ and $\mathbf{E}$ from Maxwell's equations.

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

Least detailed but highly useful.

Multi-Fluid

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

MHD

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

Kinetic Calculations

Kinetic

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

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

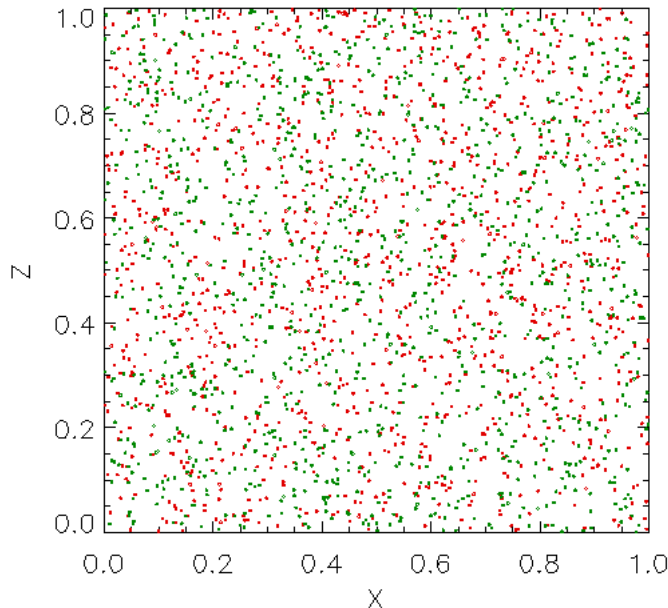
$$m \frac{d\mathbf{v}}{dt} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

$$\nabla \cdot \mathbf{E} = \frac{\rho_q}{\epsilon_0}$$

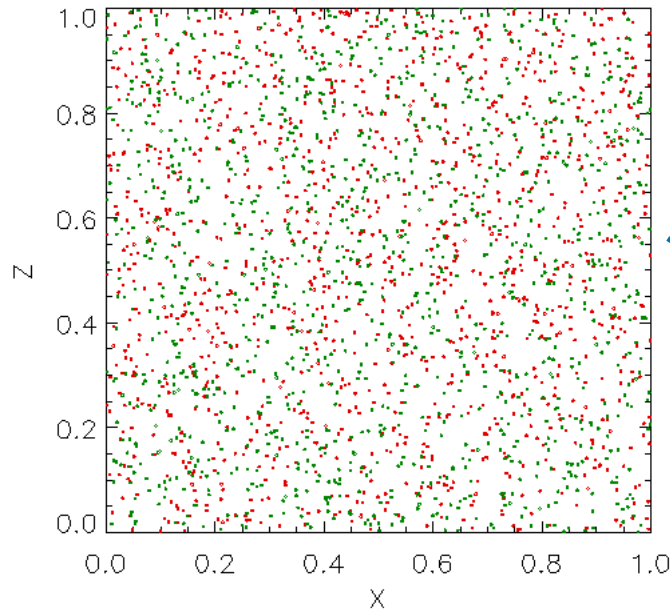
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} = \frac{1}{c^2} \frac{\partial \mathbf{E}}{\partial t} + \mu_0 \mathbf{J}$$

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



Distribution Functions

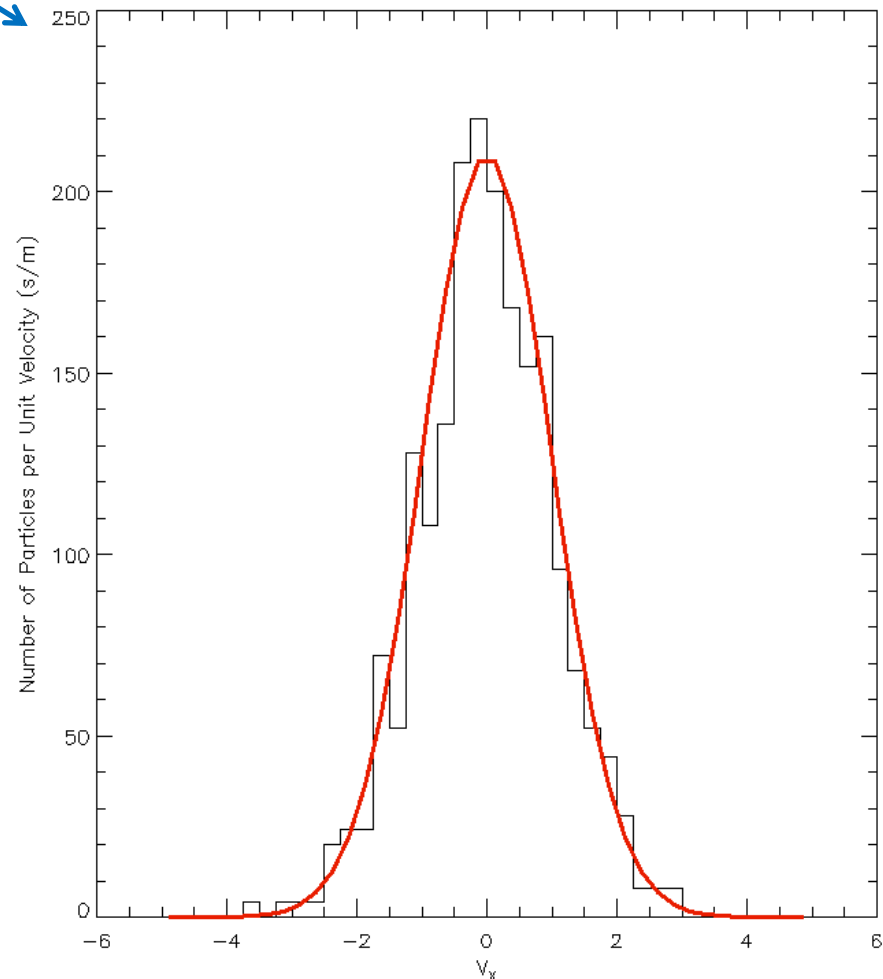


The most common type of distribution is a Maxwellian or Gaussian:

$$f = f_0 e^{-\frac{1}{2}mv^2/k_B T}$$

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

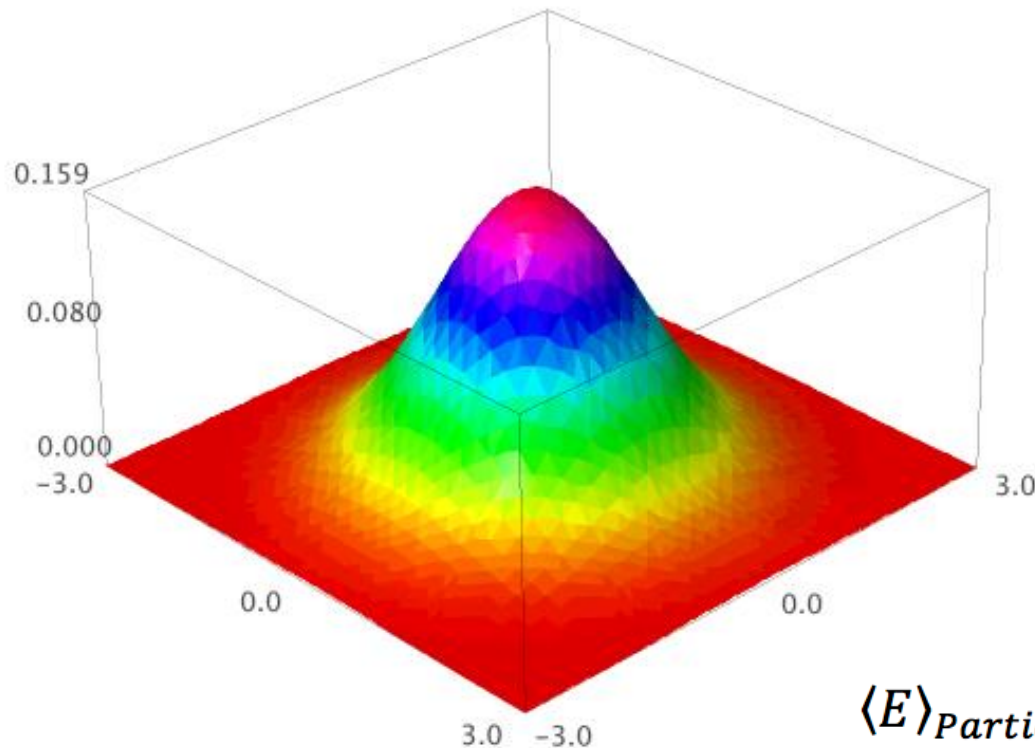
For three dimensions of velocity space, the units of f are s^3/m^6 .

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

$$nu = \int_{-\infty}^{\infty} \mathbf{v} f(\mathbf{x}, \mathbf{v}, t) d\mathbf{v}$$

$$u \equiv \frac{\int_{-\infty}^{\infty} \mathbf{v} f(\mathbf{x}, \mathbf{v}, t) d\mathbf{v}}{n}$$

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



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

Multi-Fluid Approach

Multi-Fluid

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

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

$$\nabla \cdot \mathbf{E} = \frac{\rho_q}{\epsilon_0}$$

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

$$\nabla \times \mathbf{B} = \frac{1}{c^2} \frac{\partial \mathbf{E}}{\partial t} + \mu_0 \mathbf{J}$$

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

$$\frac{\partial n}{\partial t} + \nabla \cdot n \mathbf{u} = 0$$

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

(Collisionless)

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

Ideal MHD

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

Continuity Equation:

Define:

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

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

Equation of state.

$$\mathbf{u} \equiv \frac{m_i n_i \mathbf{u}_i + m_e n_e \mathbf{u}_e}{m_i n_i + m_e n_e}$$

Force Equation (Collisionless)

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

$$P \equiv P_i + P_e$$

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

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

Frozen-In Condition

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J}$$

Ampere's Law

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

Faraday's Law

Assumed: $n_i \approx n_e$

- (1) “Principle of Quasi Neutrality”
- (2) “Frozen-In”

Basic Approaches to Plasma Physics

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MHD

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

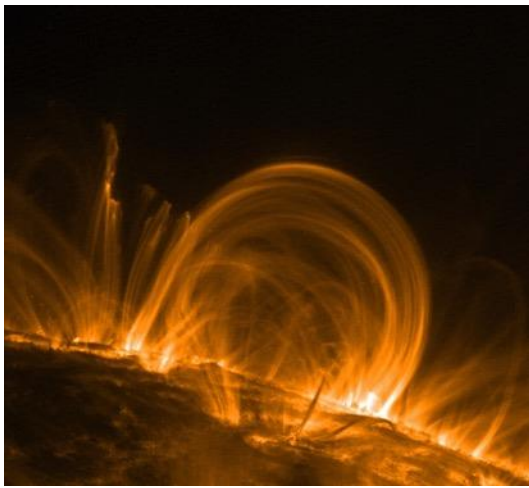
Collisional Versus Collisionless Plasmas

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 $\mathbf{B}$ and $\mathbf{E}$.
- (3) Due to low damping, collisionless plasmas are often turbulent.
- (4) Collisionless plasmas often do not have Gaussian distributions and may have energetic tails.



Heliophysics Summer School



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Quick Review of Particle Motion and Adiabatic Invariants

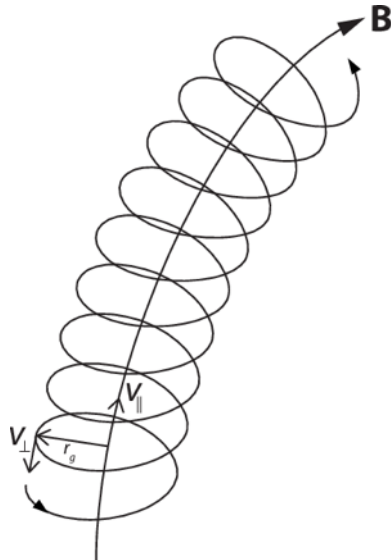
Examine the Lorentz force with a magnetic field ($\mathbf{B}$). Let $\mathbf{B}$ be in the z -direction. Let's consider motion in the x - y plane.

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

Newton:

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

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 $E = 0$.

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

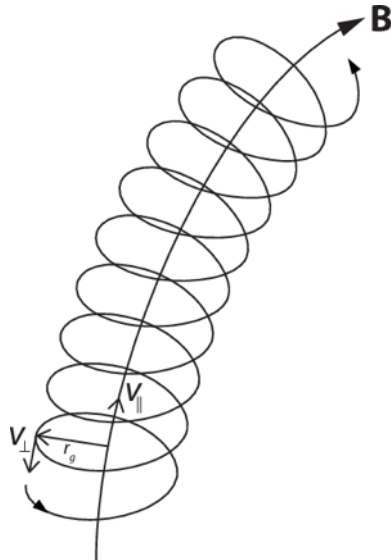
$$\frac{d^2 v_x}{dt^2} = -\Omega^2 v_x \quad \Omega \equiv \left| \frac{qB_z}{m} \right|$$

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.

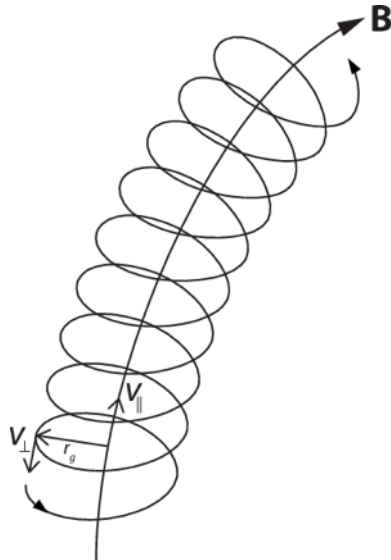
$$\frac{dv_x}{dt} = \frac{qB_z}{m} v_y \quad \frac{dv_y}{dt} = \frac{qE_y}{m} - \frac{qB_z}{m} v_x$$

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

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

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

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



ϑ is an arbitrary angle (phase).

Single Particle Motion

General Equation

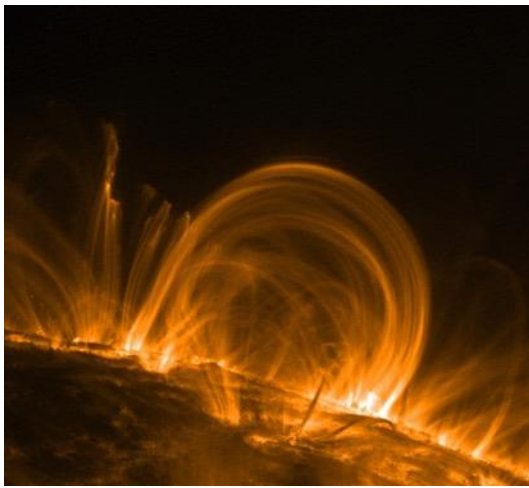
$$\mathbf{v}_E = \frac{\mathbf{E} \times \mathbf{B}}{B^2}$$

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

Other drifts:

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

$$\mathbf{v}_C = \pm \frac{v_{\parallel}^2}{\Omega R_C} \frac{\hat{\mathbf{R}}_C \times \hat{\mathbf{b}}}{B^2}$$



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Ram Pressure/Shocks

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

The collision causes a "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.



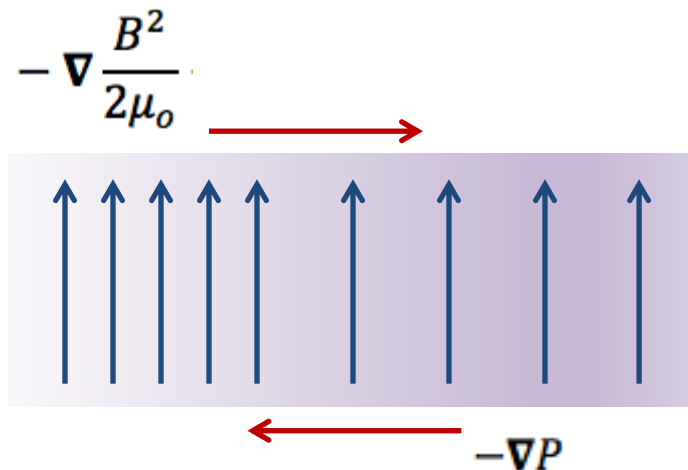
Magnetic Pressure

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho(\mathbf{u} \cdot \nabla)\mathbf{u} = -\nabla P - \nabla \frac{B^2}{2\mu_0} + \frac{(\mathbf{B} \cdot \nabla)\mathbf{B}}{\mu_0} + \rho \mathbf{g}$$

$$\mathbf{J} \times \mathbf{B} = \frac{\nabla \times \mathbf{B}}{\mu_0} \times \mathbf{B} = -\nabla \frac{B^2}{2\mu_0} + \frac{(\mathbf{B} \cdot \nabla)\mathbf{B}}{\mu_0}$$

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

$$0 = -\nabla P - \nabla \frac{B^2}{2\mu_0} \rightarrow \nabla \left(P + \frac{B^2}{2\mu_0} \right) = 0 \rightarrow P + \frac{B^2}{2\mu_0} = C$$



Ram Pressure / Shocks

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

Ram Pressure

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

Continuity Equation:

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

Compressible & 1D
(plasma shock)

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

Constant

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

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

Incompressible
(water pipe)

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

Constant

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

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

(We don't do water.)

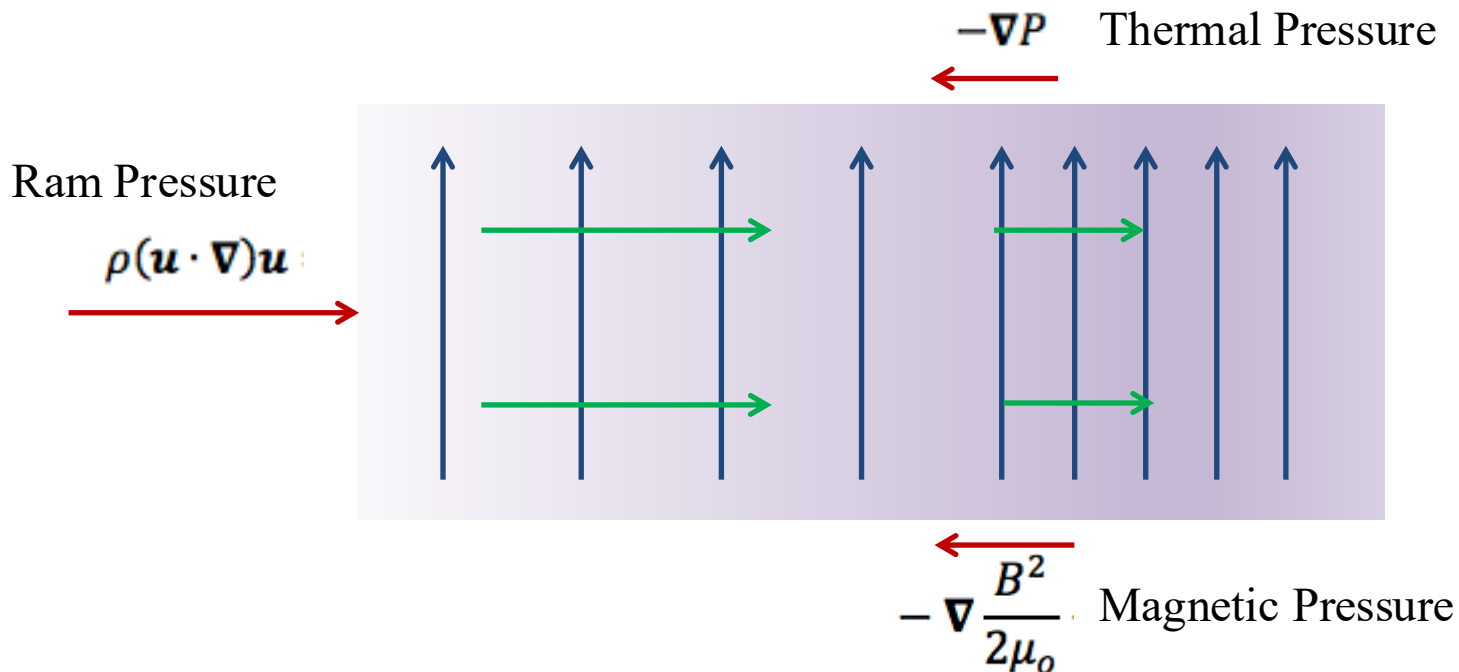
Ram Pressure / Shocks

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

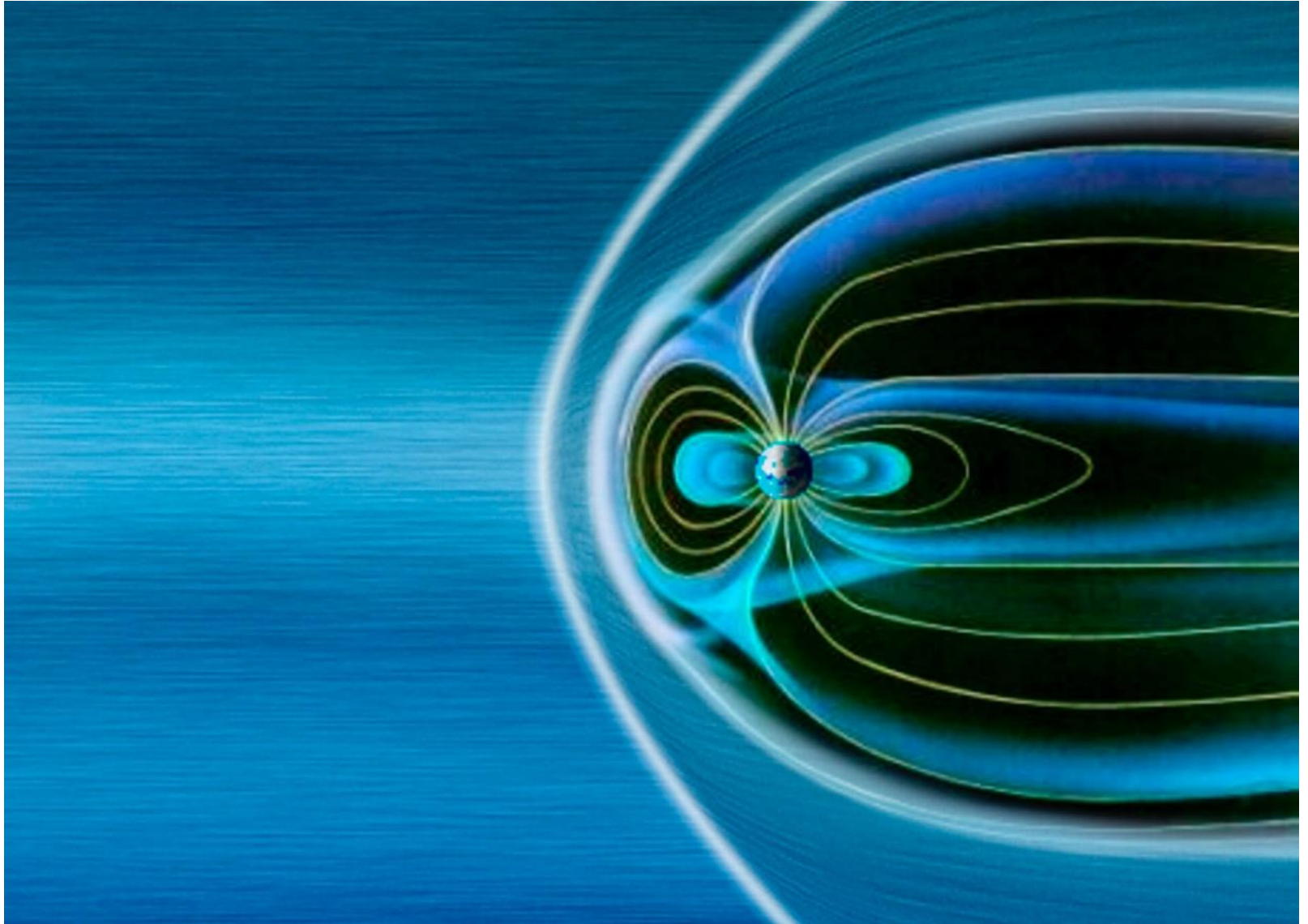
Suppose a plasma impinges on an object, which compresses the plasma as it slows the flow. Steady state, no curvature in $\mathbf{B}$, and not gravity.

