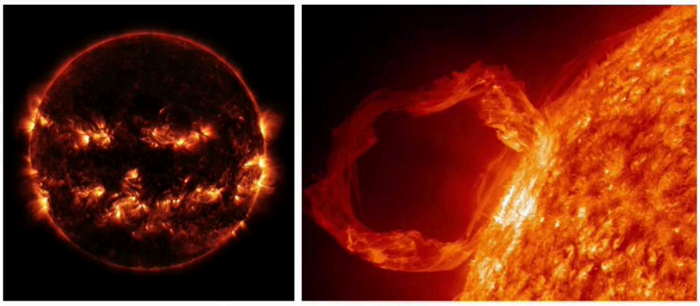


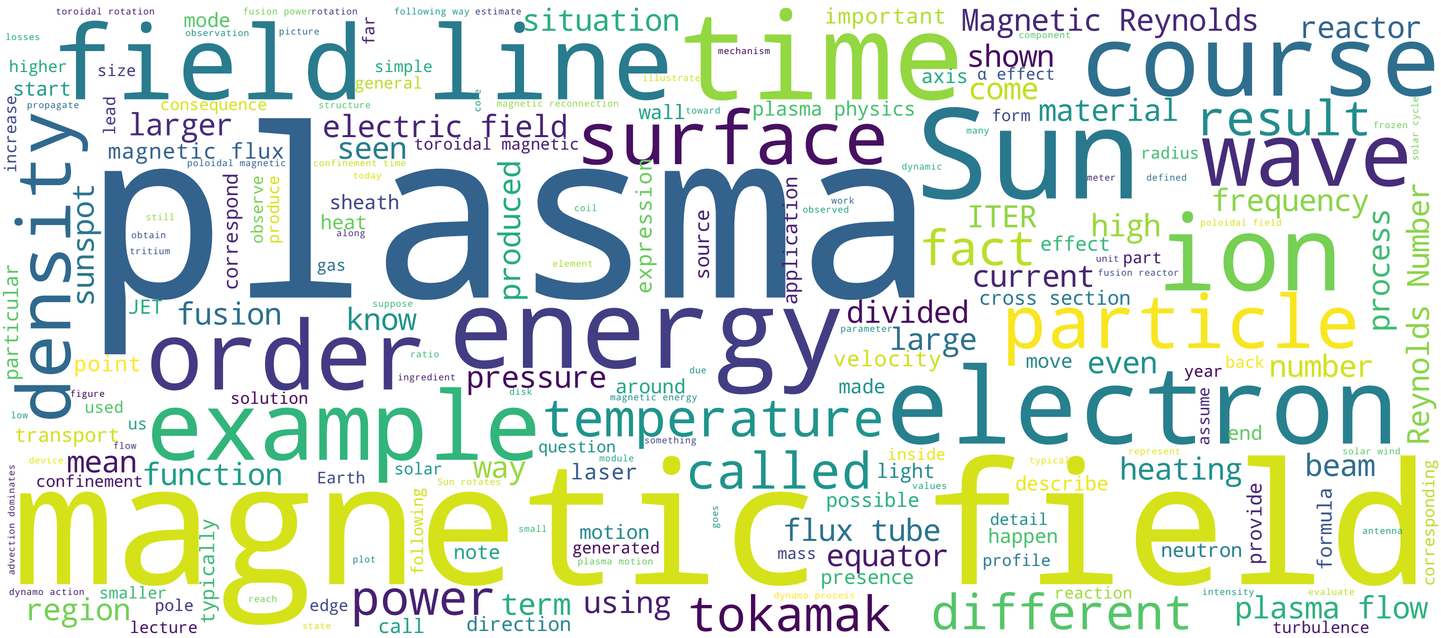
Courtesy of NASA

Dynamo: from plasma flow to magnetic fields

Plasma Physics and Application to Fusion Energy, Astrophysics and Industry

Lecture 4c

Ivo Furno



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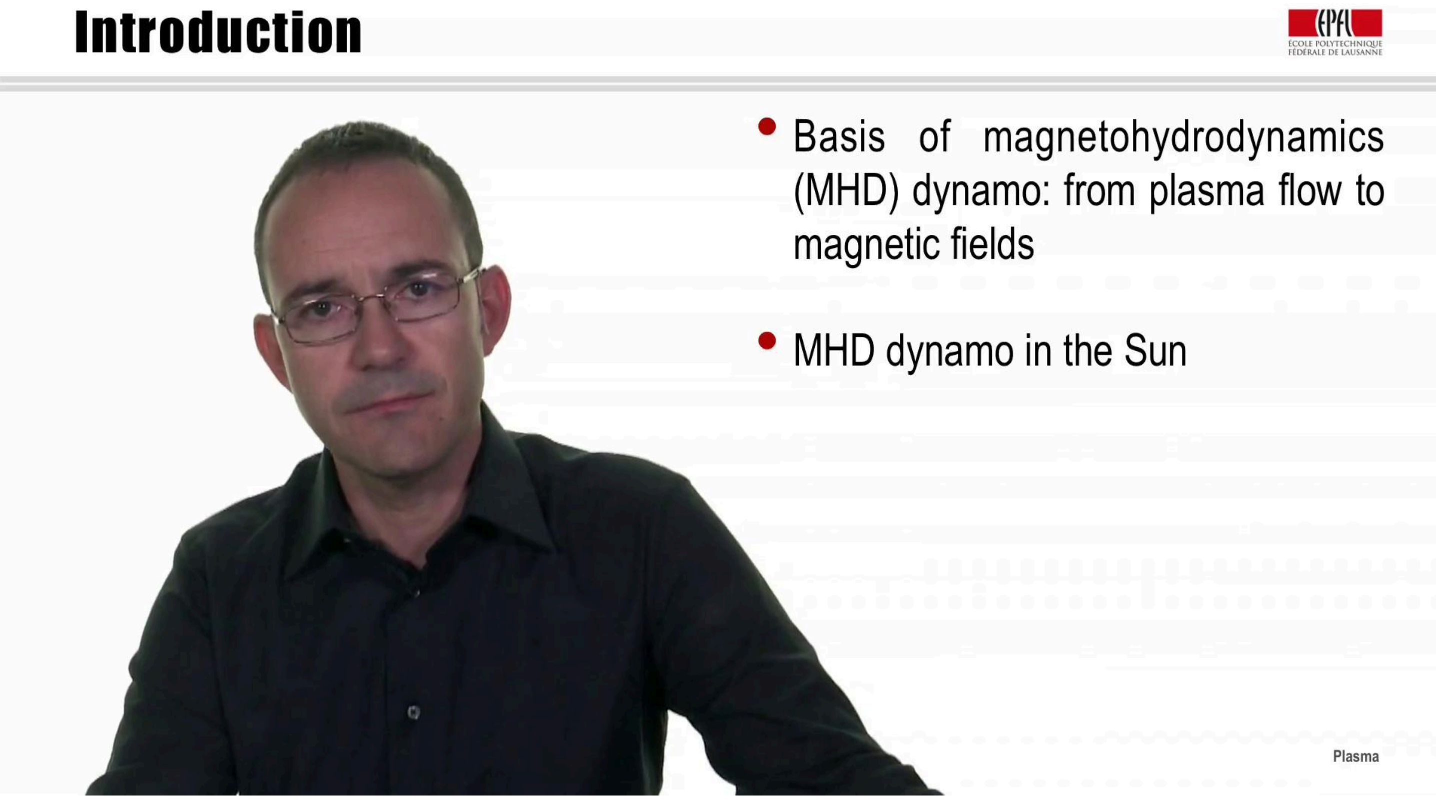


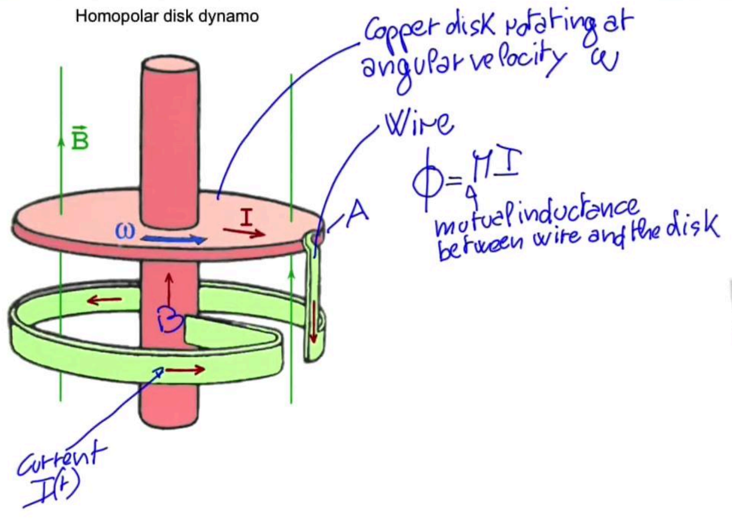
Welcome back to the course on Plasma Physics and Applications. In the last module we have reviewed observational data collected with telescopes over two centuries, and recently with satellites, that demonstrate an amazing dynamics of the magnetic fields in the Sun. We have discussed properties of the sunspots where the magnetic fields are extremely intense and the global structure of the solar magnetic field, which reverses every 11 years. In the course of this lecture I will describe how a magnetohydrodynamic dynamo which converts energy of the plasma flow into magnetic energy is at the origin of these fields. I will use the plasma physics tools that you have learned so far and I will focus on the main physics issues by skipping the complicated details.

