Imperial College London

Basic plasma physics

SPAT PG Lectures

Imogen Gingell & Julia Stawarz

16-20 October 2017

Aims

- Provide new PhD students in SPAT and the SPC section with an overview of the most important principles in space plasma physics, as necessary to understand the different research activities the group (and section) undertakes in this area.
- Provide background information for the remaining space PG lectures which will make use of many of the concepts introduced here
- ATMOS students: to enable you to fully understand and appreciate space research presented in e.g. group talks, having been introduced to key terminology and concepts.
- SPACE students: to refresh your memory, provide revision activities, and a starting point for more in depth self-study, tailored to the demands of your specific research area.

Imperial College London

Intended outcomes

After these lectures you will be better able to

- *Know* what a plasma is, *appreciate* why knowledge of plasma physics is necessary for space physics, and *explain* the concept of collective plasma behaviour
- *Recall* key plasma parameters and their definition, and *perform* quantitative calculations
- *Describe* the nature of different plasma models, specifically single particle motion and magnetohydrodynamics
- *Know* the concept of frozen in flux, and *know* its importance for understanding space physics phenomena and the formation of structure
- *Describe* and *understand* the concept of Alfven waves
- *Describe* and *understand* the concept of magnetic reconnection

Imperial College London

Structure

Monday 1:30pm – 3:00pm

Part 1: Introduction. What is a plasma?

Part 2: Single particle motion

Tuesday 1:30pm – 3:00pm

Part 3: Magnetohydrodynamics (MHD)

Part 4: Waves and magnetic reconnection

Friday 2:00pm – 3:00pm

Problem sheet solution/discussion

Part 0: Who am I? Who are you!?

Imperial College London

Part 1: Introduction. What is a plasma?

Basics

What is a plasma?

- According to the Concise Oxford Dictionary, a plasma is ‘a gas of positive ions and free electrons with little or no overall electric charge’.
- A plasma exhibits collective behaviour in response to electric and magnetic forces

Examples?

Solar wind
Magnetosphere
Planetary ionospheres
Corona
Fusion plasmas: JET, MAST, ITER…

Imperial College London

What is plasma made of?

- Physically, plasma contains ionised atoms and molecules, enough to feel the effects of electric and magnetic fields
  - Partially ionised plasma?
  - Completely ionised plasma?

- Space plasmas
  - solar wind etc: H^+ (He^{++})
  - Earth's magnetosphere: H^+, (O^+)
  - Jupiter's magnetosphere: S^+

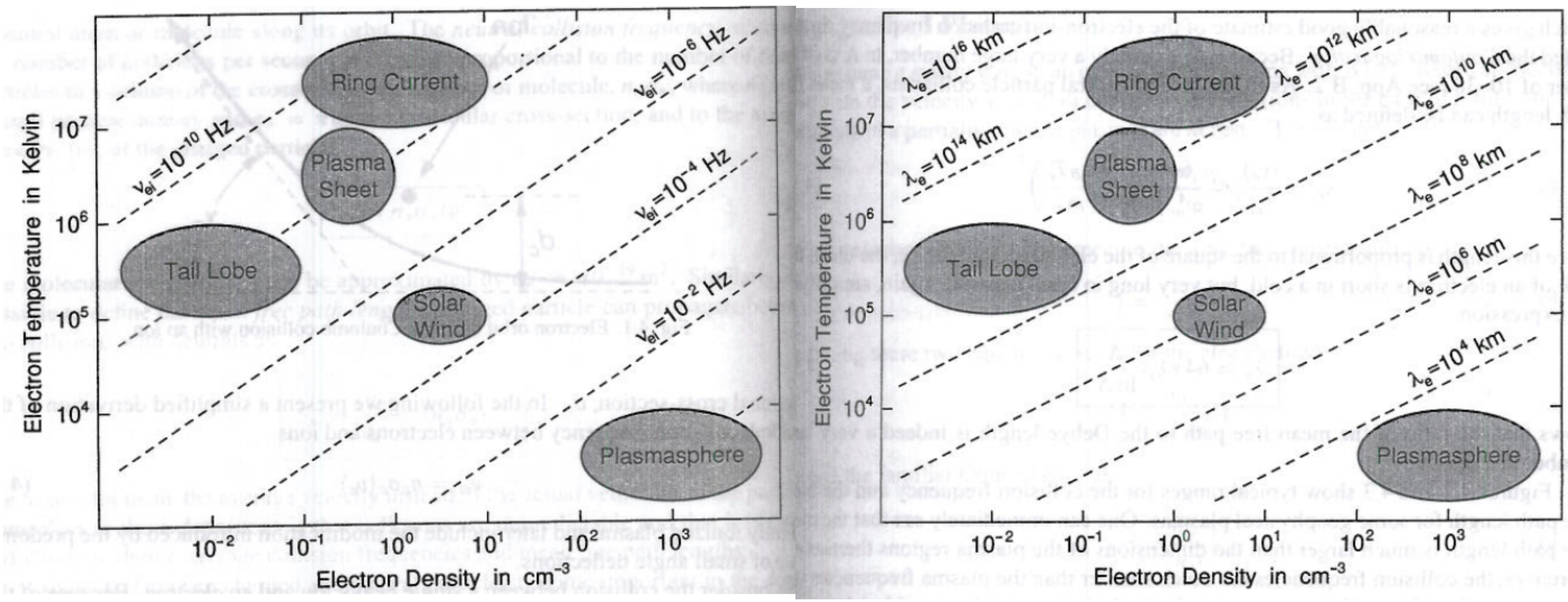
- Plasmas are neutral on 'large scales' because of their collective behaviour

- Neutral fluids are mediated by collisions…

Particle collisions

Space plasmas are very rarified: particle collisions are rare & mean free paths are long

(Figures from Baumjohann and Treumann, 1997)



Electric and magnetic forces ensure collective behaviour, even in ‘collisionless’ plasmas

Collective behaviour #1: quasineutrality

Debye shielding

An isolated excess charge +Q attracts a cloud of electrons that shield it

Potential of a point charge +Q in vacuum:

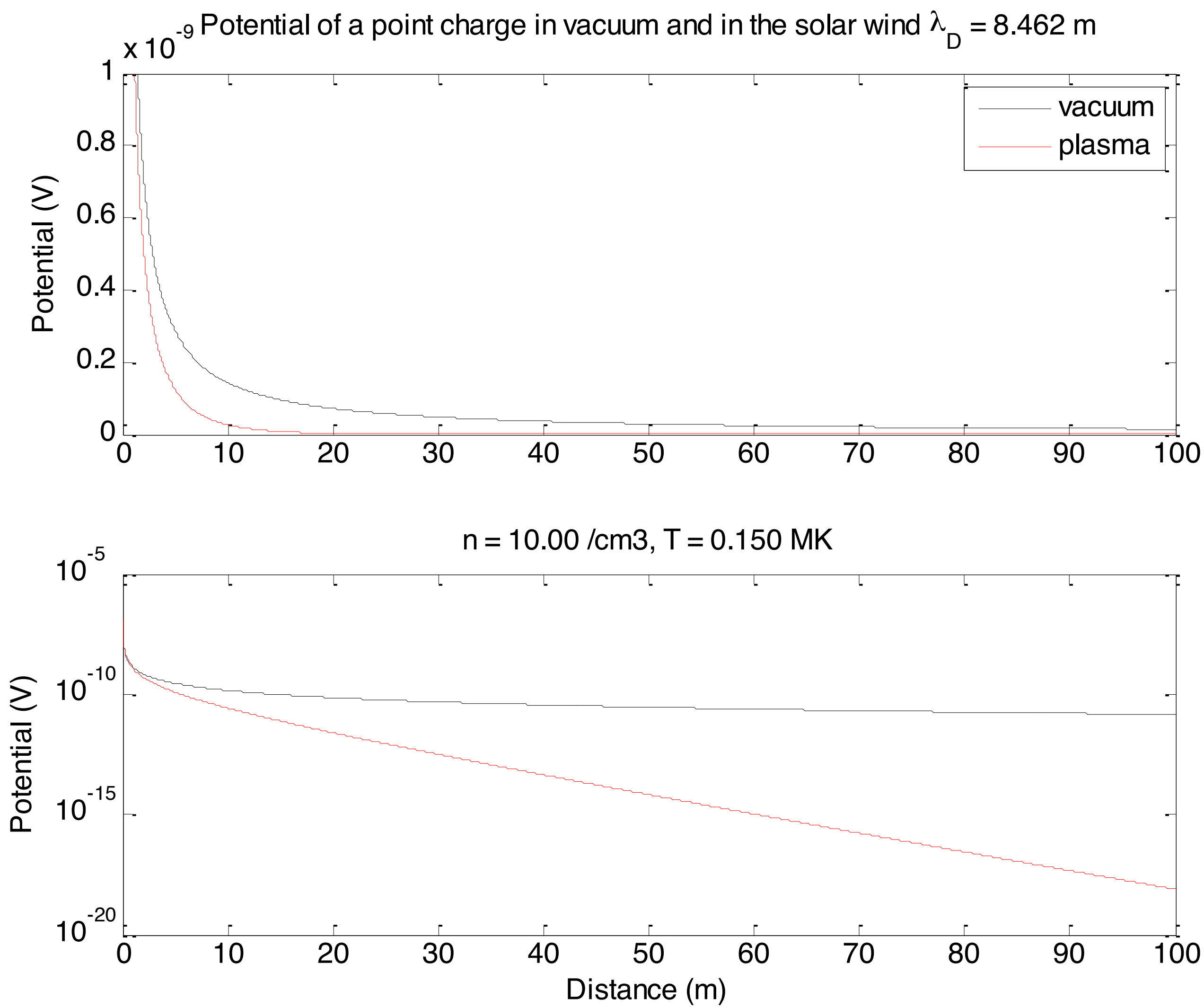
$$\varphi = \frac{Q}{4\pi\varepsilon_0 r}$$

Potential of a point charge +Q in a plasma:

$$\varphi = \frac{Q}{4\pi\varepsilon_0 r} \times \exp\left(-\frac{r}{\lambda_D}\right) \qquad \lambda_D = \sqrt{\frac{\varepsilon_0 k_B T}{e^2 n_0}}$$

Imperial College London

Debye shielding calculations

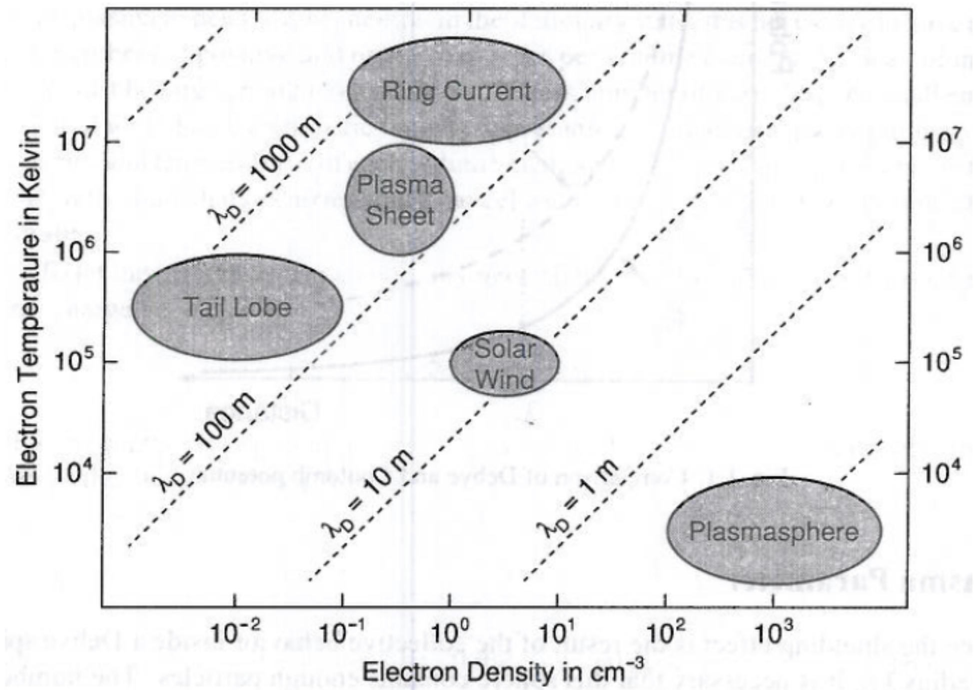


Imperial College London

Debye shielding

How many particles do you need for Debye shielding to work?