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

Object or
barrier.

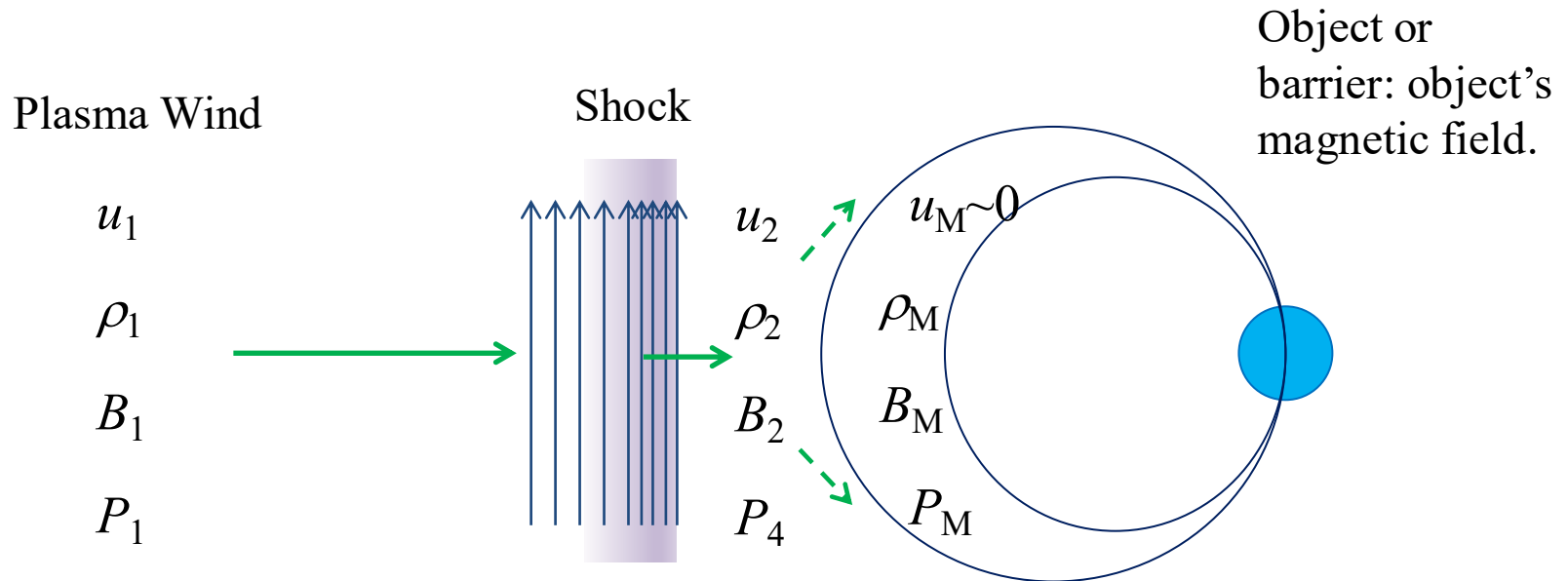


Earth's Bow Shock



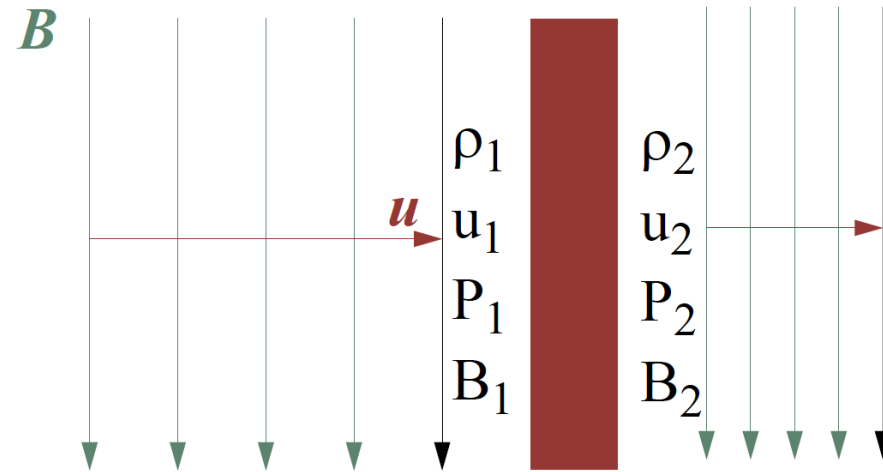
Ram Pressure / Shocks

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



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

Shocks



Rankine-Hugoniot Jump Conditions

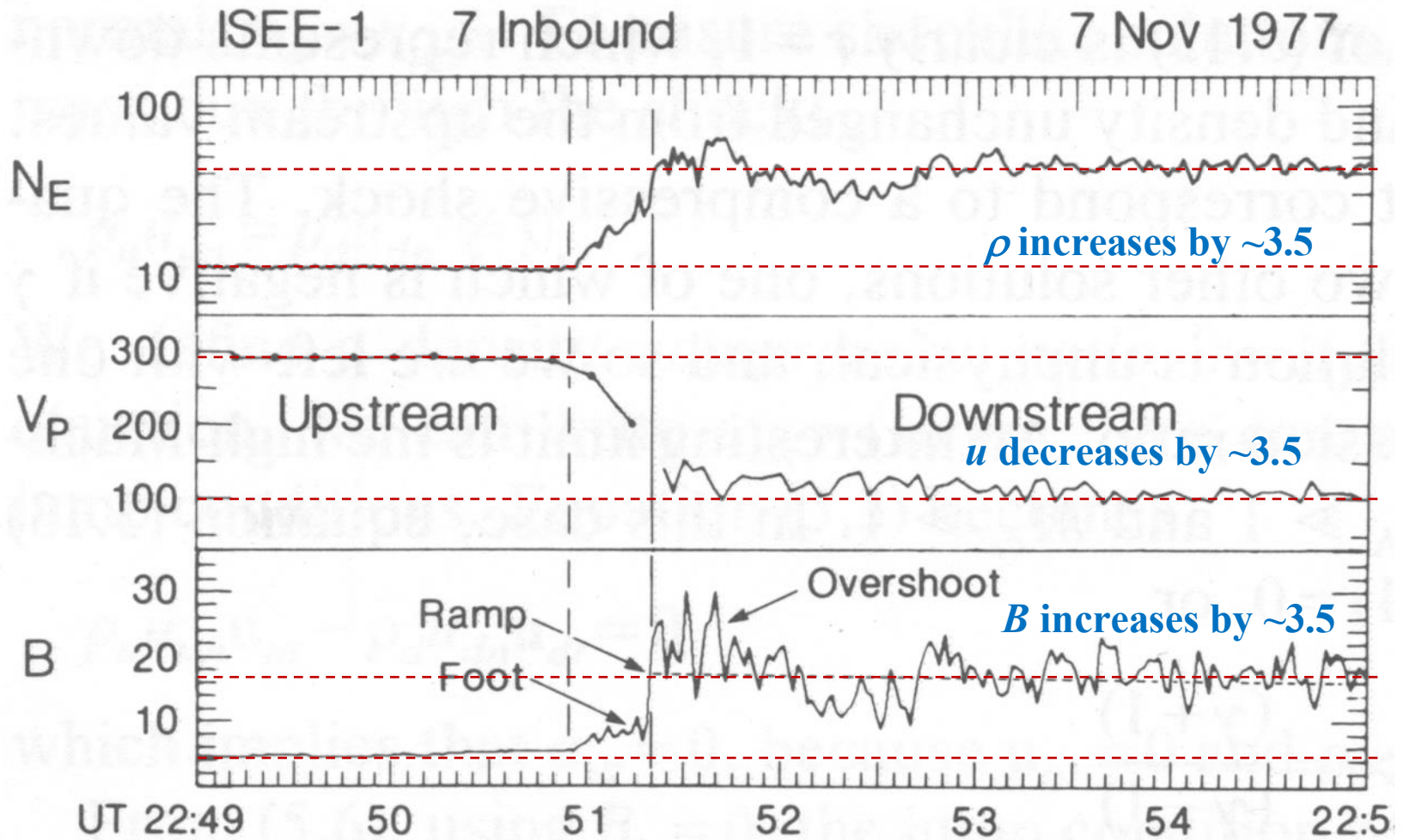
$$\rho_1 u_1 = \rho_2 u_2$$

$$B_1 u_1 = B_2 u_2$$

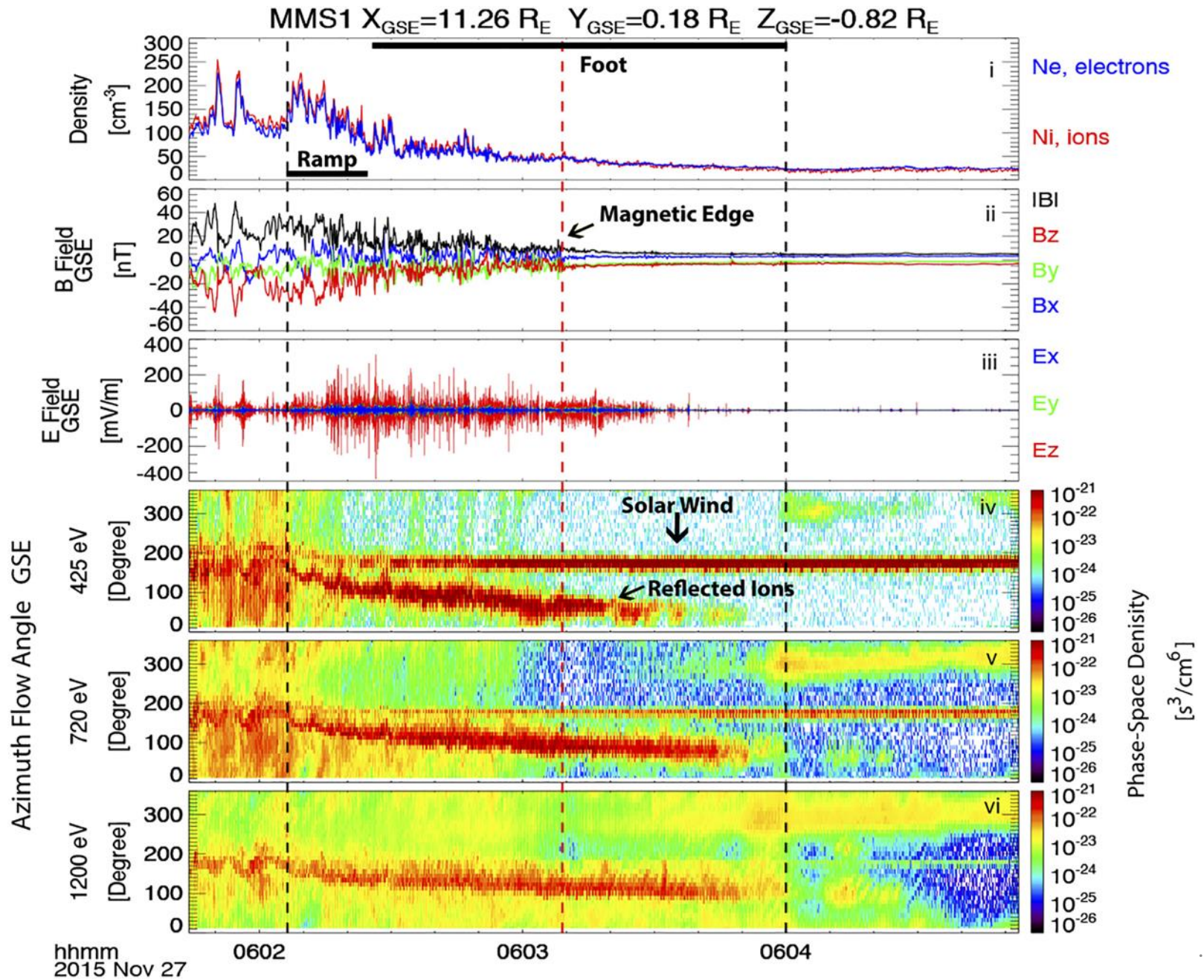
$$\rho_1 u_1^2 + P_1 + B_1^2 / 2\mu_0 = \rho_2 u_2^2 + P_2 + B_2^2 / 2\mu_0$$

$$u_1 (1/2 \rho_1 u_1^2 + \gamma / (\gamma - 1) P_1 + B_1^2 / \mu_0) = u_2 (1/2 \rho_2 u_2^2 + \gamma / (\gamma - 1) P_2 + B_2^2 / \mu_0)$$

