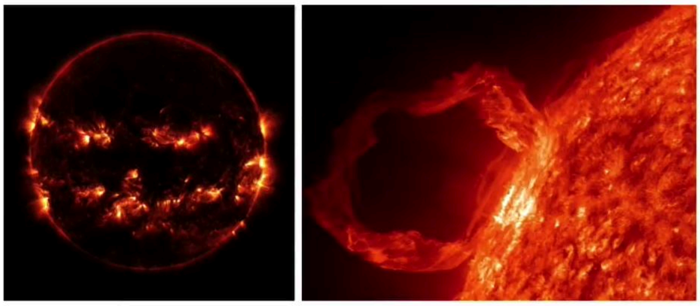
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE



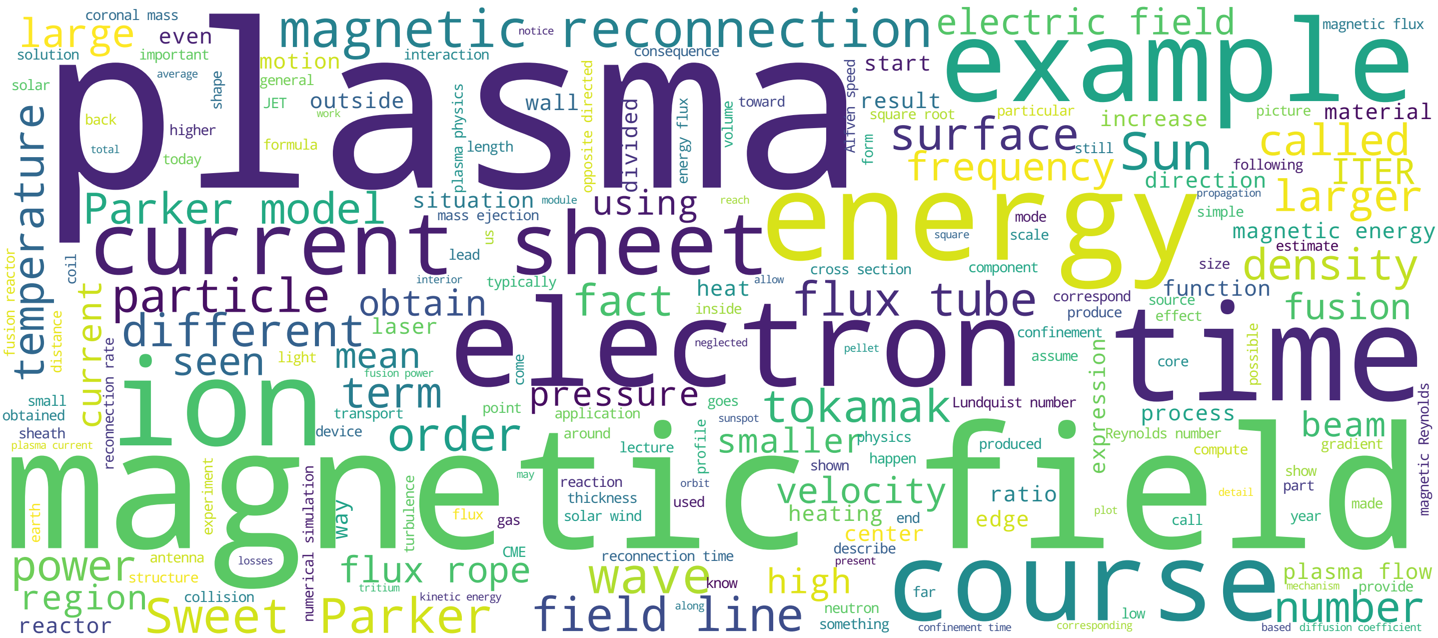
Courtesy of NASA

Reconnection: from magnetic fields to flows

Plasma Physics and Application to Fusion Energy, Astrophysics and Industry

Lecture 4d

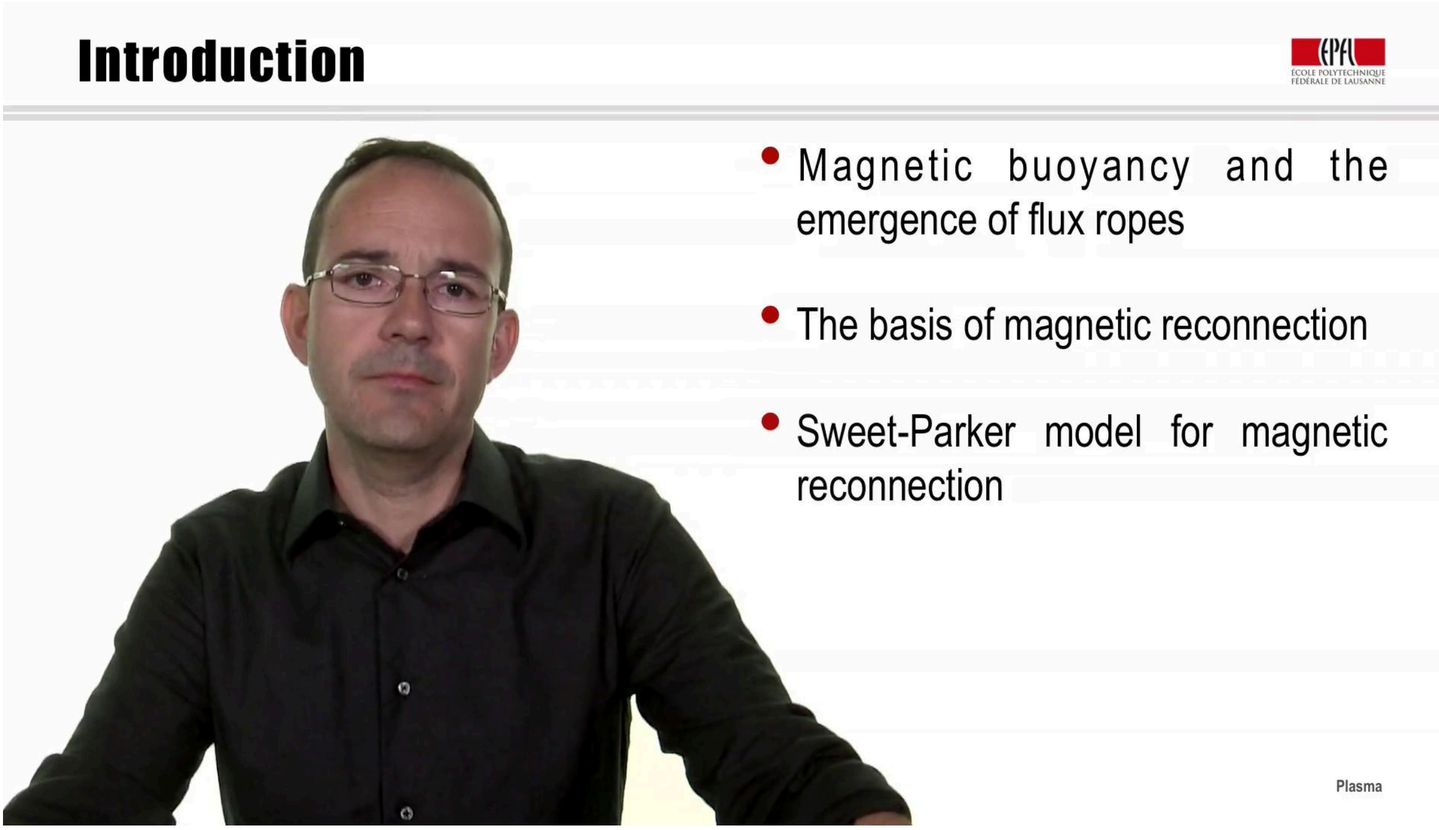
Ivo Furno



Search MOOC

Video

EPFL



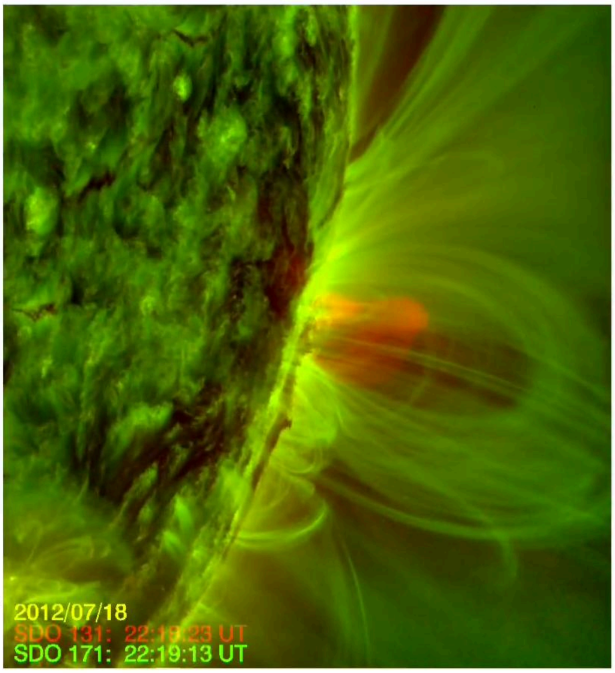
Welcome back to the course on Plasma Physics and Applications. In the last module, we have learned that at the core of the generation of magnetic fields in the Sun is a dynamo process which converts energy of the plasma flow into energy of the magnetic field. Magnetic flux ropes with large magnetic fields, form and emerge from the interior through the photosphere. In the course of this lecture, I will first describe how magnetic buoyancy can result in the emergence of the flux rope, and I will then detail how magnetic fields of different flux ropes can interact. You will discover that magnetic field lines can break, reconnect, change the topology of the fields by converting a large fraction of the magnetic energy into energy of the plasma flow. This process is called *magnetic reconnection,* and is at the core of the most spectacular event in the Sun, the *Coronal Mass Ejection (CME)* To describe it in a quantitative way, we will derive the *Sweet-Parker model* which is based on the equation of the resistive MHD that you have learned in previous modules.

