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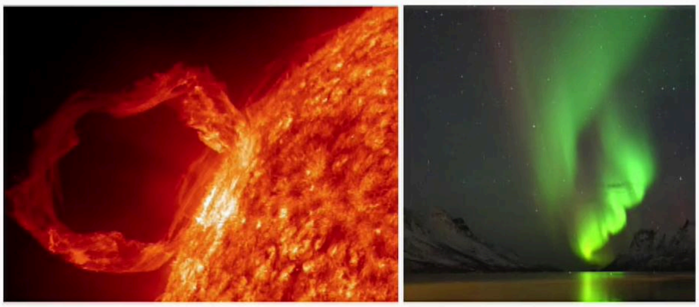


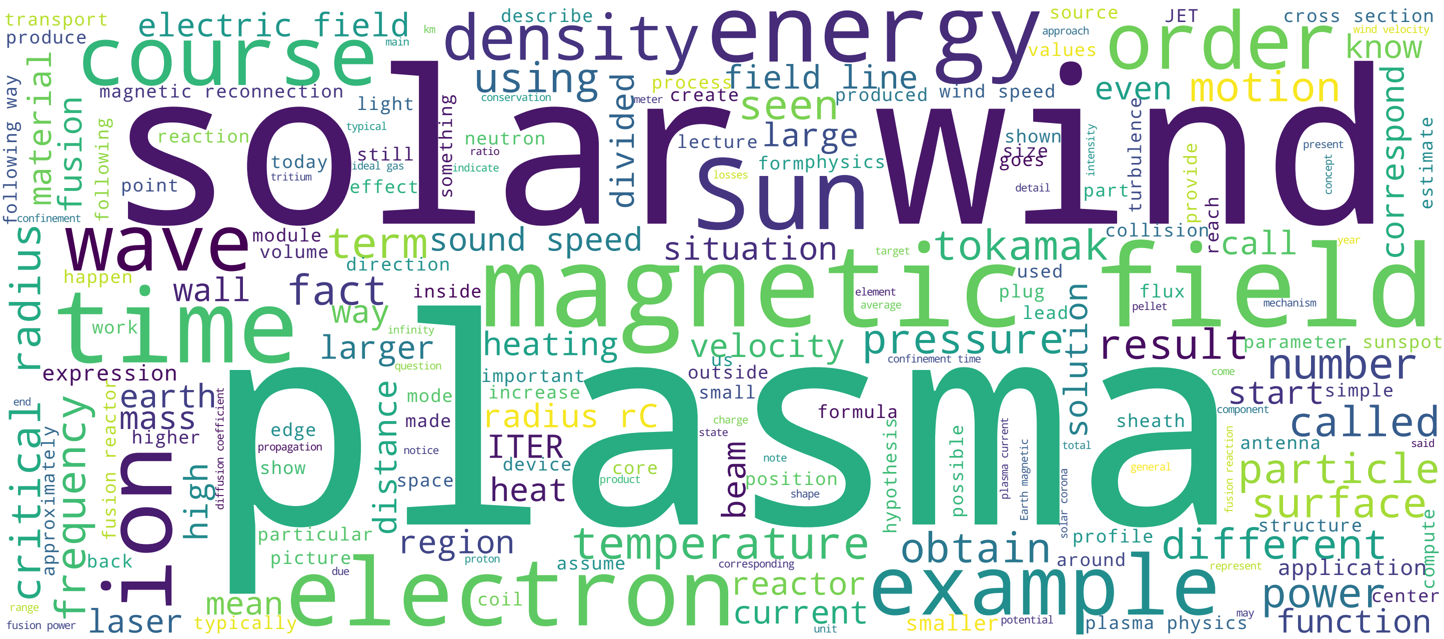
Courtesy of NASA

How does the solar wind blow?

Plasma Physics and Application to Fusion Energy, Astrophysics and Industry

Lecture 4e

Ivo Furno



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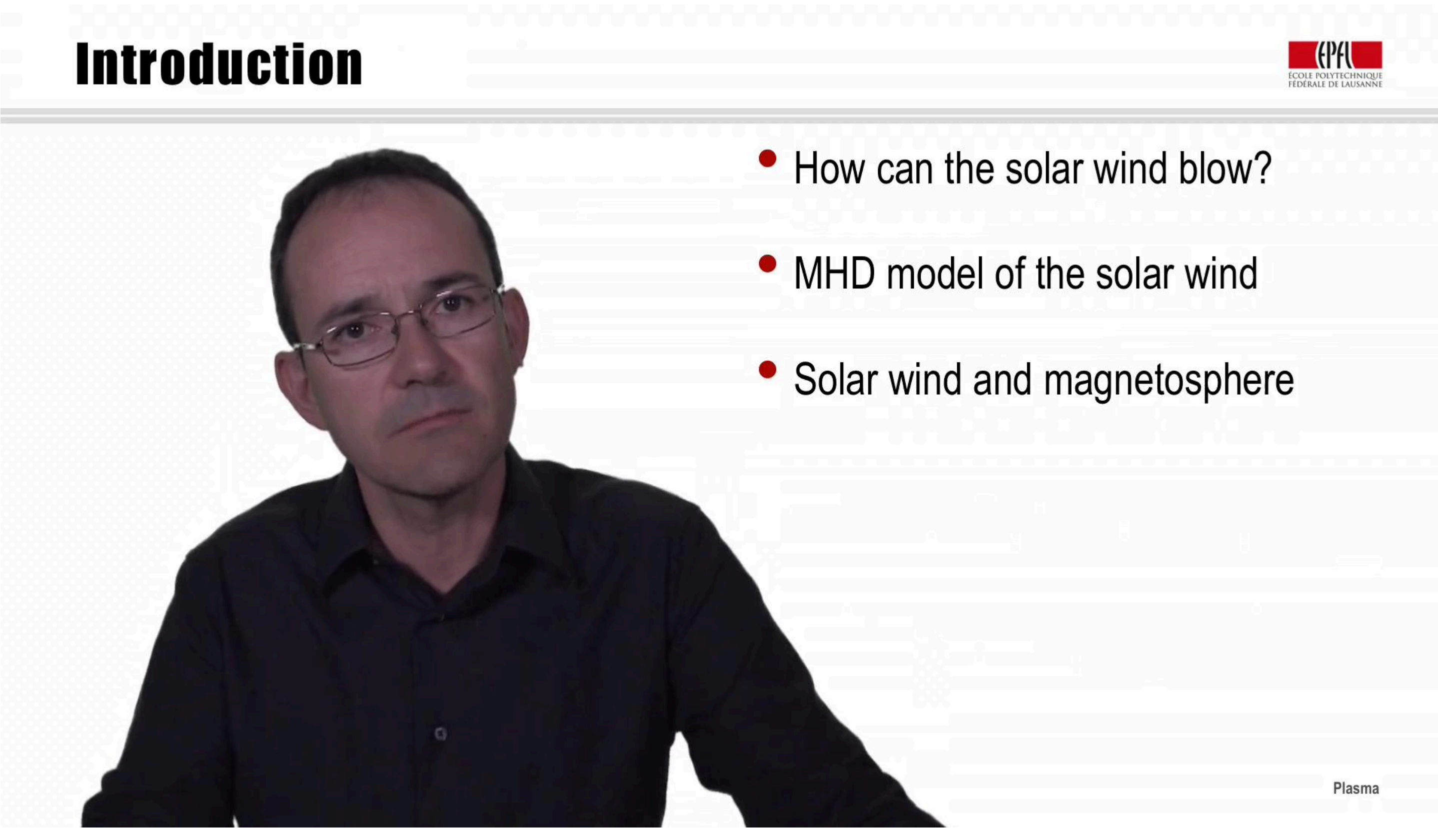