Notes

Summary

0m 06s

Basics of dynamo



- In 1919, Sir Joseph Larmor in a "brief communication" to the British Association for the Advancement of Science: "How could a Rotating Body such as the Sun become a Magnet?"
- Dynamo is the process of magnetic field generation by the inductive action of a conductive fluid: conversion of mechanical energy into magnetic energy by stretching and twisting magnetic field lines.

Plasma

The generation of magnetic fields in astrophysics is an old question. In 1919 Larmor asked, in a brief communication, the following question: "How could a rotating body such as the Sun become a magnet?" The answer to this question could be a dynamo process in which the magnetic field is generated by the inductive action of a conducting fluid. In essence, the mechanical energy of the flow can be converted into magnetic energy by stretching and twisting the magnetic field lines. Before going into the details of plasma physics, let's consider a simple mechanical dynamo as the one that is shown here, called *homopolar disk dynamo*. Let's consider a copper disk that rotates at an angular velocity ω. The rotation is externally driven, for example, by a motor, by applying a torque to the axis of the disk. A wire which is twisted about the axis as it is shown here makes a sliding contact with the disk at points A and B. This wire can carry a current that we indicate with I, which is a function of time, t. The magnetic field associated with this current has a flux Φ = M I where M is the mutual inductance between the wire and the disk.

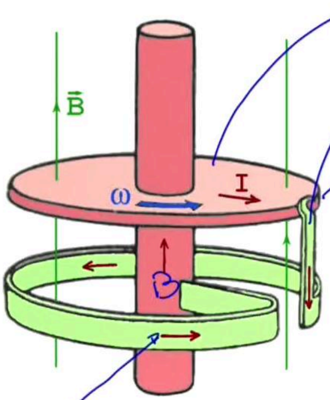
Notes

Summary

0m 54s

Basics of dynamo

Homopolar disk dynamo



Copper disk rotating at angular velocity ω

Wire

$\phi = MI$ mutual inductance between wire and the disk

$emf = \frac{\omega \phi}{2\pi}$ $\frac{2\pi}{\omega}$ s

Current $I(t)$

$\underbrace{L}_{\text{Selfinductance}}\frac{dI(t)}{dt} + \underbrace{R}_{\text{Resistance}}I = \frac{\omega M I}{2\pi}$

$\frac{dI}{dt} = \frac{1}{L}\left[\frac{\omega M}{2\pi} - R\right] I \rightarrow \frac{dI}{I} = \frac{1}{L}\left[\frac{\omega M}{2\pi} - R\right]dt$

$I = I_0 e^{\frac{1}{L}\left[\frac{\omega M}{2\pi} - R\right]t}$ $\boxed{\omega > \frac{2\pi R}{M}} \rightarrow$ flux amplification dynamo!

If $\omega < 0 \rightarrow$ no dynamo

- In 1919, Sir Joseph Larmor in a "brief communication" to the British Association for the Advancement of Science: "How could a Rotating Body such as the Sun become a Magnet?"
- Dynamo is the process of magnetic field generation by the inductive action of a conductive fluid: conversion of mechanical energy into magnetic energy by stretching and twisting magnetic field lines.

Plasma

The rotation of the disk in the presence of this magnetic flux generates a radial electromotive force [emf] which is equal to the angular velocity [ω] times the magnetic flux Φ divided by 2π. This is due to the fact that a radius of the disk cuts the magnetic flux Φ once every 2π/ω seconds. The rotation of the copper disk therefore results in a potential difference between the axis and the edge of the disk. We can therefore write the equation for the circuit in the following way: Where L is the self inductance and R is the resistance of the circuit. We can find a solution for this equation as follows: If we look at the solution, we note that if ω > 2π R/M the current will grow exponentially. This provides flux amplification, and therefore, dynamo action. We also note that if we now spin the disk in the opposite direction such that ω now is negative, no dynamo is possible, since an initial current will be damped. In this simple mechanical dynamo example, the success of the dynamo depends on the built-in axial asymmetry of the system which in this case is provided by the contorted shape that the wire that carries the electrons, -in this case, this would be the equivalent of the plasma flow,- is wound around the axis of our system.

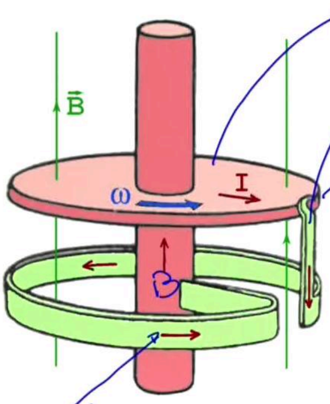
Notes

Summary

2m 35s

Basics of dynamo

Homopolar disk dynamo



Copper disk rotating at angular velocity ω

Wire

A

$\phi = MI$

mutual inductance between wire and the disk

$emf = \frac{\omega \phi}{2\pi}$ $\quad \frac{2\pi}{\omega}$ s

$\frac{dI(t)}{dt} L + RI = \frac{\omega M I}{2\pi}$

Self inductance

Resistance

Current $I(t)$

$\frac{dI}{dt} = \frac{1}{L}\left[\frac{\omega M}{2\pi} - R\right] I \rightarrow \frac{dI}{I} = \frac{1}{L}\left[\frac{\omega M}{2\pi} - R\right] dt$

$I = I_0 e^{\frac{1}{L}\left[\frac{\omega M}{2\pi} - R\right] t}$

If $\omega < 0$ → no dynamo

$\boxed{\omega > \frac{2\pi R}{M}}$ → flux amplification dynamo!

- In 1919, Sir Joseph Larmor in a “brief communication” to the British Association for the Advancement of Science: “How could a Rotating Body such as the Sun become a Magnet?”
- Dynamo is the process of magnetic field generation by the inductive action of a conductive fluid: conversion of mechanical energy into magnetic energy by stretching and twisting magnetic field lines.

Plasma

This is kind of a troubling observation for astrophysical objects, since in general they possess a very good symmetry. Somehow this suggests that in such bodies, a dynamo process must be linked to some asymmetries of their internal motion. This is very far from obvious, how this is going to happen. There is absolutely no guarantee that in a spherical rotating object, such as, for example, the Sun, the fluid, the plasma motion, can drive a suitably contorted flow to provide a dynamo effect.

Notes

Summary

4m 48s

A few theorems on dynamo

- In Cartesian coordinates (x,y,z) no field independent of z vanishing for x, y → ∞ can be maintained by dynamo action. It is impossible to generate a 2D dynamo field.
- A purely toroidal flow cannot maintain a dynamo.
- Cowling Anti-Dynamo Theorem: an axisymmetric magnetic field vanishing at infinity cannot be maintained by dynamo action.
- Dynamos with a high degree of symmetry do not work:
  - stationary axisymmetric dynamo
  - stationary centrally symmetric dynamo
  - dynamos whose velocity field is restricted to a plane.

Hence a successful dynamo has to be complicated. . . and so is its analysis.

Plasma

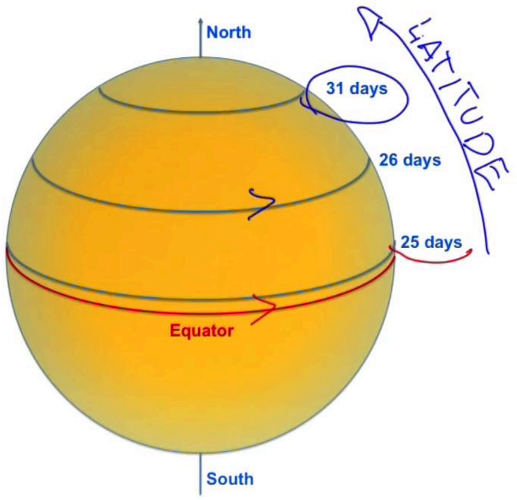
These observations that we have just made were put on solid ground by a few theorems on the dynamo action. The results of some of these theorems are recalled here without going into the demonstrations. For example, in Cartesian coordinates (x,y,z) no field independent of the coordinate z that vanishes at infinity can be maintained by a dynamo action. This is telling us that it is impossible to generate a two-dimensional dynamo field. A consequence of this theorem is that in a toroidal system, a purely toroidal flow cannot maintain a dynamo. Probably the most important of all dynamo theorems is the *Cowling Anti-Dynamo Theorem*, that states that an axisymmetric magnetic field vanishing at infinity cannot be maintained by a dynamo action. A consequence is that dynamos with a high degree of symmetry do not work. In particular, we cannot achieve a stationary axisymmetric dynamo, a stationary centrally symmetric dynamo, or dynamos whose velocity field is restricted to a plane. The result is that a successful dynamo has to be complicated, and so will be its analysis.