Notes

Summary

0m 07s

Observation of solar flux ropes during CMEs



Courtesy of NASA/SDO

Plasma

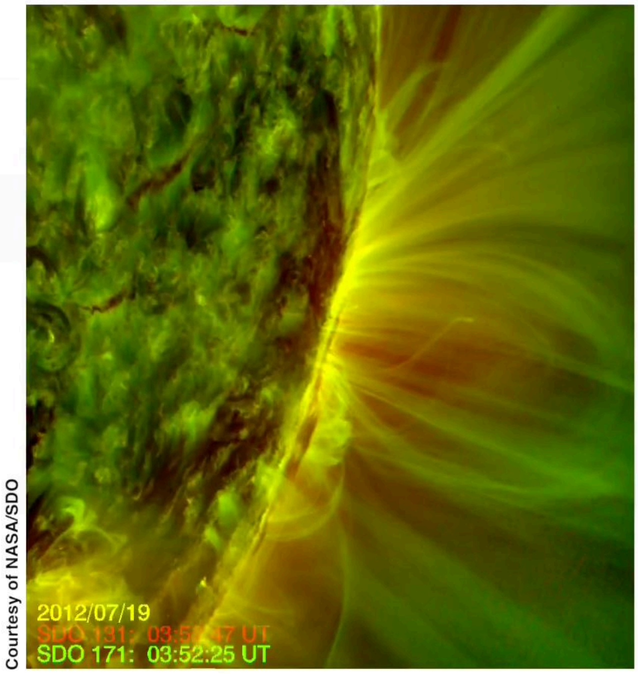
We have seen that modelling of the solar dynamo requires the emergence of bundles of magnetic field called *flux tubes* or *flux ropes*, from the interior of the Sun to the surface. The existence of flux ropes has been theorized since the early '70s, but have these flux tubes been observed in reality? The answer is *yes*. This movie was taken on July 18, 2012 from the Atmospheric Imaging Assembly and showed the Sun activity in the extreme ultraviolet. This movie showed for the first time the formation of a flux rope. On that day, a burst of light called a *flare* was caught from the Sun by the *Solar Dynamics Observatory*. These flares are very often associated with the eruption of solar material known as Coronal Mass Ejection or CME. But this one was not. Instead, the magnetic field lines in this area of the Sun's corona started to twist and kink, and the plasma started emitting very strongly, in extreme ultraviolet. The formation of the flux ropes and their twisting and kinking are clearly visible in red color in this movie. Eight hours later, on July 19, the same region of the Sun flared again.

Notes

Summary

1m 17s

Observation of solar flux ropes during CMEs



Plasma

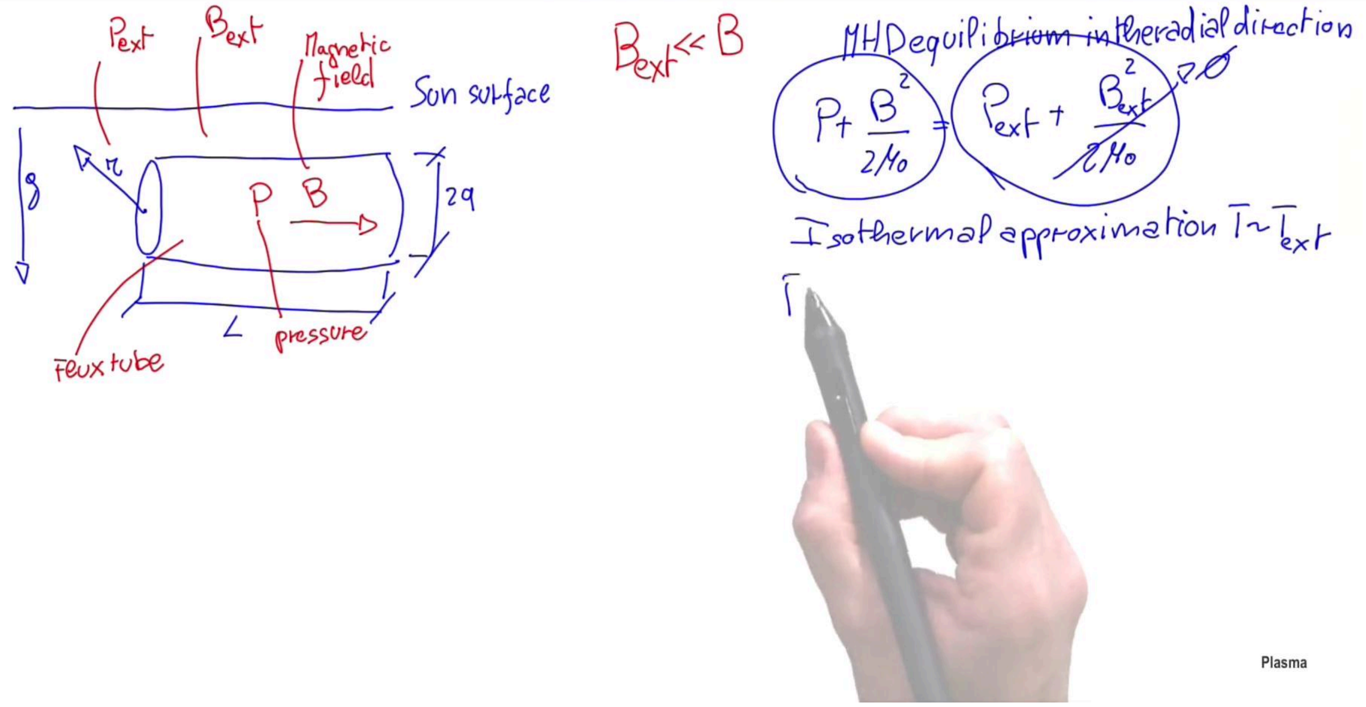
This time the flux rope connection to the Sun was cut and magnetic field escaped into space, dragging billions of tons of solar materials and this was a classic CME. To allow this process, magnetic reconnection must be at play. Before dealing with magnetic reconnection, let's see how a flux rope can emerge from the interior.

Notes

Summary

2m 43s

Rising flux tubes: magnetic buoyancy



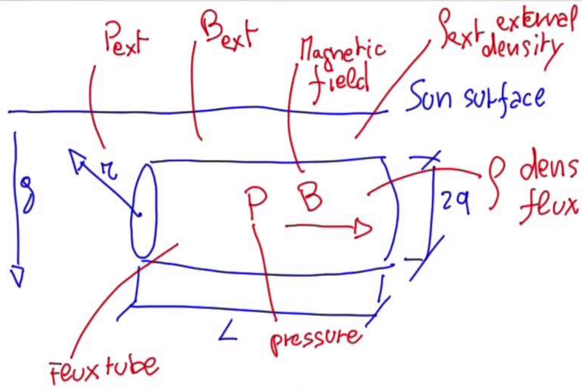
What can make the flux tube emerge? The answer is magnetic buoyancy which is similar in physics to an emerging submarine. Consider a flux tube which is immersed in the solar plasma underneath the surface, and it is perpendicularly oriented to the solar gravity. Plasma in the flux tube has a pressure P and the plasma outside the flux tube has a pressure Pext. This flux tube has a magnetic field B which is much larger than the magnetic field [Bext] characterizing the outside environment. Let's now consider a cylindrical coordinate system centered in the center of the flux tube and let's write down the MHD equilibrium in the radial direction. In this equation, the sum of the plasma pressure plus the magnetic energy inside the tube, must balance the external pressure plus the magnetic energy outside the tube. However, this last one can be neglected since the magnetic field outside the flux tube is much smaller than the magnetic field inside the tube. Let's now make the isothermal approximation and let's assume that the temperature inside and outside the flux tube is not too different.

Notes

Summary

3m 09s

Rising flux tubes: magnetic buoyancy



$B_{ext} \ll B$

MHD equilibrium in the radial direction

$$P + \frac{B^2}{2\mu_0} = P_{ext} + \cancel{\frac{B_{ext}^2}{2\mu_0}} \approx 0$$

Isothermal approximation $T \sim T_{ext}$

$$\frac{P}{\rho} \sim \frac{P_{ext}}{\rho_{ext}} \sim \frac{k_B T}{\mu}$$

$$\rho_{ext} - \rho \sim \frac{B^2/2\mu_0}{k_B T/\mu}$$

$$F_{Buoyancy} = [\rho_{ext} - \rho] V g \rightarrow$$ Pushing the flux tube towards the surface of the Sun.

Plasma

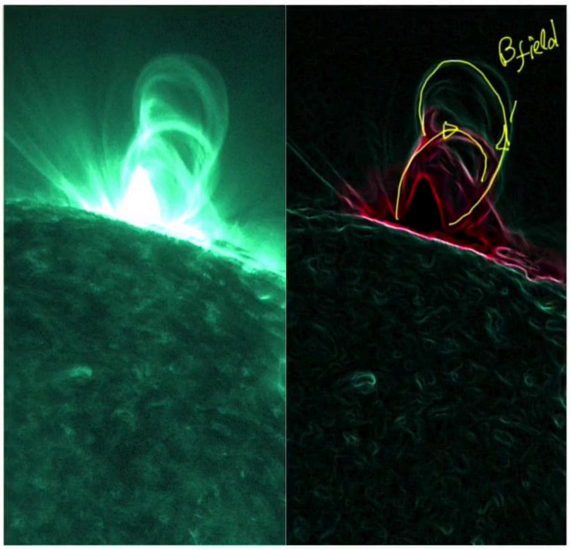
If we now assume that the flux tube is characterized by a plasma density ρ and the plasma outside the flux tube is characterized by a plasma density ρext, and we use the equation of state for ideal gas, we can write the following. From this equation, we obtain that,... which tells us that the flux tube is less dense than the surrounding plasma. Therefore the flux tube will experience a buoyancy force which can be expressed as the difference between the two densities times the volume of the flux tube times the gravitational acceleration. Just as for a submarine floating, the flux tube would be the force subject to a buoyancy force, which will tend to push the flux tube upwards towards the surface of the Sun.