Welcome back to the course on plasma physics and applications. In the last module, we have learned the fundamentals of magnetic reconnection. Through this process, a large fraction of magnetic energy goes into particle acceleration and plasma heating. Magnetic reconnection is probably one of the most important mechanisms that heats the solar corona at a temperature of the order of one million degrees Kelvin. Magnetic reconnection also plays a fundamental role during coronal mass ejections which release a huge amount of energy and plasma from the Sun. In this module, which is the last module in Plasma Astrophysics, I will describe how from a hot plasma atmosphere, the solar wind can blow. We will use a simple MHD description to derive estimates of the solar wind speed and we will see how the solar wind can shape the magnetosphere around the earth.

Notes

Summary

0m 05s

First hints of the solar wind

Comet Hale-Bopp viewed from Los Alamos, NM

Courtesy of Alex and Glen Wurden

- To explain auroras-sunspots correlation Birkeland [1908] suggested continuous particle emission from sunspots.
- Chapman and Ferraro [1931] suggested that particles were emitted from the Sun only during flares and that otherwise space was empty.
- Bierman in 1951: the cometary tails point directly away from Sun regardless of comet's velocity → must be ionized gas pushed away by the solar wind.

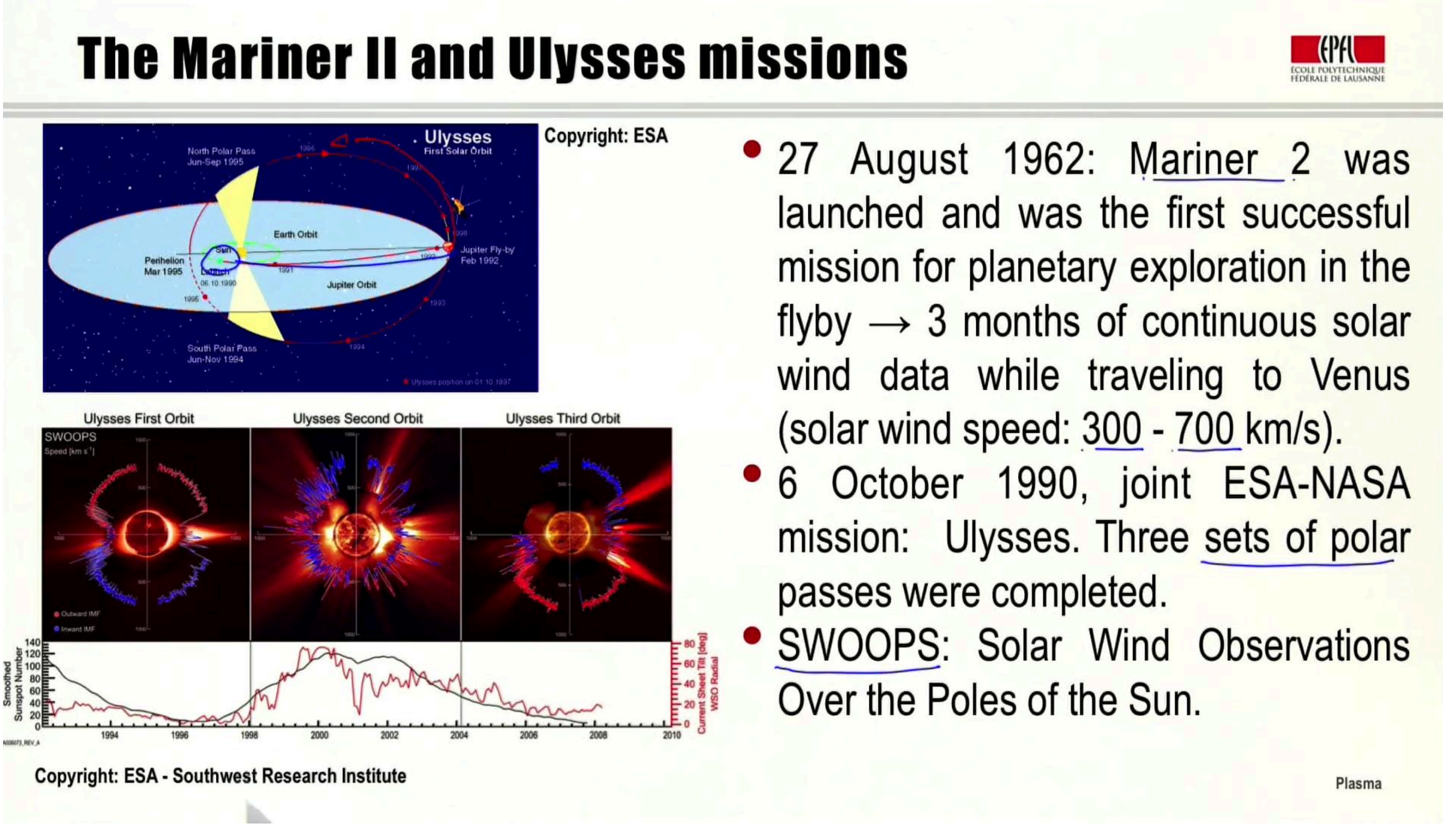
Plasma

The first hints of the solar wind came in the early 19th century when Birkeland suggested that a continuous particle emission was coming from sunspots. This was to explain the observed correlation between auroras and sunspots. About 30 years later, Chapman and Ferraro suggested that particles were emitted from the Sun only during solar flares and otherwise the space between the Sun and the earth was empty. The first real evidence of the solar wind came from comet tails. In 1951, Bierman observed that the cometary tails point directly away from the Sun regardless of the comet's velocity. It conjectured that this must be due to ionized gas pushed away by the solar wind. An example is given by this picture here that shows the comet *Hale-Bopp*, viewed from Los Alamos in New Mexico, U.S.A. As you can see, the comet has two distinct tails. The white tail is a dust tail driven by light pressure and it points away from the sun. The blue tail instead is an ion tail which is driven by the solar wind. It is not radial with respect to the Sun, as the comet has about one tenth of the speed of the solar wind.

Notes

Summary

1m 02s



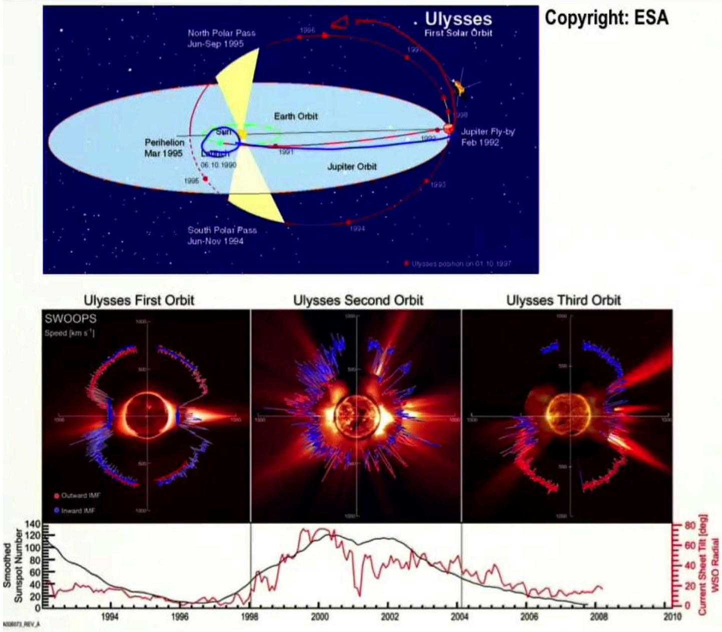
The first measurement of the solar wind came from the *Mariner 2* mission that was launched on the 27th of August, 1962. The Mariner 2 provided three months of continuous solar wind data while traveling towards Venus. It measured solar wind speed between 300 and 700 km/s. This was the first experimental proof of the existence of the solar wind. More recent data has been provided by the joint ESA-NASA mission *Ulysses*, that was launched on the 6th of October, 1990. As shown in this picture, Ulysses was launched towards Jupiter, where using the slingshot effect provided by gravity, it entered a polar orbit around the Sun. Ulysses performed three sets of polar passes. The radial plots shown here show the solar wind speed combined data from all three of Ulysses's polar orbits of the Sun, each of which takes approximately six years to complete. Ulysses was equipped with an instrument called *SWOOPS*, that stands for: Solar Wind Observations Over the Poles of the Sun. This instrument was designed to provide measurements of the solar wind speeds. The first orbit occurred during a period of solar minimum as indicated by the sunspot number.

Notes

Summary

2m 41s

The Mariner II and Ulysses missions



- 27 August 1962: Mariner 2 was launched and was the first successful mission for planetary exploration in the flyby → 3 months of continuous solar wind data while traveling to Venus (solar wind speed: 300 - 700 km/s).
- 6 October 1990, joint ESA-NASA mission: Ulysses. Three sets of polar passes were completed.
- SWOOPS: Solar Wind Observations Over the Poles of the Sun.