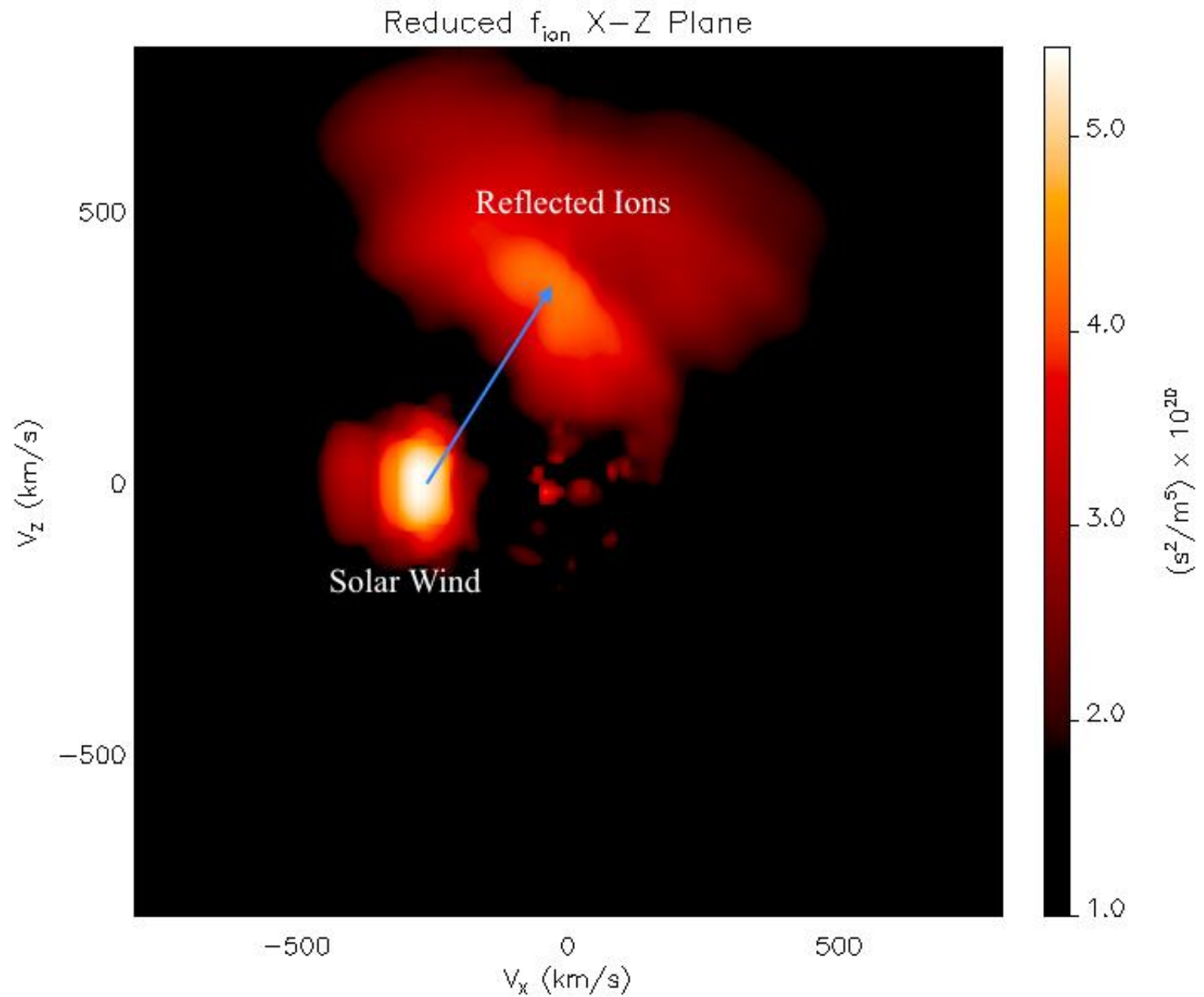
Example: Shocks

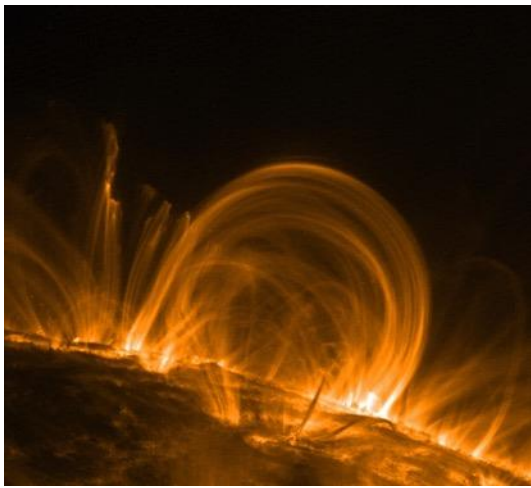


Shocks



Shocks





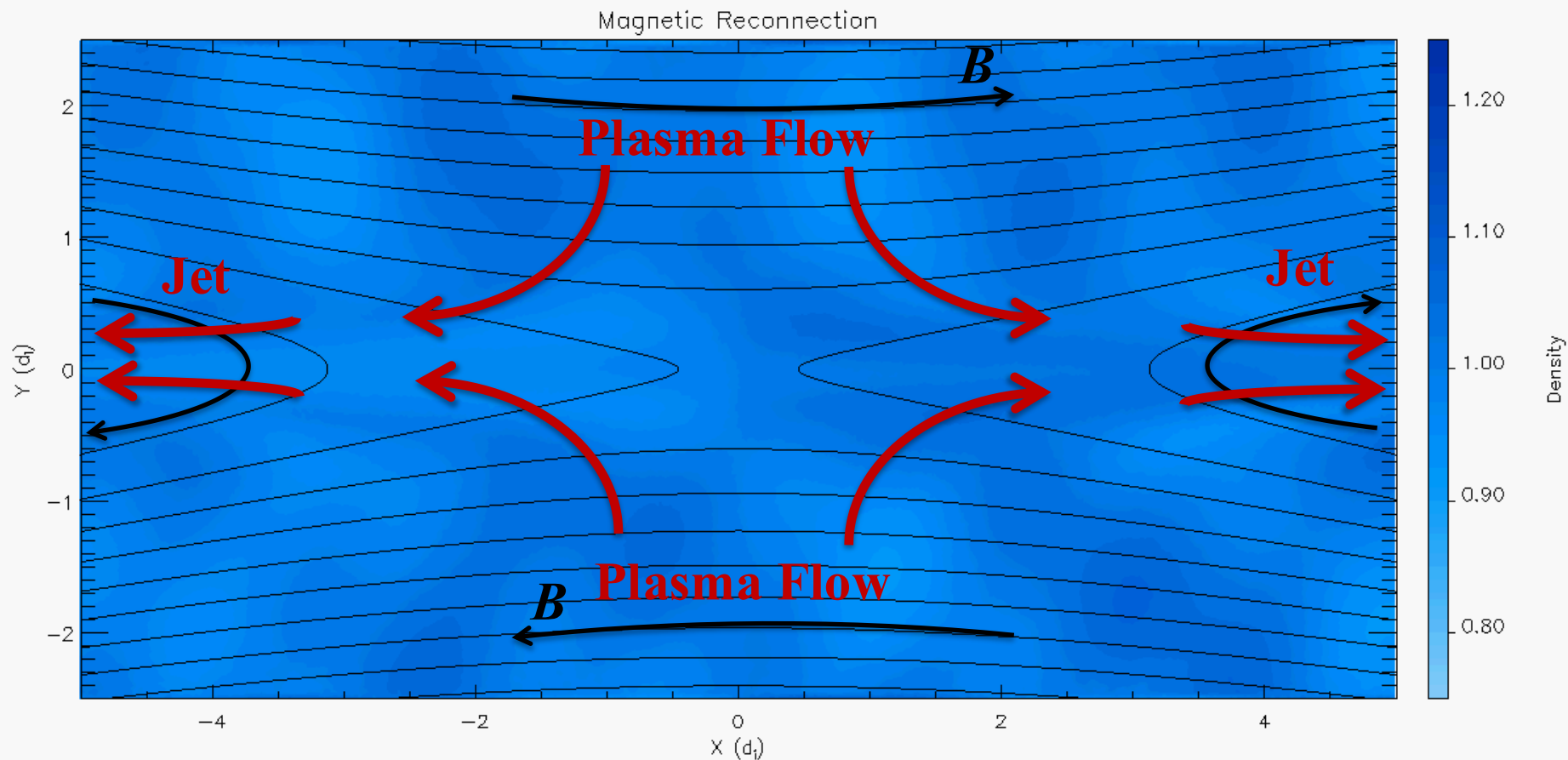
Heliophysics Summer School



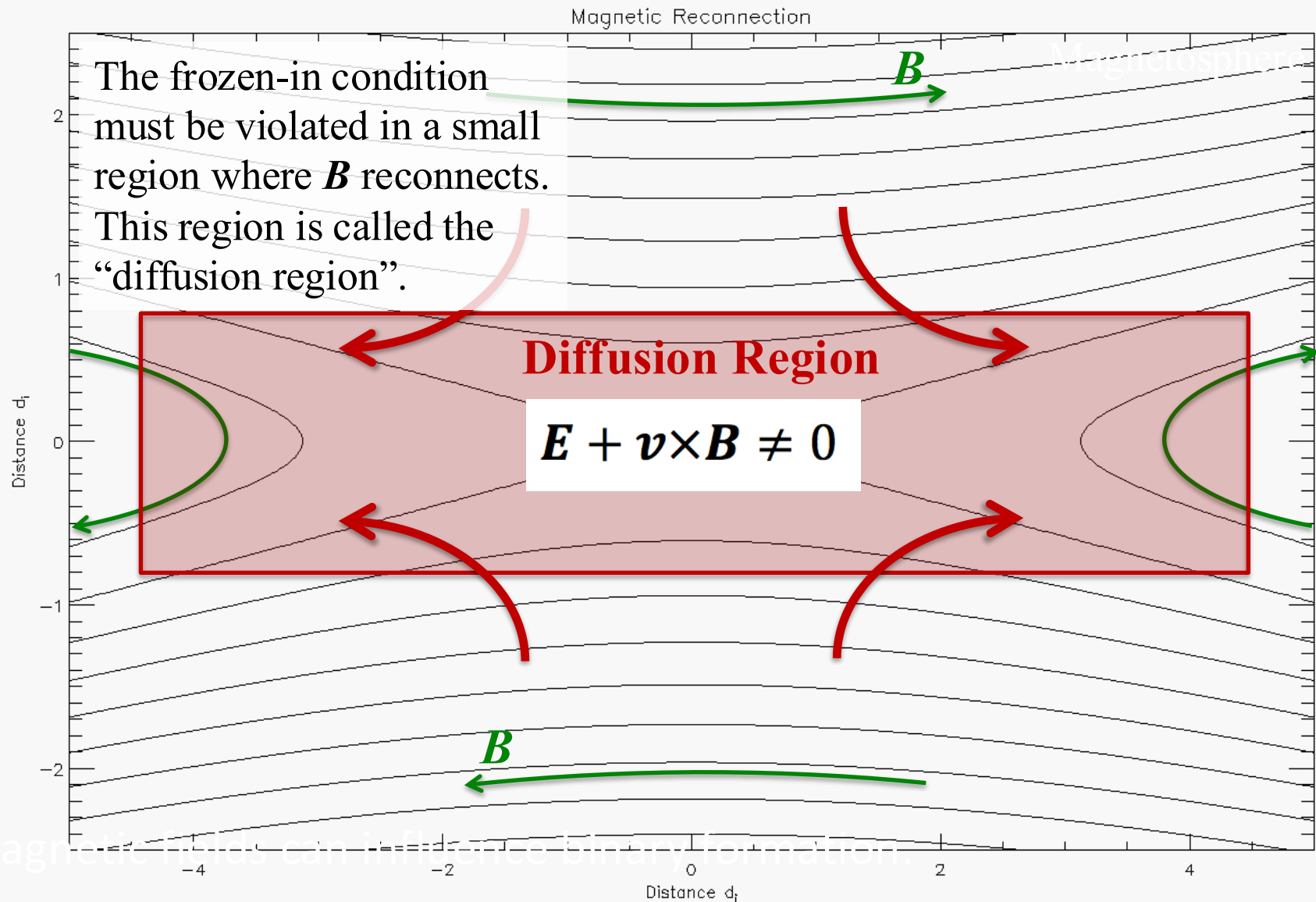
- Motivation: Why heliophysics?
- My view of plasma physics: kinetic, multi-fluid, and MHD approaches.
- Quick review of particle motion and adiabatic invariants.
- Shocks (basics) and why they are important (collisionless plasmas)
- **Magnetic reconnection (basics) and why it is important (collisionless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

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

Anti-Parallel Magnetic Reconnection



Magnetic Reconnection



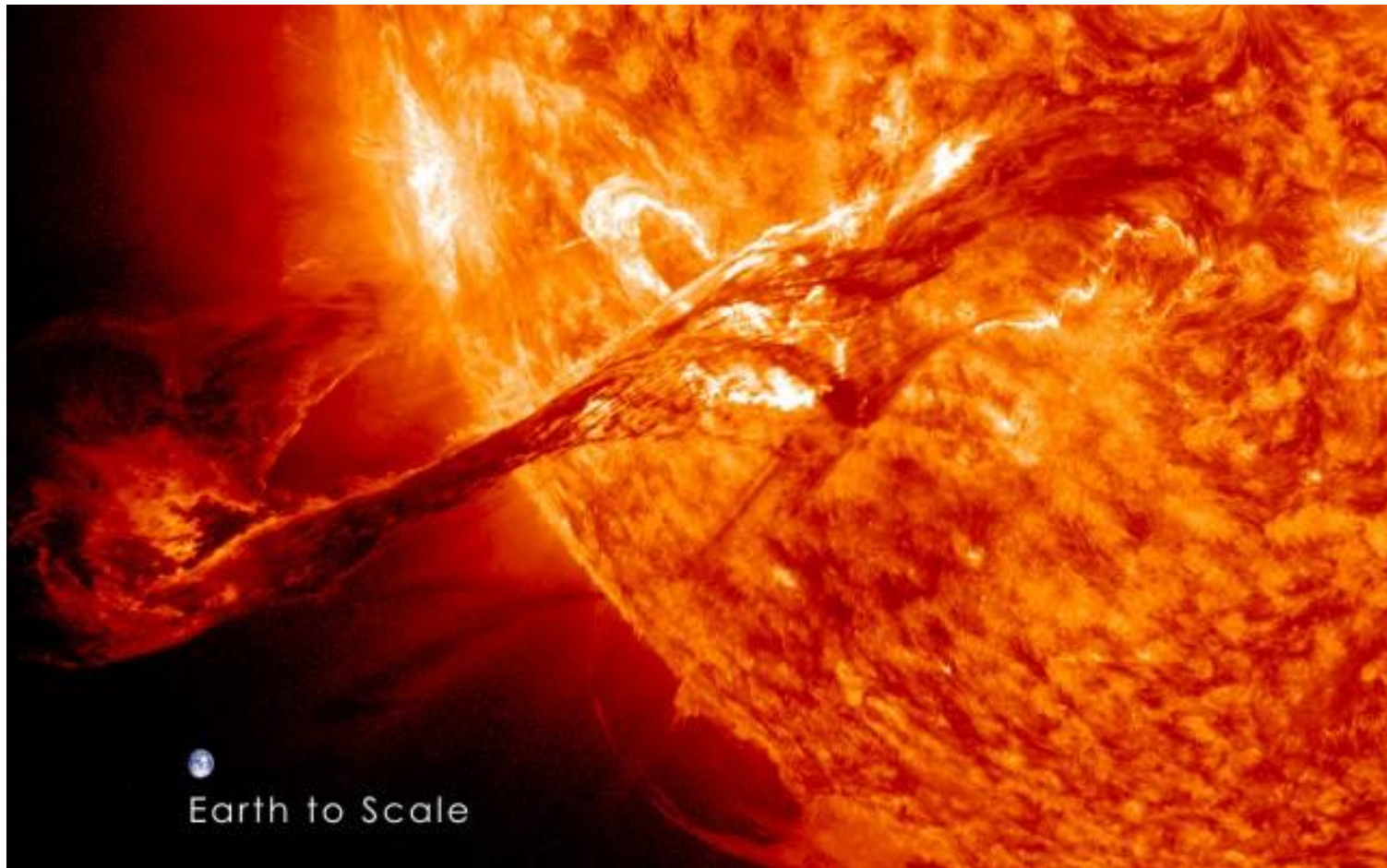
Magnetic fields can influence binary formation.

The Solar Flare Puzzle

The puzzle (1950's):

Solar flares erupt in minutes ($\sim 10^2$ 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:

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

Generalized Ohm's Law

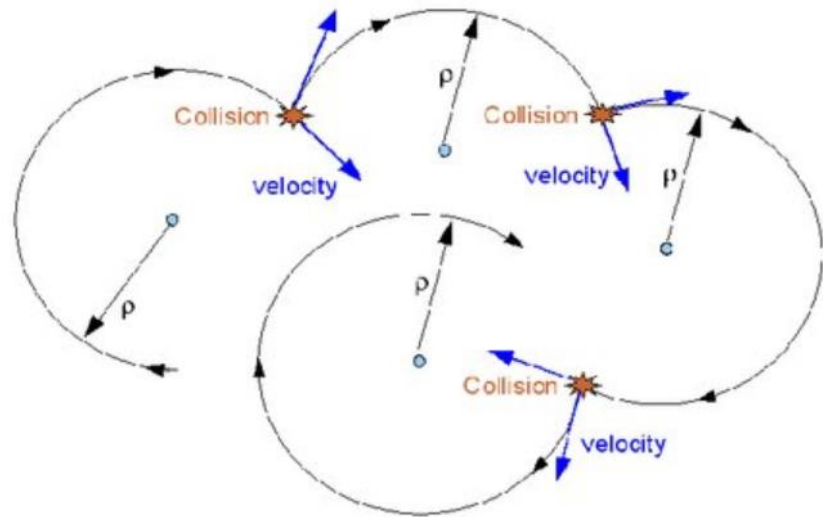
Resistance results in magnetic diffusion:

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

Use $\nabla \times \mathbf{B} = \mu_0 \mathbf{J}$

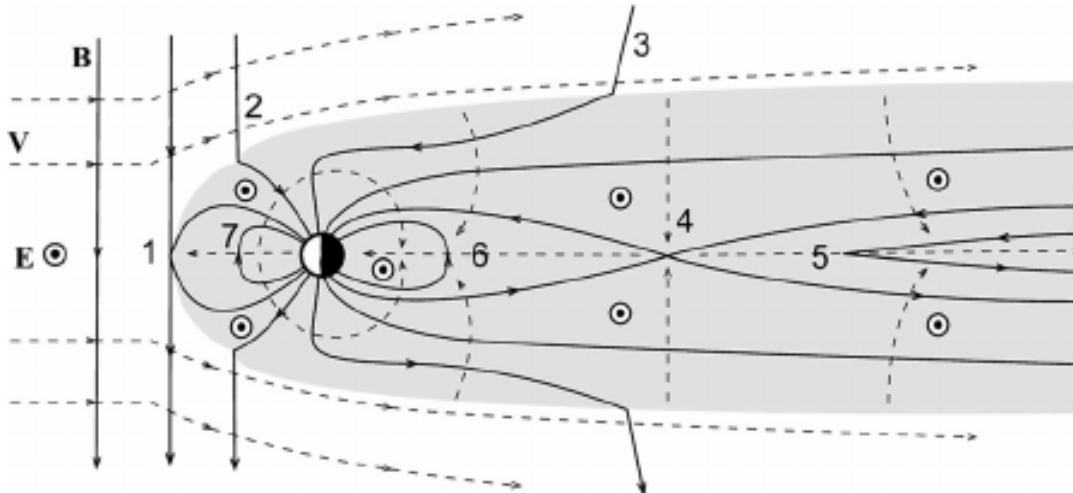
If $\mathbf{v} = 0$: $\frac{\partial \mathbf{B}}{\partial t} = \frac{\eta}{\mu_0} \nabla^2 \mathbf{B}$

$$t_D \approx \frac{\mu_0}{\eta} L^2$$



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.

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

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

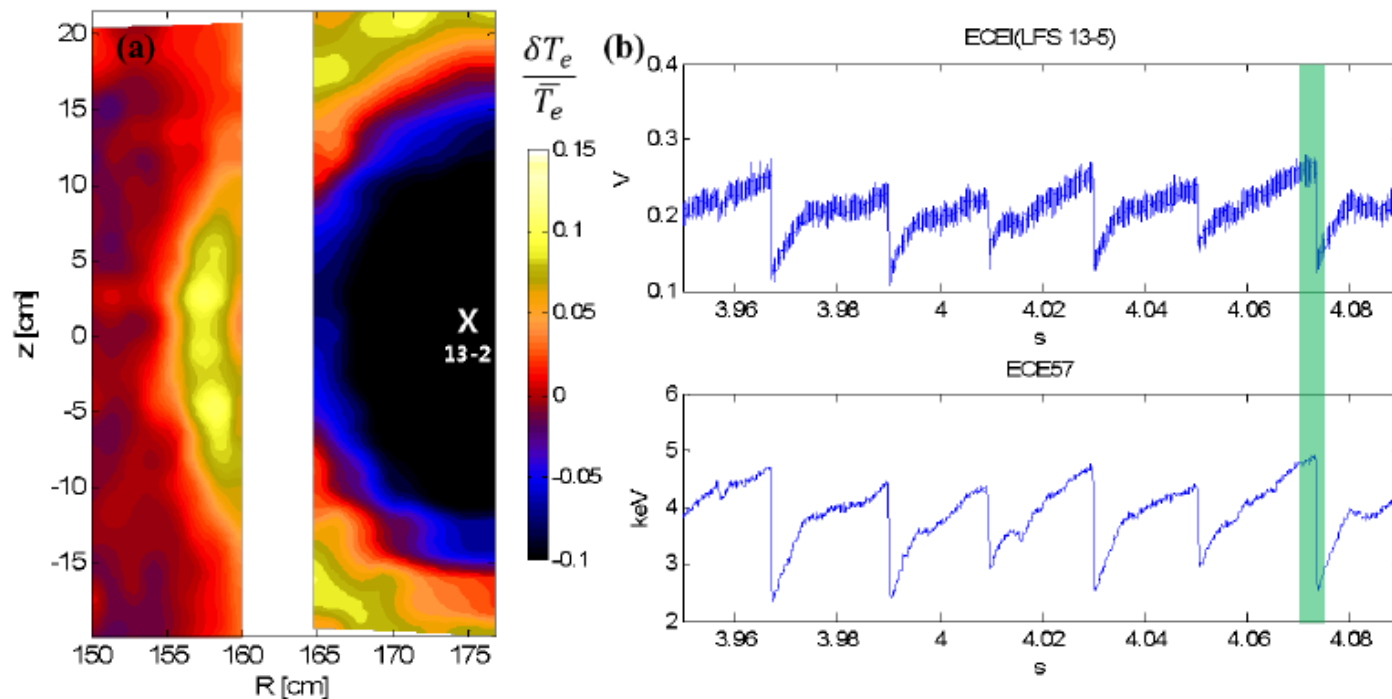
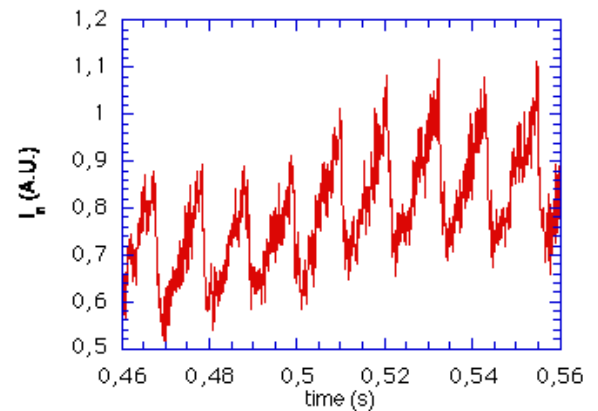
Now we have a bigger mystery! Collisionless magnetic reconnection?

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.

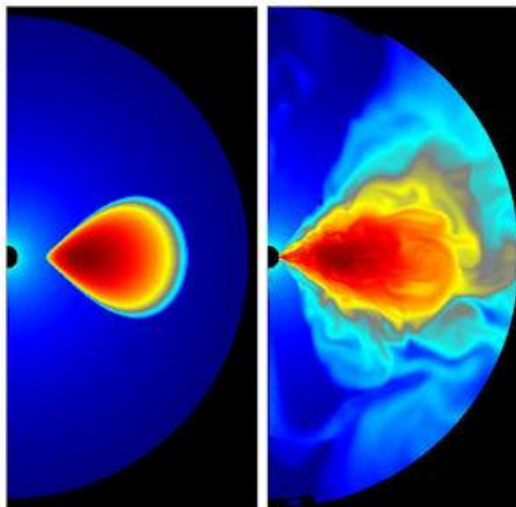
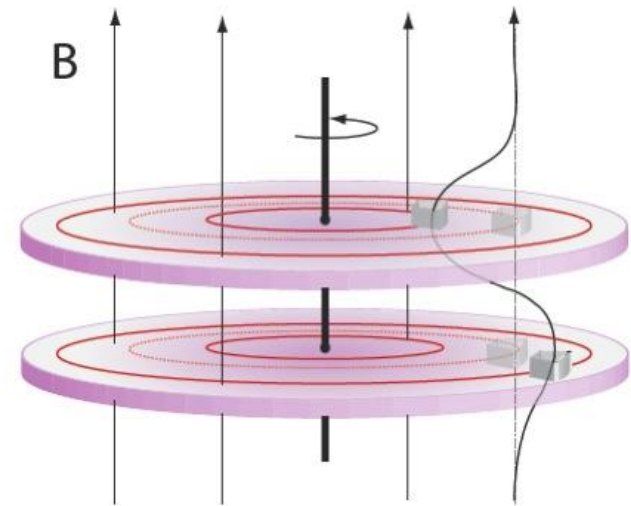


Magnetorotational Instability – Accretion Disks

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

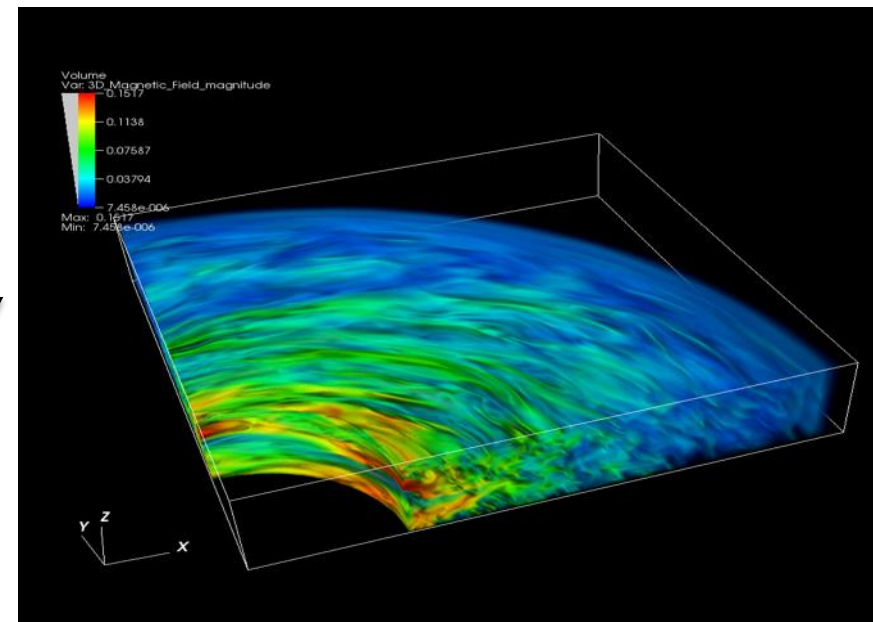
Recent work now includes magnetic reconnection and turbulence to describe the nonlinear evolution.

“If you don’t understand it, invoke magnetic reconnection or turbulence!”