Notes

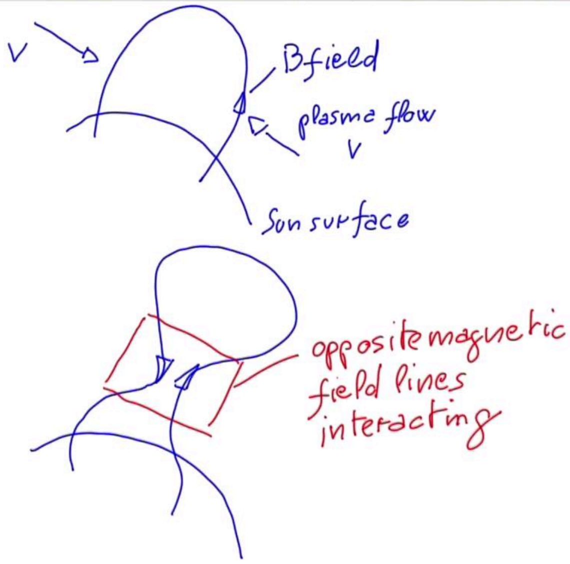
Summary

4m 39s

How do magnetic fields interact?



Courtesy of NASA/SDO



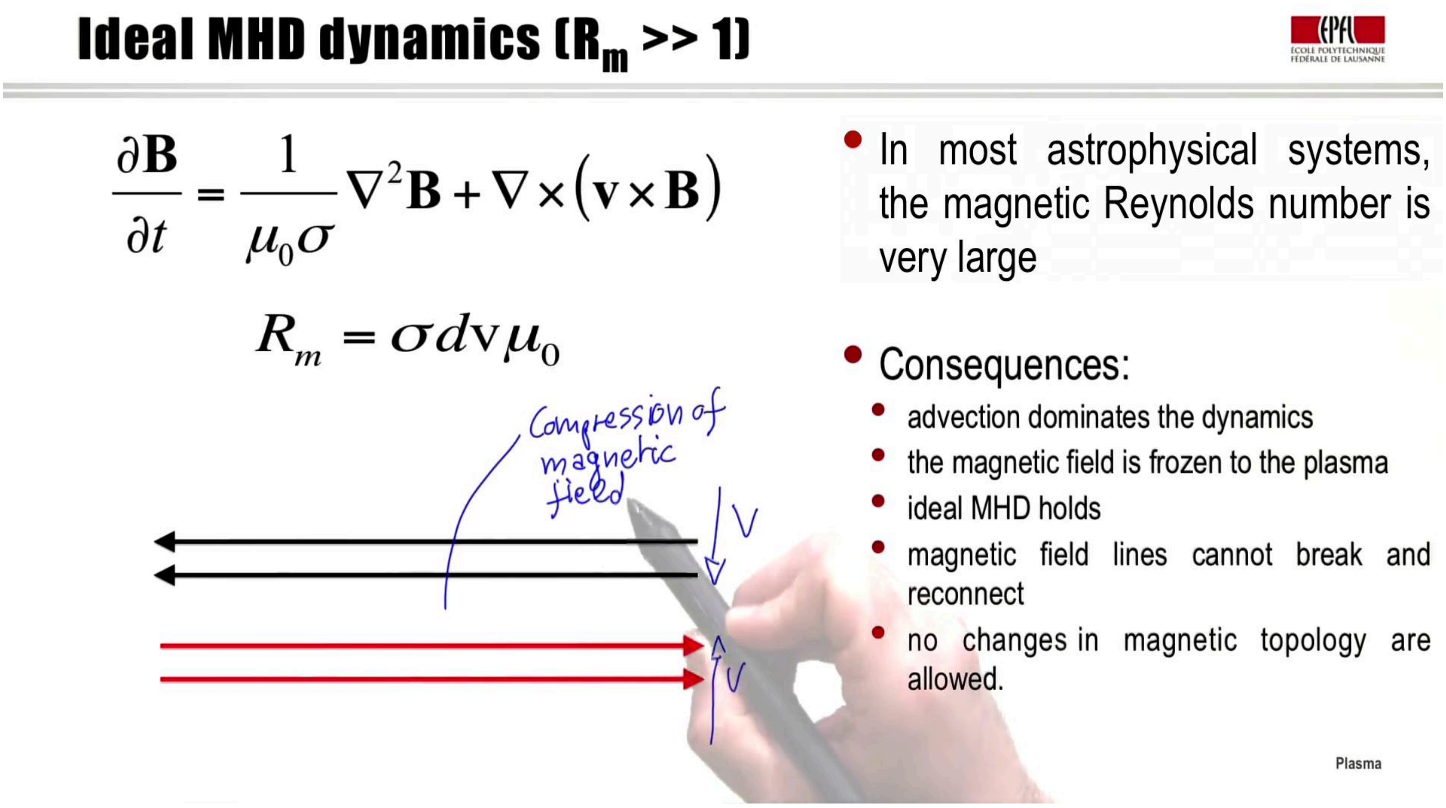
Plasma

Once flux ropes have emerged from the interior through the surface, how will they interact? And how their magnetic fields will evolve? The image on the left shows a series of magnetic loops from the previous movie, the image on the right has been processed to highlight the edges of each flux loop and make the structure more clear. Now, for the sake of the discussion, let's suppose that the magnetic fields are oriented like this in these flux ropes. We can observe that the complex 3D magnetic field can develop in which opposite directed magnetic fields are brought together by plasma flows. For example, let's suppose that in this flux rope the magnetic field is oriented in the following way and the plasma flow with a velocity v is squeezing the flux rope. In a second time, we can observe that the complex 3D magnetic field can develop in which opposite directed magnetic fields are brought together by the plasma flow, and they start to interact in a small region. In the following we will see that magnetic reconnection is the basis of the interaction of oppositely directed field lines.

Notes

Summary

5m 34s



To describe the interactions of magnetic fields, let's go back to the resistive MHD equations that you have seen in previous modules. The key parameter in this equation is the *magnetic Reynolds number* which in most astrophysical systems is much larger than 1. Let's suppose that we start from a situation where we have an opposite directed magnetic field lines as shown in this picture, which are embedded in a plasma with the magnetic Reynolds number much larger than 1. Now, we push the magnetic field lines, one against the other by using a plasma flow with a velocity v. Which are the consequences of a large magnetic Reynolds number? The advection dominates the plasma dynamics. Therefore, the magnetic field lines are frozen in the plasma and the ideal MHD holds. This means that the magnetic diffusivity term can be neglected. Another important consequence of a magnetic Reynolds number, very large is that the magnetic flux is frozen to the plasma motion and therefore, the magnetic field lines cannot break or reconnect. This means that no changes in the magnetic topology are allowed. If we keep pushing the magnetic field lines with a velocity v then we get closer and closer and the magnetic flux will be compressed between them.

Notes

Summary

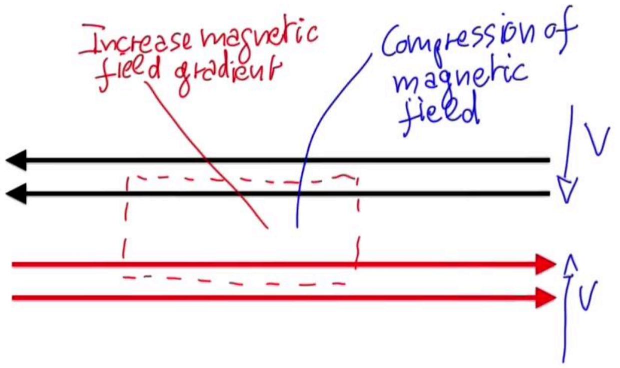
6m 58s

Ideal MHD dynamics ($R_m >> 1$)

$$\frac{\partial \mathbf{B}}{\partial t} = \frac{1}{\mu_0 \sigma} \nabla^2 \mathbf{B} + \nabla \times (\mathbf{v} \times \mathbf{B})$$

decrease R_m

$$R_m = \sigma d v \mu_0$$



- In most astrophysical systems, the magnetic Reynolds number is very large
- Consequences:
  - advection dominates the dynamics
  - the magnetic field is frozen to the plasma
  - ideal MHD holds
  - magnetic field lines cannot break and reconnect
  - no changes in magnetic topology are allowed.

Plasma

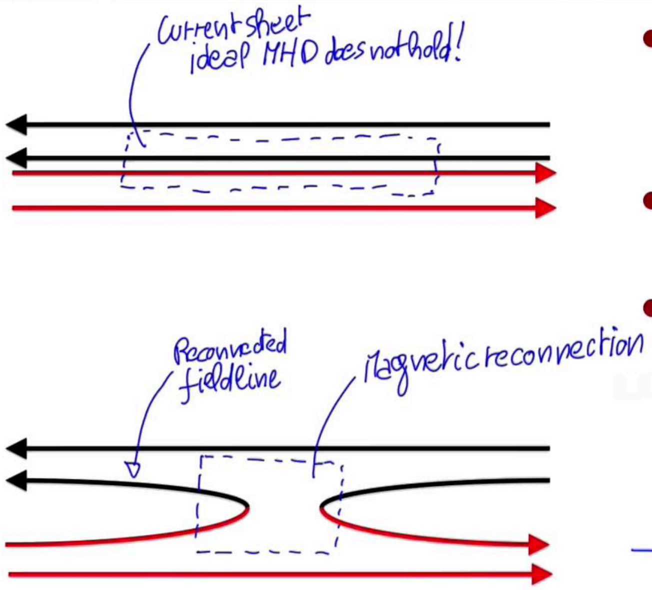
This in turn will increase the magnetic field gradient which are characterized by the special distance d and as a consequence, the magnetic Reynolds number will be decreased in a small layer across the opposite directed magnetic field lines.