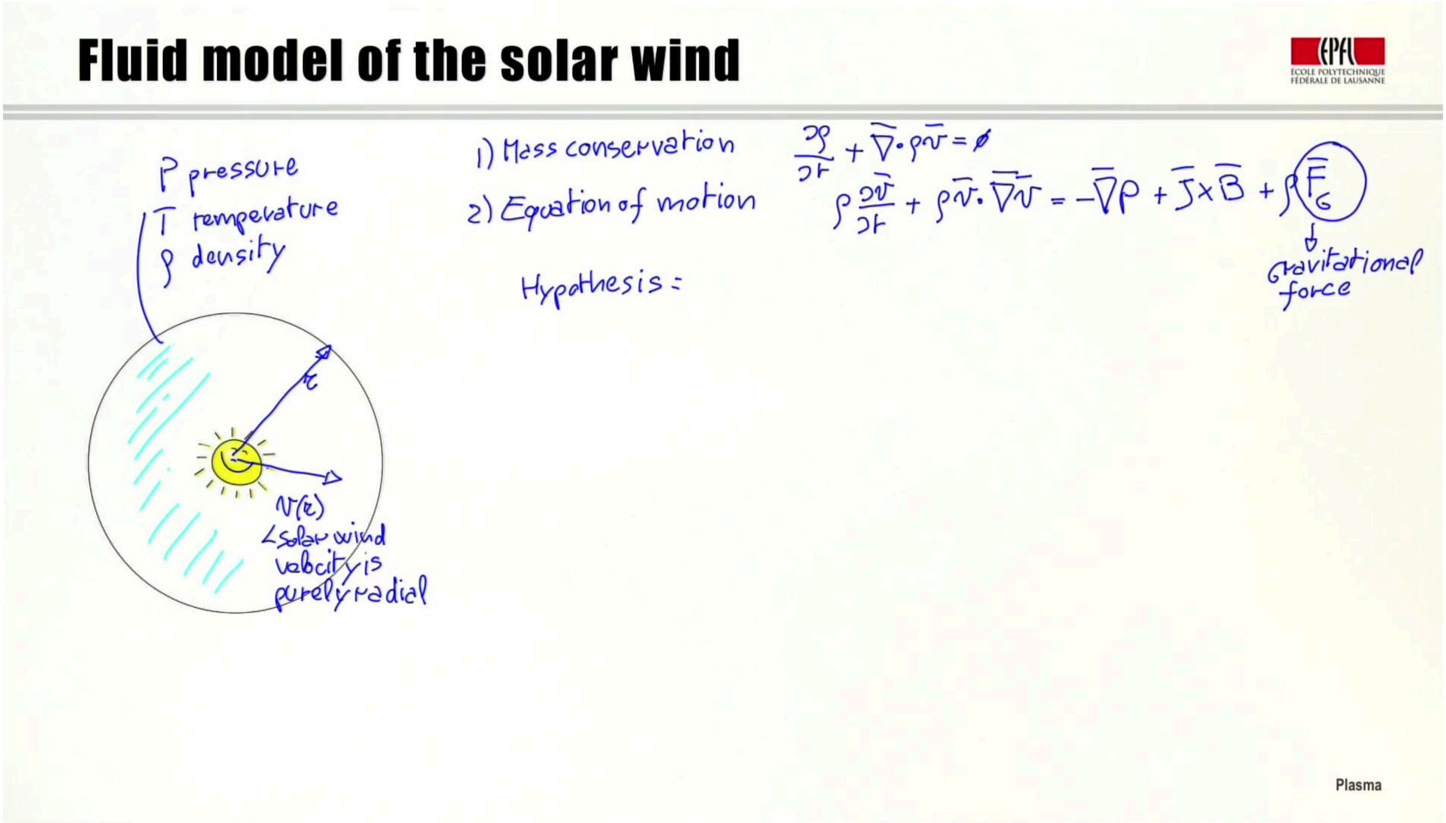
Plasma

Ulysses measured a slow wind over the Equator, of the order of 200 km/s, and fast wind over the poles of the Sun, of the order of 700 km/s. The second orbit of Ulysses corresponded to a period of maximum activity as shown by the sunspot number here, between 1998 and 2004. During the second pass, fast and slow winds were measured at all latitudes consistent with a solar maximum activity. Ulysses then completed more than 3/4 of the third orbit, as you can see here, occurring around the solar minimum cycle. During this last cycle, Ulysses also gathered information indicating that the solar wind was about 25% less powerful than it was in the previous solar minimum cycle.