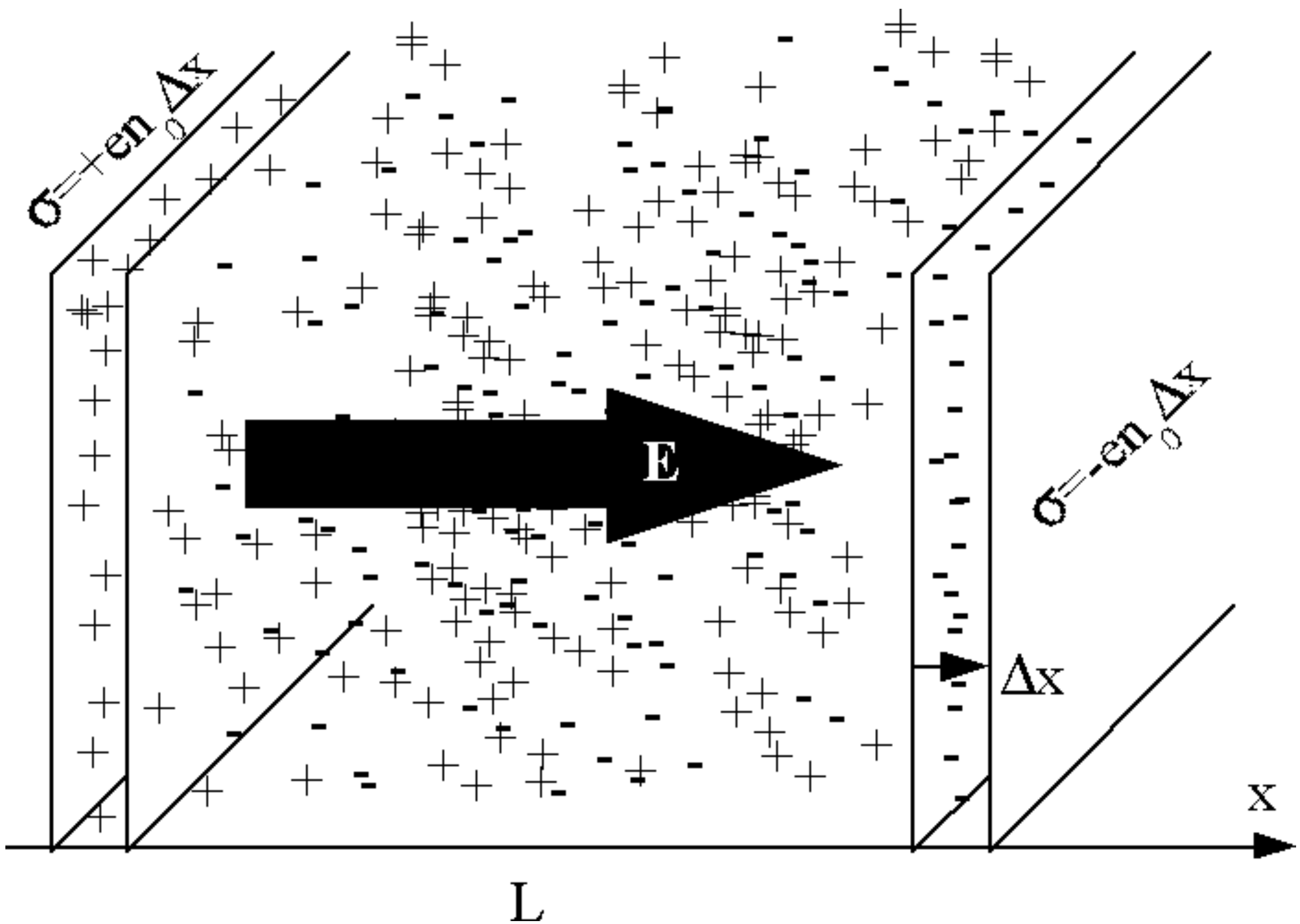
$N_D = n_0 \lambda_D^3 >> 1$



Plasmas are overall charge neutral on scales >> λ_D

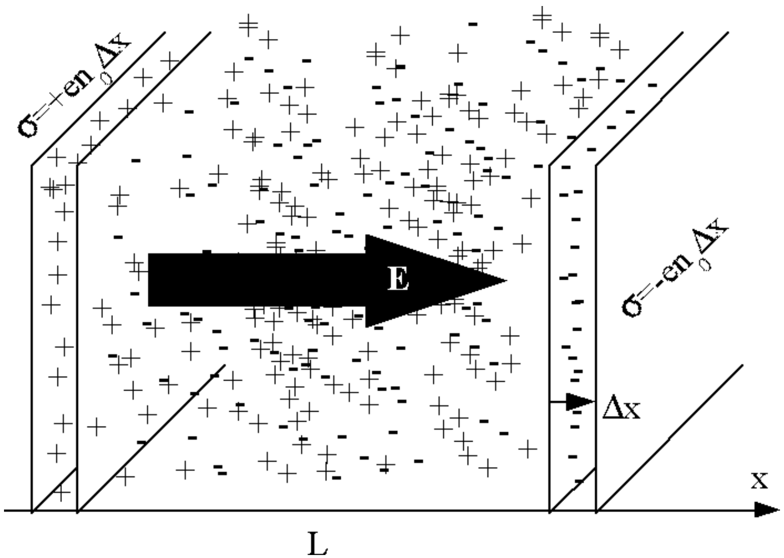
Imperial College London

Collective behaviour #2: plasma oscillations



Imperial College London

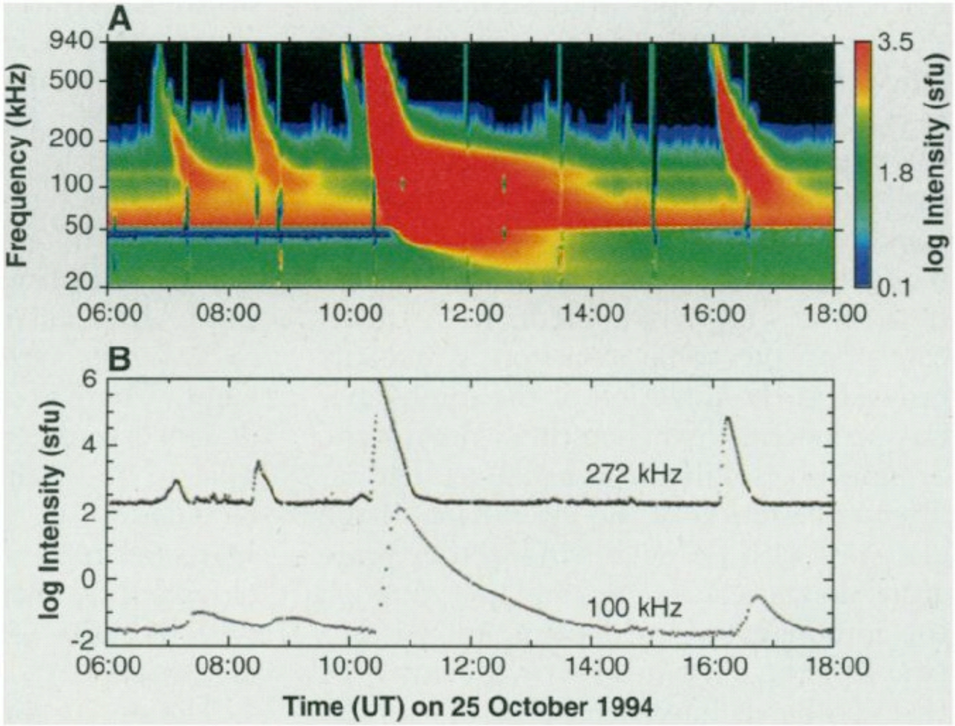
Electron plasma oscillations

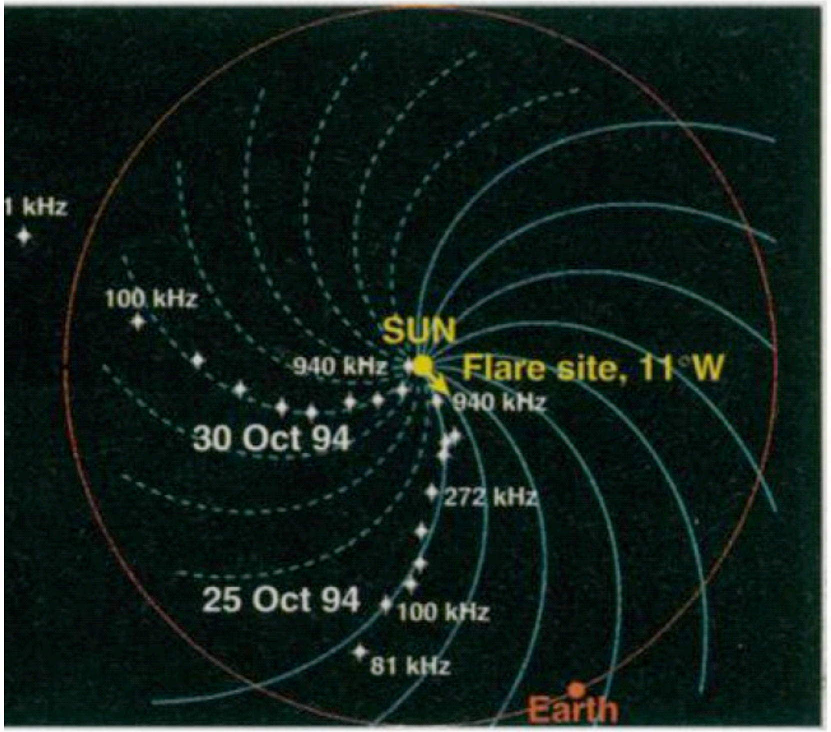


- Displacements give rise to restoring forces
- $\omega = \omega_0 = \sqrt{n_0 e^2 / m_e \varepsilon_0}$
- Independent of wavelength
- Depends only on density

Imperial College London

Plasma oscillations in space





Reiner et al., Large scale interplanetary magnetic field configuration revealed by solar radio burst, Science, 1995

'Juno, welcome to Jupiter': Nasa probe makes history as it enters into gas giant's orbit after epic 1.8 BILLION mile journey

- **Nasa probe finally reached the gas giant early this morning after a five-year, 1.8 billion-mile journey from Earth**
- **The spacecraft successfully carried out a braking manoeuvre enabling it to drop into a wide orbit around Jupiter**
- **Unlocking how the planet formed may help us to understand how Earth and the rest of the solar system developed**

By RYAN O'HARE and ELLIE ZOLFAGHARIFARD FOR MAILONLINE

PUBLISHED: 04:55, 5 July 2016 | **UPDATED:** 02:20, 6 July 2016

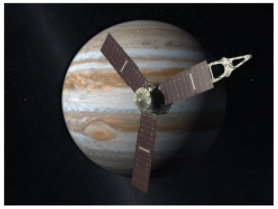
The solar-powered spacecraft which left Earth five years ago has made history by entering into Jupiter's orbit.

Nasa's Juno probe fired its main rocket engine at 4.18 am BST (11.18pm ET), slowing itself down from a speed of

Imperial College London

http://www-pw.physics.uiowa.edu/juno/audio/

Juno Waves
Audio Clips

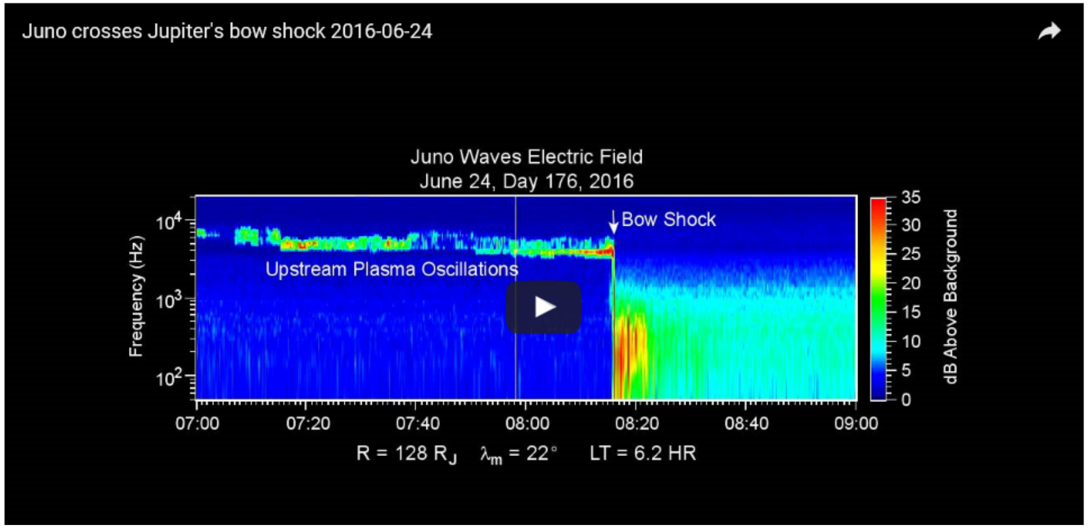


The Juno Waves instruments detect electric and magnetic components of plasma waves and radio waves that range through frequencies that include those audible to humans. Although these differ from the pressure waves that we normally think of as sound, they can be used to drive speakers and produce sounds we can hear.

Contact: William Kurth.

This video requires flash or html5.