Notes

Summary

8m 41s

Basic concepts of magnetic reconnection



- Very thin regions can form where the gradients of the magnetic field are very large.
- The magnetic field can slip through the plasma and reconnect.
- Consequences:
  - the global topology of the magnetic field changes, affecting the path of particles and heat conduction
  - magnetic energy is converted into heat, kinetic energy and fast particle energy
  - large electric currents and fields are generated at the reconnection site as well as shocks, waves and filamentation.

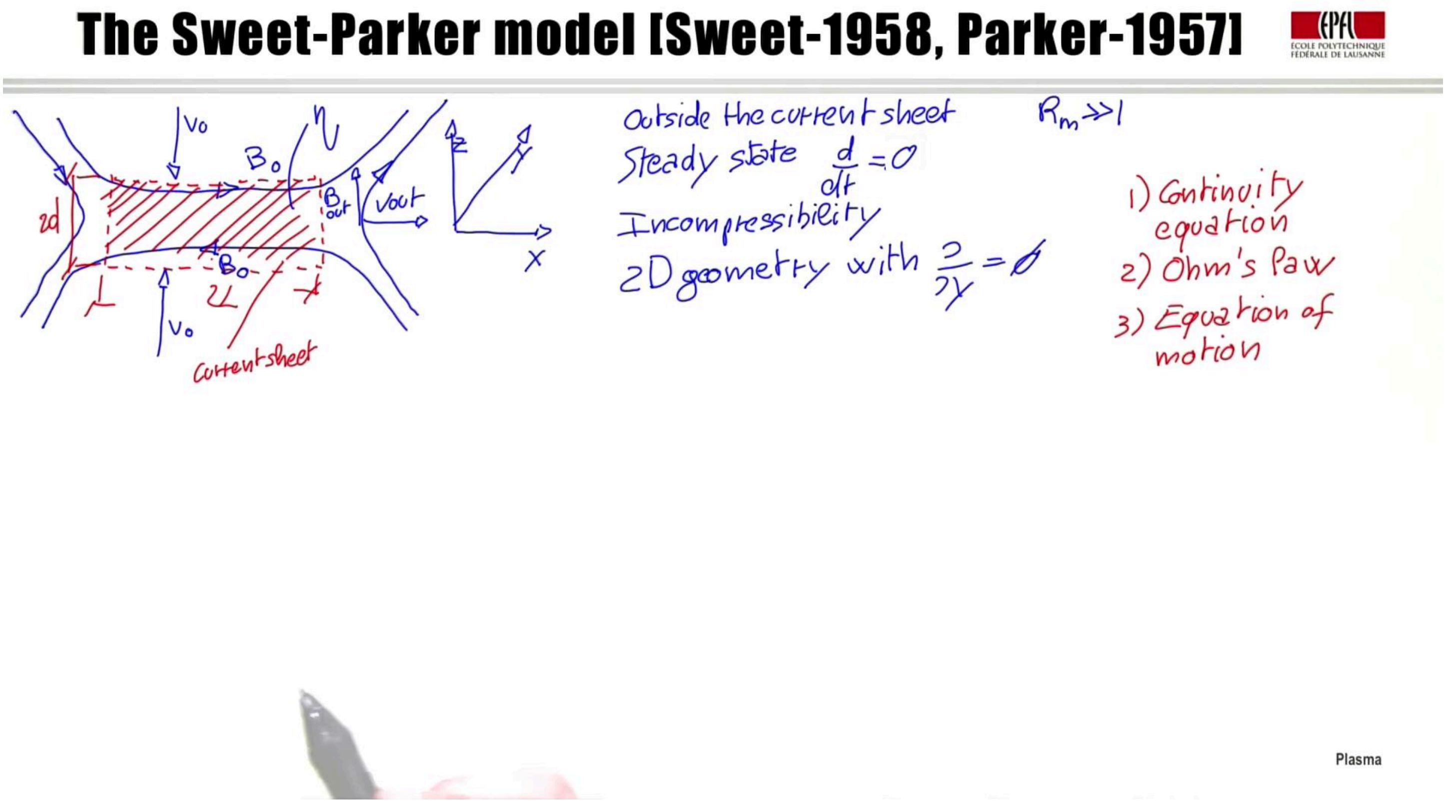
Plasma

Therefore, very thin regions can form where the gradients of the magnetic fields are very large. In this thin region, a current develops in the perpendicular plane, and the ideal MHD does not hold anymore. In this very thin region where the ideal MHD is violated, magnetic reconnection can happen. A magnetic field line which is pushed by the plasma flow against a magnetic field line which is opposite directed, will break and reconnect, thus forming a new magnetic field line. Which are the consequences of magnetic reconnection? As you can see, the global topology of the magnetic field now has changed and this affects the path of particles and heat conduction. As we will see in the following slides, the magnetic energy is converted into heat, kinetic energy and fast particles energy. During magnetic reconnection, large electric currents and fields are generated at the reconnection sites, as well as shocks, waves and filamentation.

Notes

Summary

9m 02s

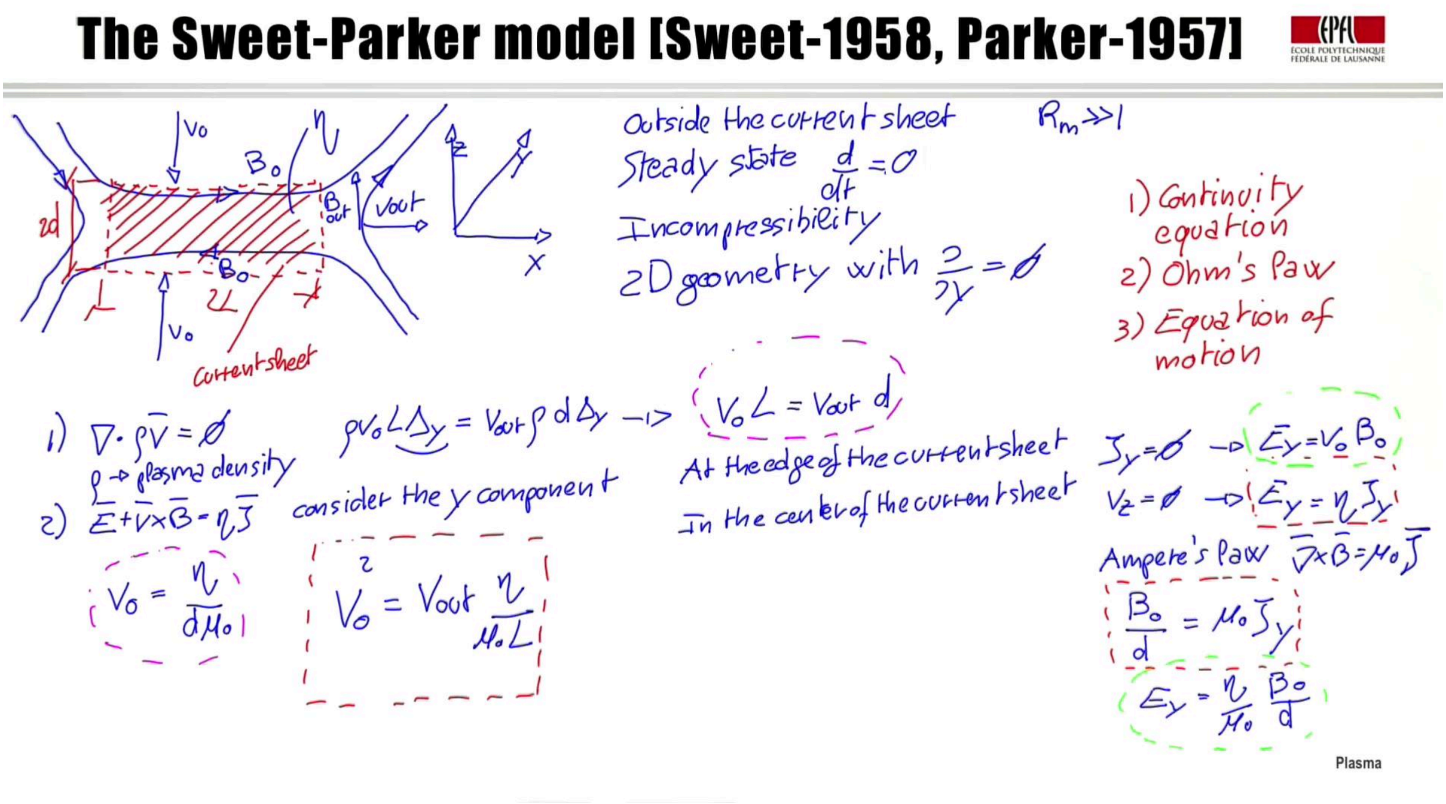


Let's now describe the magnetic reconnection dynamics using a simple model, the *Sweet-Parker model*, that was originally proposed by Sweet in 1958 and by Parker in 1957. This was the first quantitative model of magnetic reconnection to be developed. The geometry of the Sweet-Parker model is represented here. Opposite directed field lines with magnetic field intensity B_0 are brought together by a plasma flow with a velocity v_0 They form a current sheet of length 2L and thickness 2d shown here in red. Reconnection happens in the the current sheet and the new magnetic field lines are now flowing out of the current sheet with the velocity vout and a magnetic field intensity, Bout To derive the model, we made the following hypotheses: Outside the current sheet, the magnetic Reynolds number is much larger than 1. Inside the current sheet, the plasma has a resistivity indicated by eta (η). The system is in steady state, meaning that time derivatives can be neglected. The plasma is incompressible and we assume a two-dimensional geometry with d/dy = 0. To derive the Sweet-Parker model, we will use the *Continuity Equation*, the *Ohm's Law* and the *Equation of Motion*. Let's start with the Continuity Equation.