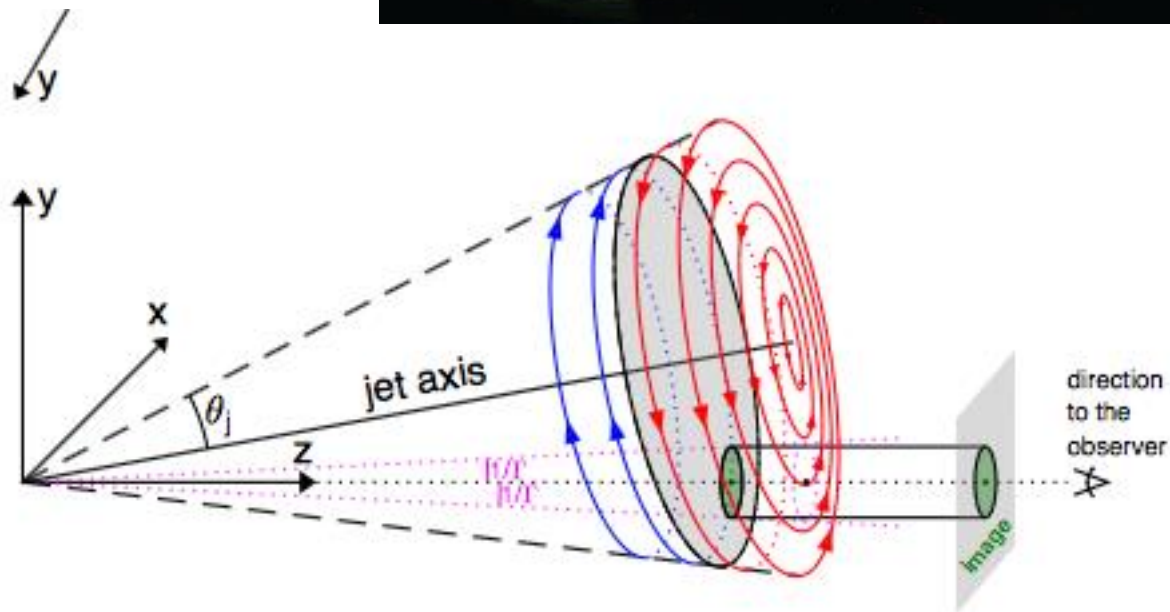
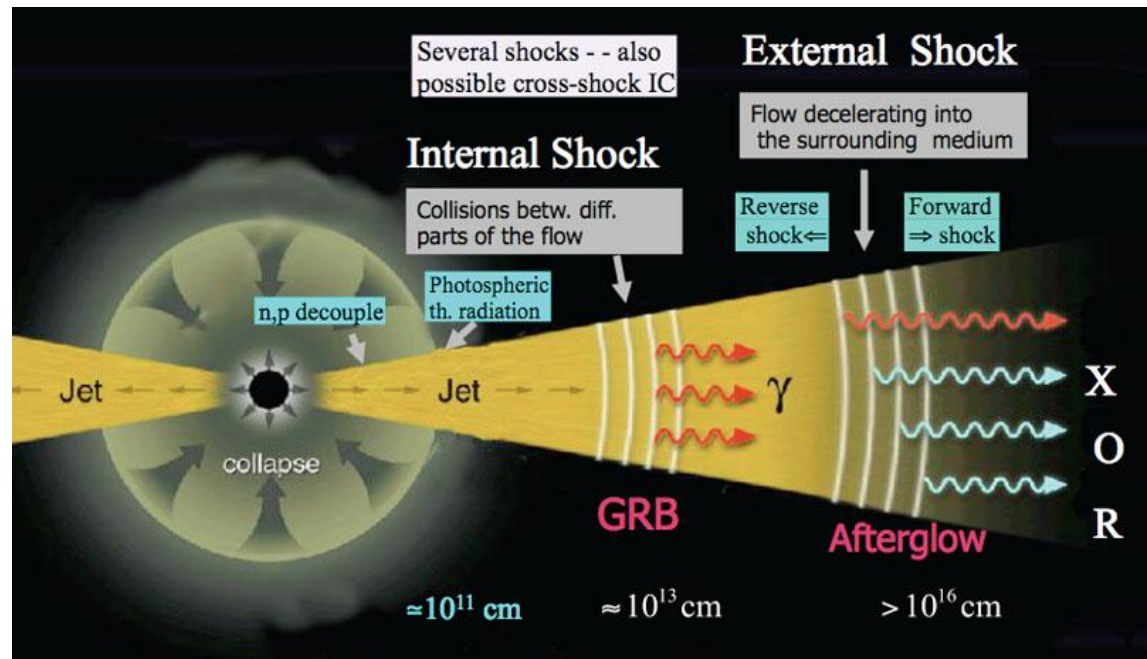
MRI simulation
near a Kerr
black hole.

MRI in an
accretion disk.



γ -Ray Bursts

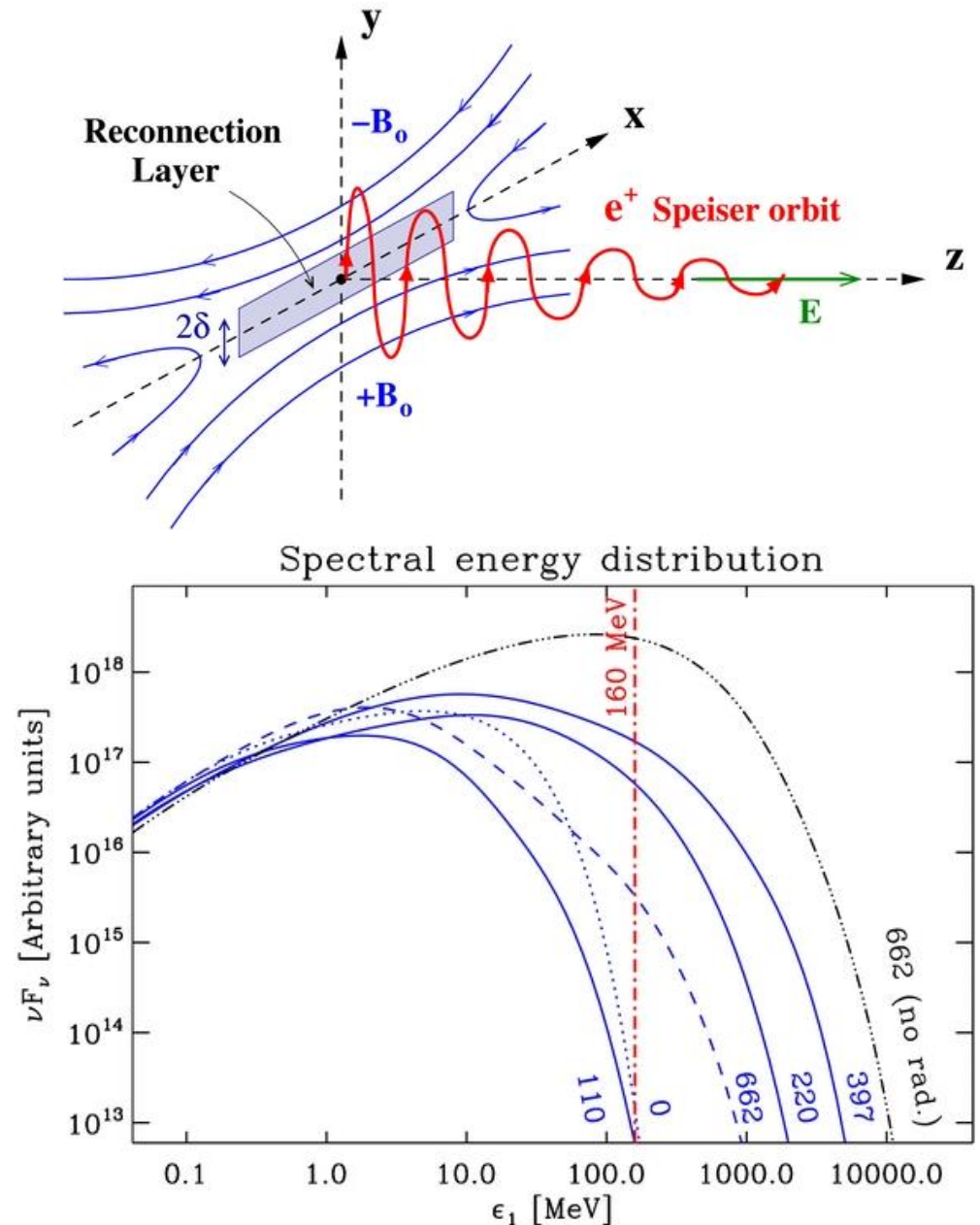
In high- σ (magnetic field energy to kinetic energy) outflows, magnetic reconnection can be more efficient than the internal shock (*Thompson 1994; Spruit et al. 2001; Lyutikov & Blandford 2002; 2003*).



Pulsar Nebulae

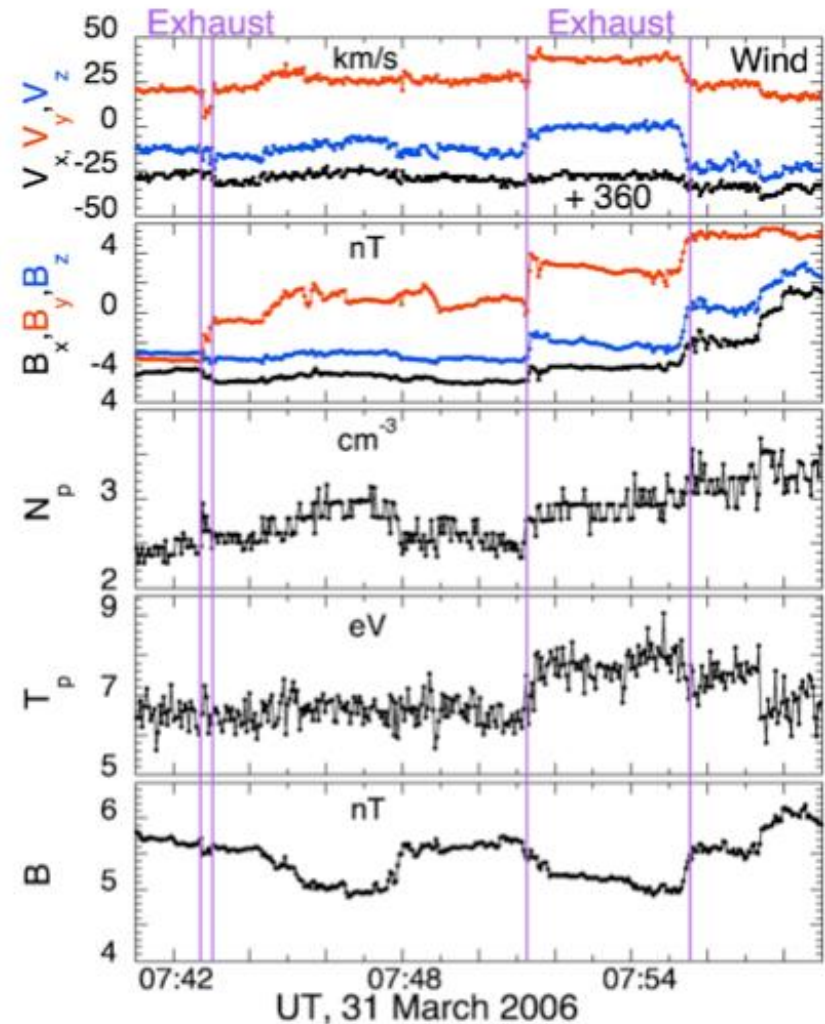
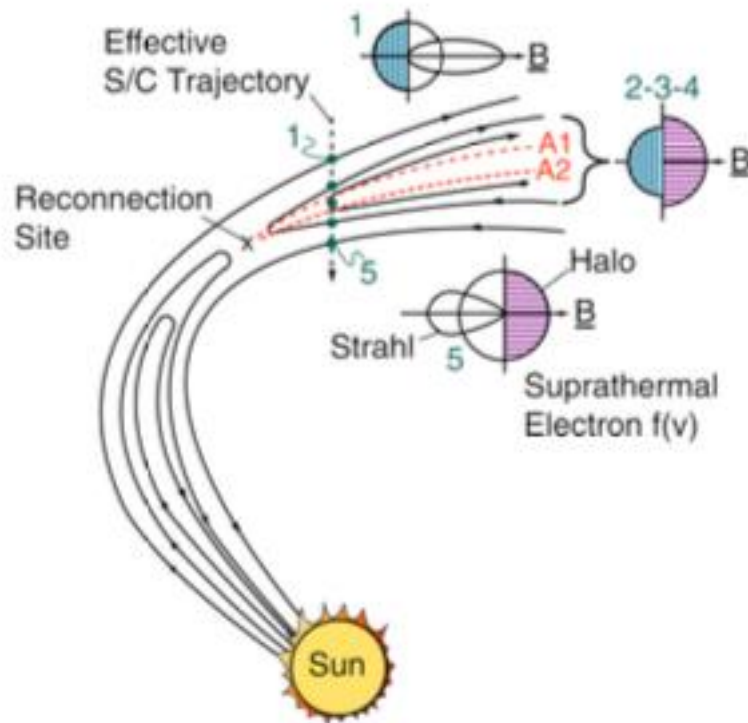
Extreme particle acceleration (beyond the radiation reaction limit) in pulsar nebulae has been inferred from synchrotron radiation. It has been postulated that particles can be accelerated well above the classical radiation reaction limit (160 MeV), by a relativistic Speiser mechanism inside of a magnetic 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)

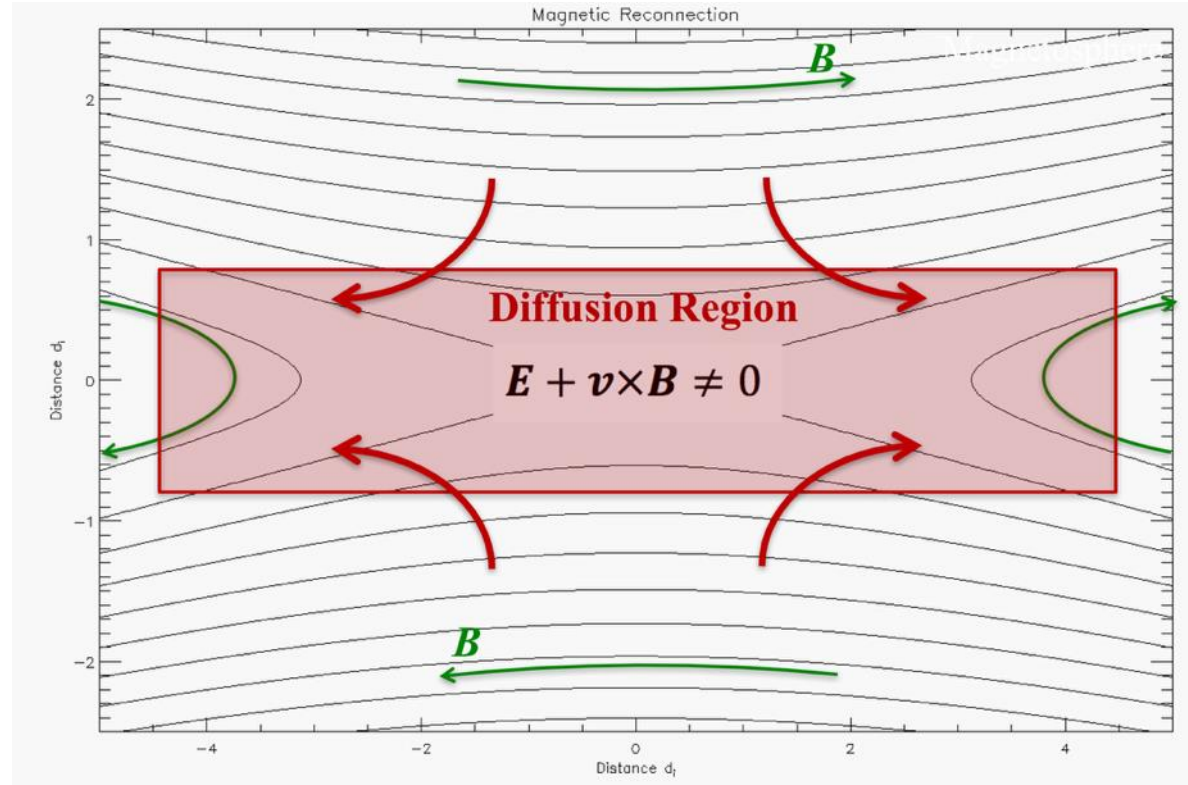


Magnetic Reconnection, a Universal Process

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?



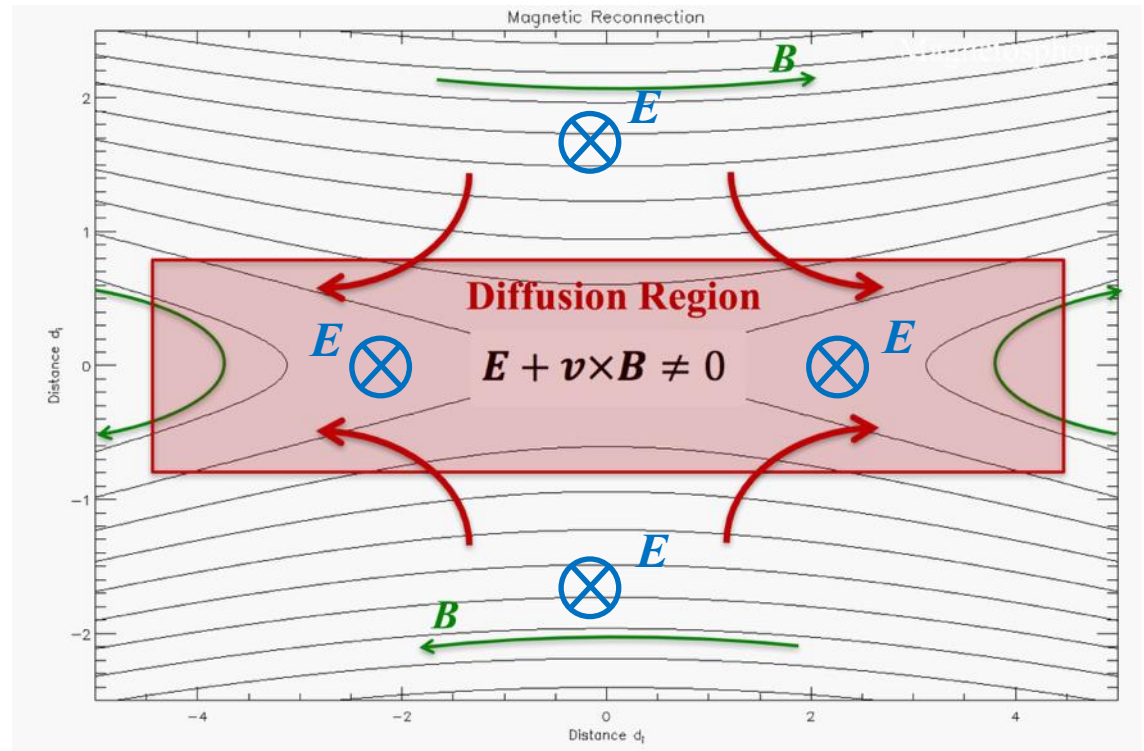
Magnetic Reconnection Research

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 $\mathbf{E} + \mathbf{v} \times \mathbf{B}$:

- Ideal MHD: 0
- Resistive MHD: $\eta \mathbf{J}$.
- Hall MHD: $\mathbf{J} \times \mathbf{B} / en$

Adding electron pressure or inertia required one to abandon MHD.



Generalized Ohm's Law:

	Resistive	Hall	Electron Pressure	Electron Inertia
	↓	↓	↓	↓
$\mathbf{E} + \mathbf{v} \times \mathbf{B} =$	$\eta \mathbf{J}$	$+\frac{\mathbf{J} \times \mathbf{B}}{en}$	$-\frac{\nabla \cdot \overline{\mathbf{P}}_e}{en}$	$+\frac{m_e}{e^2 n} \frac{D\mathbf{J}}{Dt}$

Hall Reconnection

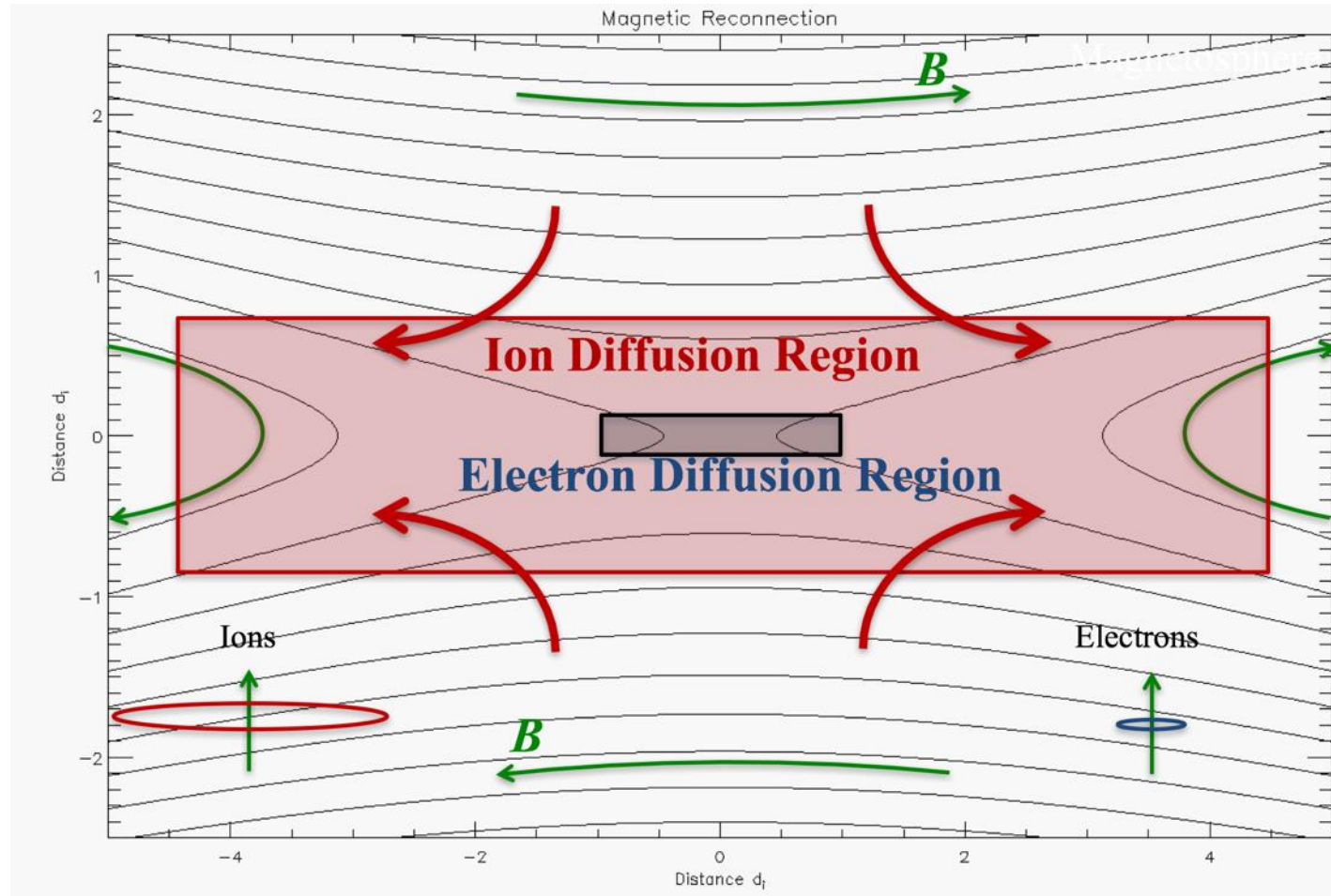
Ions, which have much larger skin depth (c/ω_{pi}) and gyroradii, decouple from $\mathbf{B}$ (via Hall term) resulting in two diffusion regions named the “ion diffusion region” and the “electron diffusion region”.

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

And since:

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

Hall MHD cannot account for magnetic energy conversion.