Notes

Summary

5m 25s

Surface rotation



- Observations of the solar surface reveal a non-uniform rotation.
- The Sun does not rotate as a solid body. It spins differentially. It rotates faster at the equator and slower at its poles.
- The equator needs 25 days whereas regions at the poles need approximately 31 days for one full revolution.

Plasma

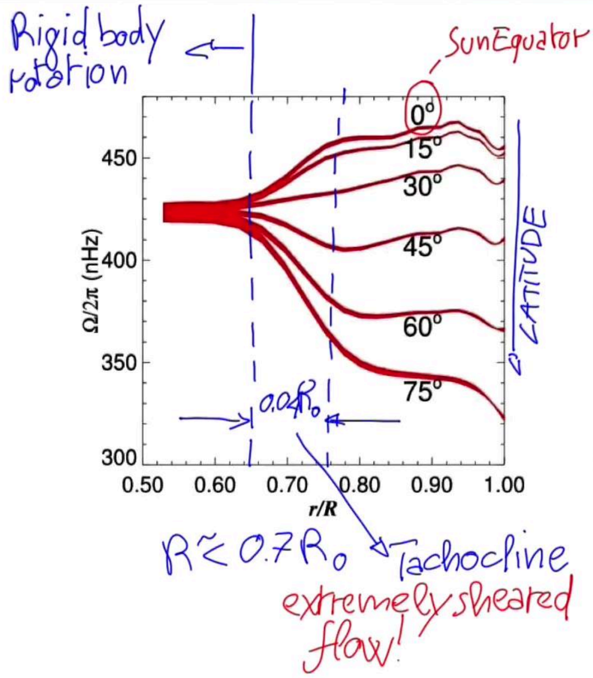
Now let's come back to the Sun and let's try to answer the following question: How does plasma flow in the Sun? Is the plasma flow sufficiently contorted such that a dynamo action can take place? Let's start from the observations of the rotation of the solar surface. We know that the Sun rotates, and the equator of the Sun rotates in approximately 25 days. If we move to larger latitude, towards the north pole of the Sun, we can observe that the surface of the Sun does not rotate as a solid body. It spins differentially. The Sun rotates faster at the equator than at its poles. While the equator needs approximately 25 days for a full revolution, the regions near the poles will need about 31 days. This observation shouldn't come as a surprise, since the Sun is not a solid body like Earth, but is instead a huge sphere of plasma and different parts of it can rotate at different speeds.

Notes

Summary

7m 02s

Interior rotation: helioseismology



- Due to opacity of the plasma, the interior of the Sun has remained a mystery until recently.
- Helioseismology indicates that the inner structure of the Sun rotates as a rigid body.
- The transition to a constant rotation rate at the bottom of the convection zone seems to be very sharp.
- The tachocline (region of strong sheared rotation) is located at a radius of at most $0.70R_0$ with a thickness of $0.04R_0$.

Plasma

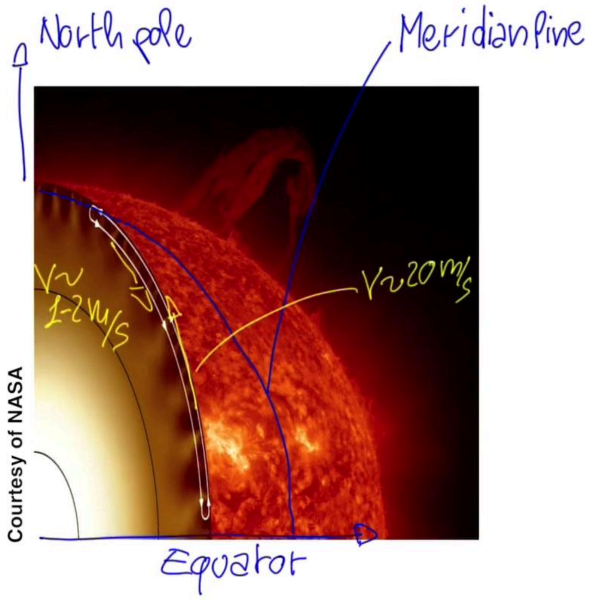
Now, what about the rotation inside the Sun? We cannot directly look through the surface of the Sun since the plasma is opaque, except for a thin layer, which is the photosphere. For this reason, the rotation in the interior has remained a mystery until the recent development of helioseismography. These consist in measuring the properties of acoustic waves which propagate, are reflected and refracted, due to the variation of the material where they propagate. The analysis of the mode structures, and the frequency of the waves allows us to determine how the rotation varies within the depth of the Sun. The most recent observations from helioseismic data are shown in this figure, which displays the toroidal rotation frequency as a function of the radius for different latitudes. Zero degrees corresponds to the Sun's equator. We observe that in the inner part of the Sun for R approximately smaller than 0.7 R_0 the Sun rotates as a rigid body at a speed between the polar and the equatorial surface speeds. The transition to a constant rotation rate happens in a very narrow region of a thickness 4% of the Sun's radius which is called the *tachocline*. In this region, the toroidal plasma flow is extremely sheared since the changes happen in a very narrow region and this differential rotation can have important consequences for the magnetic field generation as we will see later.

Notes

Summary

8m 14s

Meridional circulation



- Meridional circulation: flow along meridian lines from the equator toward the poles at the surface and from the poles to the equator below the surface. Unavoidable in turbulent, compressible rotating convective shells.
- At the surface this flow is slow ~20 m/s. The return flow toward the equator is much slower 1 to 2 m/s.
- This slow return flow would carry material from the mid-latitudes to the equator in about 11 years. → Solar cycle

Plasma

Recently helioseismography has revealed the presence of flows along the meridian lines from the equator towards the pole at the Sun's surface, and from the poles towards the equator below the surface. This is the so-called *meridional circulation*. Near the surface, the flow from the Equator to the North Pole is of the order of 20 meters per second. Slightly deeper in the Sun, the return flow from the North Pole toward the Equator is much slower, with a speed of the order of one to two meters per second. It is interesting to note that this low flow return would carry material from mid latitudes to the Equator in about 11 years, which is an important number in solar cycle.

Notes

Summary

10m 03s

MHD induction equation and Reynolds number

Magnetic field

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

Plasma conductivity

plasma flow

λ magnetic diffusivity $[m^2/s]$

B varies over spatial scale L, temporal scale τ

$$\frac{B}{\tau} = \frac{1}{\mu_0 \sigma} \frac{B}{L^2} \rightarrow \tau_\sigma = \mu_0 \sigma L^2$$

Plasma

So far we have seen that the plasma in the Sun is characterized by the presence of magnetic fields and plasma flows. How can we describe it? The key equation to describe the dynamics of magnetic fields in a plasma is the induction equation of the magnetohydrodynamics, which is shown here. In this equation, B represents the magnetic field, v is the plasma flow, and σ is the plasma conductivity. This term, usually represented with the letter λ, is the magnetic diffusivity, and in SI units it is measured in m^2/s. If we know the plasma flow and we know the velocity v, this equation provides the evolution of the magnetic field under some initial conditions. We can identify two contributions to the variation of the magnetic field. The first term describes a diffusion process which is produced by the conductivity of the plasma. The second term is a convection term and is produced by the bulk plasma motion with the velocity v. Let's assume that B varies over a spatial scale L and a temporal scale τ. Let's now consider the MHD induction equation only with the diffusion term. We can do the following estimate and come up with the resistive diffusion time which we can write in the following way.

Notes

Summary

11m 02s

MHD induction equation and Reynolds number

Magnetic field

Plasma conductivity

Diffusion

plasma flow

Advection

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

magnetic diffusivity $[m^2/s]$

B varies over spatial scale L, temporal scale τ

Astrophysical plasmas $R_m \gg 1$

Laboratory plasmas $R_m \simeq 10$

Diffusion dominates

$$\frac{B}{\tau} = \frac{1}{\mu_0 \sigma}\frac{B}{L^2} \rightarrow \tau_\sigma = \mu_0 \sigma L^2$$

Advection dominates

$$\frac{B}{\tau} = \frac{VB}{L} \rightarrow \tau_{ad} = \frac{L}{V}$$

$$\frac{\tau_\sigma \text{ diffusion}}{\tau_{ad} \text{ advection}} = \mu_0 \sigma L V = R_m$$

Magnetic Reynolds number [adimensional]