Notes

Summary

10m 15s



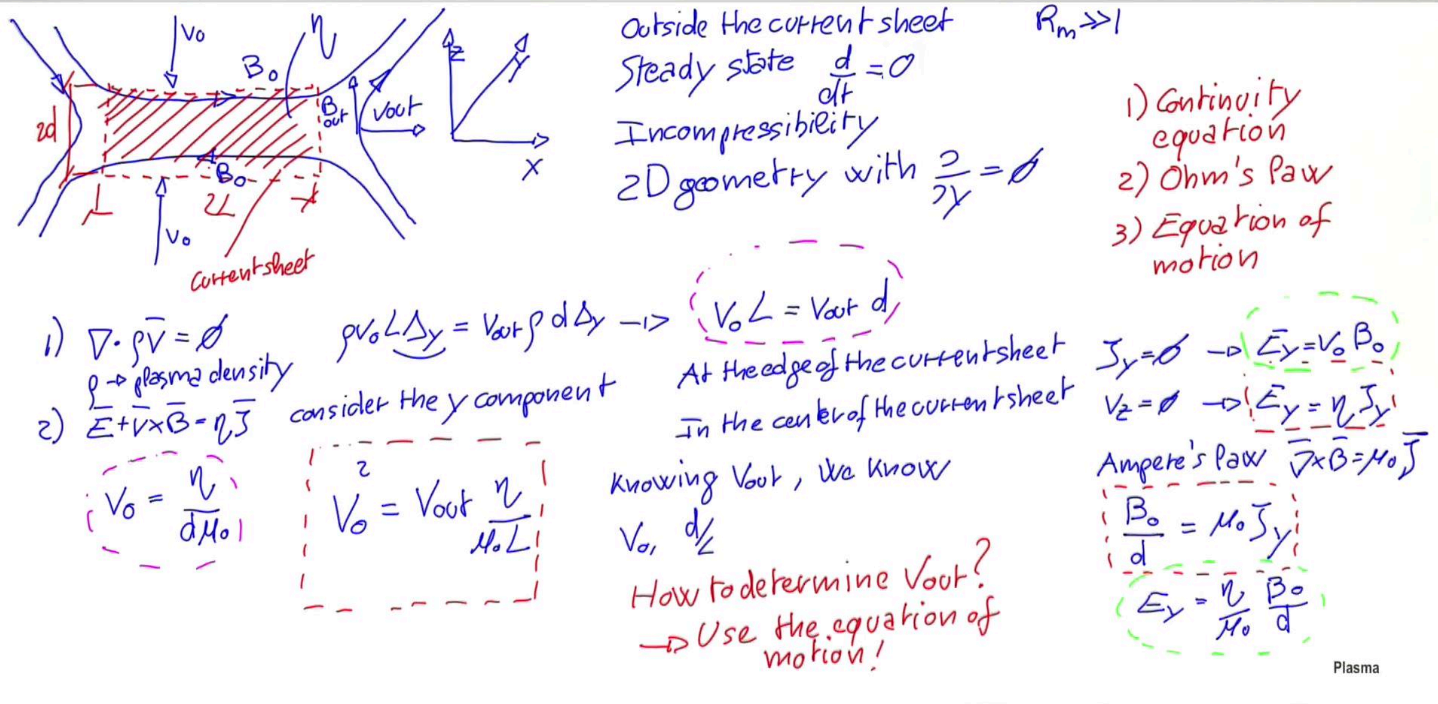
Divergence of ρv = 0 [∇·(ρv) = 0] where ρ is the mass density of the plasma. From this equation, using the coordinate system we have chosen, it's easy to write..., where Δy is the thickness of the layer in the y direction which drops out. We can therefore obtain an equation that links the outflow velocity vout to the inflow velocity v_0 via the thickness and the length of the current sheet. Let's now write the Ohm's Law and consider the y component. At the edge of the current sheet, the y component of the current density is equal to zero. Therefore, using Ohm's Law we obtain that in the center of the current sheet the flow stagnates and therefore, vz=0. We can therefore write that Ey = η Jy where η is the resistivity of the plasma, [and Jy the current density] Now writing the *Ampere's Law* in the current sheet, we can easily obtain B_0/d = μ_0 Jy. Now if we put together this equation and this equation, we obtain that Ey = η/μ_0 B_0 Using these two equations we can eliminate Ey and obtain v_0 = η / (d μ_0) If we now go back to the expression we found using the continuity equation and we use the expression for v_0 that we have just found, we can easily obtain an expression that links the outflow velocity to the inflow velocity via the resistivity and the length of the current sheet.

Notes

Summary

12m 04s

The Sweet-Parker model [Sweet-1958, Parker-1957]



Now, if we know vout, we now know the inflow velocity v_0 and the shape of the current sheet characterized by thickness divided by its length. The question is, how do we determine the outflow velocity?

Notes

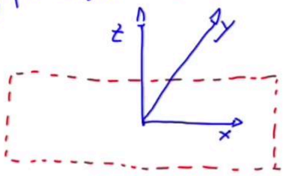
Summary

13m 55s

The Sweet-Parker model [Sweet-1958, Parker-1957]

MHD equation of motion for a steady state plasma

$$\rho(\bar{v}\cdot\nabla)\bar{v} = -\cancel{\nabla p} + \bar{J}\times\bar{B}$$



$$(\bar{J}\times\bar{B})_x = J_y B_{out} \simeq \frac{B_{out} B_0}{d\mu_0}$$

The Lorentz force accelerates the plasma from rest to V_{out} over a distance L, so:

$$\rho(\bar{v}\cdot\nabla)V_x = \rho\frac{V_{out}^2}{L} \qquad \frac{B_{out}B_0}{d\mu_0} = \rho\frac{V_{out}^2}{2}$$

Conservation of magnetic flux $\quad \frac{B_0}{L} = \frac{B_{out}}{d}$

$$\boxed{V_{out} = \frac{B_0}{\sqrt{\rho\mu_0}} = V_{Alfvén}}$$

The plasma is accelerated to the Alfvén speed!

$$S = \frac{\mu_0 V_{Alfvén} L}{\eta}$$

Lundquist number

Plasma

We will use the *Equation of Motion.* Let's write down the MHD equation of motion for a steady state plasma. Let's now consider the current sheet with an xyz reference system centered in its center. Let's make the further hypothesis that the gradient of the pressure can be neglected, and let's first compute the Lorentz force that acts along the current sheet in the x direction as follows: The Lorentz force accelerates the plasma from rest to the outflow velocity vout over a distance L the lenght of the current sheet. So we can write: ρ (v • ∇) vx = ρ vout / L Using the previous espression, we can obtain Bout B_0 / (d μ_0)= ρ vout²/2 Now using the conservation of the magnetic flux we can obtain this simple expression B_0/L = Bout/d which allows to compute the outflow plasma velocity and by recalling the definition of the Alfvén speed we obtain this important result that the plasma is accelerated at the Alfvén speed by reconnection process. If we now define the *Lundquist number* which is an dimensionless number and we recall the formulas that we have derived so far, we have fully characterized the current sheet in the Sweet-Parker model.

Notes

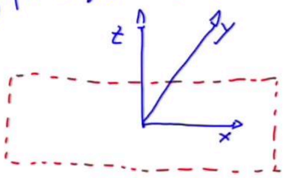
Summary

14m 12s

The Sweet-Parker model [Sweet-1958, Parker-1957]

MHD equation of motion for a steady state plasma

$$\rho(\bar{v}\cdot\nabla)\bar{v} = -\cancel{\nabla p} + \bar{J}\times\bar{B}$$



$$(\bar{J}\times\bar{B})_x = J_y B_{out} \simeq \frac{B_{out} B_0}{d\mu_0}$$

The Lorentz force accelerates the plasma from rest to V_{out} over a distance L, so:

$$\rho(\bar{v}\cdot\nabla)V_x = \rho\frac{V_{out}^2}{L} \qquad \frac{B_{out}B_0}{d\mu_0} = \rho\frac{V_{out}^2}{L}$$

Conservation of magnetic flux $\quad \frac{B_0}{L} = \frac{B_{out}}{d}$

$$\boxed{V_{out} = \frac{B_0}{\sqrt{\rho\mu_0}} = V_{Alfvén}}$$

The plasma is accelerated to the Alfvén speed!

$$S = \frac{\mu_0 V_{Alfvén} L}{\eta}$$

Lundquist number

$$V_0 = \frac{V_{Alfvén}}{\sqrt{S}} << V_{Alfvén}$$

$$\frac{d}{L} = \frac{1}{\sqrt{S}} \rightarrow \text{very thin sheet}$$

In astrophysical systems

$$S >> 1$$

Plasma

In particular, we obtained that the inflow velocity is equal to the Alfvén speed divided by the square root of the Lundquist number. And the current sheet geometry defined the ratio d/L scales like 1 over the square root of the Lundquist number. Since in astrophysical systems the Lundquist number is usually much larger than 1, this formula tells us that in the Sweet-Parker model the current sheet is very thin. And this formula tells us that the plasma is flowing into the current sheet with the velocity which is much smaller than the Alfvén speed.