Featured Juno Audio



12 September 2013 Last updated at 19:11

Share

Jonathan Amos
Science correspondent
More from Jonathan | Follow Jonathan on Twitter

Voyager-1 departs to interstellar space

COMMENTS (37)

It's the relentless question that Voyager-1 scientists get asked all the time: "Are we nearly there yet?"

I myself have asked it three times of Ed Stone this past year.

When I sat down with the mission's project scientist in California in August 2012, his response was much the same as always: "My best estimate is that it will be in the next couple of years, but it may be in the next couple of days. It's unknown."

Not anymore. As we chatted on that hot summer day, Voyager-1 was actually just a "couple of weeks" from crossing into interstellar space.

Data gathered by the Plasma Wave Science (PWS) instrument on Voyager has now prompted the team to announce the exit occurred on 25 August 2012

More from Jonathan

Riding a 'bucking bronco' in space

'Supermodel' Goce set for re-entry

'First starlight' instrument ready

Mars rover celebrates a year of discovery

Top Stories

The land of hope is Tory - Cameron

Man detained for random bus stabbing

Berlusconi U-turn on confidence vote NEW

Labour demands apology from Mail

Obama cuts Asia trip over shutdown

Features

The argument gene
Do people get all their opinions from their parents?

Lowering the bar
Al-Qaeda brings in new members and affiliates

Living costs quiz
Do you know how much everyday goods cost?

Imperial College London

Voyager 1 evidence: plasma oscillations!

Gurnett et al., Science, 341, 1489, 2013 (12 September 2013 published online)

In Situ Observations of Interstellar Plasma with Voyager 1

D. A. Gurnett,[1*] W. S Kurth,[1] L. F. Burlaga,[2] N. F. Ness[3]

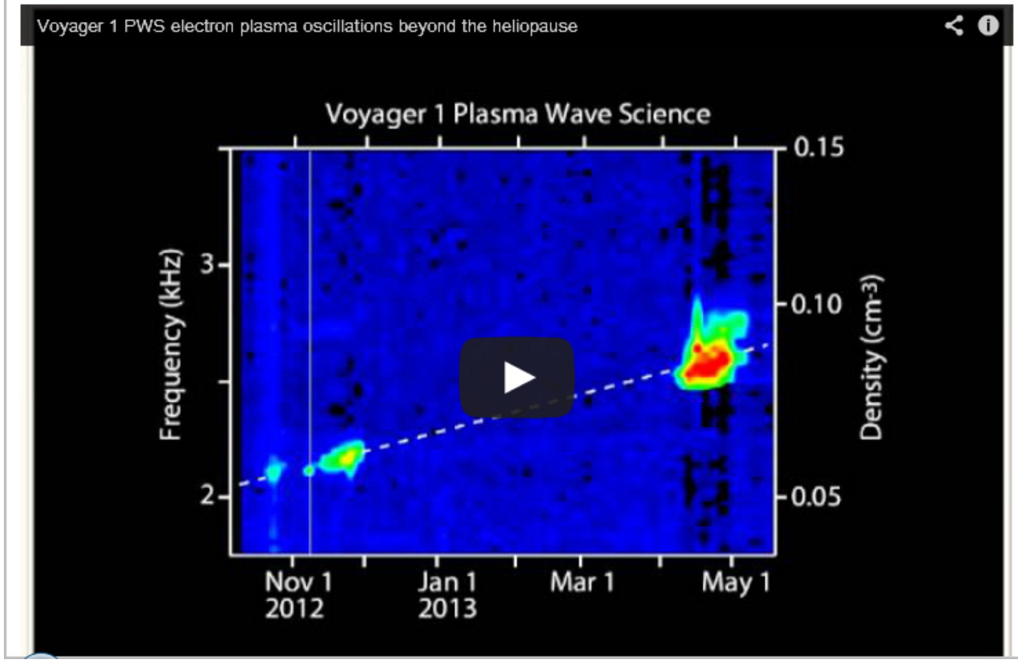
Launched over 35 years ago, Voyagers 1 and 2 are on an epic journey outward from the Sun to reach the boundary between the solar plasma and the much cooler interstellar medium. The boundary, called the heliopause, is expected to be marked by a large increase in plasma density, from about 0.002 per cubic centimeter (cm^{-3}) in the outer heliosphere, to about 0.1 cm^{-3} in the interstellar medium. On 9 April 2013, the Voyager 1 plasma wave instrument began detecting locally generated electron plasma oscillations at a frequency of about 2.6 kilohertz. This oscillation frequency corresponds to an electron density of about 0.08 cm^{-3}, very close to the value expected in the interstellar medium. These and other observations provide strong evidence that Voyager 1 has crossed the heliopause into the nearby interstellar plasma.

Sonification of Voyager 1 plasma data

VOYAGER-1 PWS:
ELECTRON PLASMA OSCILLATIONS BEYOND THE HELIOPAUSE

Voyager PWS
The University of Iowa

This video requires flash or html5.



Part 2: Single particle motion

Single particle motion

A great deal of insight can be gained by examining the behaviour of a single particle in applied electric and magnetic fields

This particle could be a special ‘test particle’ (e.g. a energetic proton)

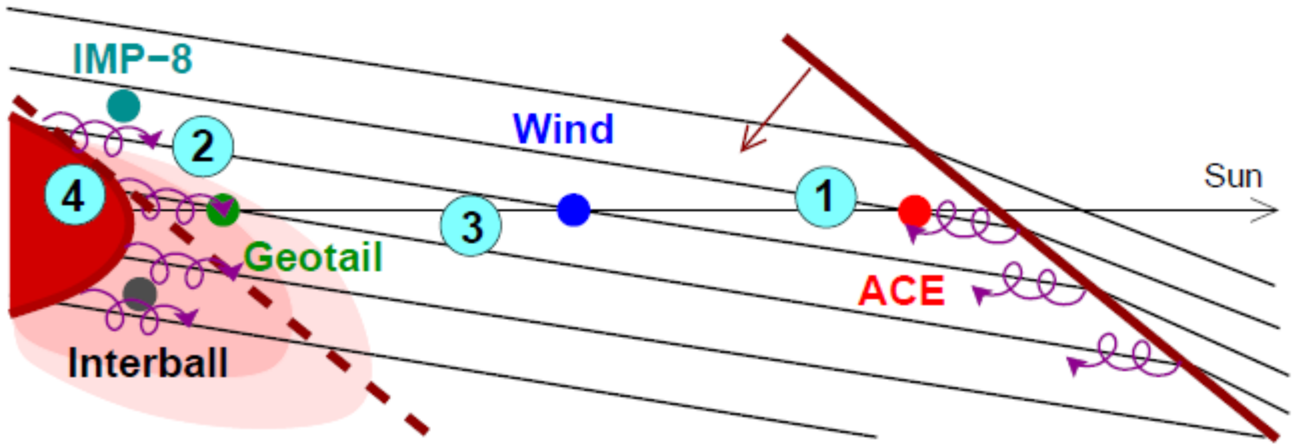
Or representative of the general plasma population

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

$$\mathbf{F} = m\, d\mathbf{v}/dt$$

Imperial College London

Example of test particle calculations – shock acceleration



1. seed population accelerated by the IP shock
2. reacceleration by the bow shock + radio emissions
3. acceleration of trapped particles as the shocks approach each other
4. acceleration and release as the shocks collide

Hietala *et al.*, JGR (2011); ApJL (2012).

Single particle motion #1: uniform magnetic field only

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

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

Parallel motion: v_{par} = constant

Perpendicular motion:

Gyromotion $mv_{perp}^2/R = qv_{perp}B$

Lamor radius: $R_L = mv_{perp}/|q|B$

Cyclotron frequency: $\Omega_C = qB/m$

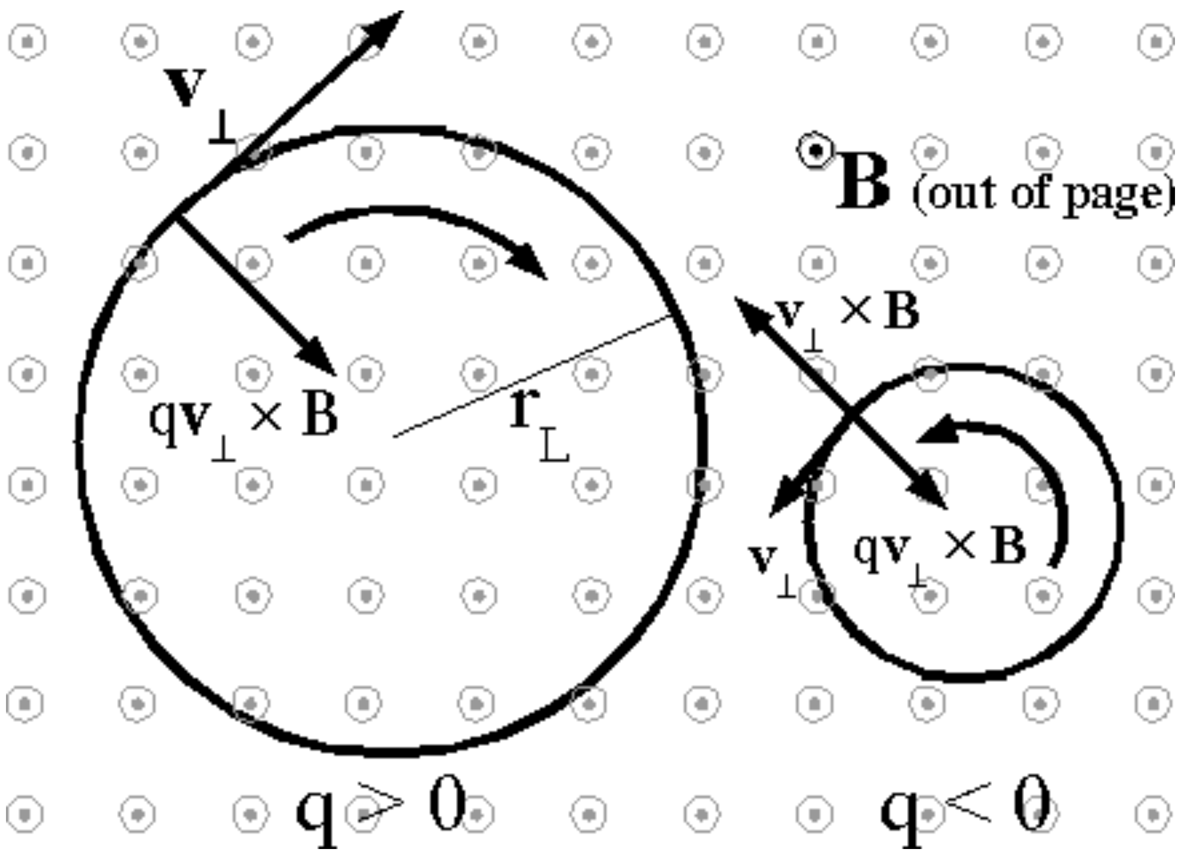
Which way do ions and electrons gyrate?

Ions (positive): left handed

Electrons (negative) right handed

Imperial College London

Cyclotron motion



Single particle motion #1: uniform magnetic field only

Constant motion along field

+

Gyration about the field

=

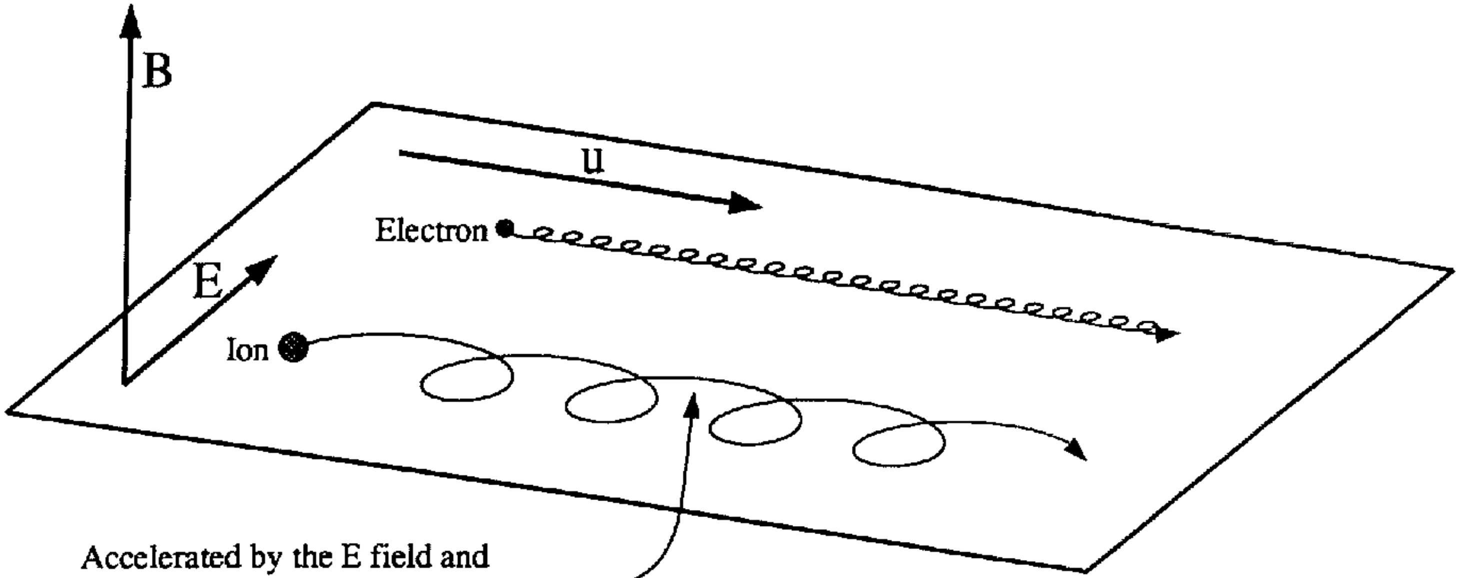
Helical particle motion

Implication: particles tied to field lines

Definition: Pitch angle = $\tan^{-1} v_{perp}/v_{par}$

Single particle motion #2: uniform electric & magnetic field

- All particles drift in the same direction
- Change frame: can remove the electric field and the particles undergo simple gyromotion