$R_m \gg 1 \rightarrow$ Advection dominates

$R_m \ll 1 \rightarrow$ Diffusion dominates

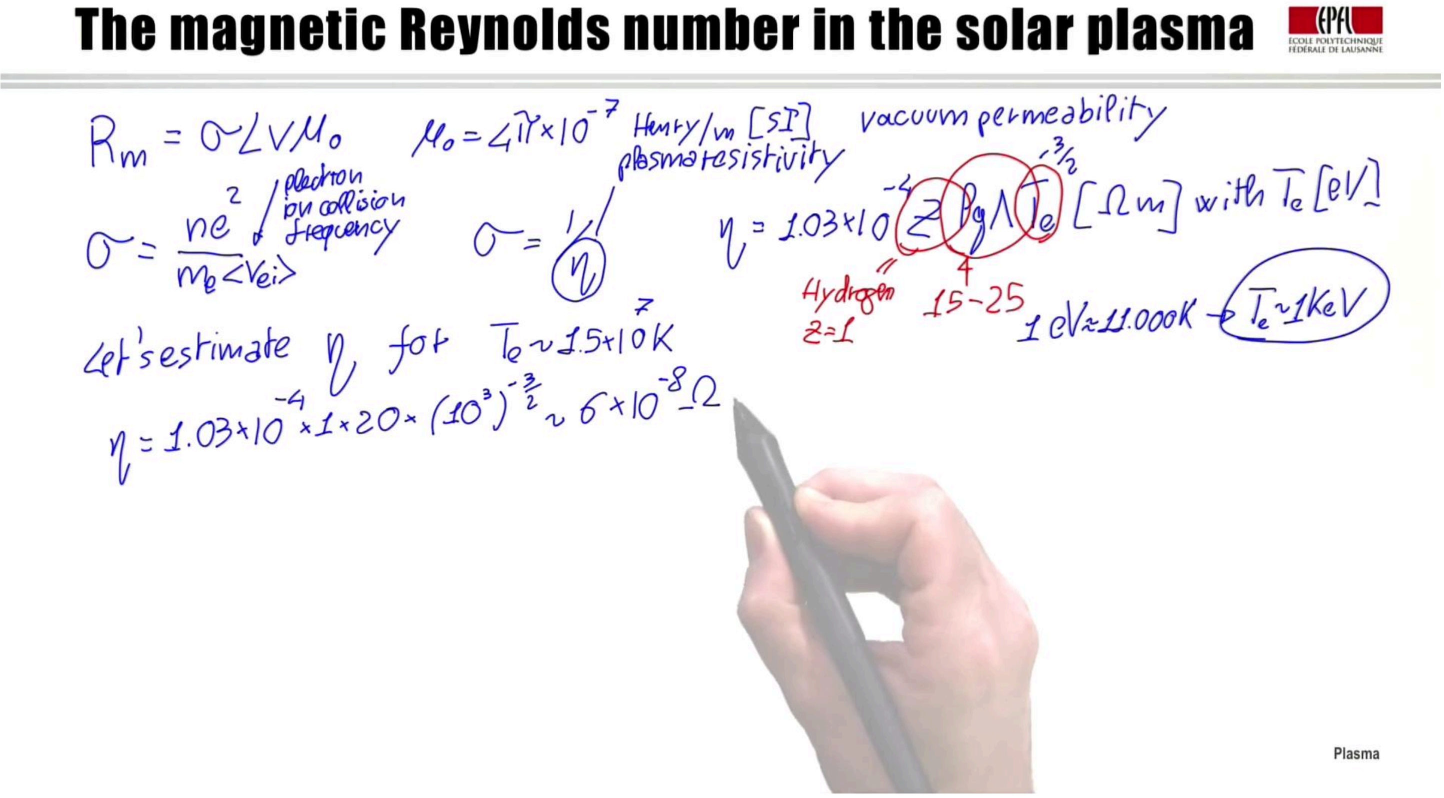
Plasma

Since we have ignored the advection term, this resisted diffusion time will provide the timescale over which the magnetic field changes if diffusion dominates. Let's now consider only the advection term and ignore diffusion. We can use the induction equation and estimate the advection time this way. The advection time that we have estimated provides the timescale over which the magnetic field would change if advection dominates the process. How can we decide whether diffusion or advection dominates the plasma dynamics? We can take the ratio of the two times and use the expression that we have just computed and we come up with the following: This formula defines the *Magnetic Reynolds Number* which is a dimensionless number, usually indicated with Rm. If the Magnetic Reynolds Number is much larger than one, advection dominates. In the opposite limit, if the Magnetic Reynolds Number is much smaller than one, then diffusion dominates. As we will see in the following, in astrophysical plasmas typically, the Magnetic Reynolds Number is much larger than one, while in laboratory experiment it is usually small, typically of the order of 10 or 15.

Notes

Summary

12m 45s

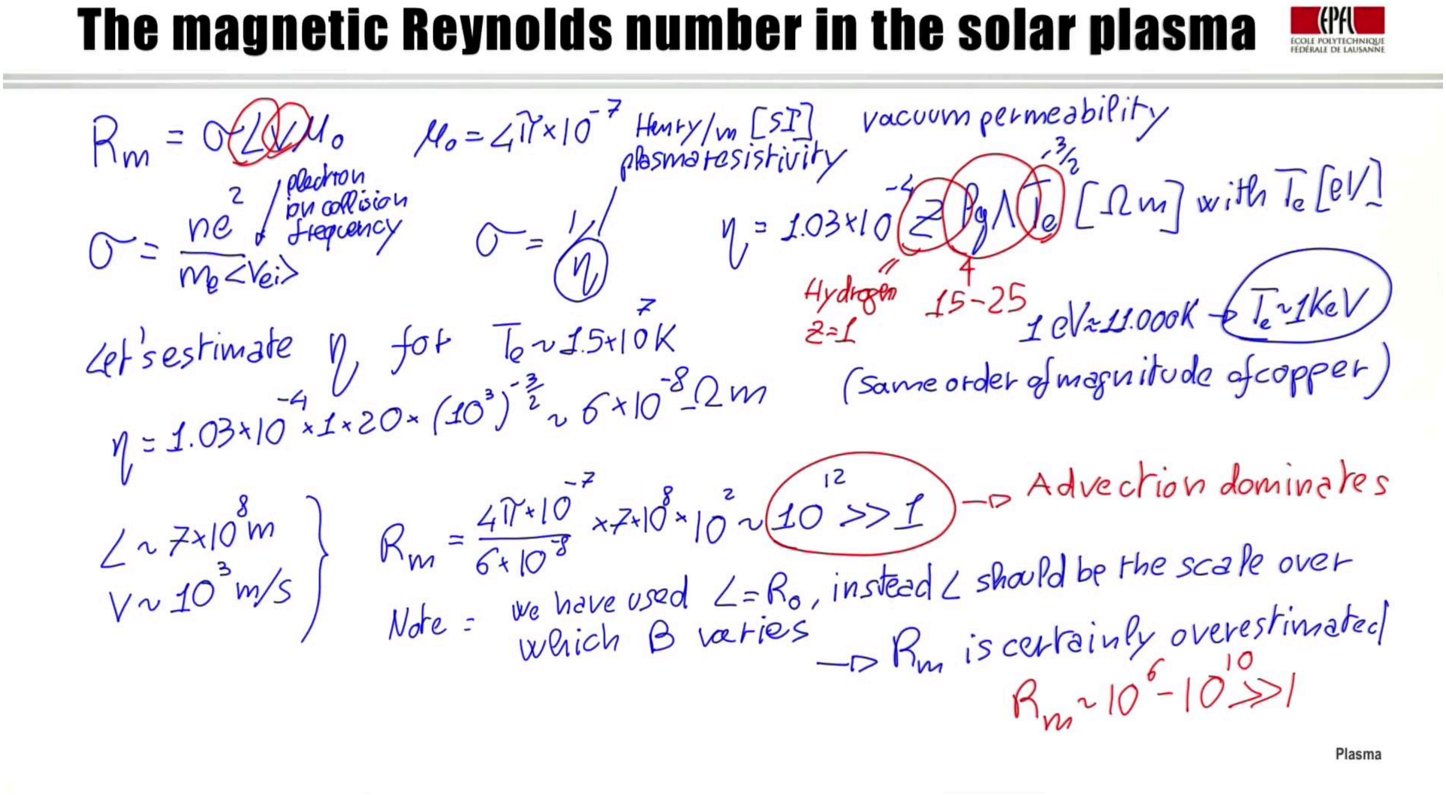


Let's now evaluate the Magnetic Reynolds Number for solar plasmas. In order to do that, we need to recall the value of the vacuum permeability in SI units [4π x 10^{-7} Henry/m]. To do that, we also need to recall the expression of the plasma conductivity that you have derived in a previous module which is written this way, and which involves the estimate of the electron-ion collision frequency [<vei>]. We can now recall that the plasma conductivity is the inverse of the plasma resistivity, and for the plasma resistivity we can use a very useful formula in SI units, as follows: This formula involves the Coulomb logarithm [log Λ], with a value usually between 15 and 25. The effective *Z* of the plasma, that we assume equal to one by taking a hydrogen plasma and the electron temperature, which in this formula is expressed in electron volts [eV]. Let's now estimate the plasma resistivity using the temperature that we have computed previously, which is of the order of 1.5 x 10^7 Kelvin. We recall that 1 eV is equivalent approximately to 11,000 Kelvin, and we can take a temperature of the order of 1 keV. Let's plug these numbers into the formula We end up with a resistivity of the order of 6.