Notes

Summary

15m 53s

Energy balance

The sheet is thin and elongated $\quad d/L = 1/\sqrt{S}$

$V_{out} = V_{Alfvén}$

The magnetic field at the exit of the current sheet is: $\quad B_0 V_0 = B_{out} V_{out} \rightarrow B_{out} = B_0/\sqrt{S}$

Flux of E.M. energy → Poynting flux $\quad \frac{\bar{E}\times\bar{B}}{\mu_0} \rightarrow \frac{E B_0}{\mu_0} = \frac{V_0 B_0^2}{\mu_0}, \qquad E = V_0 B_0$

$$\frac{\text{kinetic energy flux}}{\text{magnetic energy flux}} = \frac{\frac{1}{2}\rho V_0^2}{\frac{B_0^2}{\mu_0}} = \frac{V_0^2}{2 V_{Alfvén}^2} \ll 1$$

→ most of the inflow energy is magnetic

$$\text{outflowing magnetic energy} = \frac{E B_{out} d}{\mu_0} \ll \frac{E B_0 L}{\mu_0}$$

since $B_{out} \ll B_0$ and $d \ll L$

Plasma

Let's now do some energy considerations. In the Sweet-Parker model, the sheet is thin and elongated. The plasma outflows from the current sheet at Alfvén velocity. We can also compute the magnetic field at the exit of the current sheet using the flux conservation. And we obtain that it is much smaller than the magnetic field, than the entrance of the magnetic field, since it scales like 1 over the square root of the Lundquist number. Let's now recall the flux of the electromagnetic energy is given by the *Poynting flux*. And let's compute the Poynting flux at the edge of the current sheet. We have obtained this expression by recalling that $E = v_0 B_0$. We can now use this expression to compute the ratio of the kinetic energy flux by the magnetic energy flux. Recalling that the inflow plasma velocity is much smaller than the Alfvén velocity we can easily conclude that most of the inflow energy is of magnetic nature. What about the outflow in magnetic energy? This can be easily estimated, and by recalling that Bout is much smaller than B_0, and small d is much smaller than L, we obtain the result that the outflowing magnetic energy can be neglected.

Notes

Summary

16m 38s

Energy balance

The sheet is thin and elongated $d/L = 1/\sqrt{S}$

$V_{out} = V_{Alfvén}$

The magnetic field at the exit of the current sheet is: $B_0 V_0 = B_{out} V_{out} \Rightarrow B_{out} = B_0/\sqrt{S}$

Flux of E.M. energy → Poynting flux $\dfrac{\bar{E}\times\bar{B}}{\mu_0} \rightarrow \dfrac{E B_0}{\mu_0} = \dfrac{V_0 B_0^2}{\mu_0}$, $\quad E = V_0 B_0$

$$\frac{\text{kinetic energy flux}}{\text{magnetic energy flux}} = \frac{\frac{1}{2}\rho V_0^2}{\frac{B_0^2}{\mu_0}} = \frac{V_0^2}{2 V_{Alfvén}^2} \ll 1$$ → most of the inflow energy is magnetic

$$\text{outflowing magnetic energy} = \frac{E B_{out}\, d}{\mu_0} \ll \frac{E B_0 L}{\mu_0}$$ since $B_{out} \ll B_0$ and $d \ll L$

$$\frac{\text{outflowing kinetic energy flux}}{\text{Inflowing magnetic energy flux}} = \frac{\frac{1}{2}\rho V_{out}^2 \times V_{out} \times d}{V_0 \frac{B_0^2}{\mu_0} L} = \frac{1}{2}\frac{V_{out}^2}{V_{Alfvén}^2} = \frac{1}{2}$$

Half of the incoming magnetic energy is converted into plasma kinetic energy!

Plasma

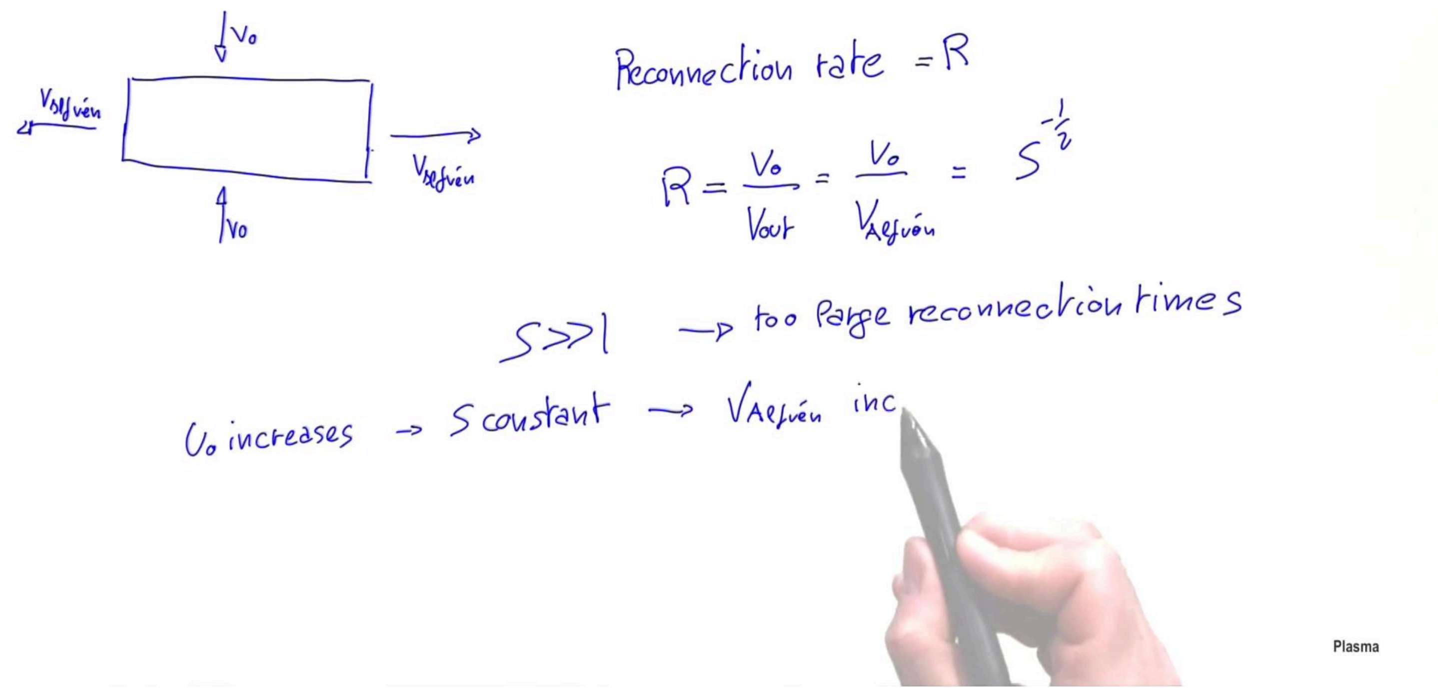
Let's now compute the ratio of the outflowing kinetic energy flux to the inflowing magnetic energy flux. We obtain the important result that during magnetic reconnection in the simple Sweet-Parker model, half of the incoming magnetic energy is converted into plasma kinetic energy. I will not demonstrate it, but the other half is converted into heat by Joule dissipation. Therefore, the reconnection layers act as a source of hot and fast plasma.

Notes

Summary

18m 21s

How fast is Sweet-Parker reconnection?



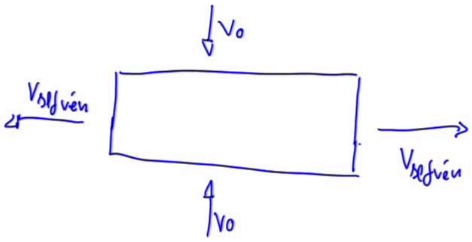
How fast is this process? The plasma enters the current sheet at the velocity v_0. This is also the rate at which the magnetic flux enters the current sheet. In this region, the plasma slips from the magnetic fields and flow out at the Alfvén speed along the current sheet. No more plasma can enter and carry magnetic flux until the previous one has left. An important parameter to define how fast the reconnection is happening is the so-called *Reconnection rate*. This is defined as the ratio of the incoming flow velocity to the outcoming flow velocity. And in the Sweet-Parker model it is equal to v_0 / vAlfvén. This shows that in the Sweet-Parker model the reconnection rate scales like the inverse of the square root of the Lundquist number. Since the Lundquist number is much larger than 1 for many astrophysical systems, The Sweet-Parker rate leads to reconnection times that are many orders of magnitude larger than those that are observed. If we want to accelerate the reconnection rate, and you increase v_0 externally from the outside for a fixed Lundquist number, the reconnection rate remains constant and therefore, the Alfvén velocity must increase to maintain the same ratio.

Notes

Summary

19m 01s

How fast is Sweet-Parker reconnection?



Reconnection rate $= R$

$$R = \frac{V_0}{V_{out}} = \frac{V_0}{V_{Alfvén}} = S^{-\frac{1}{2}}$$

$S \gg 1 \rightarrow$ too large reconnection times

V_0 increases $\rightarrow$ S constant $\rightarrow$ $V_{Alfvén}$ increases $\rightarrow$ B_0 increases

Plasma

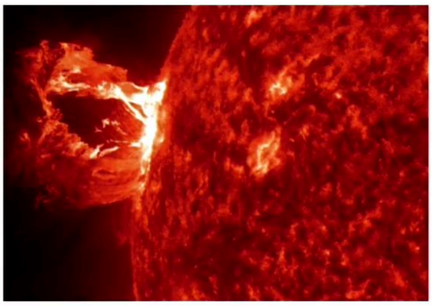
This is obtained by increasing the Alfvén velocity by increasing the incoming magnetic field. Therefore, pushing the reconnection harder from the outside, does not increase the reconnection rate in the Sweet-Parker model but only compresses the magnetic field.