Imperial College London

Single particle motion #2: uniform electric & magnetic field

Parallel

$$m\, d\mathbf{v}_{par}/dt = q\mathbf{E}_{par}$$

Perpendicular

$$\mathbf{v}_{perp} = (\mathbf{E} \times \mathbf{B})/B^2$$

Summary:

- a parallel electric field accelerates the particle along the field line
- a perpendicular electric field causes particle drift perpendicular to the field line
- **E x B drift is a very important concept**

Single particle motion #3: general force + magnetic field

For a general force on a particle, we can use the **ExB** result, since **F** = q**E**

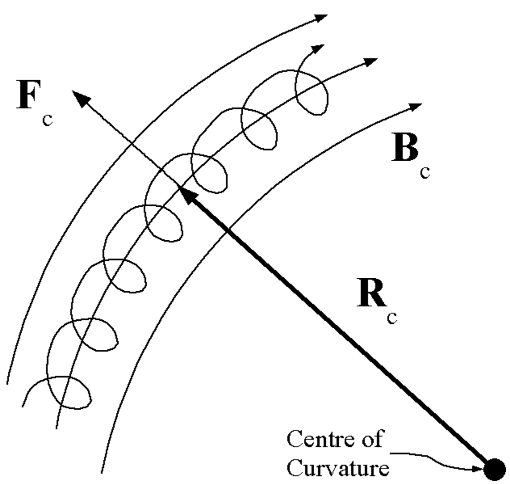
A general force F will lead to a particle drift v_D where $\mathbf{v}_D = \mathbf{F}\times\mathbf{B}/qB^2$

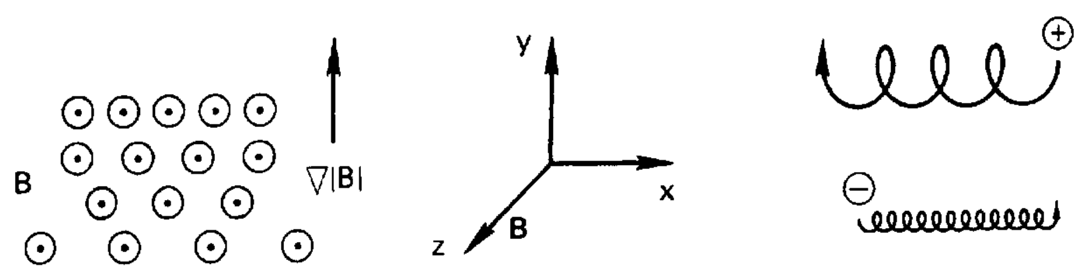
Curvature drift:

$\mathbf{F}_C = m(v_{par})^2/R_C \; \mathbf{R}_C$

Gradient drift:

$\mathbf{v}_D = m(v_{perp})^2/2qB^3 \; (\mathbf{B}\times\nabla|\mathbf{B}|)$





Imperial College London

Magnetic mirrors

$$\mu_M = m v_{perp}^2 / 2B$$

μ_M is the magnetic moment of the particle (current x area)

The magnetic moment is an adiabatic invariant

Constant of the motion if conditions are slowly varying

Slowly varying means $L \gg R_L$, $T \gg 1/\Omega_C$

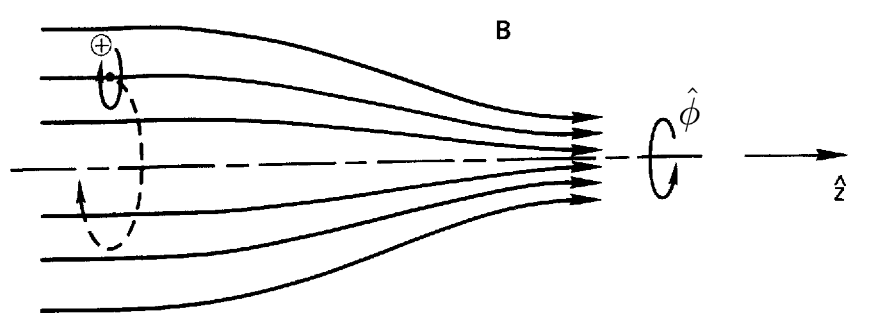
Magnetic mirrors

$$\mu_M = m(v_{perp})^2 / 2B$$

Since μ_M is constant, if the magnetic field strength increases then the perpendicular velocity increases

Velocity is conserved, so the parallel velocity decreases

Can trap a particle in a 'magnetic bottle'



Magnetic mirrors exist in space

SPACE .COM

Like 775k +1 Fo

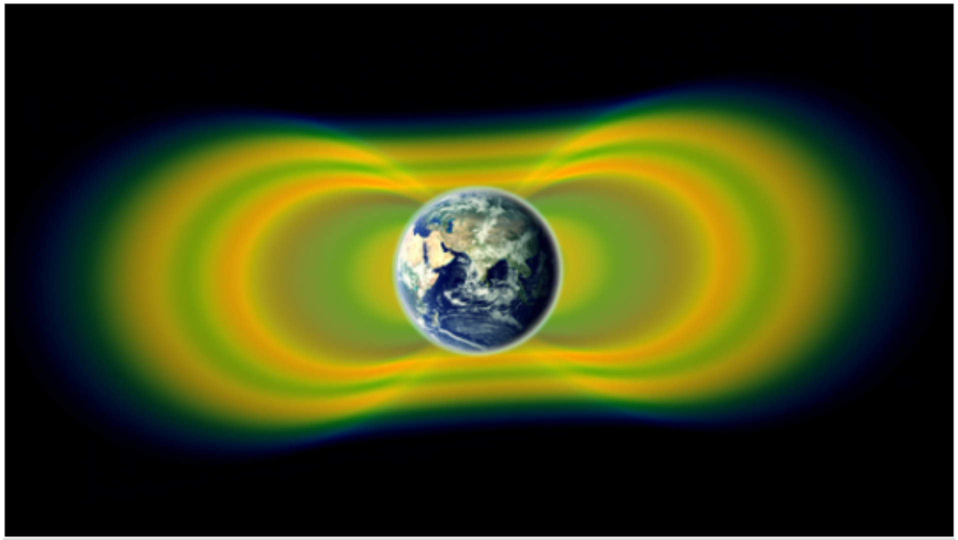
TECH SPACEFLIGHT SCIENCE & ASTRONOMY

TRENDING: Comet ISON // Skywatching Guide // Mars Rover Curiosity // Solar Flares // Space P

NASA Discovers New Radiation Belt Around Earth

by Charles Q. Choi, SPACE.com Contributor | February 28, 2013 02:01pm ET

26 Share
0 Tweet
2 Share
1 Share



Two giant swaths of radiation, known as the Van Allen Belts, surrounding Earth

Pin it

Imperial College London

Part 3: Magnetohydrodynamics (MHD)

Imperial College London

Magnetohydrodynamics (MHD)

- MHD = fluid dynamics + electrodynamics
- Treats the plasma as a single conducting fluid (ignore the ions and electrons).
- Simplest plasma model
- The equations can be derived from kinetic theory. We will not do this here.
- Many assumptions…

Imperial College London

Assumptions

- Long scale lengths
    - Scale lengths are much bigger than the Debye length
    - In fact, scale lengths much bigger than the ion Lamor radius
    - We are therefore ignoring particle effects, plasma is a ‘juice’
- Slow speeds
    - No relativity
    - Velocities are much less than the speed of light
    - No displacement current
- Long time scales
    - The underlying plasma populations are Maxwellian (collisional)
- Quantification is based around the Alfven speed $V_A = B/\sqrt{\mu_0 \rho}$ (more later)

Imperial College London

Fluid equation #1: continuity equation

$$\partial\rho/\partial t = -\nabla\cdot(\rho\boldsymbol{u})$$

$$\partial\rho/\partial t = -\rho\nabla\cdot\boldsymbol{u} - \boldsymbol{u}\cdot\nabla\rho$$

$$(\partial/\partial t + \boldsymbol{u}\cdot\nabla)\rho = -\rho\nabla\cdot\boldsymbol{u}$$

$$D\rho/Dt = -\rho\nabla\cdot\boldsymbol{u}$$

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

Comment: if plasma is incompressible, div(**u**) = 0.

Fluid equation #2: momentum equation

m**a** = **F**

$$\rho D\boldsymbol{u}/Dt = -\nabla P + \boldsymbol{J}\times\boldsymbol{B}$$

Right hand side is force/volume

Since $\boldsymbol{J} = 1/\mu_0 \, \nabla\times\boldsymbol{B}$

$$\rho D\boldsymbol{u}/Dt = -\nabla(P + B^2/2\mu_0) + (\boldsymbol{B}\cdot\nabla)\boldsymbol{B}/\mu_0$$

Thermal pressure, magnetic pressure, and magnetic tension

The **plasma beta** is the ratio of magnetic to plasma pressure

Imperial College London

Fluid equation #3: energy equation

$$\frac{D}{Dt}\left(\frac{P}{\rho^{\gamma}}\right)=0$$

- Basically treat the plasma as adiabatic
- Energy equation can be considerably more complex – heat flow, radiation, joule heating…
- Can rewrite using continuity equation

$$\frac{DP}{Dt}=-\gamma P\nabla\cdot\boldsymbol{u}$$

Maxwell's Equations

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

$$\mu_0 \boldsymbol{J} = \nabla \times \boldsymbol{B} \Rightarrow \quad \nabla \cdot \boldsymbol{J} = 0$$

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

$$\nabla \cdot \boldsymbol{E} = \rho_q / \varepsilon_0 = 0$$

Comments: MHD assumes quasi-neutrality so $\rho_q = 0$

Because of quasineutrality, we can't use Gauss's law to describe the electric field – need another equation

Ohm's law

- Ohm's law connects the electromagnetic properties with the fluid properties.

$$\boldsymbol{E} = -\boldsymbol{u} \times \boldsymbol{B} + \boldsymbol{J}/\sigma$$

- This is the simplest form of Ohm's law.

- The ratio of the two terms on the right hand side is the magnetic Reynolds number R_M.

$$\frac{\boldsymbol{u} \times \boldsymbol{B}}{\boldsymbol{J}/\sigma} \sim \frac{uB\sigma}{B/(\mu_0 L)} \sim uL\sigma\mu_0 = R_M$$

- If $R_M >> 1$, can neglect the second term, and we have 'ideal MHD'

- $R_M >> 1$ in many space plasmas

Magnetic induction equation

This describes the evolution of the magnetic field

$$\partial \boldsymbol{B}/\partial t = \nabla \times (\boldsymbol{V} \times \boldsymbol{B}) + 1/\mu_0 \sigma \nabla^2 \boldsymbol{B}$$

Convection Diffusion

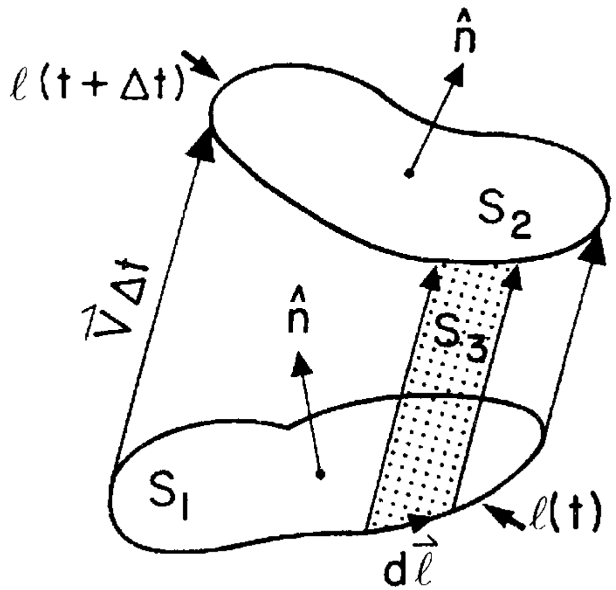
R_M = convection/diffusion

If $R_M >> 1$, there is no diffusion of the magnetic field through the plasma

If $R_M << 1$, the magnetic field diffuses rapidly.