Notes

Summary

14m 31s

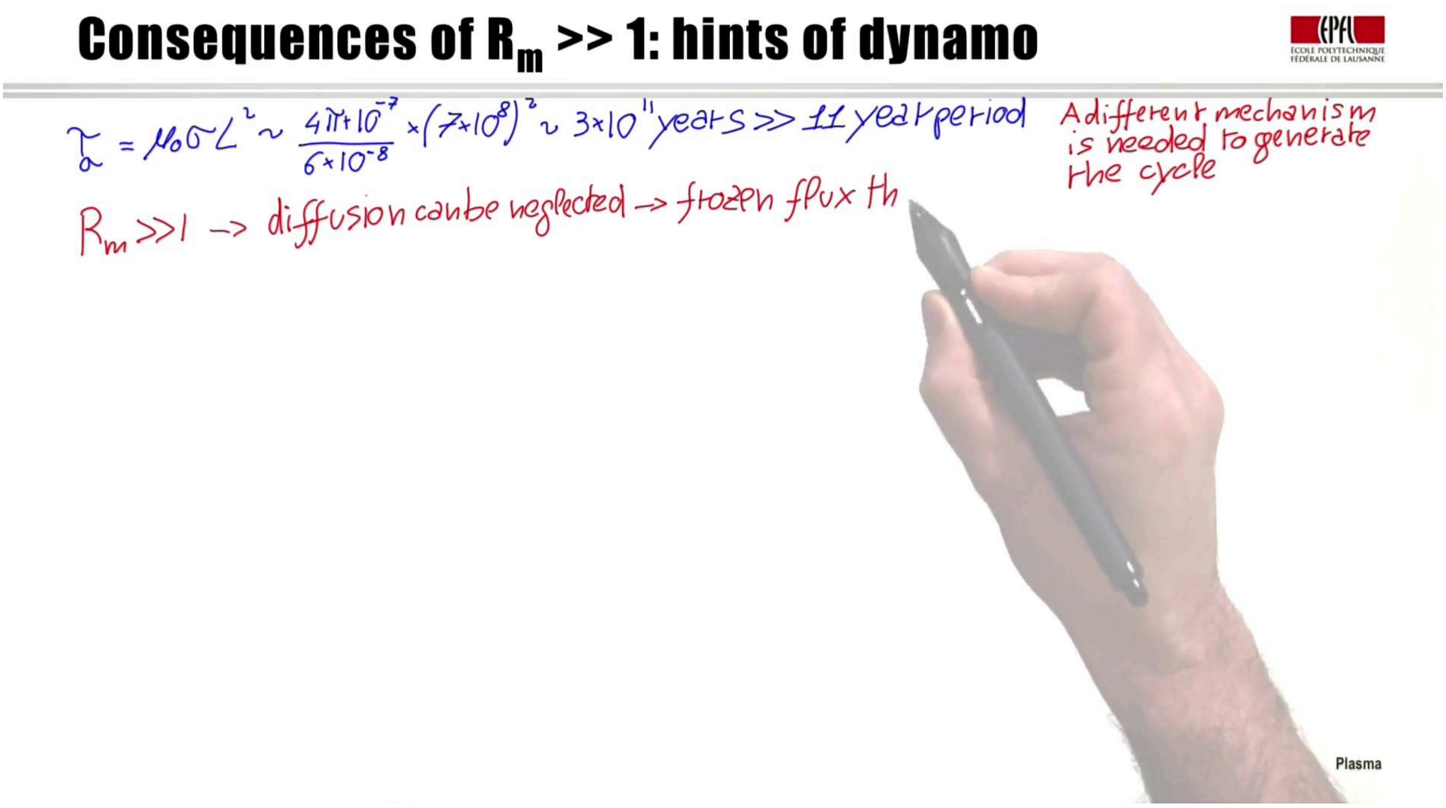


x 10⁻⁸ Ωm. We can observe that a hydrogen plasma at the temperature of approximately 1 keV has about the same order of magnitude of the resistivity as copper. Now, in order to compute the Magnetic Reynolds Number, we have to assume a typical scale length and a typical velocity. For the typical scale length, we can assume the radius of the Sun, 7. x 10^8 m, and for a typical velocity we use 1 km per second, which is the typical speed of the plasma flow at the surface of the Sun. If you now plug these numbers into the formula for the Magnetic Reynolds Number, we end up with a value of 10^{12}, which is much larger than 1, telling us that in the Sun, the advection dominates the plasma dynamics. There is a note of caution, however. We have used as an estimate for *L* the radius of the Sun. Instead, L should be the scale over which the magnetic field varies. The result is that the Magnetic Reynolds Number is certainly overestimated. More precise estimates end up with values between 10^6 and 10^{10}, which are numbers much larger than 1, telling us that diffusion can be neglected in the dynamics of solar plasmas over such large spatial scales, where advection dominates.

Notes

Summary

16m 16s



Let's now explore some consequences of this large magnetic Reynolds number. Let's suppose that the magnetic field existed at the time when the Sun was born and let's evaluate how long it would take for this field to decay by magnetic diffusion. We can compute the resistive diffusion time in the following way and we come up with a number which is approximately 3. x 10^{11} years. This is an extremely long period of time, much longer than the 11-years period that we observe for the solar cycle. This is suggesting that a different mechanism, other than simple resistive diffusion is needed to generate the solar cycle. One possibility is, of course, that the magnetic field is amplified by the plasma fluid motion, such that the mechanical energy of the flow is transformed into magnetic energy. In other words, we need a dynamo process. Now we'll see how this could be possible. For a large Magnetic Reynolds Numbers, we have just seen that diffusion can be neglected and this results in an important property for the dynamic of the plasma. You have seen in module 3 that under this condition, the *frozen flux theorem* holds.

Notes

Summary

17m 56s

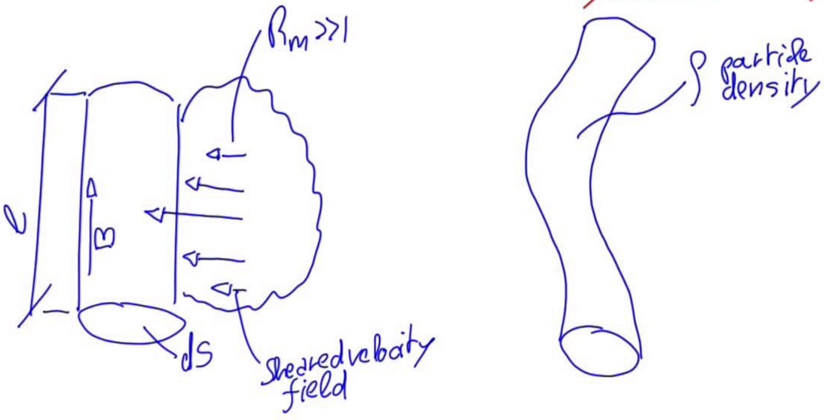
Consequences of R_m >> 1: hints of dynamo

$\tau = \mu_0 \sigma L^2 \sim \frac{4\pi \times 10^{-7}}{6\times 10^{-8}} \times (7\times 10^{8})^2 \sim 3\times 10^{11}$ years >> 11 year period

A different mechanism is needed to generate the cycle

$R_m \gg 1 \rightarrow$ diffusion can be neglected $\rightarrow$ frozen flux theorem

field lines are frozen into the plasma



$B\,dS = $ constant

$\rho\, dS\, \ell = $ constant

Plasma

This implies that the magnetic flux through any closed contour in the plasma, each element of which moves with the local plasma velocity, is a conserved quantity. This, in turn, implies that the magnetic field lines must move with the plasma. In other words, the field lines are frozen in the plasma. Let's now consider a flux tube which is defined as a topologically cylindrical volume whose sides are defined by the magnetic field lines. Let's suppose that this flux tube is embedded into a plasma which has a huge magnetic Reynolds number. Let's suppose that now the plasma moves with a sheared velocity field perpendicular to the flux tube. As a result of this motion, since the magnetic field lines are frozen into the plasma, the magnetic flux tube will be deformed. Let's suppose that the flux tube is characterized by a plasma with particle density ρ. During its motion, the flux through the surface dS must be conserved, since the magnetic field is frozen into the plasma and the frozen flux theory holds. At the same time, the total number of particles is also conserved during the motion and the total number of particles can be expressed in this way.

Notes

Summary

19m 23s

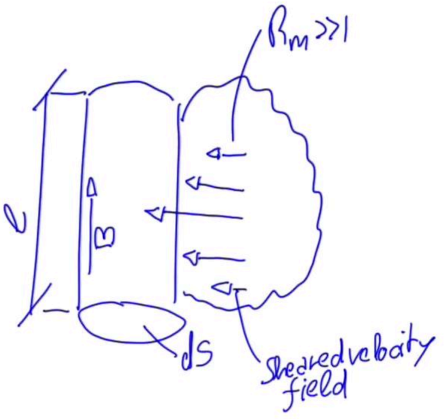
Consequences of R_m >> 1: hints of dynamo

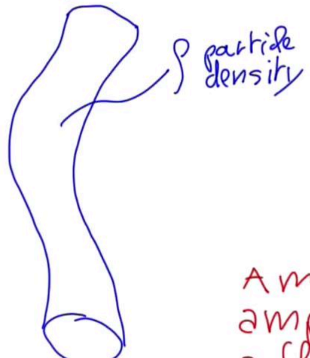
$\tau_d = \mu_0 \sigma L^2 \sim \frac{4\pi\times10^{-7}}{6\times10^{-8}} \times (7\times10^{8})^2 \sim 3\times10^{11}$ years >> 11 year period

A different mechanism is needed to generate the cycle

$R_m >> 1$ -> diffusion can be neglected -> frozen flux theorem

field lines are frozen into the plasma





$B\, ds = \text{constant}$

$\rho\, ds\, \ell = \text{constant}$

$B \propto \rho \ell$

A magnetic field can be amplified by stretching a flux tube (or field line) when $R_m >> 1$!