Notes

Summary

20m 30s

Estimates for solar flares and sawteeth



Courtesy of NASA/SDO

Typical time scales ~ 100 s

$$\tau_{SP} = \frac{L}{u_0} = \frac{L}{\mathrm{v}_A}\sqrt{S}$$

$L \sim 10^5\,\mathrm{km}$ $\quad B \sim 100 - 1000\,\mathrm{Gauss}$

$n \sim 2.5\times10^9\,\mathrm{cm}^{-3}$ $\quad T_e \sim 10^7\,K$

$\mathrm{v}_A \sim 10^8\,\mathrm{cm\,s}^{-1}$ $\quad \tau_{SP} \sim 10^7\,s \gg 100\,s$

Plasma

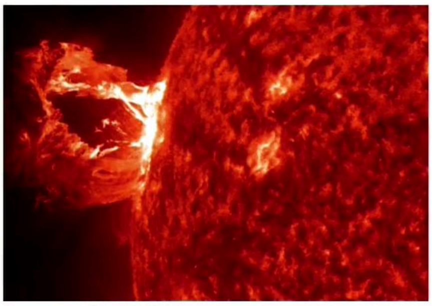
Let's now apply the Sweet-Parker model to two examples of magnetic reconnection in nature. The first example is a *Coronal Mass Ejection*. A picture of a CME is shown here, where a beautiful prominence eruption produced a CME on April 16, 2012. Typical timescales for CME's are of the order of a hundred seconds. Magnetic reconnection is believed to be responsible for CME's. Let's try to estimate the reconnection time from the Sweet-Parker model using the following formula. If we plot typical numbers for a coronal mass ejection into this formula, we end up with a prediction of a approximately 10^7s which is much larger than typical timescales which are usually observed. Therefore, the Sweet-Parker reconnection model produces a dynamics which is far too slow to describe coronal mass ejections.

Notes

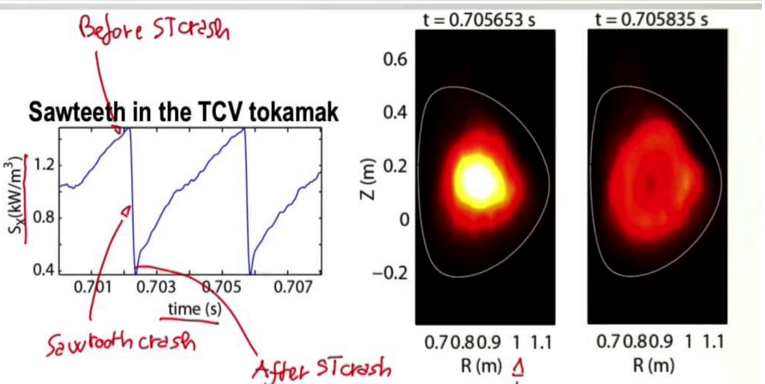
Summary

20m 52s

Estimates for solar flares and sawteeth



Courtesy of NASA/SDO



$\tau_{ST} \sim 10\text{-}50\mu s$

$L \sim 10^5\,\mathrm{km}$	$B \sim 100-1000\,\mathrm{Gauss}$	$L \sim 1\,\mathrm{m}$	$B \sim 1000\,\mathrm{Gauss}$
$n \sim 2.5\times10^9\,\mathrm{cm}^{-3}$	$T_e \sim 10^7 K$	$n \sim 10^{19}\,\mathrm{m}^{-3}$	$T_e \sim 1KeV$
$\mathrm{v}_A \sim 10^8\,\mathrm{cm\,s}^{-1}$	$\tau_{SP} \sim 10^7 s$	$\mathrm{v}_A \sim 10^8\,\mathrm{cm\,s}^{-1}$	$\tau_{SP} \sim 1-10\,\mathrm{ms}$

Sweet-Parker rate is too slow!

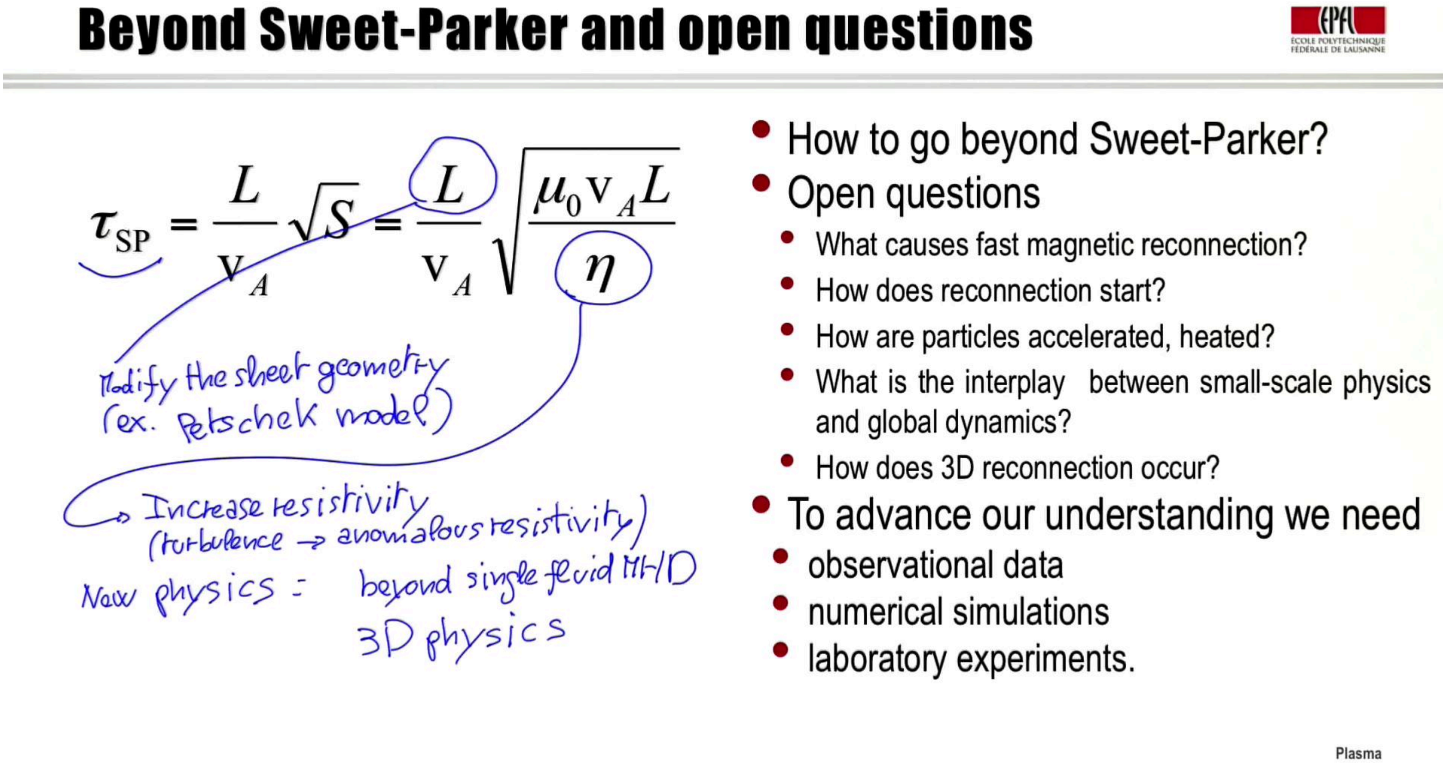
Plasma

As a second example of magnetic reconnection, let's consider the *Sawtooth Instablity* in tokamaks, in which plasma energy and particles are periodically expelled from the center of the plasma towards the edge. This picture shows an example of sawtooth in a TCV discharge [observed] using the central soft x-ray emission which is roughly proportional to the square of the electron density and the electron temperature as a function of time. The central soft x-ray emissivity drops dramatically over a very fast timescale during the so-called *sawtooth crash*. The poloidal cross-section profile of the soft x-ray before and after the sawtooth crash clearly displays the redistribution of energy associated with sawteeth. Sawtooth crashes happen on the TCV tokamak on timescales of the order of 10 to 50 microseconds. This is the time during which magnetic reconnection occurs. If we estimate the Sweet-Parker reconnection time using typical values for TCV plasmas, we obtain reconnection time of the order between 1 and 10 millisecond which is too large if compared with experimental values. In the two cases of magnetic reconnection that we have seen, the Sweet-Parker rate is too slow.