Imperial College London

Flux freezing in ideal plasmas



(1) Fluid elements which lie initially on a field line remain on the same field line in a perfectly conducting fluid

(2) The magnetic flux through a surface bounded by a closed contour moving in a perfectly conducting fluid is constant.

- If the plasma expands, the field strength drops (visualised as a spreading out of the field lines).
- If the plasma moves transverse to the field its connection to other parts of the plasma via the magnetic field is unchanged.

Frozen in flux

In most regions of astrophysical plasma, magnetic diffusivity is low/ ‘infinite’ conductivity

- The magnetic field is said to be “frozen in”

This means:

- As the plasma evolves, it looks like the magnetic field lines are moving with the plasma
- If the plasma is compressed, the field lines move together and the field strength increases
- If the field lines bend, they exert a restoring force on the plasma

You can ascribe ‘identity’ to the magnetic field lines

Warning: the frozen in flux theorem is one of the most useful and misunderstood theories in plasma physics

Derivation – any plasma textbook, but see Dendy, 1900

Jim Dungey, J. Geophys. Res., 99, 19189, 1994

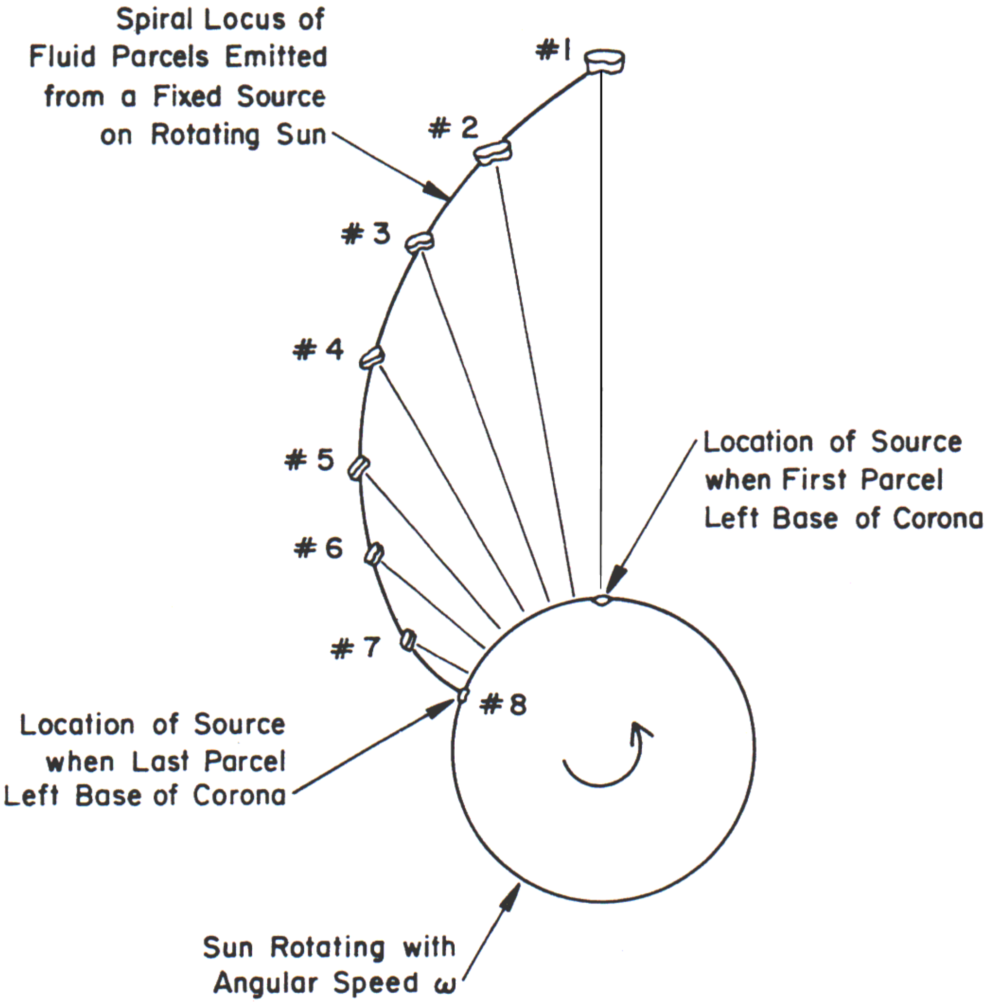
"The most attractive feature of MHD is the familiar 'frozen field' theorem. To any mathematician struggling with partial differential equations, this must seem like finding a priceless jewel, and it must be even more priceless to those who prefer pictures to equations."

The Parker spiral (Parker, Astrophys.J., 128, 664, 1958)

•Magnetic field frozen into plasma

•Solar rotation combined with radial solar wind expansion produces wound magnetic field

•Can trace the Parker spiral using plasma radio emissions.



Imperial College
London

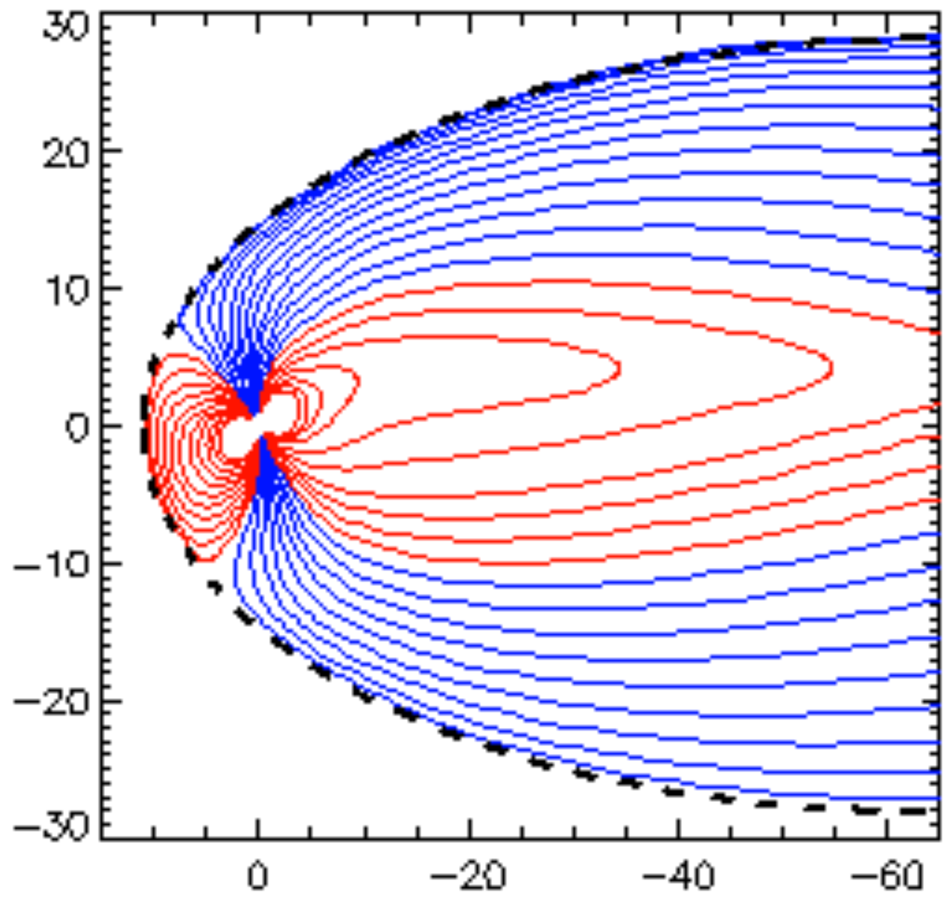
The Magnetopause

Different regions of plasma cannot interpenetrate

•The magnetopause separates solar wind and magnetosphere

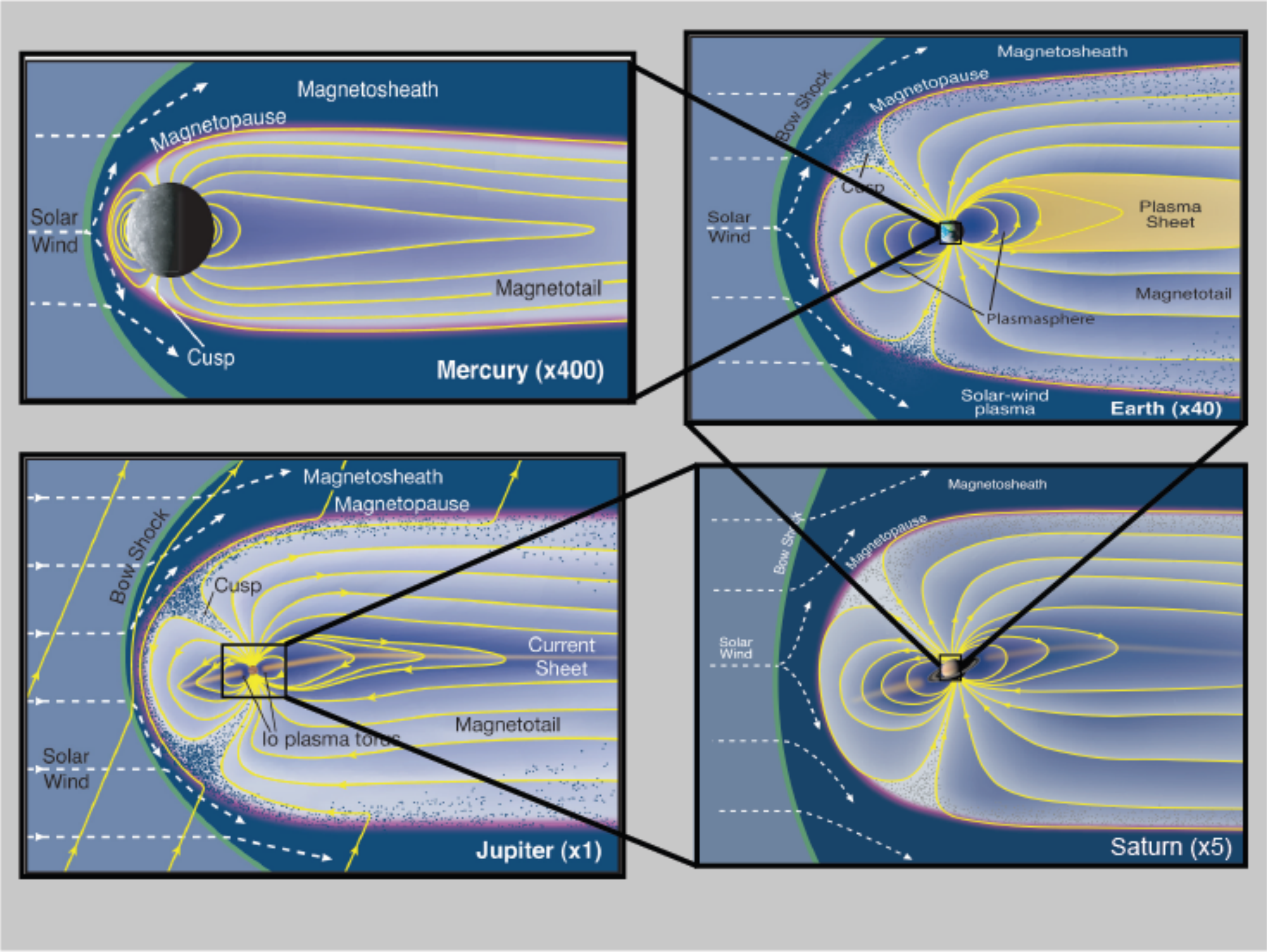
•Solar wind ram pressure balances magnetospheric magnetic field pressure (low beta)

•Consequence: the Earth's magnetic field carves a bubble in the solar wind



Imperial College London

Other planets have magnetospheres



Imperial College London

Concluding thoughts

- MHD is useful!!
  - It contains many important concepts
  - Things that occur in MHD often occur in real plasmas (in modified form)
  - e.g. waves exist, but they may be damped.

- It provides important insight into the behaviour of real space plasmas

- Because MHD is often tractable, it is used even when it is not strictly appropriate to do so
  - e.g. global simulations of the solar wind – magnetosphere interaction

- It does not explain many important phenomena
  - Wave particle interactions
  - Non thermal particles
  - Etc.