Notes

Summary

4m 35s

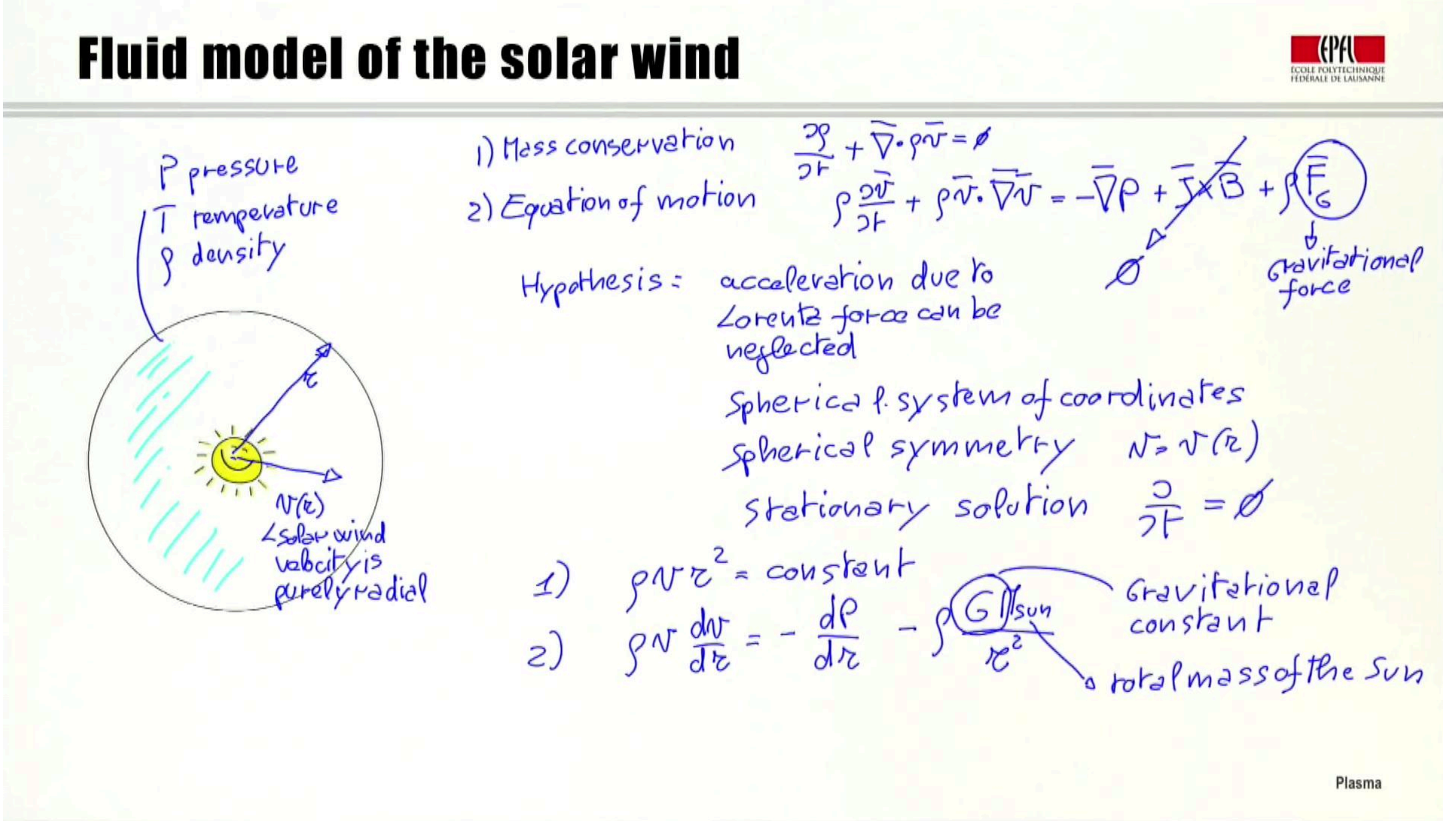


So far, we have reviewed experimental data of the solar wind. We will now derive a simple model in which the pressure imbalance between the Sun and the interstellar medium drives the wind. Historically, this was the first theory that was developed by Parker in the early 50s, which allows to derive many important results. However, the fluid description does not take into account kinetic effects which turn out to be important to describe the solar wind, and therefore, more refined theories would be required. Now, let's derive the fluid model. Let's make the assumption of a spherical symmetry and let's use a spherical system of reference where we indicate the position of the solar wind with respect to the center of the Sun by the distance that we indicate with r. Let's make the assumption that the solar wind has a velocity v(r) which is purely radial, and which is a function of the distance r. The plasma in this region is characterized by a pressure P, temperature T, and the density ρ. Let's use the mass conservation equation and the equation of motion. which we write in the following way: Where FG is the gravitational force due to the mass of the Sun.