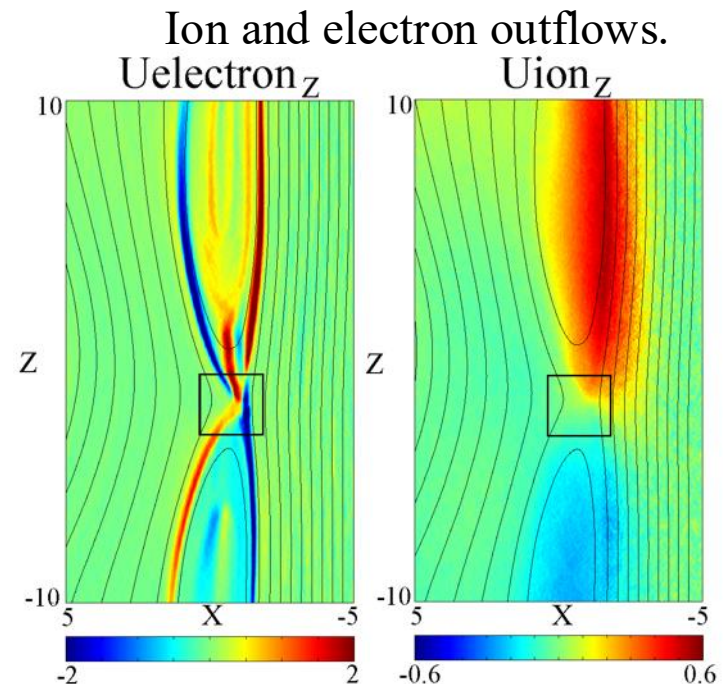
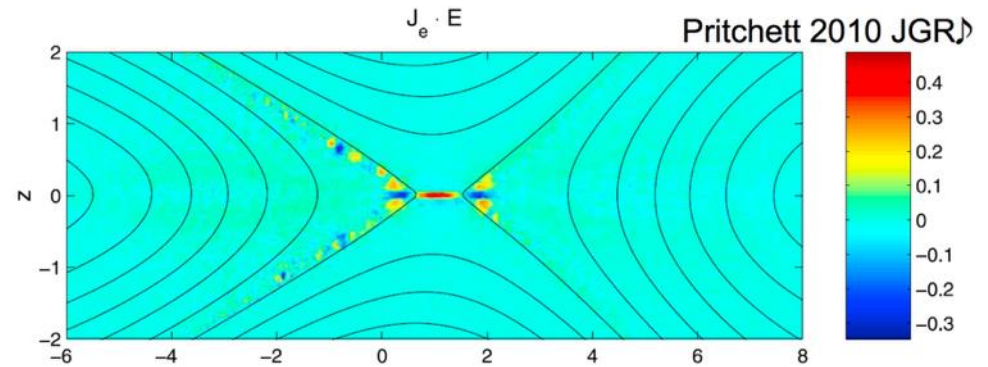


PIC Simulations

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

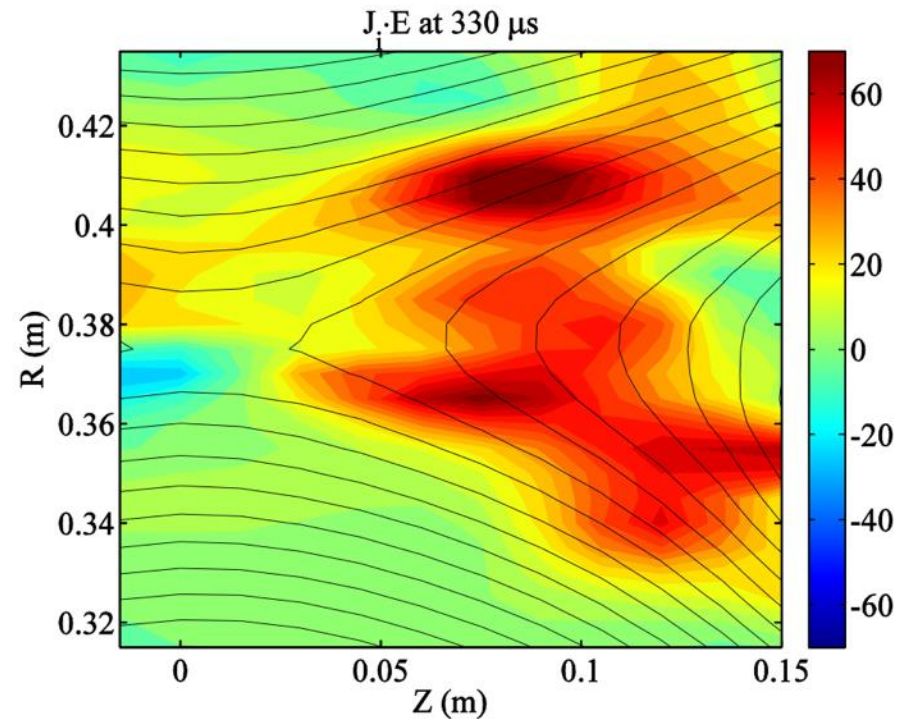
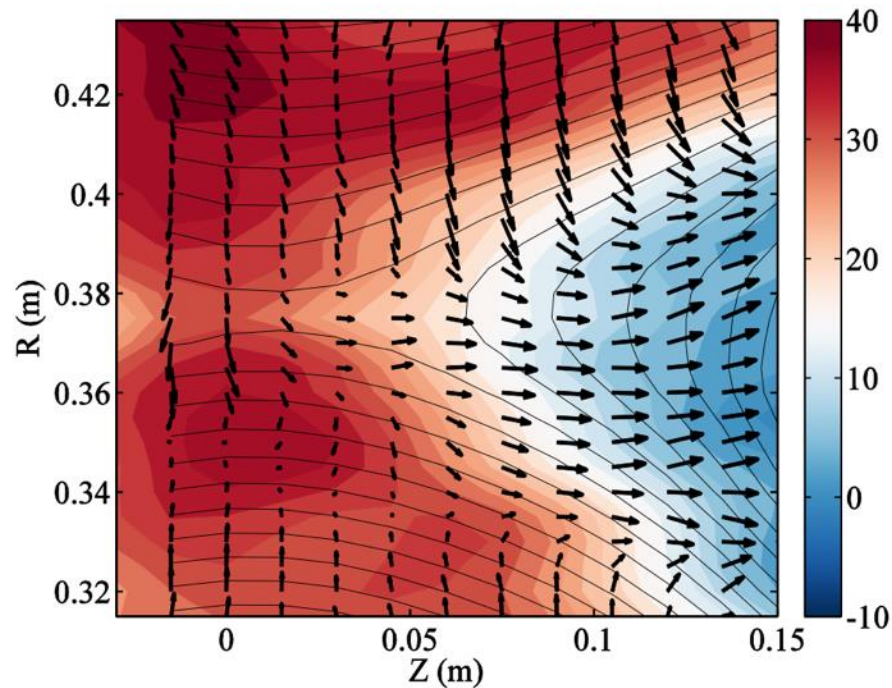
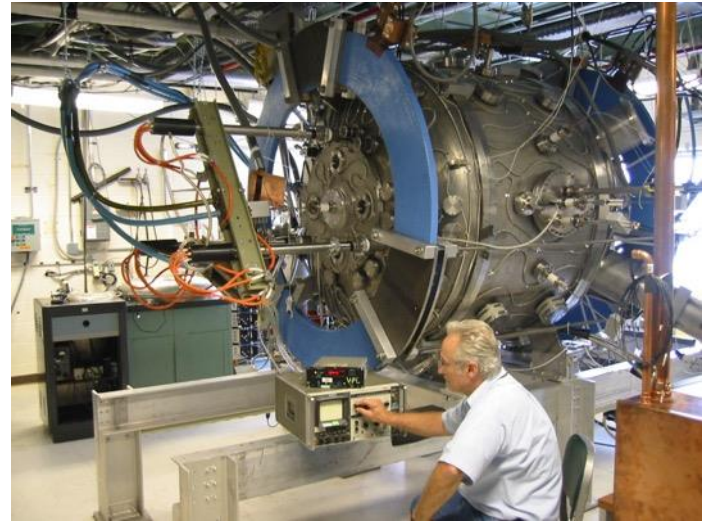
Primarily in 2D.

- (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...



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:

$$E + v \times B = \underset{\substack{\text{Resistive} \\ \downarrow}}{\eta J} + \underset{\substack{\text{Hall} \\ \downarrow}}{\frac{J \times B}{en}} - \underset{\substack{\text{Electron Pressure} \\ \downarrow}}{\frac{\nabla \cdot \overline{P_e}}{en}} + \underset{\substack{\text{Electron Inertia} \\ \downarrow}}{\frac{m_e}{e^2 n} \frac{DJ}{Dt}}$$

Out-of-Plane Current
(perpendicular crescent)

MMS2
outward

**out-of-plane
electrons**

$\log f (s^3/cm^6)$
-30 -25

MMS1
outward

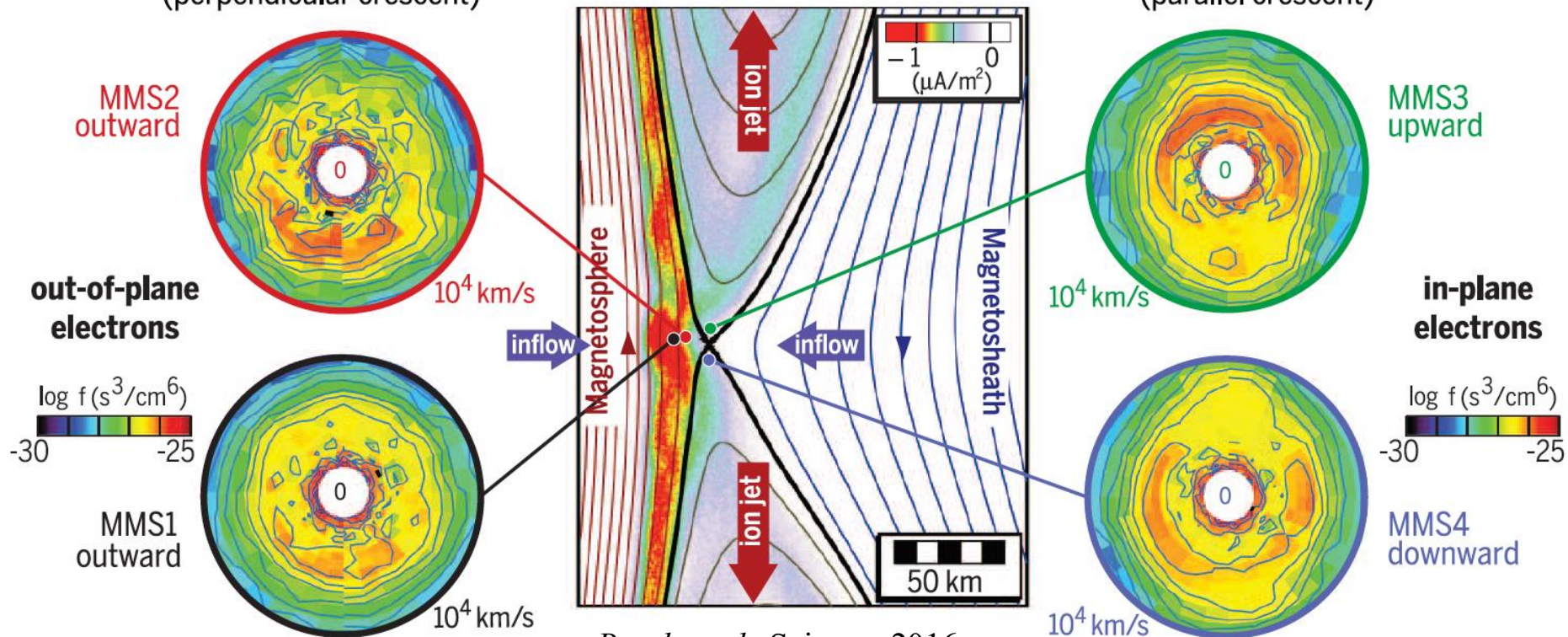
Electron Outflow
(parallel crescent)

MMS3
upward

**in-plane
electrons**

$\log f (s^3/cm^6)$
-30 -25

MMS4
downward



Burch et al., Science, 2016

Space Measurements of Magnetic Reconnection

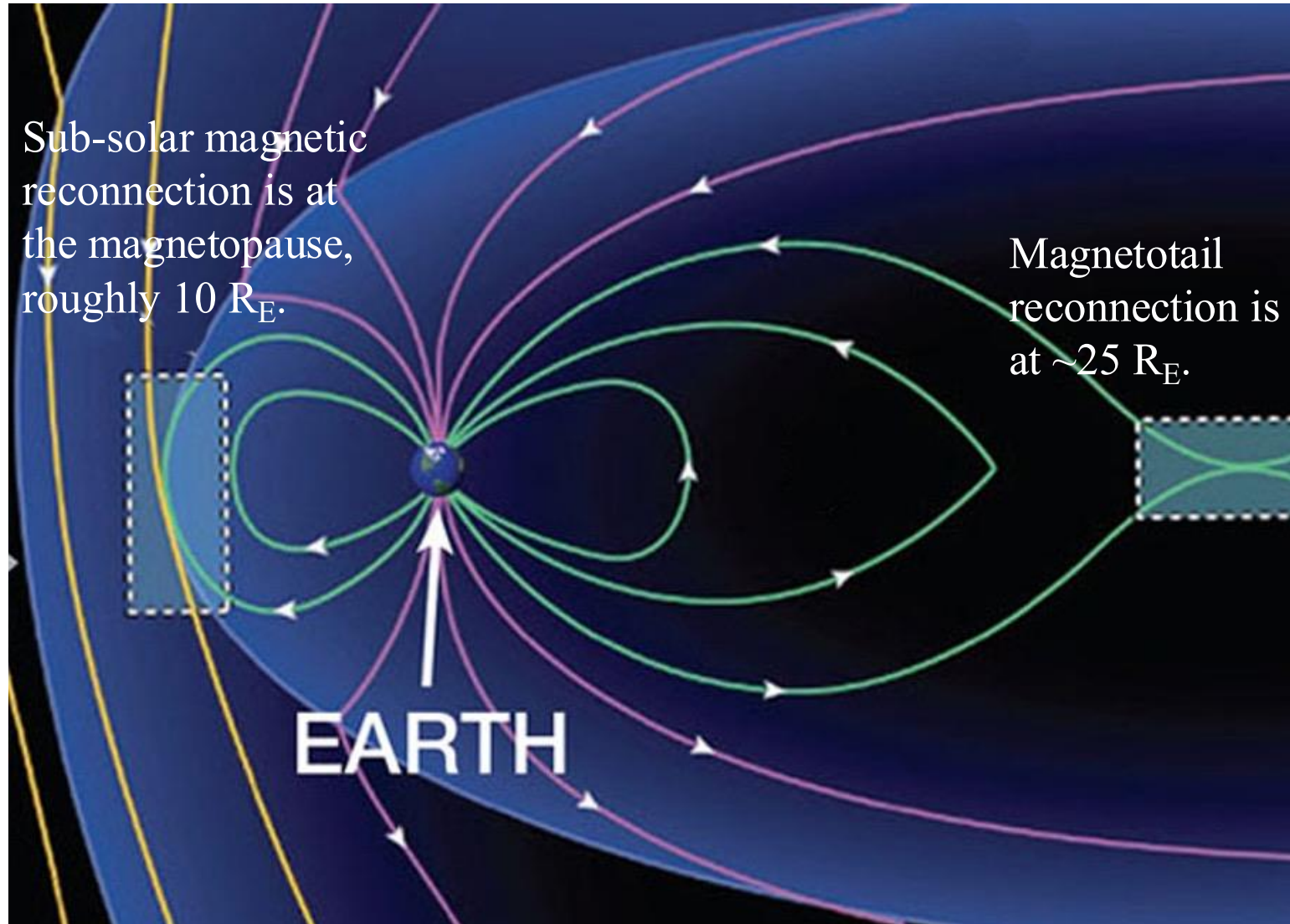
Generalized Ohm's Law:

$$E + v \times B = \underset{\substack{\text{Resistive} \\ \downarrow}}{\eta J} + \underset{\substack{\text{Hall} \\ \downarrow}}{\frac{J \times B}{en}} - \underset{\substack{\text{Electron Pressure} \\ \downarrow}}{\frac{\nabla \cdot \overline{\overline{P_e}}}{en}} + \underset{\substack{\text{Electron Inertia} \\ \downarrow}}{\frac{m_e}{e^2 n} \frac{DJ}{Dt}}$$

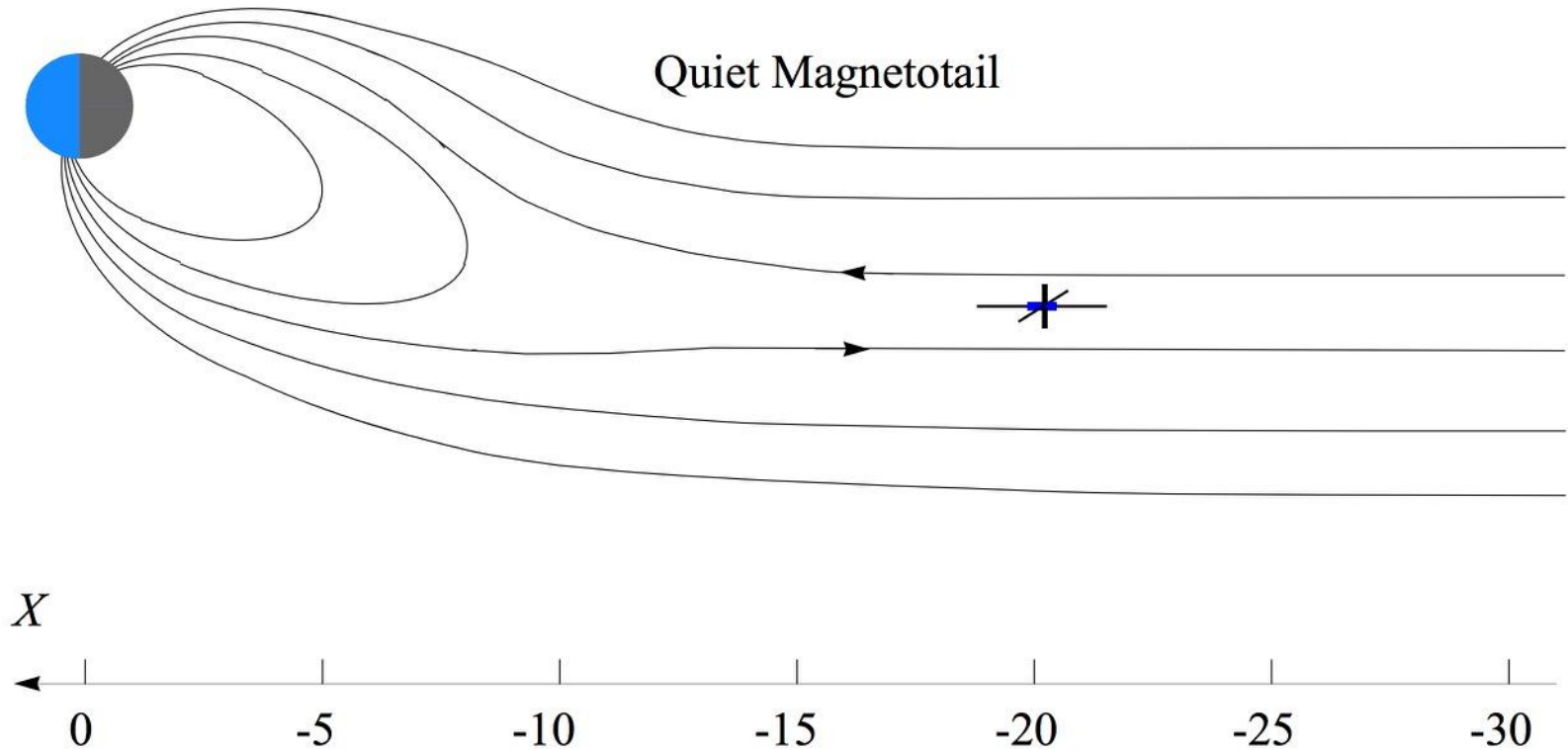
What MMS observed in the electron diffusion region of anti-parallel magnetic reconnection:

- (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: $T_{\parallel} > T_{\perp}$ (partly predicted by some).
- (d) Strong, localized energy conversion $\mathbf{J} \cdot \mathbf{E} > 0$ (predicted, except MMS observes much higher values and much more structure.)