Imperial College London

Part 4: Waves and magnetic reconnection

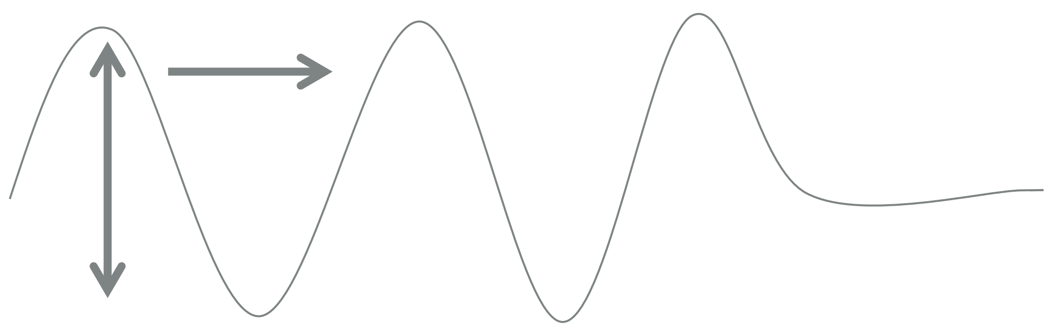
Alfvén waves

- Magnetic field lines behave as if they have a tension: Recall:

$$\rho D\mathbf{u}/Dt = -\nabla(P + B^2/2\mu_0) + (\mathbf{B}\cdot\nabla)\mathbf{B}/\mu_0$$

Thermal pressure, magnetic pressure, and magnetic tension

- Consider a massive string, tension T, and mass density/unit length ρ_0:



Alfvén waves

- If you shake the string, a wave will propagate, with speed v

$v = \sqrt{T/\rho_0}$

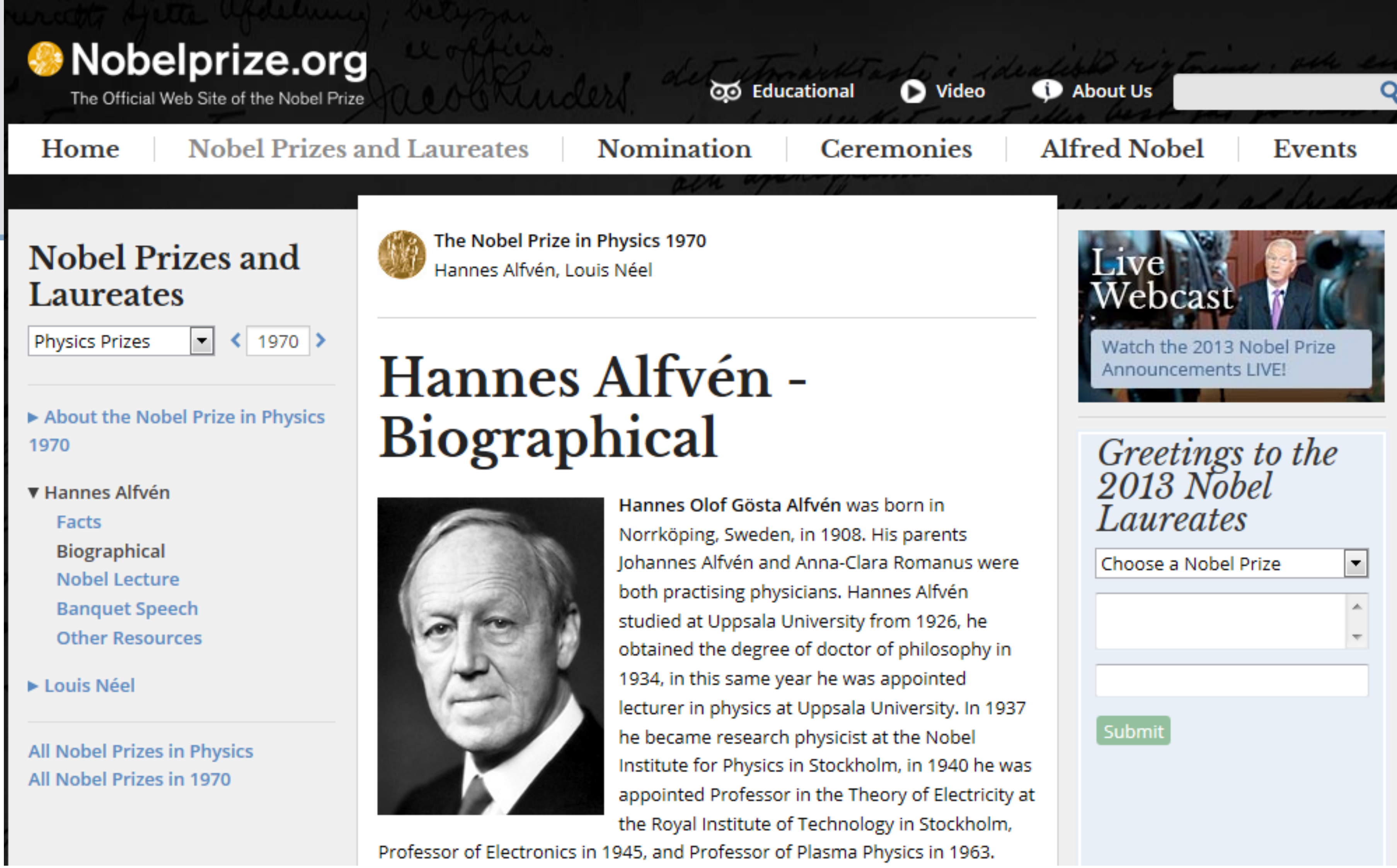
- By analogy, if the magnetic field tension is

$T = B^2/\mu_0$

- And the mass density is ρ_0 then

$V_A = \sqrt{B^2/\mu_0 \rho_0}$

- This magnetic tension wave is known as an **Alfvén wave.**



Citiation includes '…In particular, Alfvén discovered the existence of hitherto unsuspected magneto-hydrodynamical waves, the so-called Alfvén waves….'

Imperial College London

Derivation

We need four of the ideal MHD equations (cold plasma, P = 0)

$$D\rho/Dt = -\rho\nabla\cdot\boldsymbol{u}$$

$$\rho D\boldsymbol{u}/Dt = -\nabla(P + B^2/2\mu_0) + (\boldsymbol{B}\cdot\nabla)\boldsymbol{B}/\mu_0$$

$$DP/Dt = -\gamma P\nabla\cdot\boldsymbol{u}$$

$$\partial\boldsymbol{B}/\partial t = \nabla\times(\boldsymbol{V}\times\boldsymbol{B}) + 1/\mu_0\sigma\nabla^2\boldsymbol{B}$$

Derivation

Firstly, assume small perturbations $X = X_0 + X_1$

Secondly, examine properties of plane waves

$$X = X \exp(i(\boldsymbol{k} \cdot \boldsymbol{r} - \omega t))$$

This means that you can replace derivatives with:

$$\partial/\partial t \rightarrow -i\omega$$

$$\nabla \rightarrow i\boldsymbol{k}$$

Imperial College London

Linearised equations with plane wave solution

$$\rho_1 + \rho_0 \, \boldsymbol{k} \cdot \boldsymbol{u}_1 = 0$$

$$-\omega \rho_0 \, \boldsymbol{u}_1 = -\boldsymbol{k} (\boldsymbol{B}_0 \cdot \boldsymbol{B}_1 / \mu_0) + (\boldsymbol{k} \cdot \boldsymbol{B}_0 / \mu_0) \boldsymbol{B}_1$$

$$-\omega \boldsymbol{B}_1 = \boldsymbol{k} \times (\boldsymbol{u}_1 \times \boldsymbol{B}_0)$$

Two solutions: one is $\mathbf{k} \cdot \mathbf{u}_1 = 0$

It can be shown that $\mathbf{B}_0 \cdot \mathbf{B}_1 = 0$, and so with some work..

$$-\omega \rho_0 \, \boldsymbol{u}_1 = (\boldsymbol{k} \cdot \boldsymbol{B}_0 / \mu_0) \boldsymbol{B}_1$$

$$-\omega \boldsymbol{B}_1 = (\boldsymbol{k} \cdot \boldsymbol{B}_0) \boldsymbol{u}_1$$

Dispersion relation

$$\omega^2 - (\mathbf{k}\cdot\mathbf{B}_0)^2/\mu_0\rho_0 = 0$$

$$\omega^2 = (\mathbf{k}\cdot\mathbf{V}_A)^2$$

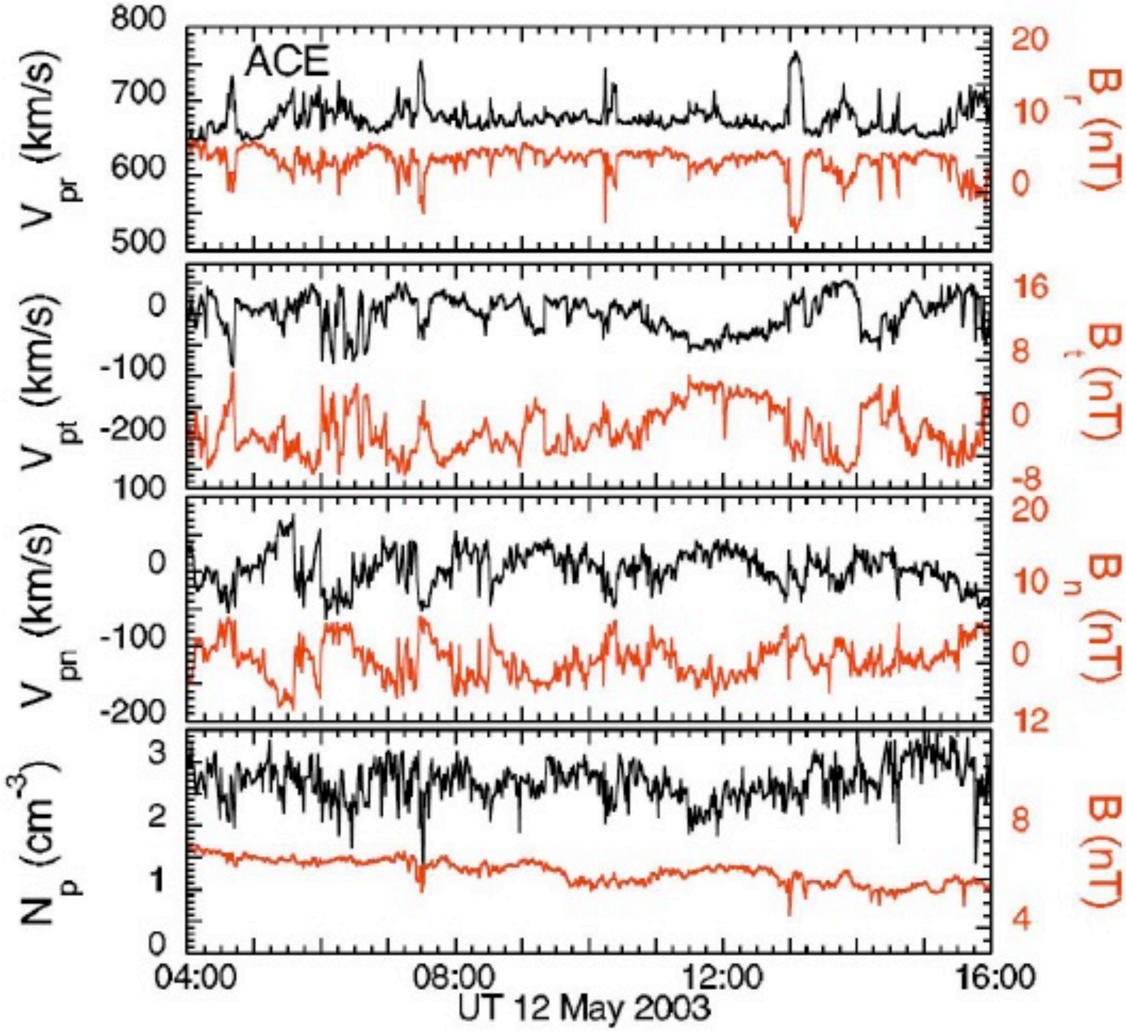
We have derived the dispersion relation of Alfvén waves in a cold ideal MHD plasma

Properties

- Incompressible
- Propagates along the field
- Driven by magnetic tension
- Perturbation is perpendicular to $\mathbf{B}_0$.
- Phase speed = group speed = V_A.