Plasma

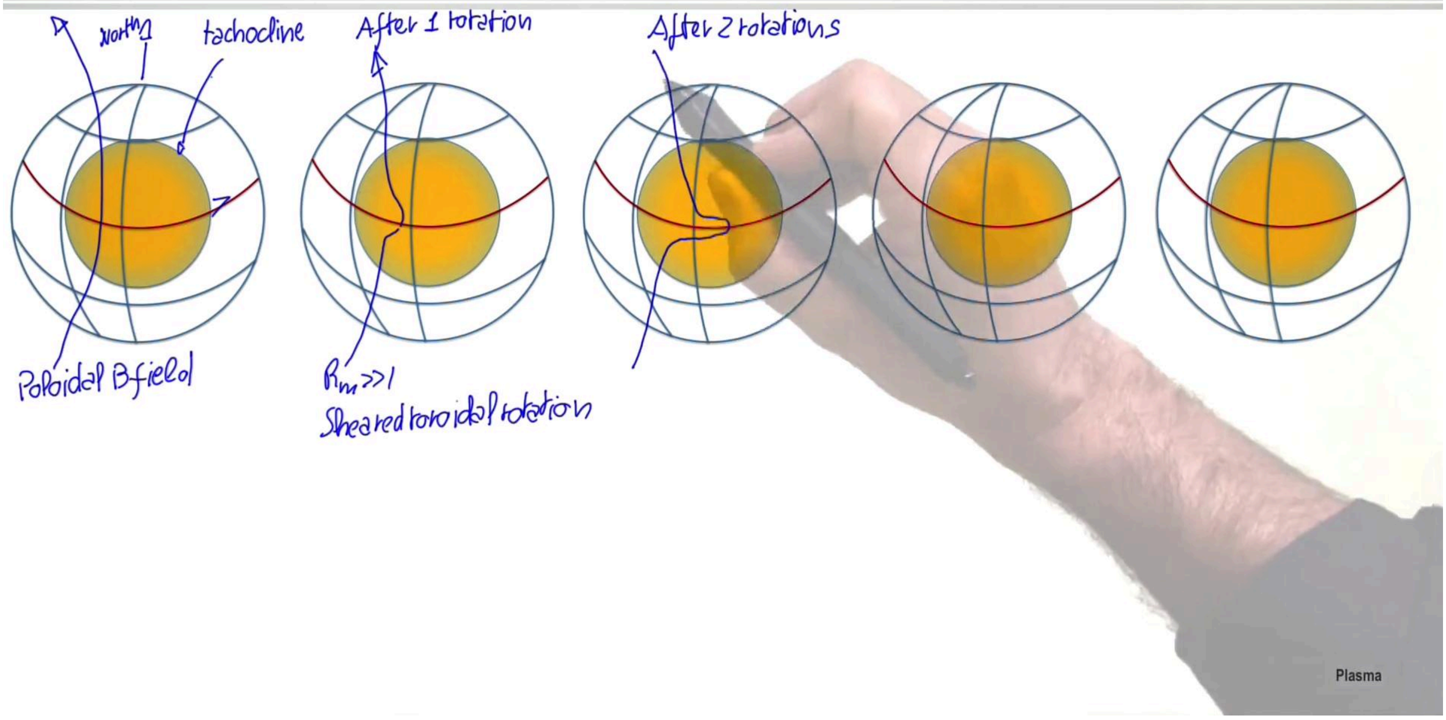
Putting together these two formulae we obtain that the magnetic field is proportional to the length of the flux tube. The important result of this formula is that the magnetic field can be amplified by stretching a flux tube or a field line when the magnetic Reynolds number is much larger than one.

Notes

Summary

20m 53s

The Ω-effect



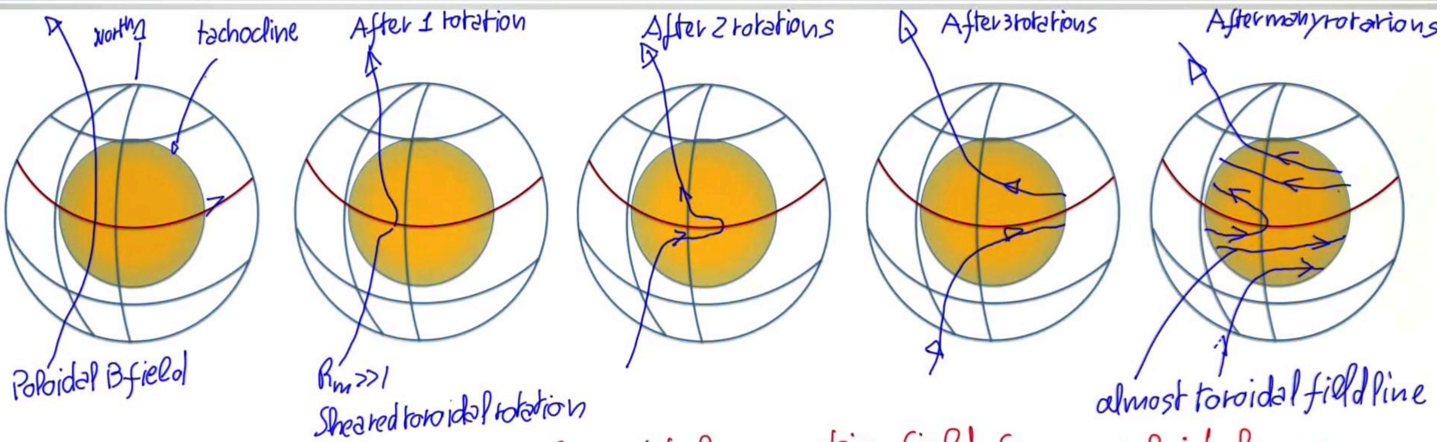
With these ingredients, let's now come back to the Sun and let's see how the first step of a solar dynamo may work. In this figure, the inner sphere identifies the position of the tachocline region where the solar toroidal rotation has a strong velocity shear. The Sun rotates in this direction, and the North is indicated by this arrow. Let's start with a poloidal magnetic field which is oriented in the meridian plane as shown here. This field could be, for example, a primordial magnetic field when the Sun was born. This is the initial state of our Sun. Let's see what happens after one toroidal rotation. Two ingredients are important here: the first ingredient is a huge magnetic Reynolds number and the second ingredient is a sheared toroidal rotation with the equator of the Sun spinning faster than the poles of the Sun. Due to the huge magnetic Reynolds number, the magnetic field lines are frozen in the plasma motion. Therefore, since the plasma motion has a sheared toroidal rotation the magnetic field line will be deformed in the following way being stretched more at the Equator than at the Poles. After two rotations, this stretching effect at the Equator will be amplified and the magnetic field line will look like this.

Notes

Summary

21m 15s

The Ω-effect



Results = 1) Generation of toroidal magnetic field from a poloidal one
2) The magnetic field is amplified due to the frozen flux theorem

Ω-effect   poloidal B → toroidal B
α-effect

Plasma

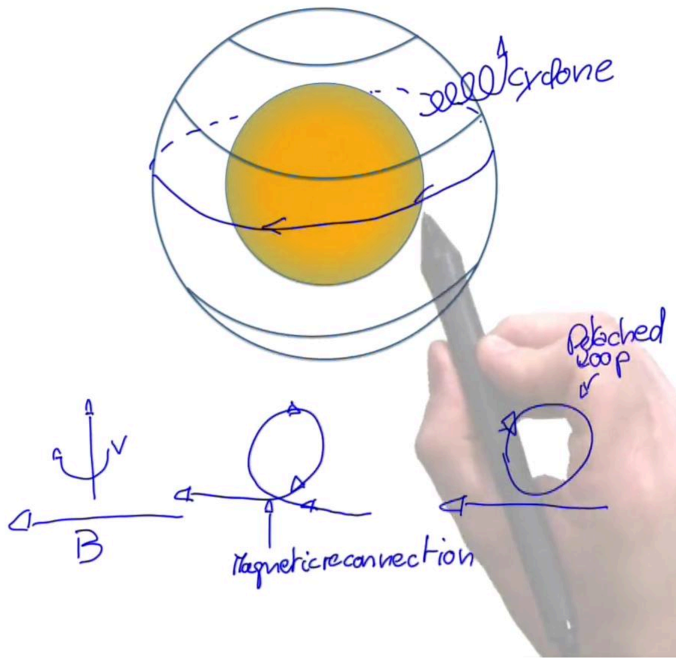
The process will go on, and after three rotations, the magnetic field line may look like this one. After many rotations, the magnetic field lines will look like this one where the original poloidal magnetic field is now transformed in a magnetic field line which is almost completely toroidal near the equator. The first result of this process is that a toroidal magnetic field is generated from a poloidal one. The second important result is obtained by observing that the original magnetic field line has been stretched by the sheared flow in the plasma. As a consequence, the magnetic field is amplified due to the frozen flux theorem. This effect of toroidal magnetic field generation from a poloidal magnetic field and the subsequent intensification of the toroidal magnetic field is usually referred to as the *Omega Effect* [Ω-effect], and this is a well established process in the solar dynamo physics. Now to complete the cycle, we need a mechanism that allows us to convert a toroidal magnetic field into a poloidal one. This mechanism is less clear, and one possible solution is the so-called *Alpha Effect* [α-effect].