Magnetotail Reconnection

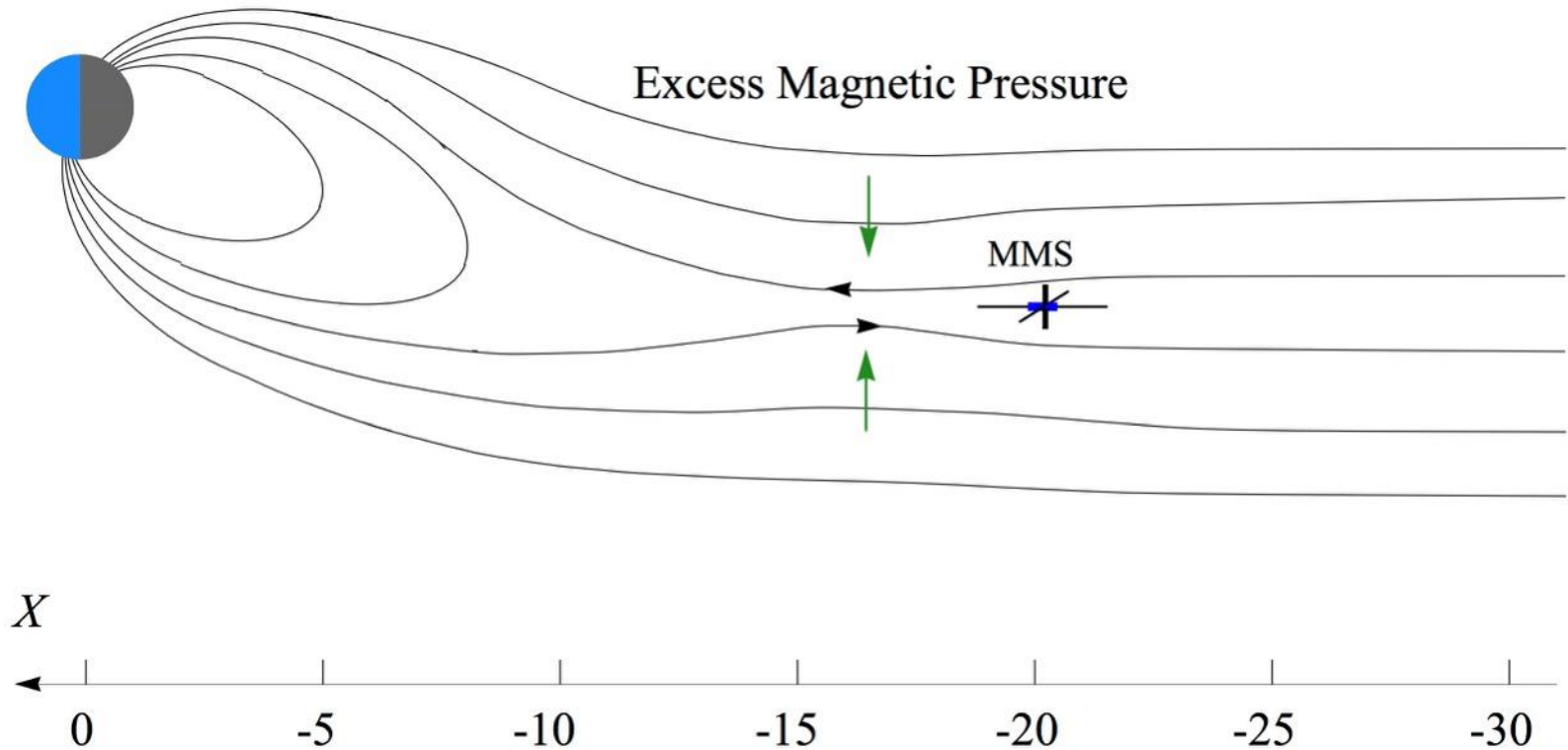


Magnetotail Reconnection



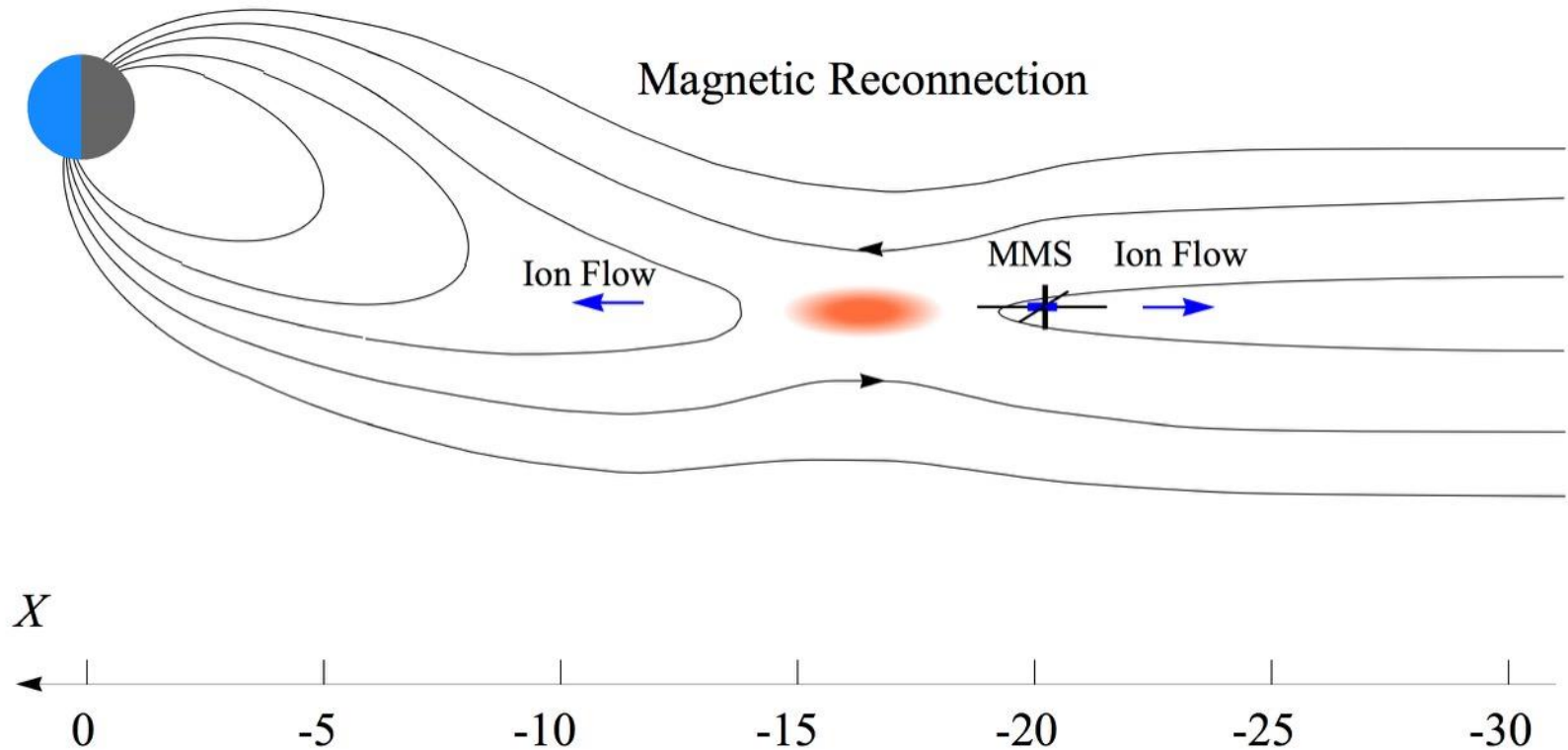
MMS is at $-20 R_E$.

Magnetotail Reconnection



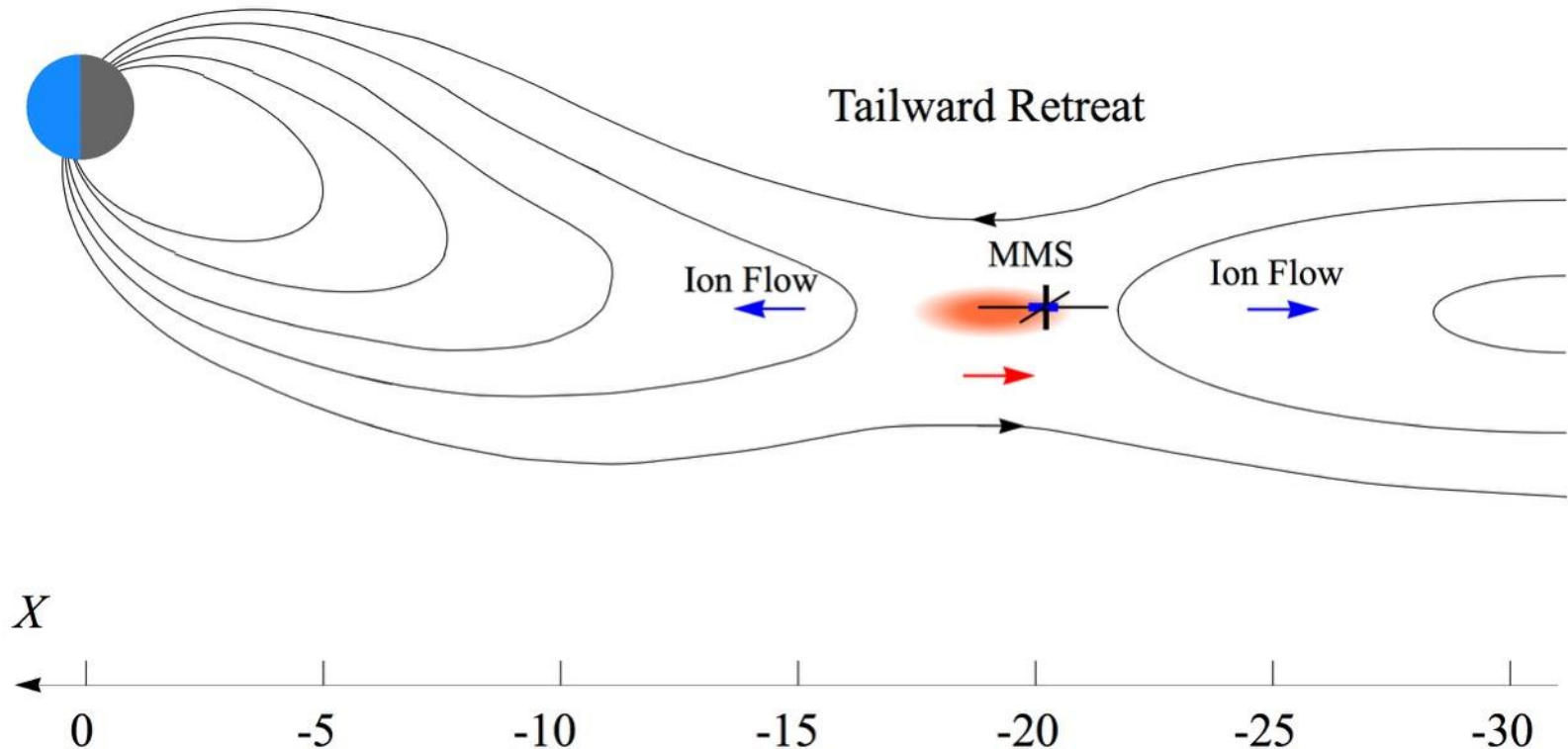
Excess magnetic pressure can cause the current sheet to thin.

Magnetotail Reconnection



Magnetic reconnection can initiate at $\sim -15 R_E$.
MMS observes a tailward flow typically several 100's of km/s.

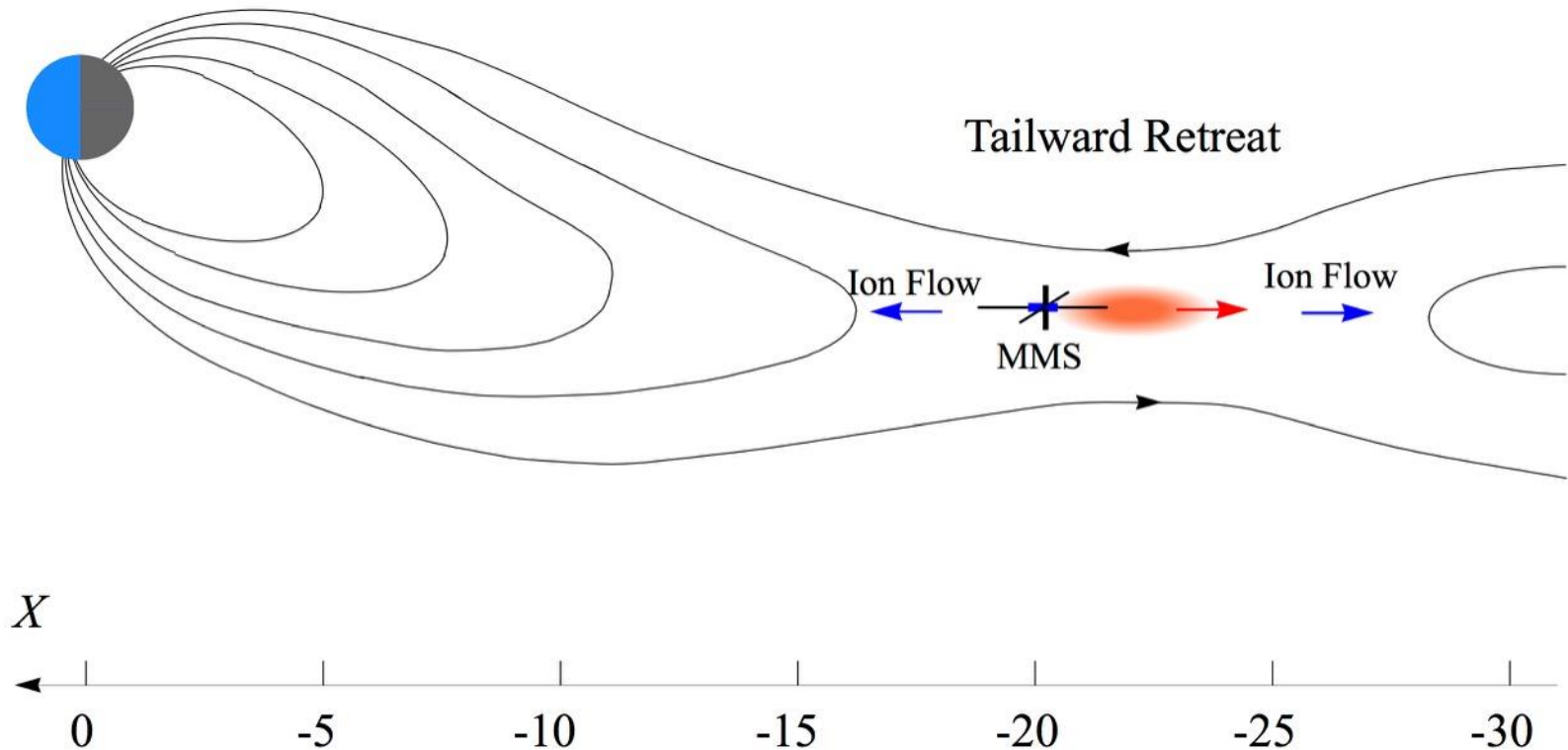
Magnetotail Reconnection



The magnetic reconnection region often retreats tailward. MMS can observe the magnetic reconnection.

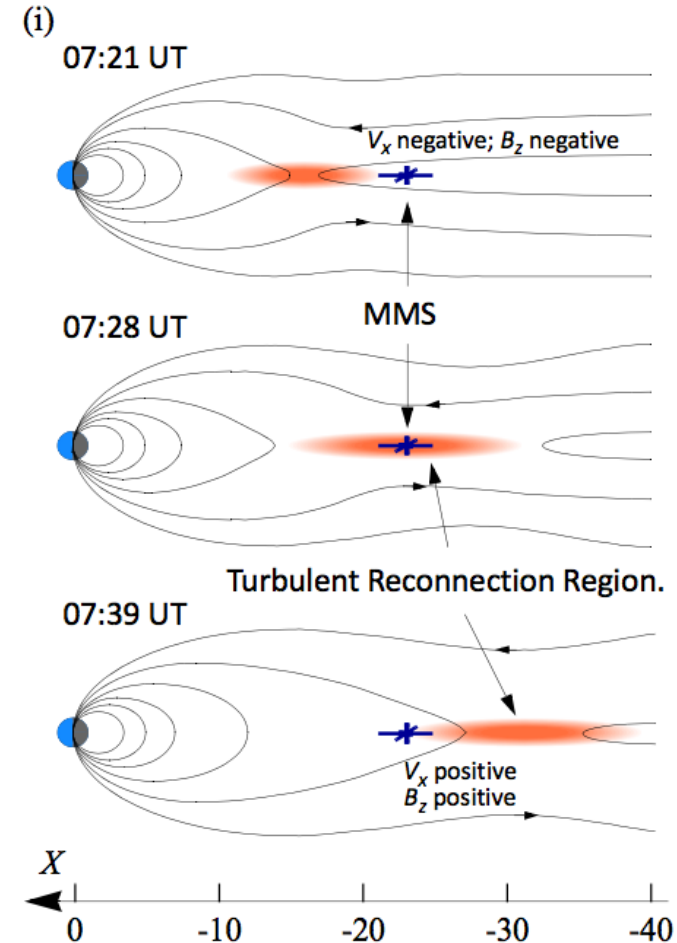
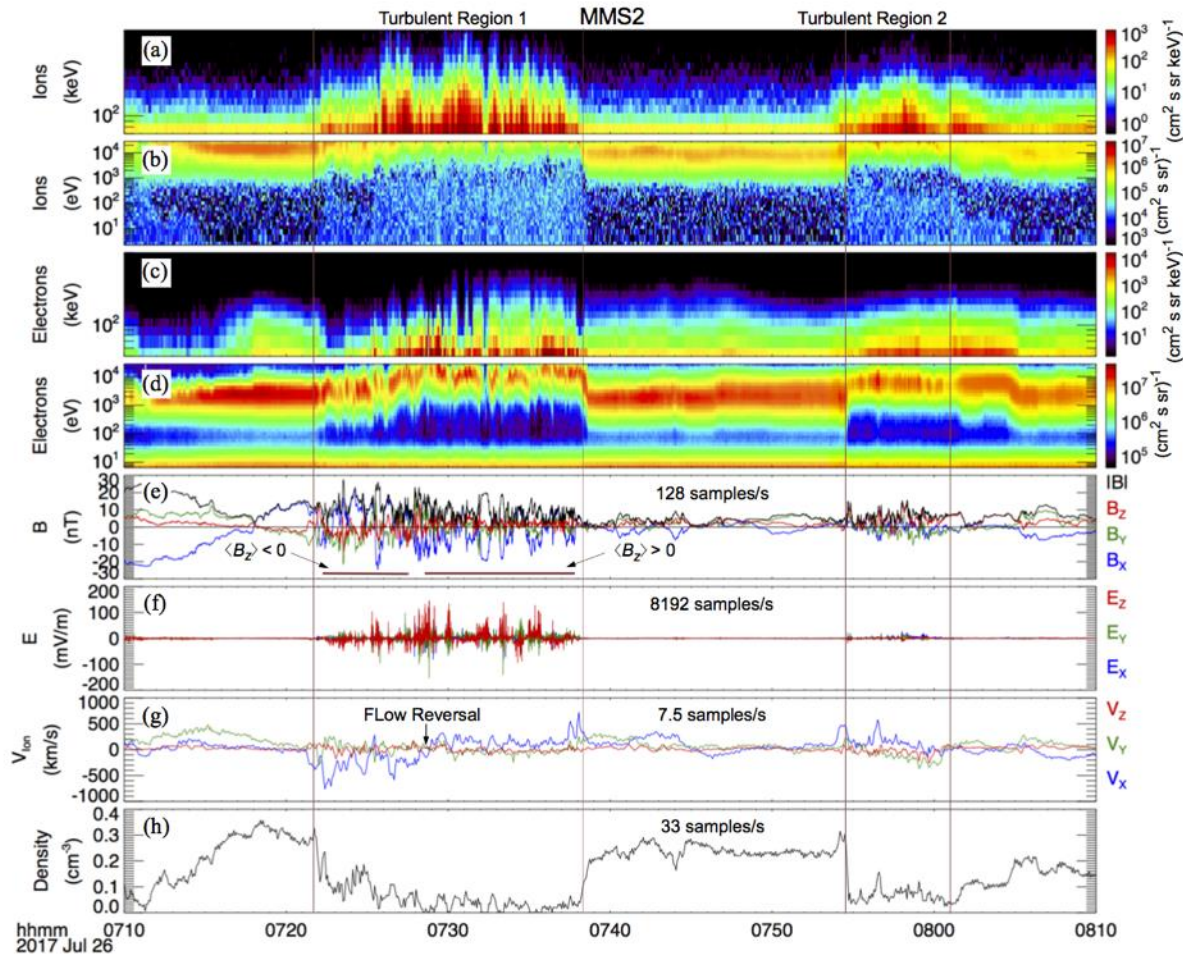
(1) $\mathbf{B} = 0$. (2) V_x goes negative to positive. (3) B_z goes negative to positive.