Gosling et al., Ap J., 695, L213, 1999

Alfvenic fluctuations in the solar wind



$$\frac{\delta B}{B_0} = -\frac{\delta v}{V_A}$$

Imperial College London

Magnetosonic waves

- Like ordinary sound waves, but have to account for the fact that there is both magnetic pressure and thermal pressure

$$\rho \frac{D\mathbf{u}}{Dt} = -\nabla\left(P + \frac{B^2}{2\mu_0}\right) + \frac{(\mathbf{B}\cdot\nabla)\mathbf{B}}{\mu_0}$$

Thermal pressure, magnetic pressure, and magnetic tension

Sound waves:

$$v = \sqrt{\gamma P/\rho}$$

Magnetosonic waves:

$$v = \sqrt{\gamma P/\rho + \frac{B^2}{\rho\mu_0}} = \sqrt{(C_S)^2 + (V_A)^2}$$

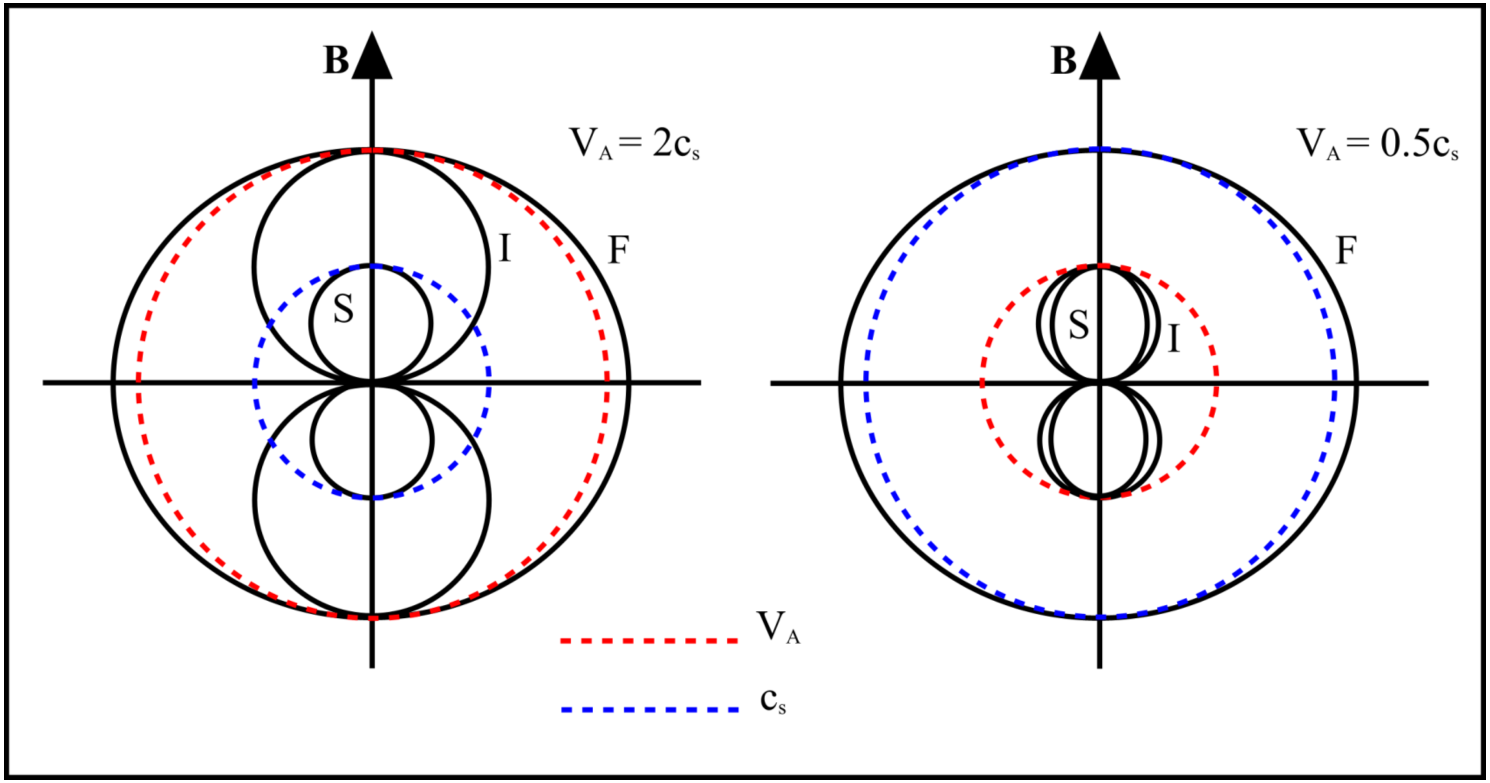
Warm single fluid MHD

- Wave properties found in same way as for cold MHD
  - Don’t neglect plasma pressure
  - Linearize waves
  - Apply plane wave solution
  - Derive dispersion relationship

$$\omega = \pm V_A k_{//} \qquad \omega^2 = \frac{k^2}{2}\left\{ c_{ms}^2 \pm \left[\left(V_A^2 - c_s^2\right)^2 + 4V_A^2 c_s^2 \frac{k_\perp^2}{k^2} \right]^{\frac{1}{2}} \right\}$$

- Intermediate wave = shear Alfvén wave
- Fast magnetosonic mode (thermal + magnetic pressure in phase)
- Slow magnetosonic mode (thermal + magnetic pressure out of phase)

Wave propagation properties



- Wave propagation is not isotropic
  - Intermediate always propagates at the Alfven speed along the field
  - Only the fast mode propagates perpendicular to the field
  - Group velocity is not the same as phase velocity (speed or direction)

Imperial College London

Magnetic reconnection a fundamental plasma process

In most regions of astrophysical plasma, magnetic diffusivity is low

- magnetic field is “frozen in”

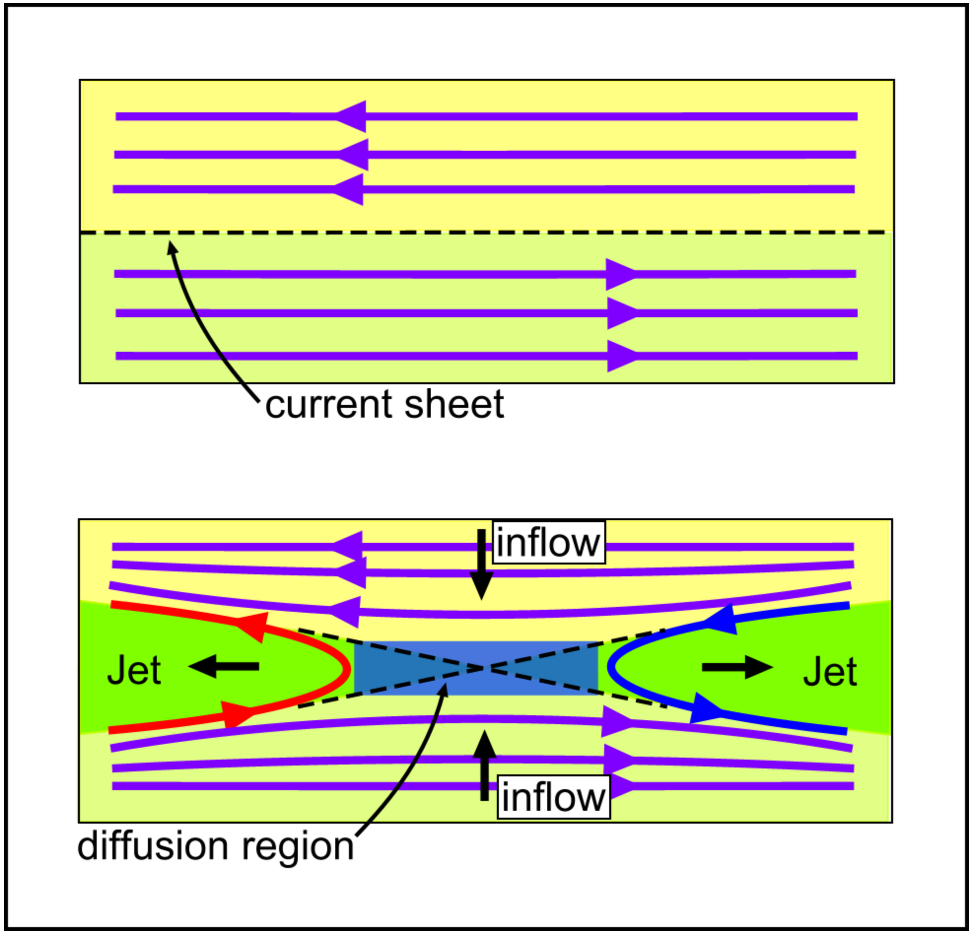
Different regions of plasma cannot interpenetrate

- boundary layers form
- magnetic energy can be stored

Magnetic Reconnection may occur within the boundary layer

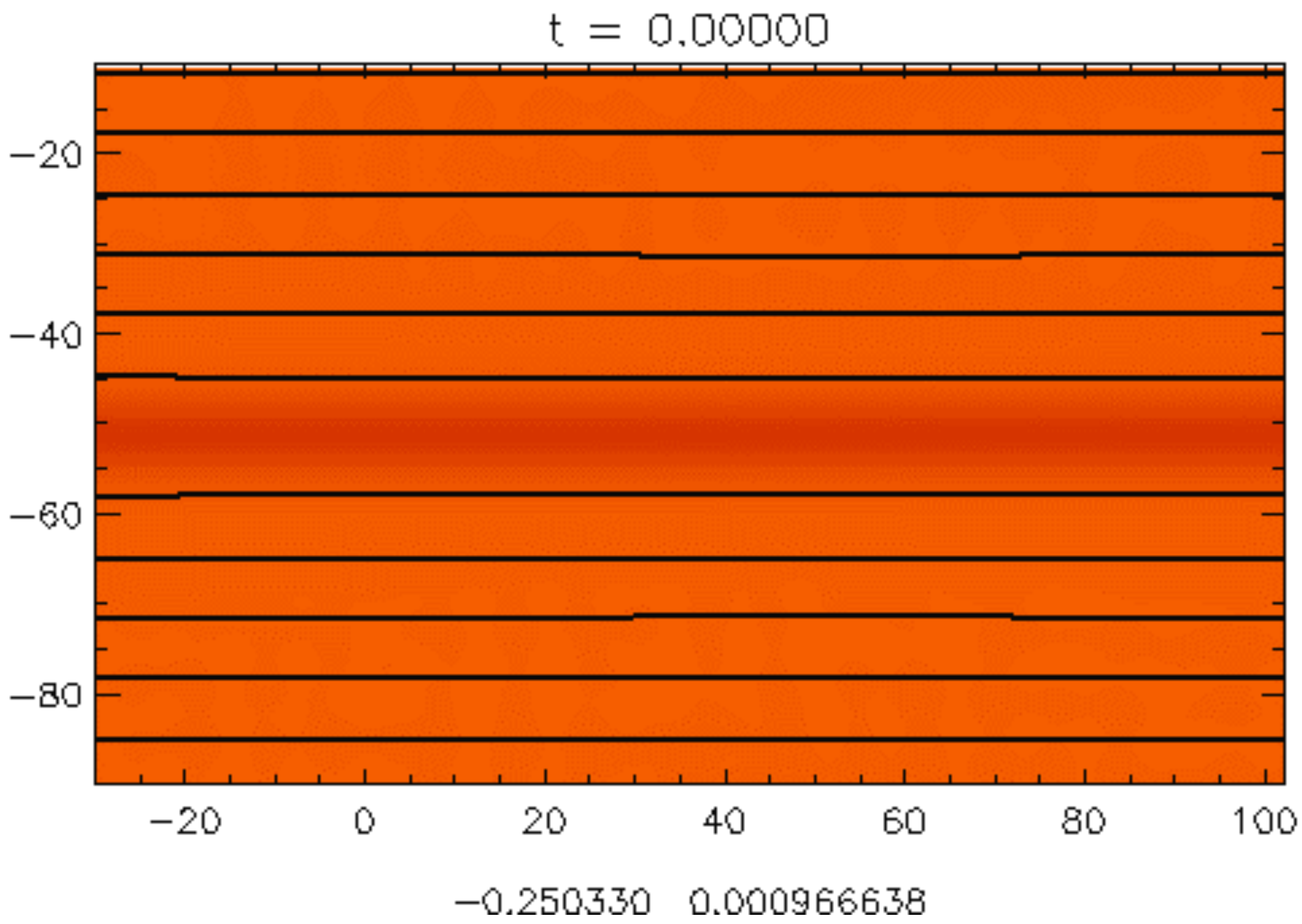
- Energy released
- Changed topology
- Particle acceleration

The central diffusion region plays a crucial role, because this is where the plasma demagnetises.