Notes

Summary

22m 51s

The α-effect (Parker-1955)



- The original α-effect relies on small scale turbulent motions whose twisting action can transform a toroidal field line into a poloidal field line.
- The turbulent motions must have non-zero fluid helicity → screw-like vortices (cyclones).
- Averaging over many cyclonic events leads to the production of a large-scale poloidal field.
- This mechanism is formalized in the *mean-field electrodynamics*.

Plasma

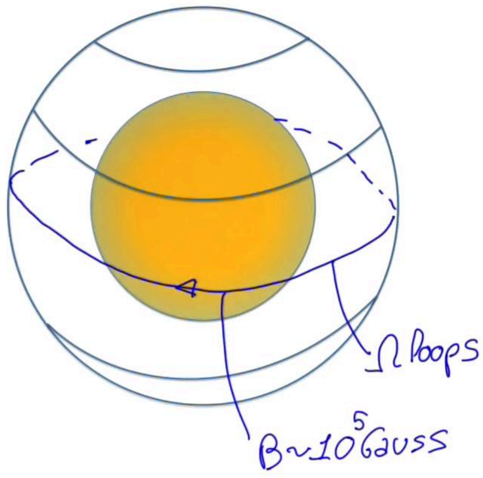
The main idea of the α-effect was originated by Parker in 1955. The main idea is that a turbulent flow which has particular features can twist a toroidal field line into a poloidal one. For example, if you have a convection of plasma in a rotating frame, this can generate turbulence which is characterized by a non-zero fluid helicity. The turbulent flow can look like corkscrew vortices with an unequal number of right-handed vortices and left-handed vortices. Let's now consider a magnetic field line that is immersed in a plasma that exhibits such a complex cyclonic flow. These vortices can simply lift the magnetic field line up, and twist it. In the contact point where now two oppositely directed magnetic field lines touch, magnetic reconnection can happen. We will talk in detail about magnetic reconnection in the next module, but for now just keep in mind that reconnection allows magnetic field lines to break and change their topology. The magnetic field loop can eventually detach from the original field line. Let's now consider an equatorial magnetic field line which is almost completely toroidal.

Notes

Summary

24m 34s

The Babcock-Leighton mechanism



- Developed in the 1960's, it was obscured by mean-field electrodynamics.
- Magnetographs over solar cycles 21 and 22 provided evidence that the polar field reversal is triggered by the decay of the magnetic field in active regions (sunspots).
- If the toroidal magnetic field is too strong, turbulence cannot twist the magnetic field lines thus reducing the dynamo effect → revival of BL mechanism.

Plasma

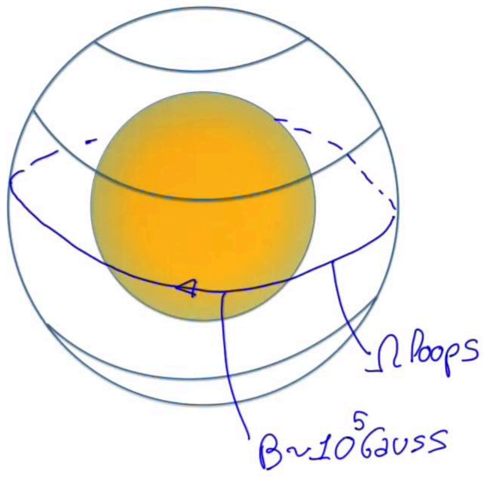
If many of these detached loops are produced, by averaging over many cyclonic events, turbulent events, these can lead to the production of a large-scale poloidal field. This can be observed in this figure where the combination of many turbulent events results in an equivalent generation of a macroscopic toroidal current which in turn would produce a large-scale poloidal magnetic field. This mechanism has been formalized in the mean-field electrodynamics. An alternative and similar mechanism to transform a toroidal magnetic field back into a poloidal magnetic field is the *Babcock-Leighton mechanism*. It was originally developed in the 1960's but for a long time it was obscured by the success of the mean-field electrodynamics and the α-effect. However, recently, over the cycle 21st and 22nd, the magnetograph provided evidence that the polar field reversal is triggered by the decay of the magnetic field in the sunspots. The first time, it was noted that the end result of the first stage of the dynamo mechanism, could result in magnetic field lines, the so-called *Ω-loops* which are toroidally oriented, which are extremely intense, of the order of 10^5 Gauss.

Notes

Summary

26m 12s

The Babcock-Leighton mechanism



- Developed in the 1960's, it was obscured by mean-field electrodynamics.
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Plasma

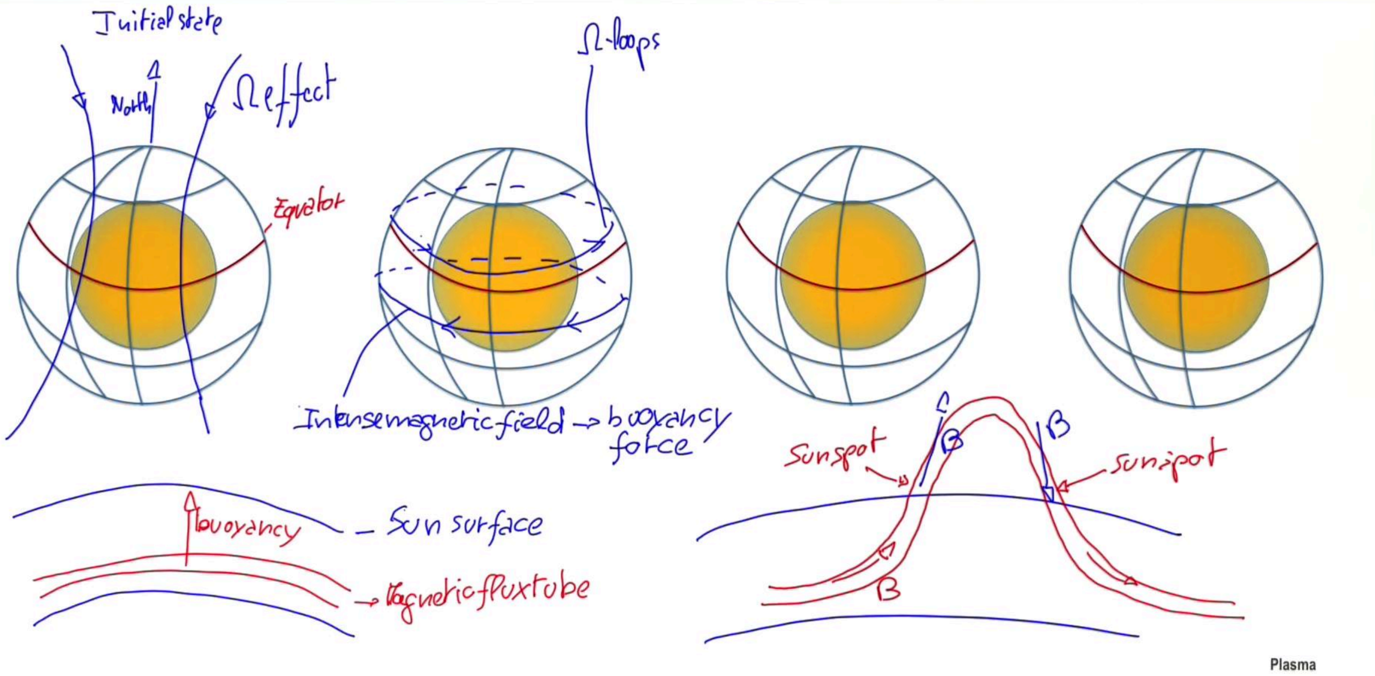
If the toroidal magnetic field in this field line is too strong, it is likely that turbulence cannot twist the magnetic field and this would reduce the dynamo effect. This has produced, in recent years, a revival of the Babcock-Leighton mechanism.