Magnetotail Reconnection

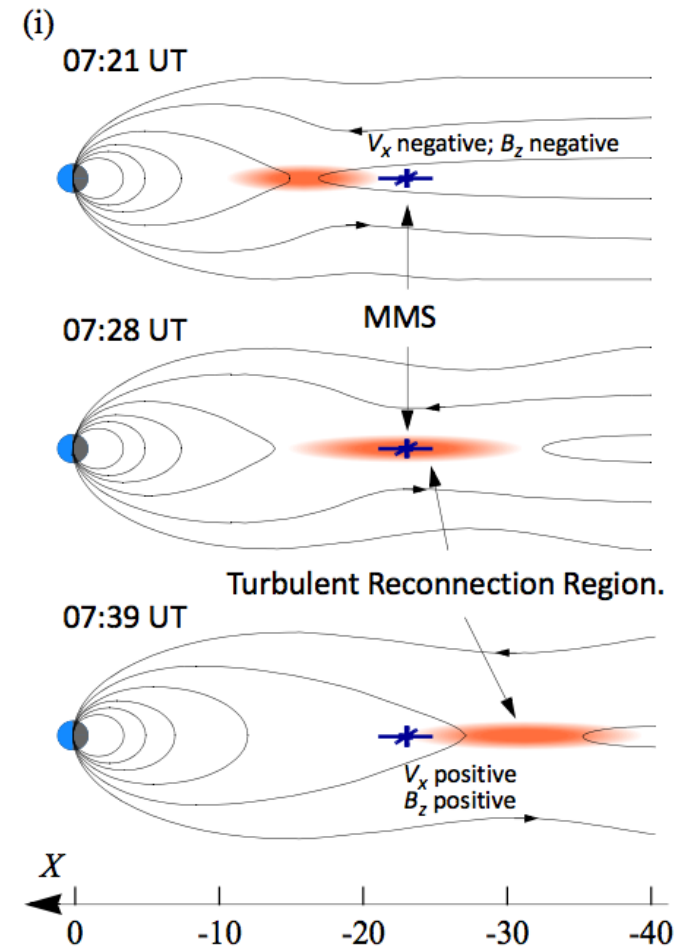
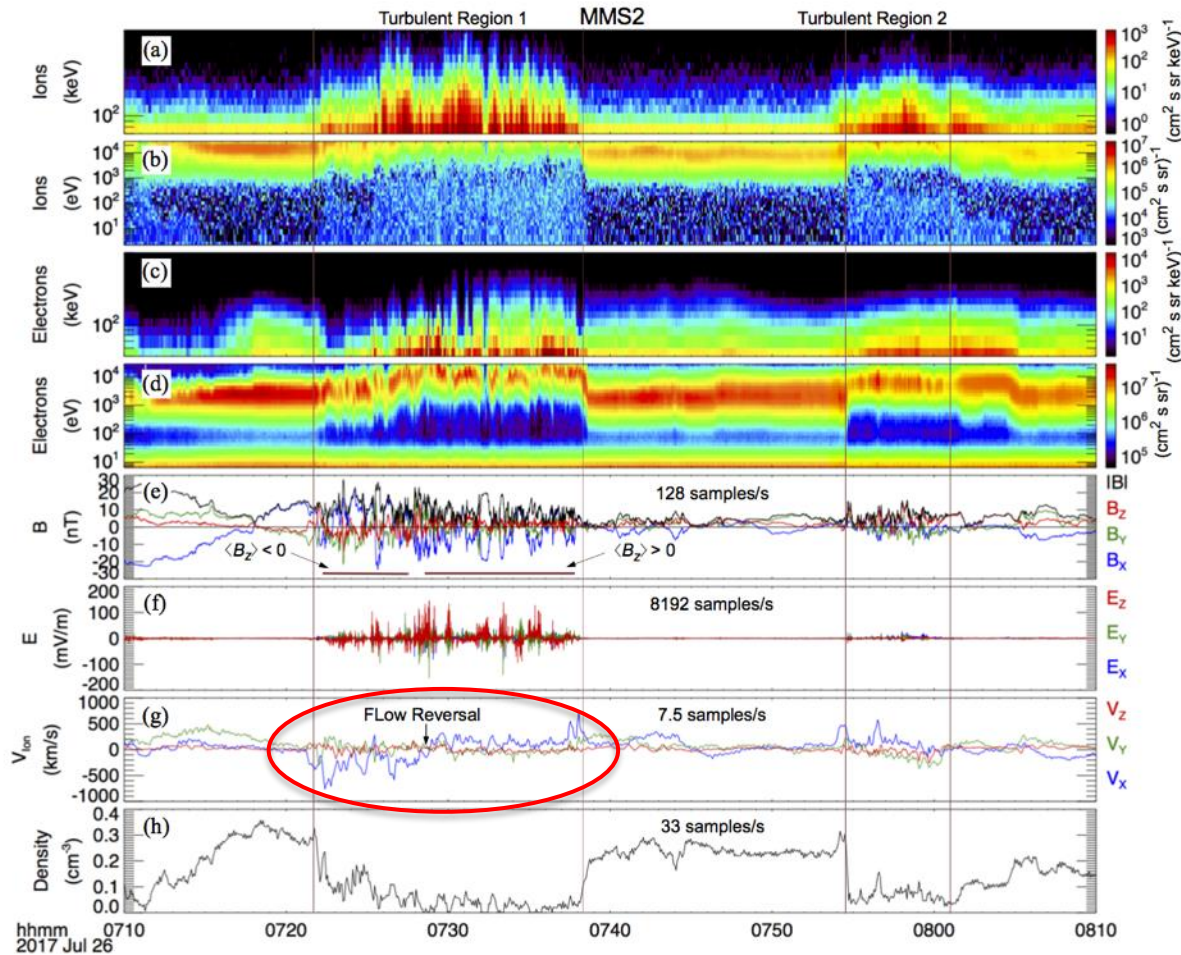


After the magnetic reconnection region retreats, MMS observes a earthward flow and B_z positive. “Flow reversal” is an excellent indicator.

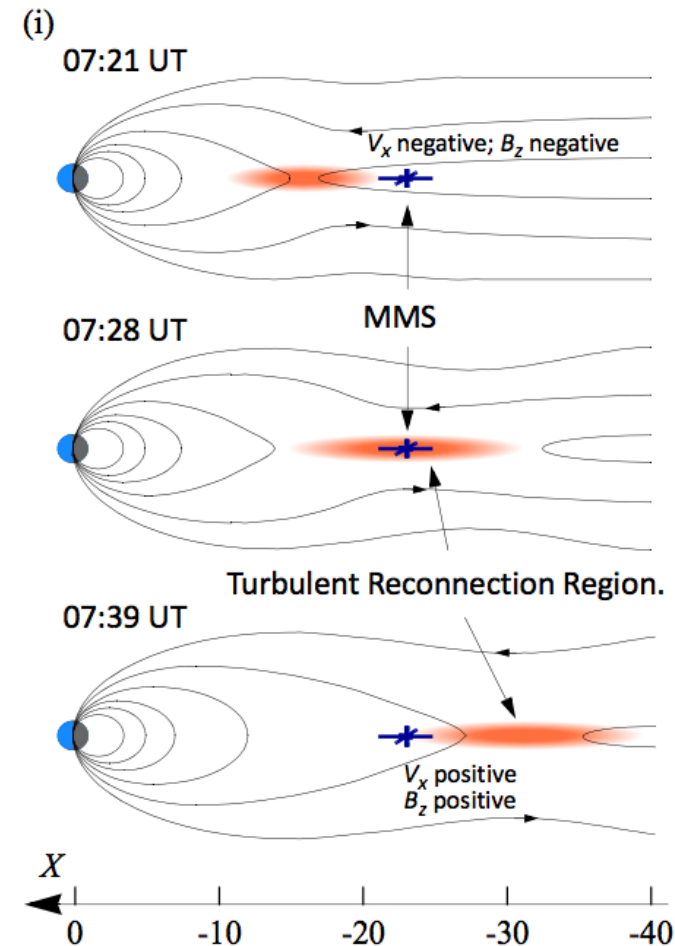
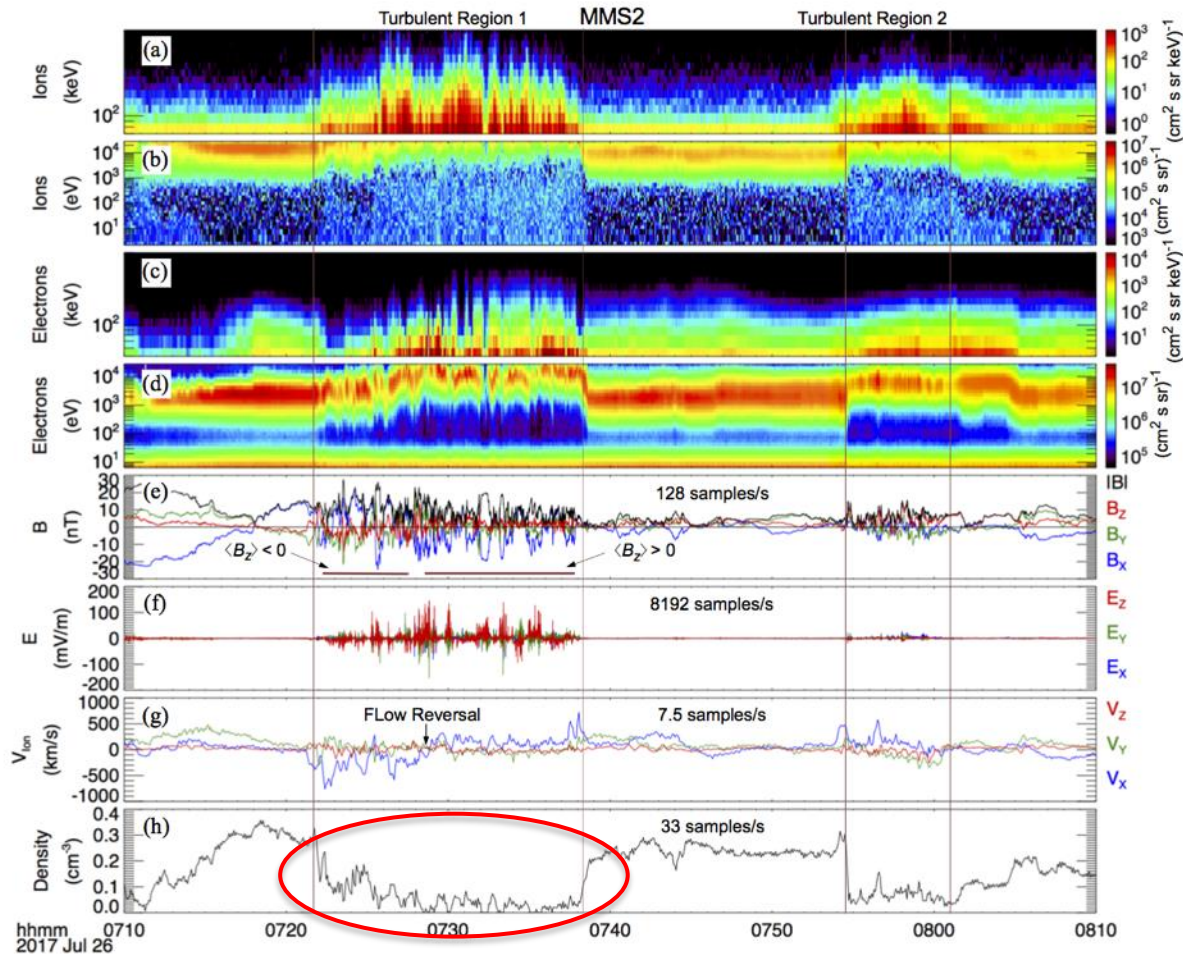
Electron Acceleration: Near-Earth Event



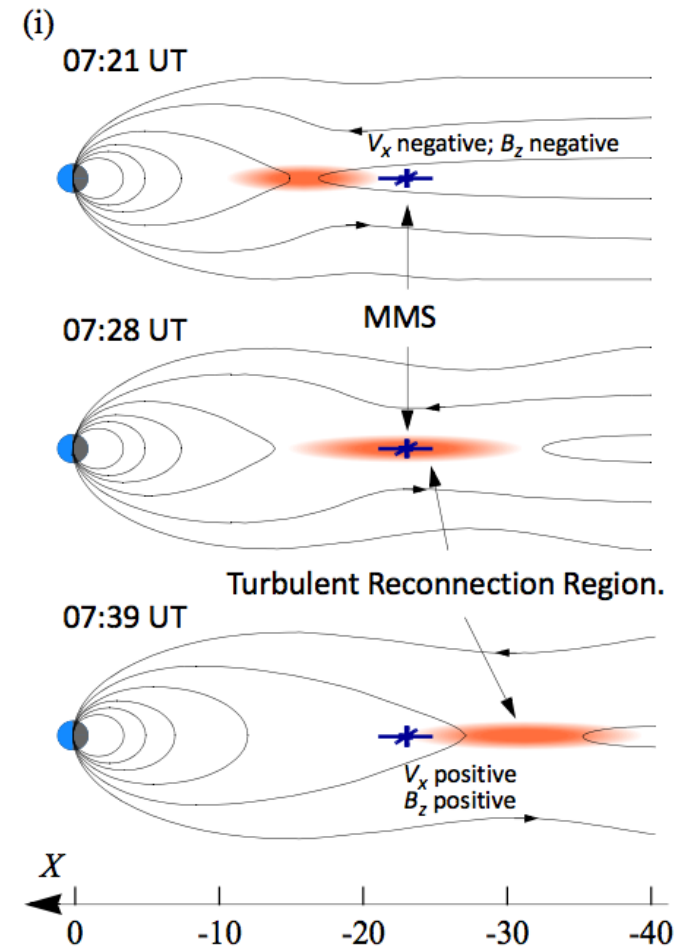
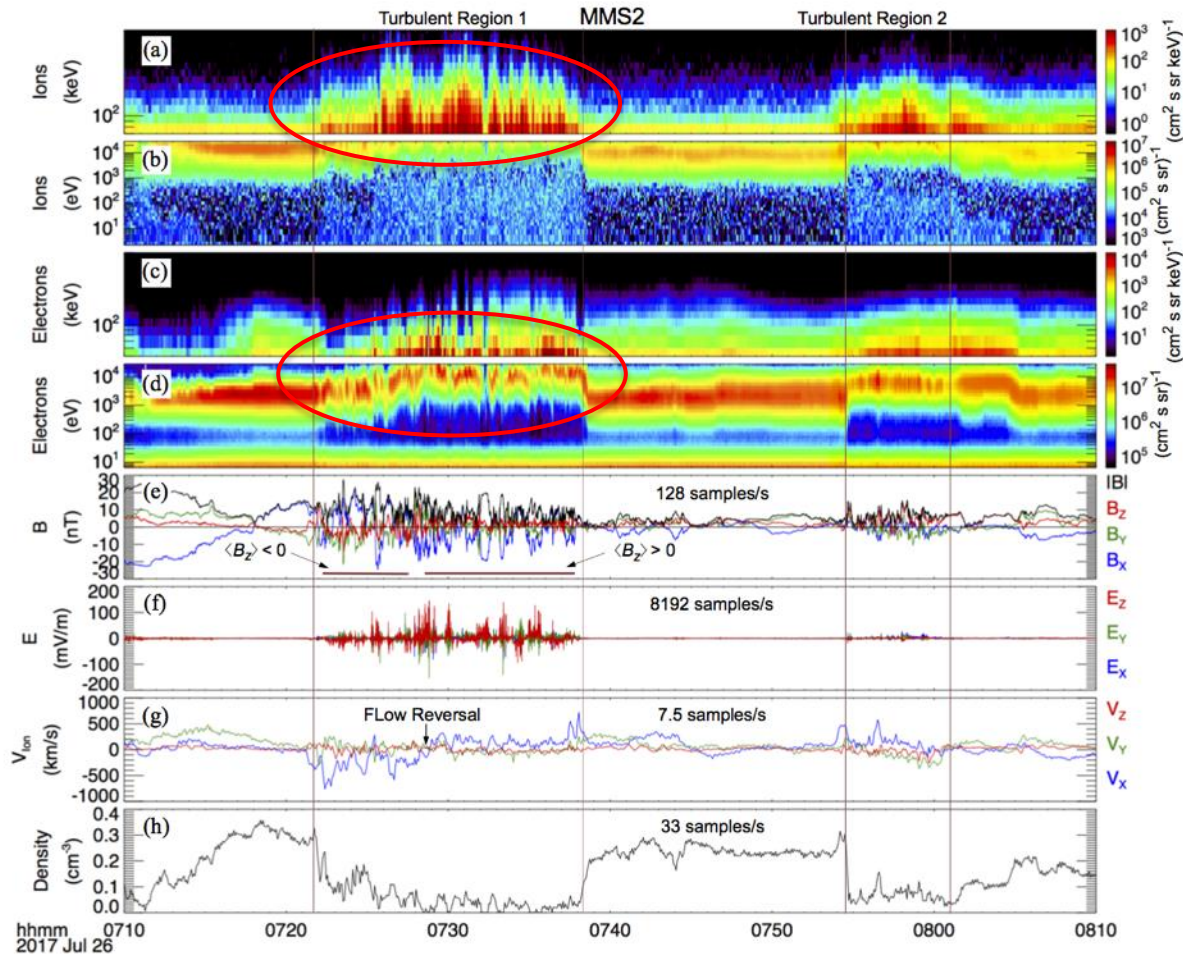
Electron Acceleration: Near-Earth Event



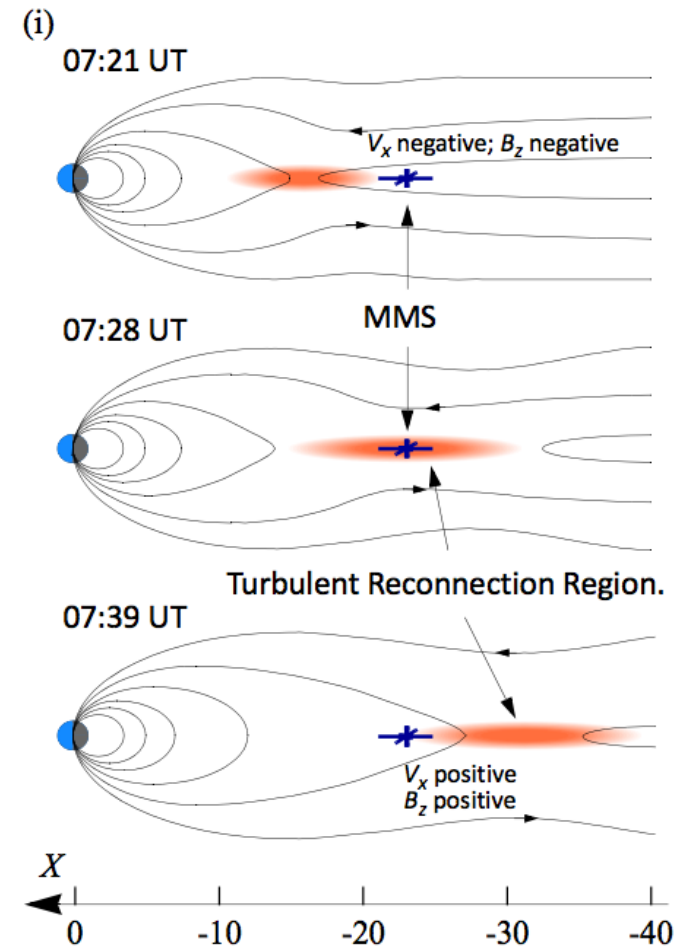
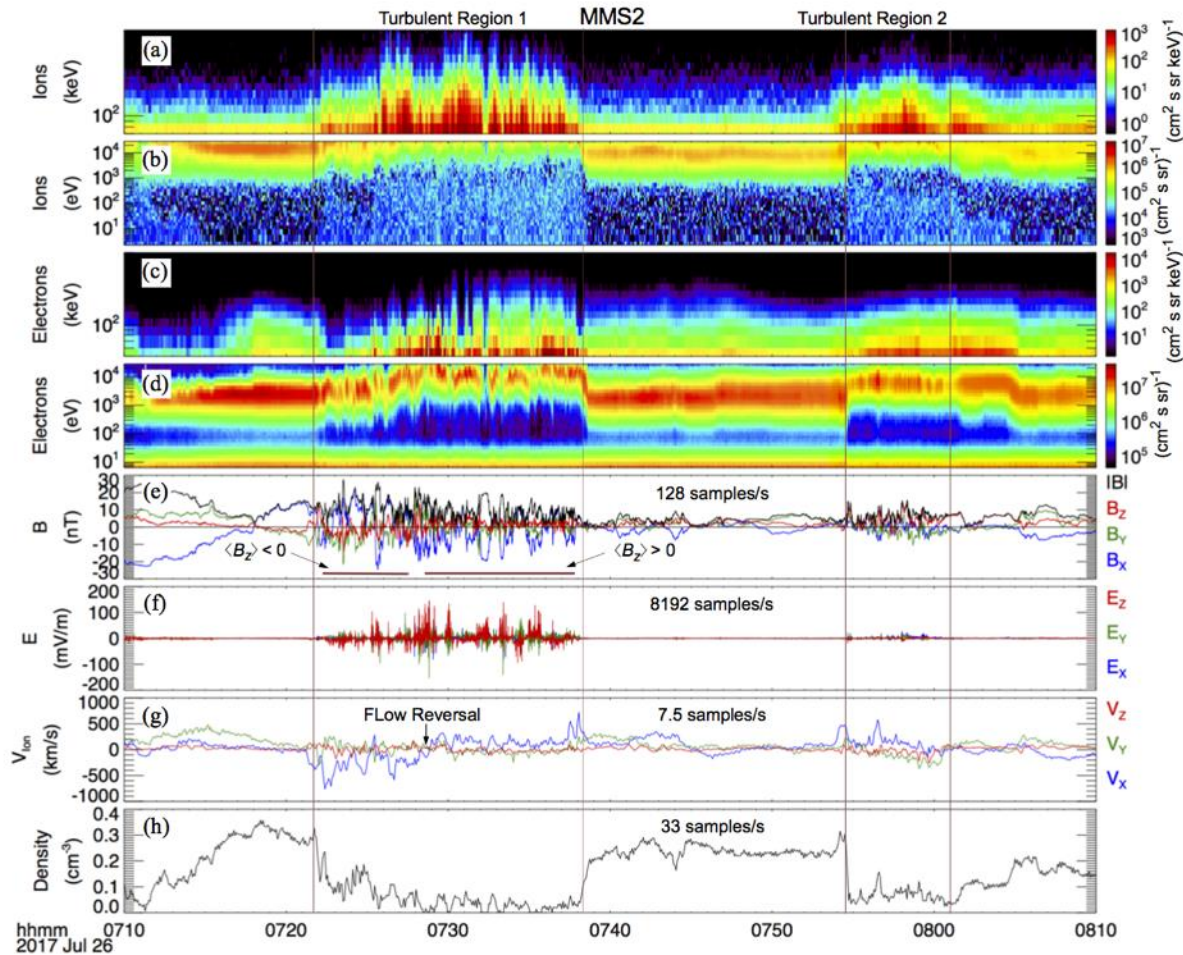
Electron Acceleration: Near-Earth Event

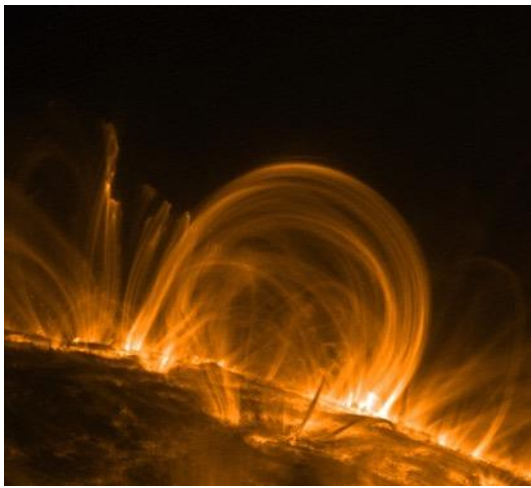


Electron Acceleration: Near-Earth Event



Electron Acceleration: Near-Earth Event





Heliophysics Summer School



Part 2

- Particle Acceleration Basics.
- Magnetotail Reconnection
- **Turbulent acceleration: electrons.**
- Turbulent acceleration: ions.