Notes

Summary

5m 50s

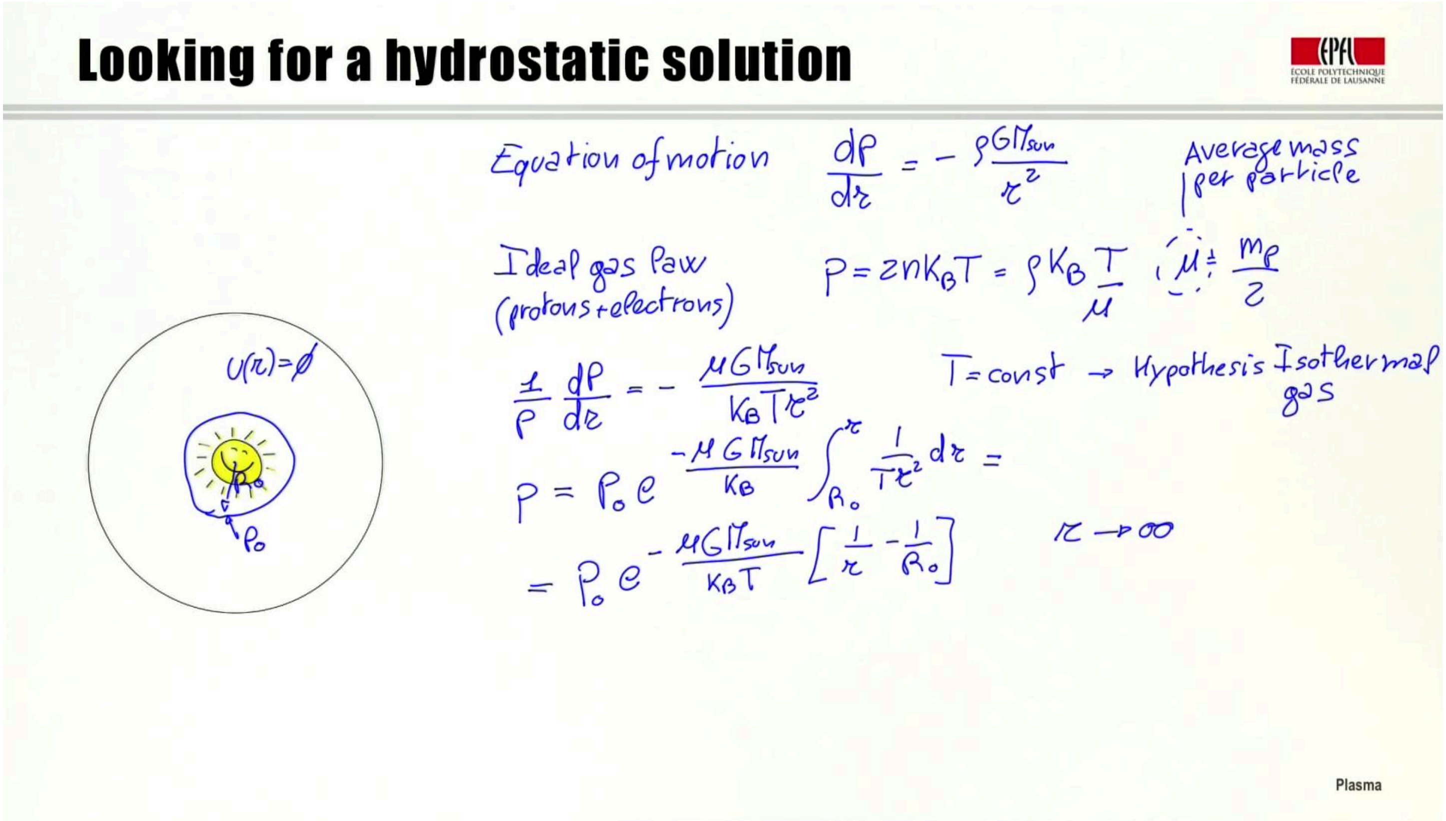


Let's make the further hypothesis that the acceleration due to the Lorentz Force can be neglected and therefore drop the J × B term. As we said at the beginning, we are using a spherical system of coordinates and we have also assumed spherical symmetry, such that every parameter is only a function of the radial distance from the Sun. For example, the velocity of the solar wind. Let's make a further hypothesis, and let's look for a stationary solution by imposing that the time derivatives are equal to zero [∂/∂t = 0]. We can then write the mass conservation equation, and the equation of motion in the following way: Where G is the gravitational constant and Msun is the total mass of the Sun.

Notes

Summary

7m 27s



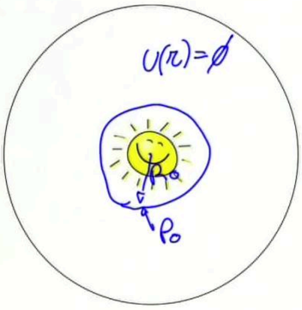
Let's now look for a hydrostatic solution by making the hypothesis that the wind has zero velocity. By dropping the radial velocity in the previous equation, we can rewrite the equation of motion. We can then assume that we can treat the plasma in the solar wind as an ideal gas and therefore using the ideal gas law for protons plus electrons. In this formula, KB is the Boltzmann Constant and μ is the mass of the proton divided by two [μ = mp/2] which is the average mass per particle. Using the ideal gas law, we can therefore write the equation of motion in the following way:... Let's now make a further simplifying hypothesis, and let's assume that the plasma is isothermal everywhere. If we now define a radius R_0, where we know that the plasma is at pressure P_0, we can integrate this equation between R_0 and r. Where the temperature T can be taken out of the integral since we have assumed that it doesn't depend on the radial position r. This formula provides the value of the pressure at a certain distance r from the Sun, provided that we know the starting pressure P_0 and the starting radius R_0. Let's see what happens if we consider the pressure at infinity.

Notes

Summary

8m 24s

Looking for a hydrostatic solution



Equation of motion $\quad \frac{dP}{dr} = -\frac{\rho G M_{sun}}{r^2}$

Average mass per particle

Ideal gas law (protons+electrons) $\quad P = 2nK_BT = \rho K_B \frac{T}{\mu} \quad \mu \doteq \frac{m_p}{2}$

$$\frac{1}{\rho}\frac{dP}{dr} = -\frac{\mu G M_{sun}}{K_B T r^2}$$

T = const → Hypothesis Isothermal gas

$$P = P_0 \, e^{-\frac{\mu G M_{sun}}{K_B}\int_{R_0}^{r} \frac{1}{T r^2} dr} =$$

$$= P_0 \, e^{-\frac{\mu G M_{sun}}{K_B T}\left[\underbrace{\frac{1}{r}}_{\to 0} - \frac{1}{R_0}\right]} \qquad r \to \infty$$

Finite pressure at infinity

↓

NOT PHYSICAL RESULT !