Imperial College London

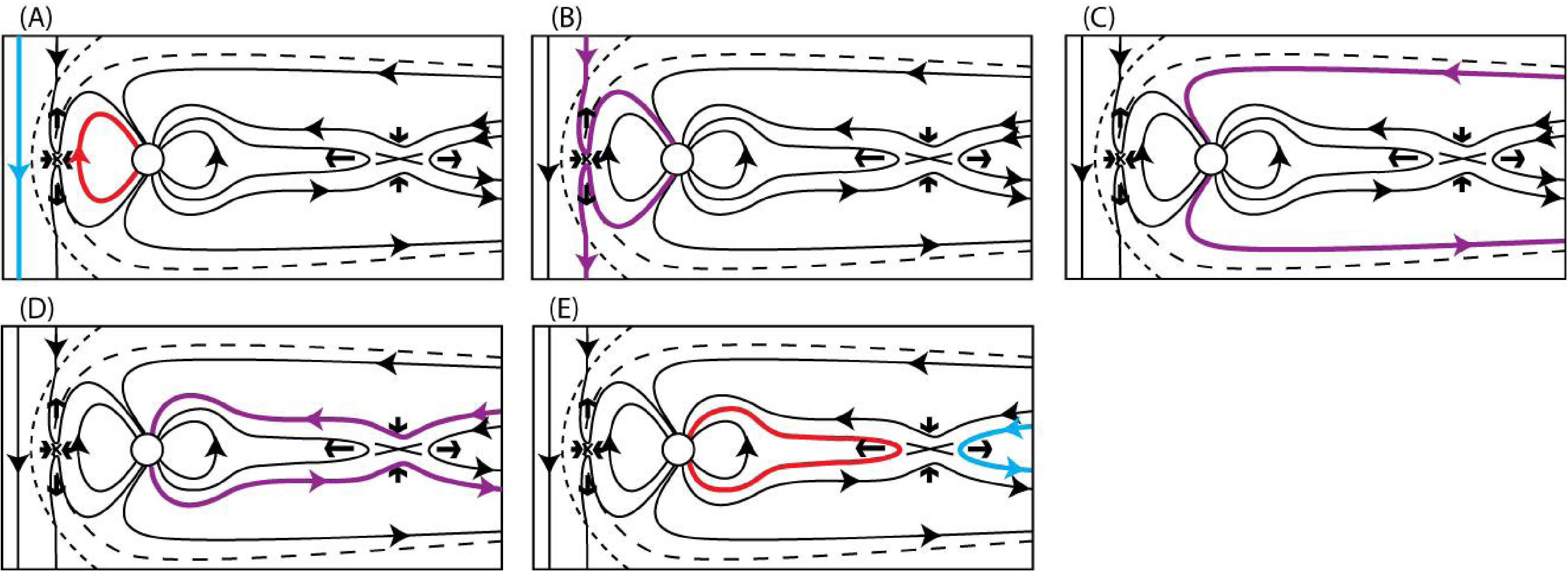
Computer simulation of magnetic reconnection



Simulation of magnetic reconnection (M Shay University of Delaware)

Imperial College London

The open magnetosphere



Imperial College London

The open magnetosphere – Dungey, 1961

PHYSICAL REVIEW LETTERS

VOLUME 6 JANUARY 15, 1961 NUMBER 2

INTERPLANETARY MAGNETIC FIELD AND THE AURORAL ZONES*

J. W. Dungey†
Ionosphere Research Laboratory, The Pennsylvania State University, University Park, Pennsylvania
(Received November 10, 1960; revised manuscript received December 22, 1960)

The discovery[1] of a regular interplanetary magnetic field by Pioneer V has reawakened interest in Hoyle's[2] suggestion that the primary auroral particles are accelerated at neutral points in the combination of an interplanetary field and the geomagnetic field. Hoyle pointed out that the latitude of the aurora would depend on the distance of the neutral points from the earth and hence on the interplanetary field strength in the observed sense. The estimated particle energy was also reasonable. Dungey[3] discusses the accelerating mechanism. Here a qualitative model of the whole field is outlined and is found to be confirmed by the observed S_D current system.

Consider a model with interplanetary plasma moving relative to the earth, this "wind" lying approximately in the ecliptic plane, and an interplanetary field pointing roughly southward. The problem with no interplanetary magnetic field has been studied by several authors,[4] but the inclusion of this field alters the problem radically. The basic and awkward problem is that of the flow of plasma round the earth. This has not been solved but will be sketched using the physical picture of hydromagnetics. The flow in a plane containing the neutral points is shown in Fig. 1. The flow near the neutral points is controlled by the strong current density existing there (3). The reverse flow between the neutral points is important; it has to flow round the earth, but does so in a normal aerodynamic way. A steady laminar flow will be assumed here for simplicity, but it should be noted that large variations of the field were detected by Pioneer I.[5] Denoting the local wind velocity by $\vec{u}$, the electric field $\vec{E}$ is approximately $-\vec{u}\times\vec{H}/c$ everywhere outside the ionosphere except near the neutral points. In a steady state $\vec{E}$ has a potential, which is constant on a line of force, with the same exceptions. Far from the earth $\vec{E}$ points out of the paper and the direction is still much the same near the neutral points and in the equatorial part of the region of reverse flow. In order to deduce the ionospheric currents, the topology of the magnetic field must be considered.

In Fig. 1 there will be two lines (not in the plane shown) connecting the neutral points and together forming an approximately circular closed curve C near the equatorial plane. The lines from one neutral point will cover a surface, topologically similar to half a cylinder, extending from C to infinity to the south and a surface like half a doughnut bounded by C and intersecting the earth's surface in a closed curve A in the northern hemisphere. The lines from the other neutral point complete the cylinder and doughnut and each neutral point has two lines on the other's surfaces. The cylinder and doughnut separate regions where lines of force have both, one, or no feet on the ground, the other ends going to infinity.

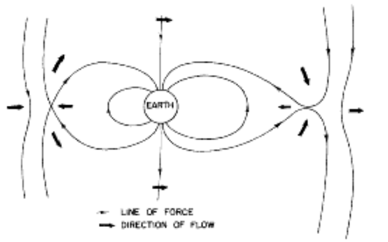


FIG. 1. Interplanetary plasma flow in a plane containing neutral points.

The plane of Fig. 1 is at constant potential by symmetry. Consider lines of force leaving the earth in a circle of longitude perpendicular to Fig. 1. The electric field fed in near the pole points out of the paper. Lines outside the curve A (that is, at lower latitude), however, pass through the equatorial plane and $\vec{E}$ here is out of the paper; following the potential up lines of force then gives a reversal of $\vec{E}$ at the curve A, because the lines from the equatorial plane have turned through more than 90°. Consequently the equipotentials in the ionosphere are as shown in Fig. 2. These equipotentials resemble the S_D current lines and the explanation is that Hall conductivity dominates in the ionosphere. Study of the conductivities σ_0, σ_1, and σ_2 in the ionosphere shows that the electric field will extend with only slight diminution down to the E layer, so that the integrated conductivity is appropriate and the current density is nearly perpendicular to $\vec{E}$. The phase of the current may be obtained by taking the direction of $\vec{j}\times\vec{H}$ at the pole to be opposite to that of $\vec{u}\times\vec{H}$ far out and then a wind from the sun fits the observations.

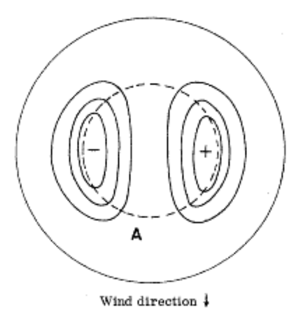


FIG. 2. Equipotentials in northern hemisphere for plasma winds of Fig. 1.

The fit with observed S_D suggests the truth of the model. S_D must involve currents in the ionosphere driven from outside and the sudden reversal at the auroral zone seems to require neutral points. If the interplanetary field is northward the topology is quite different, the surface of lines of force enclosing the earth but not meeting it. It is therefore concluded that there is an approximately southward field.

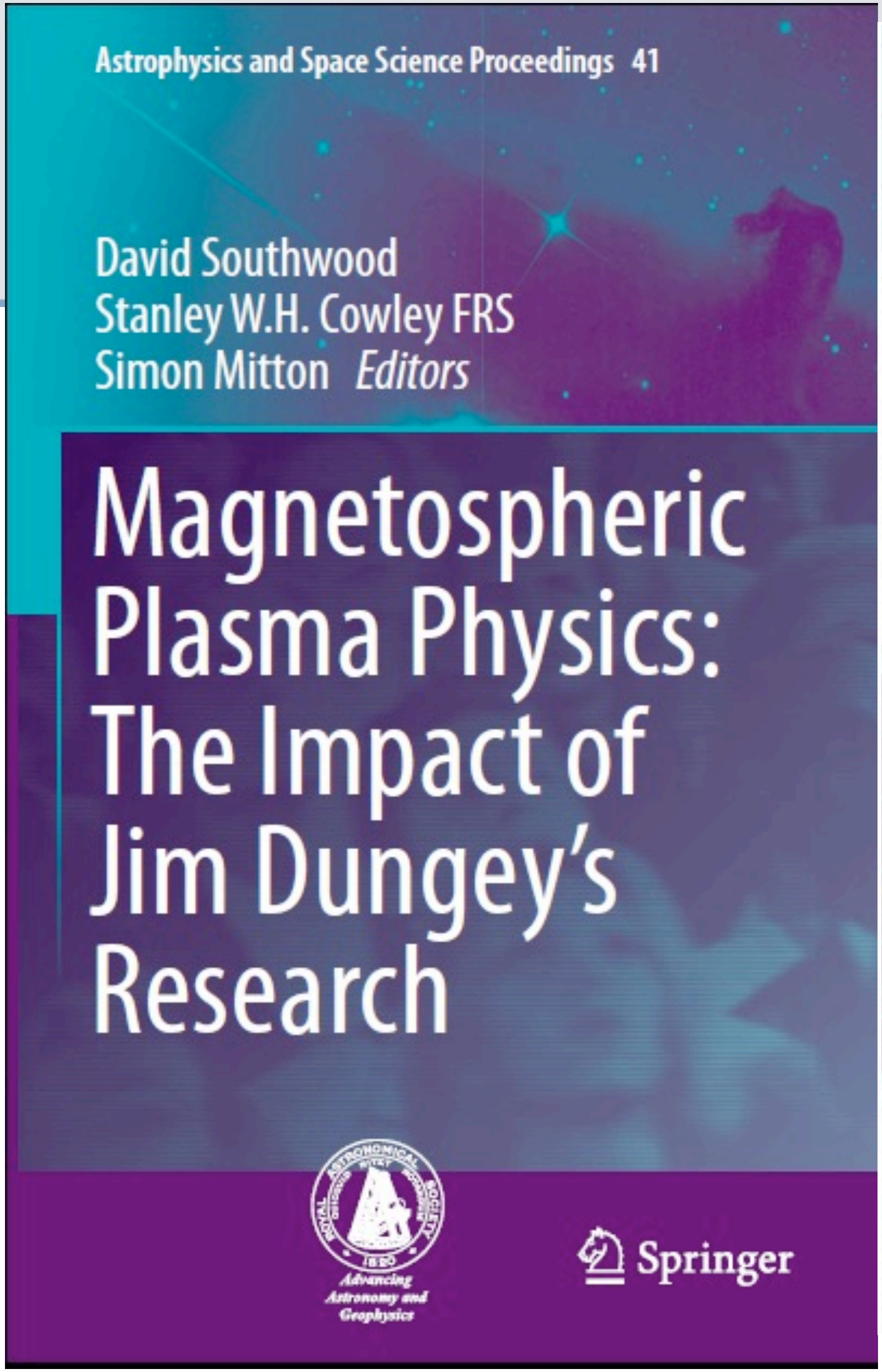
One consequence of the flow in Fig. 1 is a mixing of the interplanetary plasma into the outer atmosphere, which will upset the equilibrium under gravity which would exist in the absence of such a flow. The whistler data suggest that plasma is being lost far out.[6]

The connection between the neutral points and auroras is obvious in this model, but it remains to study the motion of individual particles and the effect of turbulence. The outer Van Allen belt also remains to be discussed; the return flow in Fig. 1 must not upset its symmetry about the geomagnetic axis. The model predicts an asymmetry for auroras: for a wind from the sun there should be proton auroras before midnight and electron auroras after midnight. Recent results[7] from IGY data are of great interest in connection with the model presented here and promise substantial advances in our understanding of the subject.

*The research reported in this work has been sponsored by the Geophysics Research Directorate of the Air Force Cambridge Research Center, Air Research and Development Command, and, in part, by the National Science Foundation.

†Present address: Atomic Weapons Research Establishment, Aldermaston, England.

[1]P. J. Coleman, Jr., L. Davis, and C. P. Sonnett, Phys. Rev. Letters 5, 43 (1960).
[2]F. Hoyle, Recent Researches in Solar Physics (Cambridge University Press, New York, 1958), Sec. 27.
[3]J. W. Dungey, Cosmic Electrodynamics (Cambridge University Press, New York, 1958), Secs. 6.4 and 8.4.
[4]D. B. Beard, J. Geophys. Research 65, 3559 (1960).
[5]C. P. Sonett, Phys. Rev. Letters 5, 47 (1960); C. P. Sonett, E. J. Smith, and A. R. Smith, Proceedings of the First International Space Sciences Symposium, edited by H. K. Kallman Bijl (North Holland Publishing Company, Amsterdam, 1960), p. 921.
[6]R. L. Smith and R. A. Helliwell, J. Geophys. Research 65, 2583 (1960).
[7]T. N. Davis, J. Geophys. Research 65, 3497 (1960).


Astrophysics and Space Science Proceedings 41
David Southwood
Stanley W.H. Cowley FRS
Simon Mitton Editors
Magnetospheric Plasma Physics: The Impact of Jim Dungey's Research
Advancing Astronomy and Geophysics
Springer


1909
N
W
E

Imperial College London

Summary

- Key concepts
- Single particle motion
- Magnetohydrodynamics
- Waves and magnetic reconnection

BUT there are many things we haven't discussed!!