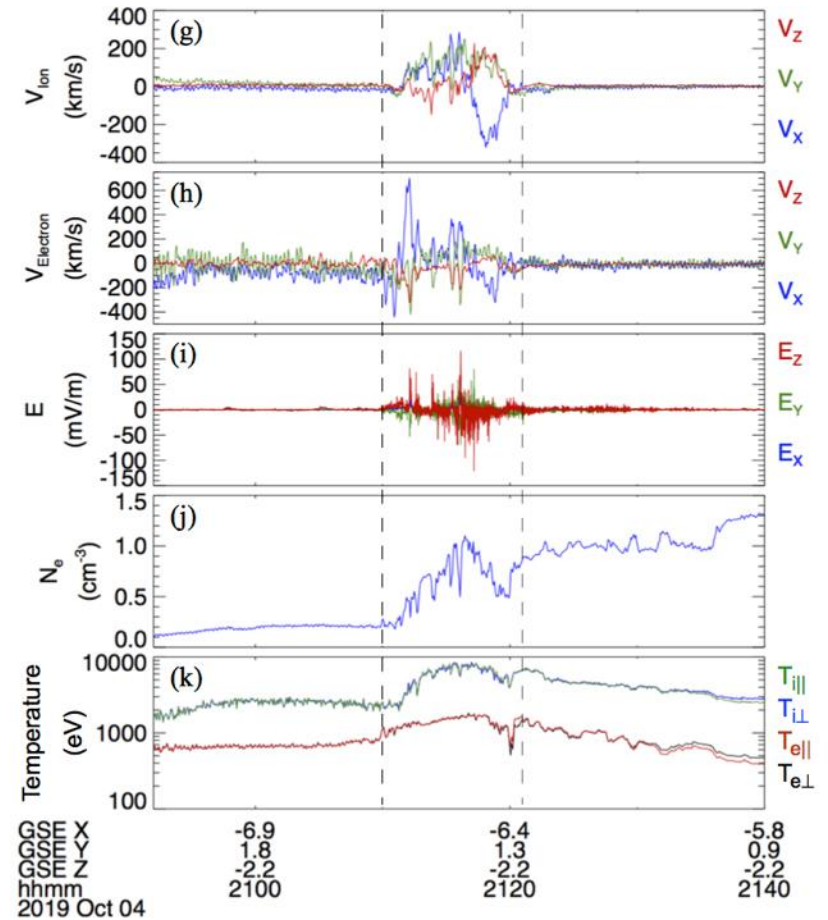
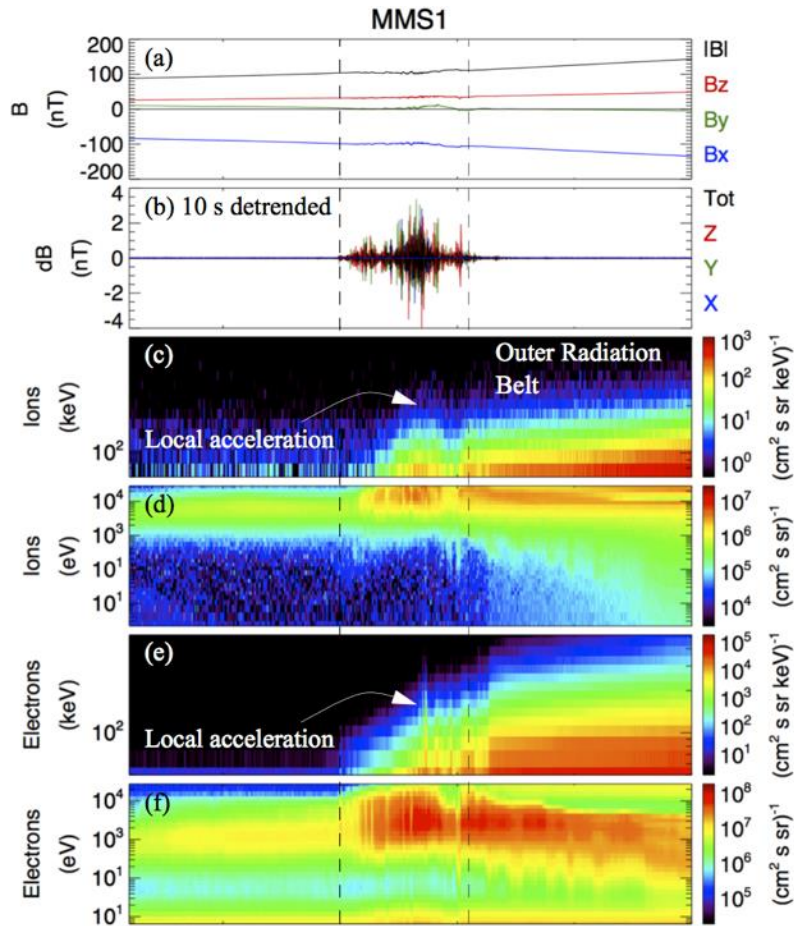
Prof. Robert Ergun
Email: ree@lasp.colorado.edu

Magnetotail Reconnection

Electron Acceleration

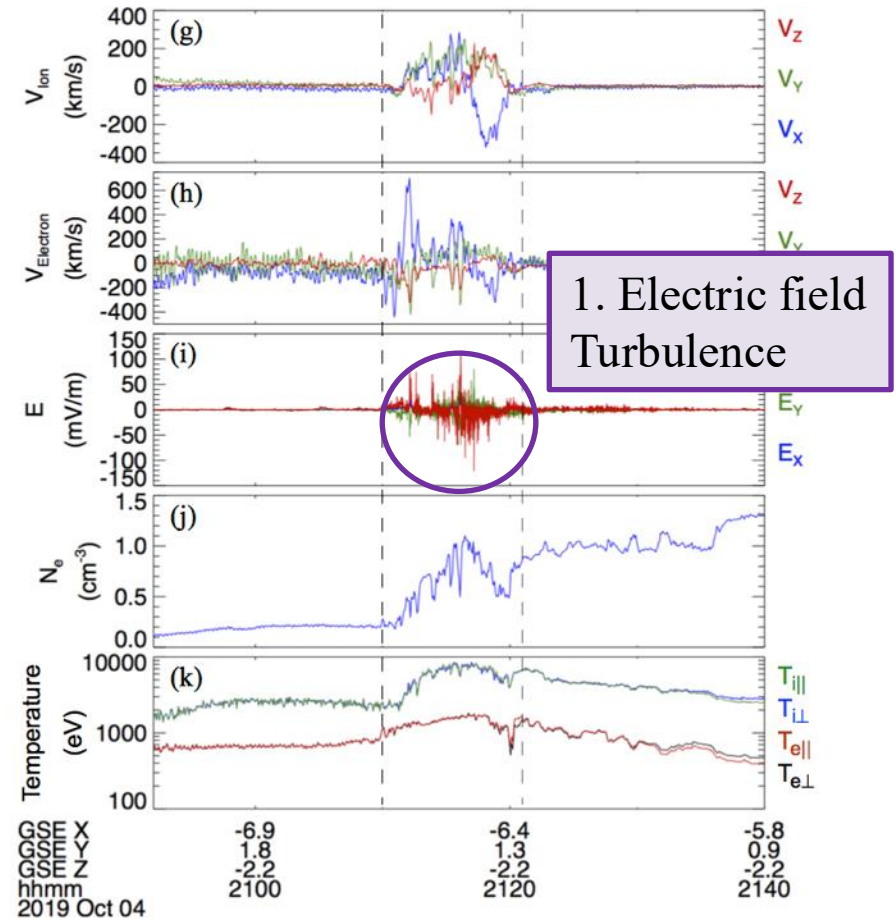
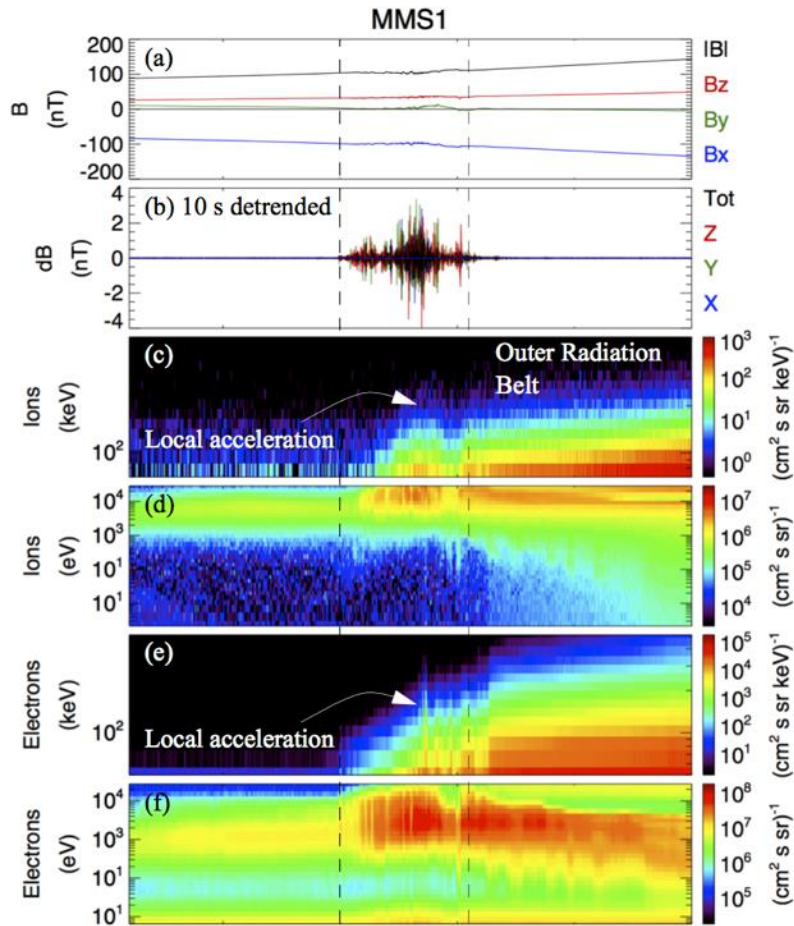
- Electron acceleration can be dominated by stochastic energization in strong turbulence, when present.
- Electron acceleration is a natural consequence of turbulence: higher-energy particles are first in line receiving dissipated energy.
- Electron acceleration in turbulence can be greatly amplified by trapping in a magnetic depletion.

Electron Acceleration: Near-Earth Event



Ergun, Usanova, et al., 2022; Usanova & Ergun, 2022

Electron Acceleration: Near-Earth Event

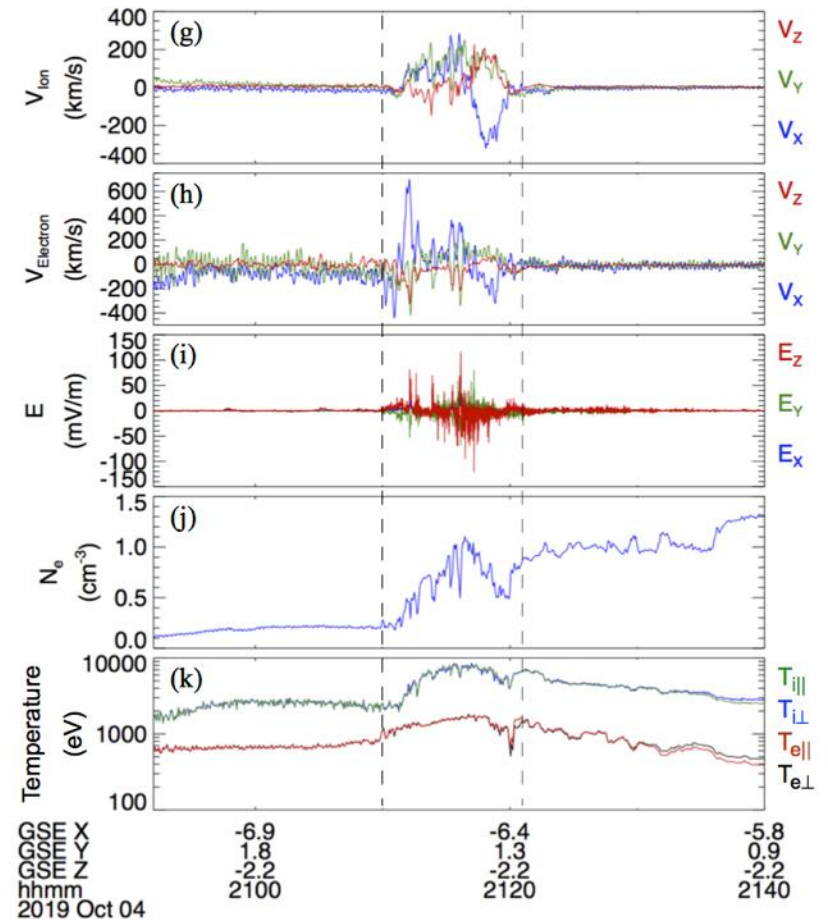
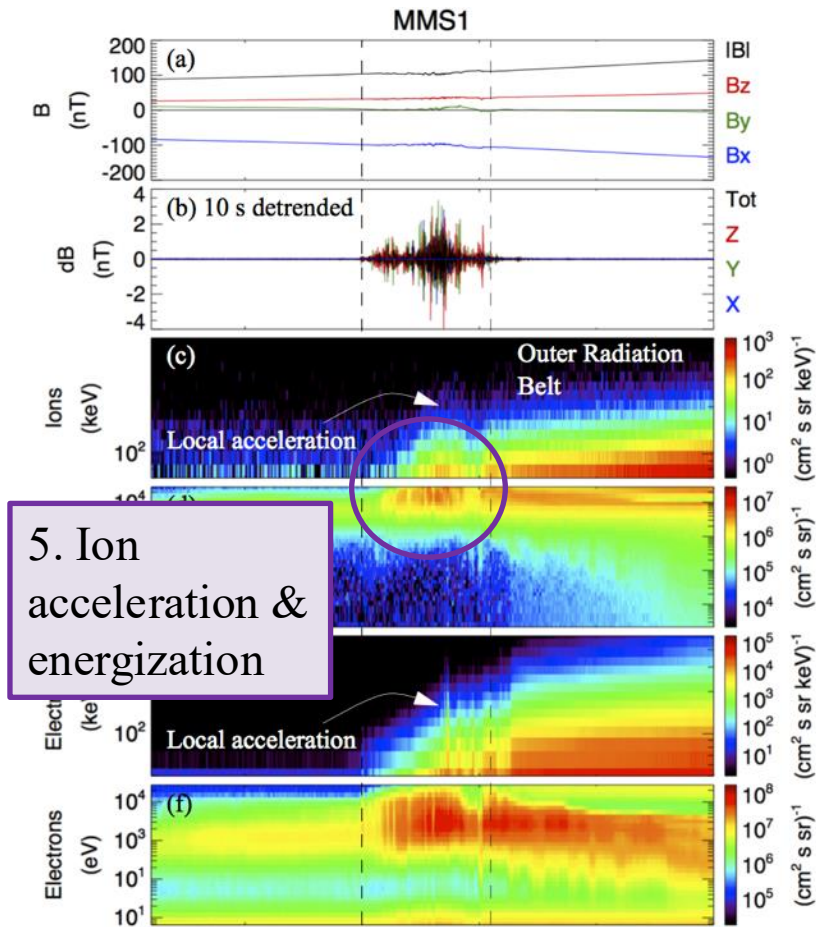


Ergun, Usanova, et al., 2022; Usanova & Ergun, 2022



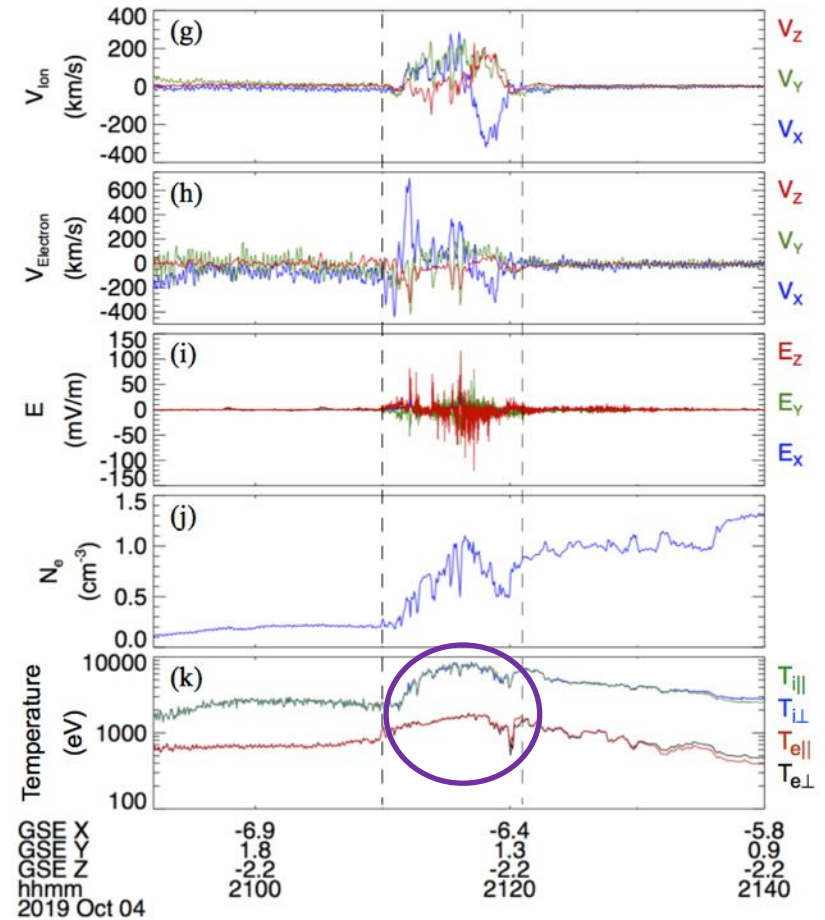
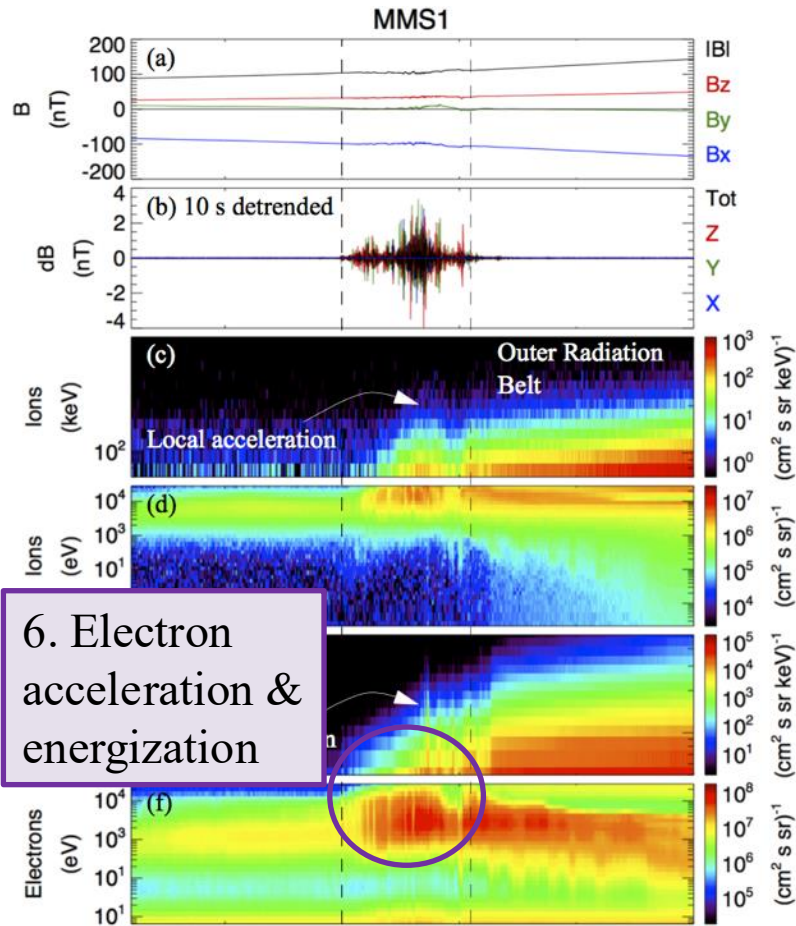
Ergun, Usanova, et al., 2022; Usanova & Ergun, 2022

Electron Acceleration: Near-Earth Event



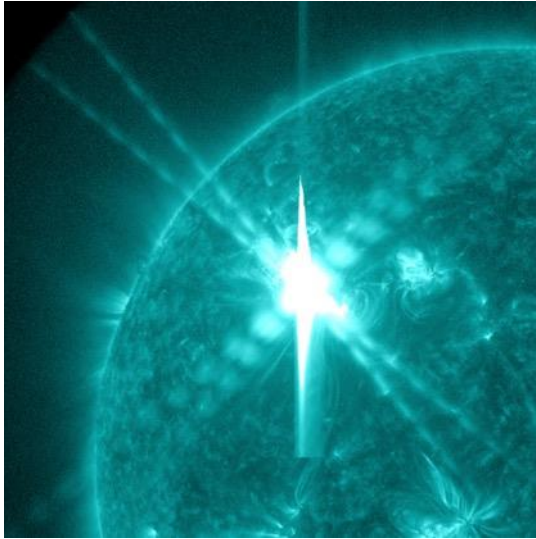
Ergun, Usanova, et al., 2022; Usanova & Ergun, 2022

Electron Acceleration: Near-Earth Event

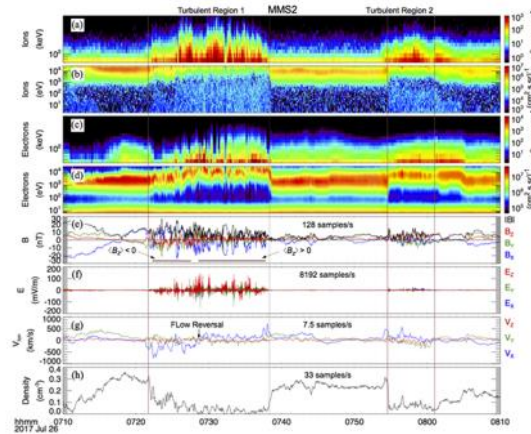


The Physics Part of Heliophysics

Magnetic Reconnection



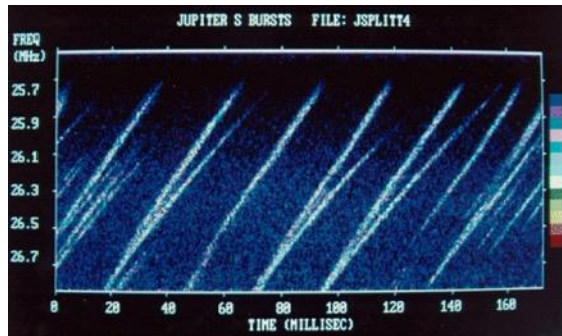
Turbulence



Particle Acceleration



Radio Emissions



Solar and Stellar Winds



Shocks