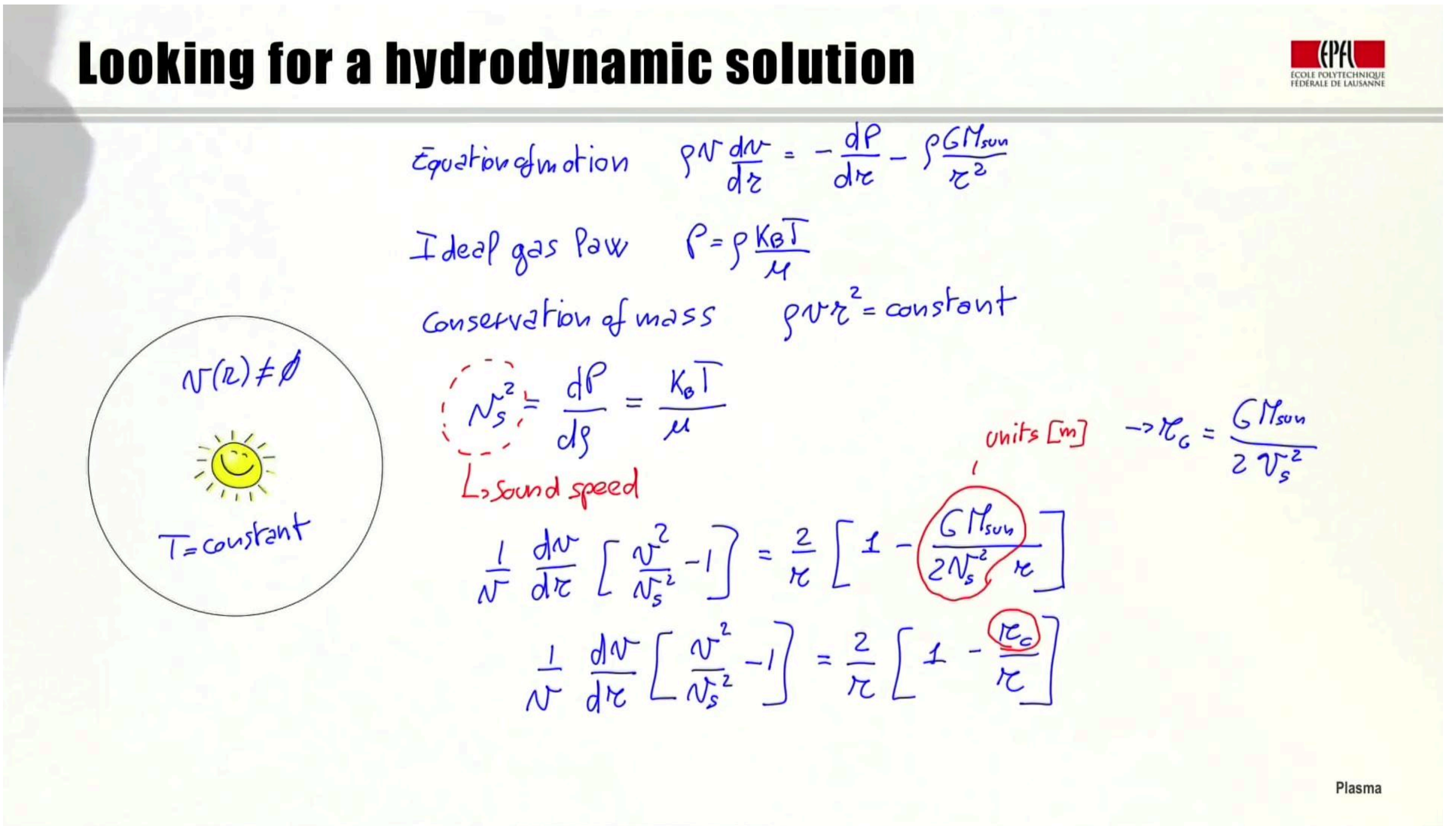
Plasma

This term will go to zero, resulting in a final pressure at infinity which is a non-physical result. We can therefore conclude that looking for a hydrostatic solution has led us to a non-physical result. Therefore the hypothesis that the solar wind speed is equal to zero doesn't work.