Notes

Summary

22m 04s



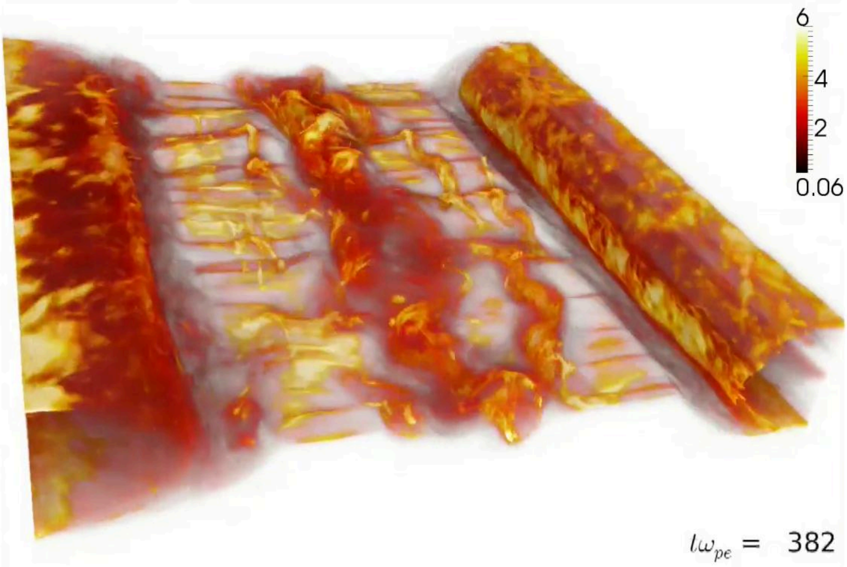
How can we go beyond Sweet-Parker? If we want to decrease the reconnection time [τSP], we can, for example act on the sheet thickness [L] by modifying the sheet geometry. One example is the *Petschek model* for magnetic reconnection. Or, we could, for example increase the resistivity by introducing turbulence which may give rise to anomalous resistivity. Or, we could introduce new physics into our model by going for example beyond single fluid MHD Or, by introducing three dimensional physics. All these ways are the subjects of intensive studies in the scientific community. However, a number of open question remains for magnetic reconnection. Among the most important open questions are: "What are the causes of the fast reconnection rate?" "How does reconnection start? And when it starts, how are particles accelerated and heated?" "What is the interplay between the small scale physics that happens in the current sheet and the global dynamics of the plasma?" And probably one of the most difficult questions is "How can we model three-dimensional magnetic reconnection?" To advance our understanding in the future, we will need more observational data, numerical simulations and laboratory experiments.

Notes

Summary

23m 44s

Numerical simulations of magnetic reconnection



Courtesy of W. Daughton, LANL

Plasma

As an example of numerical simulation, I show you here a movie, which is obtained from one of the most advanced numerical simulations of magnetic reconnection from a fully kinetic model. The simulation employed two trillion particles with 8 billion cells and was performed on the blue water machine at the University of Illinois. The movie shows the volume rendering of the current density during the magnetic reconnection. The complexity of this process, well-beyond the simple Sweet-Parker model is revealed by the development of a fully three-dimensional turbulence in the current sheet.

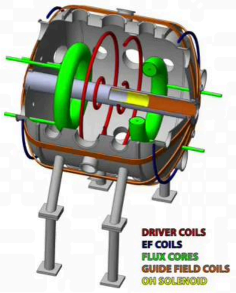
Notes

Summary

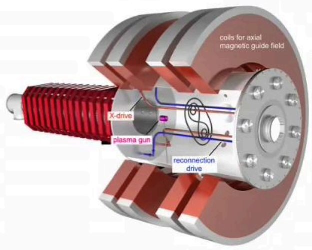
25m 30s

Laboratory experiments on magnetic reconnection

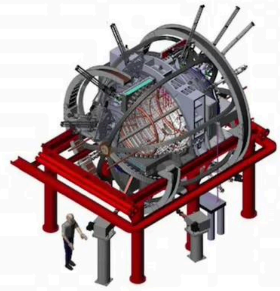
FLARE
(Facility for LAboratory Reconnection Experiments)
Courtesy of H. Ji, PPPL



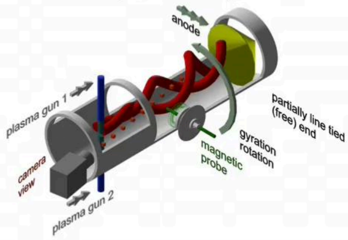
VINETA II
(Versatile Instrument for studies on Nonlinearity, Electromagnetism, Turbulence, and Applications)
Courtesy of O. Grulke, MPI - Greifswald



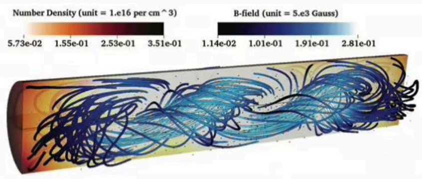
TREX
Terrestrial Reconnection Experiment
Courtesy of J. Egedal, UW - Madison



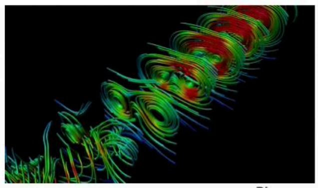
RSX
Reconnection Scaling Experiment
Courtesy of T. Intrator, LANL



SSX
The Swarthmore Spheromak Experiment
Courtesy of M. Brown, Swarthmore College



BPSF
Basic Plasma Science Facility
Courtesy of of W. Gekelman, UCLA



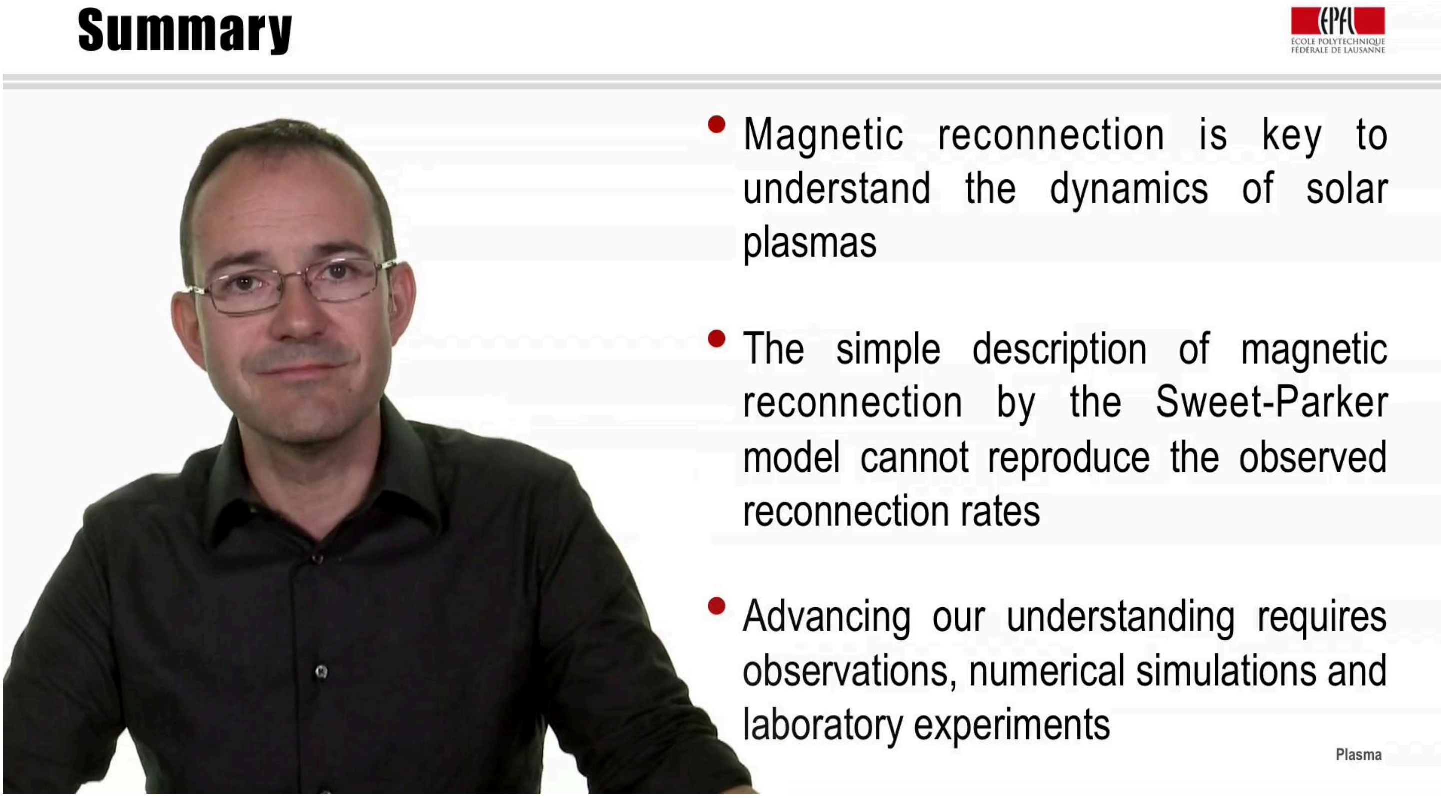
Plasma

Numerical simulations are important to shed light on reconnection physics. They must be compared against experimental data. These are difficult, if not impossible to obtain from distance observations using telescopes and satellites. An important role can be therefore played by laboratory experiments which provide easy diagnostic access and control experimental conditions. A number of magnetic reconnection laboratory experiments has been developed in the past and is presently under development with different geometries from two-dimensional to fully three-dimensional and also covering different plasma regimes from Sweet-Parker to two-fluid MHD and kinetic reconnection. These will provide an important test bed for reconnection theories and simulations.

Notes

Summary

26m 09s



In this module, we have explored the dynamics of solar flux tubes. They are advected by the plasma flow and their opposite magnetic fields reconnect, change the plasma topology, and dissipate the large amount of magnetic energy that goes into particle acceleration plasma heating. Although the basics of magnetic reconnection can be caught by the simple two-dimensional Sweet-Parker model, the predictions of the reconnection time are not in agreement with experimental data which show much faster dynamics, for example, in coronal mass ejections or sawteeth in tokamaks. In the future, advancing our understanding of magnetic reconnection will require the use of observational data, sophisticated numerical simulation and experiments in well controlled and diagnosed laboratory devices. In the next module, we will explore how the plasma dynamics in the Sun can shape the surrounding environment by generating the solar wind.

Notes

Summary

27m 08s