Notes

Summary

27m 56s

The Babcock-Leighton mechanism



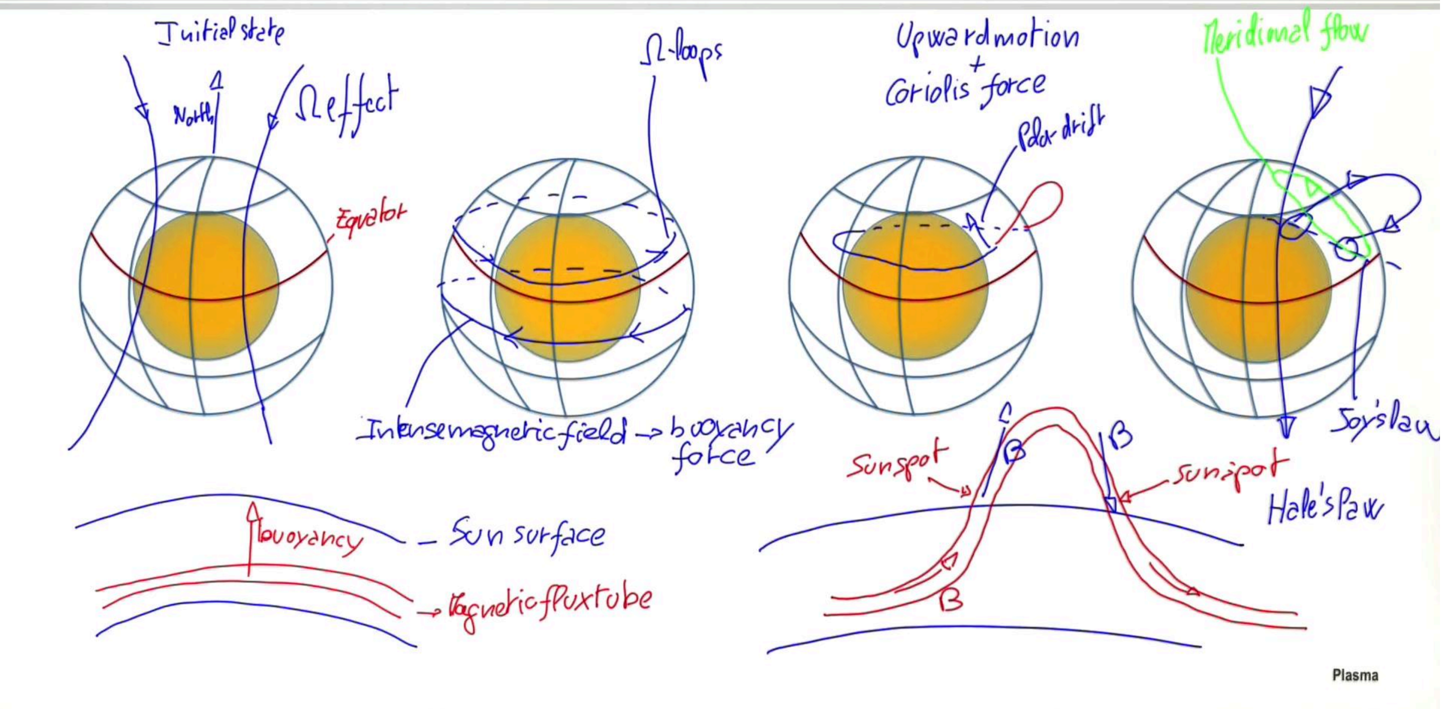
To illustrate the Babcock-Leighton mechanism, let's consider the initial state where only magnetic field lines, which are poloidal, are observed on the Sun and they enter into the Sun from the North Pole and they exit from the Sun in the South Pole. The Equator of the Sun is indicated here by the red line. As a result of the Ω-effect, we end up during the first stage of the dynamo process with Ω-loops which are magnetic field lines that are purely toroidal, and they are oriented as shown here. In the Northern Hemisphere the magnetic field is directed in the direction of the rotation of the Sun. In the Southern Hemisphere, the magnetic field points in the opposite direction. As a result of the stretching of the magnetic field lines, intense magnetic fields can be generated. This gives rise to a buoyancy force that we will describe in more detail in the next module. In the region where the magnetic field is particularly intense, the buoyancy force tends to lift the magnetic flux tube through the Sun's surface. By being lifted by the buoyancy force, the magnetic flux tube now can exit the surface of the Sun forming two sunspots. We also note that the polarity of magnetic fields in these two sunspots is inverted.

Notes

Summary

28m 17s

The Babcock-Leighton mechanism



This inverted polarity in the sunspots is consistent with Hale's Law, that we have seen in the previous module. Under the effect of the upward motion of the flux tube and the Coriolis force, the sunspot that is following will experience a drift toward the Pole. This upward drift produces a tilt between the leading and the following sunspot which is consistent with Joy's Law. The last step of this complex dynamo mechanism involves the transport of a decaying magnetic field towards the <poles by the meridional circulation. Here the magnetic field in the sunspot will eventually reverse the polarity of the pre-existing magnetic field.

Notes

Summary

29m 59s

Beyond the kinematic dynamo: the tough problem

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

+ equation of motion
+ conservation of mass
+ conservation of energy
+ equation of state
+ initial and boundary conditions

- A drastic simplification of the MHD system of equations by specifying a priori the form of the flow field u: kinematic dynamo.
- Helioseismology has revealed with good accuracy two large-scale flow components: differential rotation throughout the interior, and meridional circulation.
- Numerical simulations are needed for the full dynamo problem.

Plasma

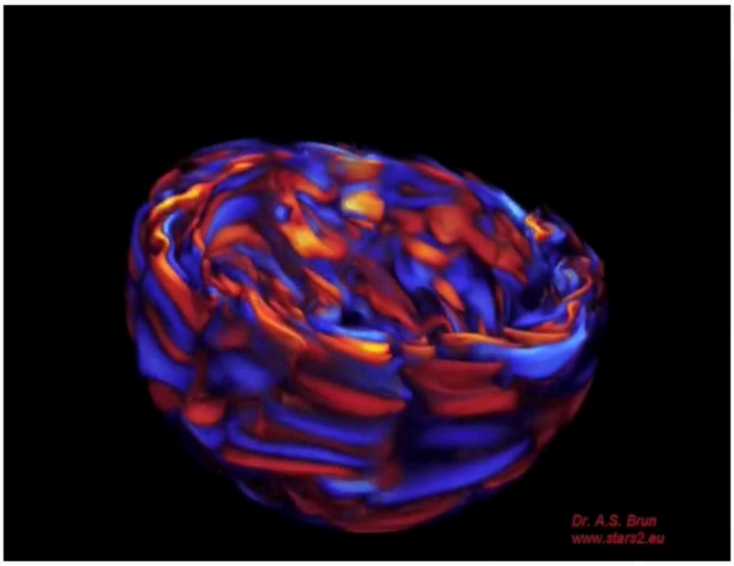
Is this the end of the story? Did we fully understand the dynamo in the Sun? The answer is, of course: no! We have made a drastic simplification of the MHD system of equations by specifying *a priori* the form of the flow field u and deriving the corresponding magnetic field B. We have tried to solve the so-called *kinematic dynamo*. Although extremely simplified, the kinematic dynamo problem has brought incredible results. This is due to the fact that thanks to helioseismology, we know with good accuracy the two large-scale flow components, which are the differential rotation inside the interior of the Sun and meridional circulation at the surface of the Sun. The real problem to be solved is much tougher than the kinematic dynamo. Together with the induction equation we should use the equation of motion, conservation of mass, conservation of energy, some equation of state, and of course, all these should be coupled to initial and specific boundary conditions. This problem is obviously too difficult to be solved analytically and numerical simulations are needed for the full dynamo problem.

Notes

Summary

30m 58s

Dynamo numerical simulations



Courtesy of A. S. Brun,
A. Brun et al., 2004 (ApJ)

Plasma

In this movie, what you're seeing is the longitudinal component of the magnetic field-- red corresponds to positive polarity and blue to negative polarity-- in a global convecting dynamo simulation. After cropping the sphere, the time evolution shows the two main dynamo ingredients, the Ω- and the α- effects. The Ω-effect is linked to the shearing of the large-scale differential rotation and the α- effect is linked to the twisting convective motion that regenerates the poloidal component of the field, hence closing the dynamo loop.

Notes

Summary

32m 30s

Summary

- Kinematic MHD dynamos require large Reynolds numbers and complex sheared flow.
- In the Sun, the Ω-effect converts poloidal field into toroidal field. The field amplification is by stretching magnetic field lines (frozen flux).
- α-effect: the toroidal field is converted back into poloidal field to close the loop.

Plasma

In the early 1900's, the famous scientist Sir Larmor asked the question: "How could a rotating body such as the Sun become a magnet?" Today we know that the answer requires a dynamo process that converts energy of the plasma flow into magnetic energy. In this module we have reviewed the basis of kinematic dynamo and showed that two ingredients are key in this process: the large magnetic Reynolds number in the Sun, which results in field lines that are frozen to the plasma motion and the presence of a complex velocity field with differential rotation. The Ω-effect allows the conversion of a poloidal field into a toroidal one, which is subsequently amplified. Some sort of α-effect can then convert it back into a poloidal field, thus resulting in a cycle that mimics the observed solar cycle. While the dynamo plays a fundamental role in the dynamics of the Sun, the opposite process, magnetic reconnection, is also at play, creating the most spectacular events in the Sun such as the solar flares. This will be the subject of the next module in which I will describe how magnetic flux tubes interact and by reconnecting, they can transform energy of the magnetic field into plasma kinetic energy.

Notes

Summary

33m 08s