Notes

Summary

10m 20s

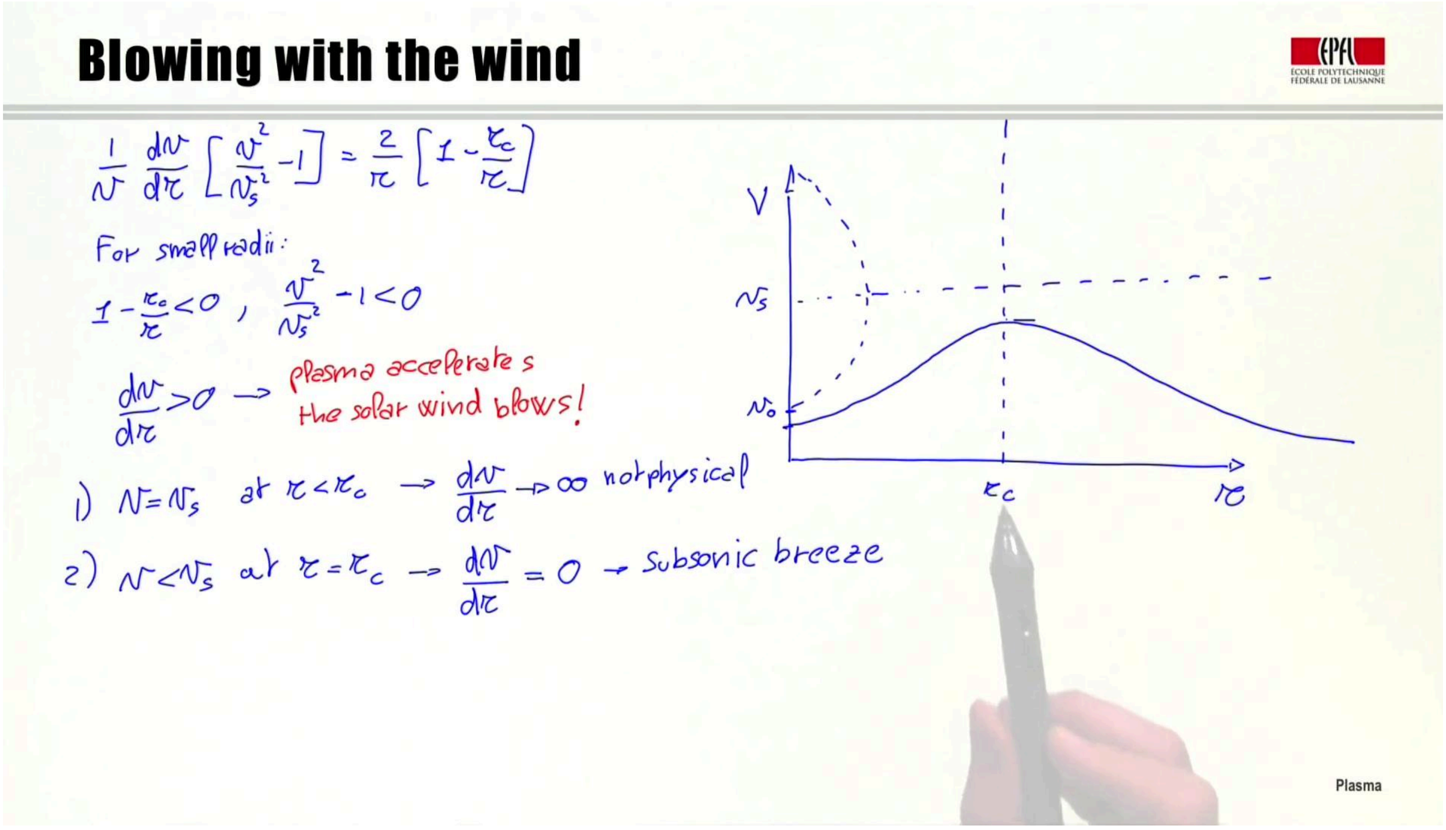


Let's now go back to the original equation of motion and let's look for a hydrodynamic solution by dropping the hypothesis that the solar wind velocity is equal to zero, and therefore allowing a finite velocity. [v(r) ≠ 0] We can write down the equation of motion and make as before, the assumption of an isothermal plasma. We can write down the ideal gas law as before, and use the conservation of mass. We have to remember that for an isothermal gas, we can define the sound speed [vs] as the derivative of the pressure with respect to the density. [$vs^2 = dP/d\rho = KB\ T/\mu$] Using these expressions and plugging them back into the equation of motion, we obtain: We note that this factor has the units of meters, and therefore we can define a critical radius rC equal to the gravitational constant times the mass of the Sun divided by two times the sound speed square. [rC = (G Msun)/ (2 vs^2)] Therefore we can cast the equation of motion as... ... where we have introduced the critical radius rC.

Notes

Summary

10m 54s

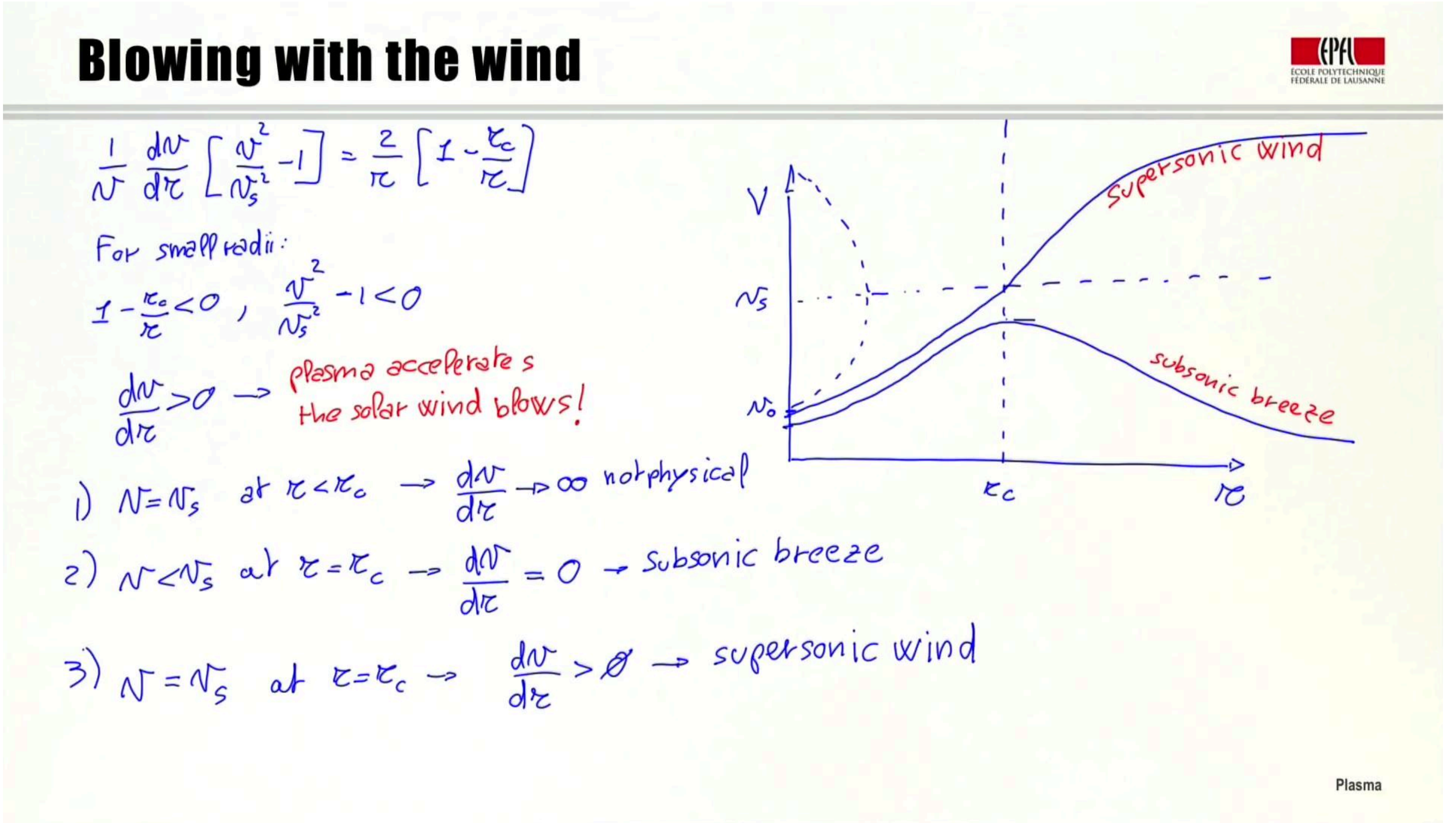


Let's now see which are the consequences of this equation. For small radii, one minus the critical radius divided by the radius is smaller than zero and at the same time, if we suppose that the starting velocity of the solar wind is small compared to the sound speed, we can also write that... Therefore, this term and this term in these equations are both negative, which results in a dv/dr which is positive. This means that the plasma that starts at a certain velocity accelerates, and therefore a wind blows. Now, let's try to identify families of solutions of this equation. In the r-v space as drawn here. On a velocity.vs. radial position plot, let's identify the critical radius rC and the sound velocity vs. If the solar wind starts at a certain velocity, v_0 and reaches the sound speed at a radius which is smaller than the critical radius, dv/dr will go to infinity and this is not a physical solution, which is outside the scope of this simple fluid treatment, which would result in a trajectory schematically drawn here. The second family of solutions is represented by a wind that starts at initial velocity v_0, and accelerates up to a certain maximum velocity at the critical radius rC.

Notes

Summary

12m 24s

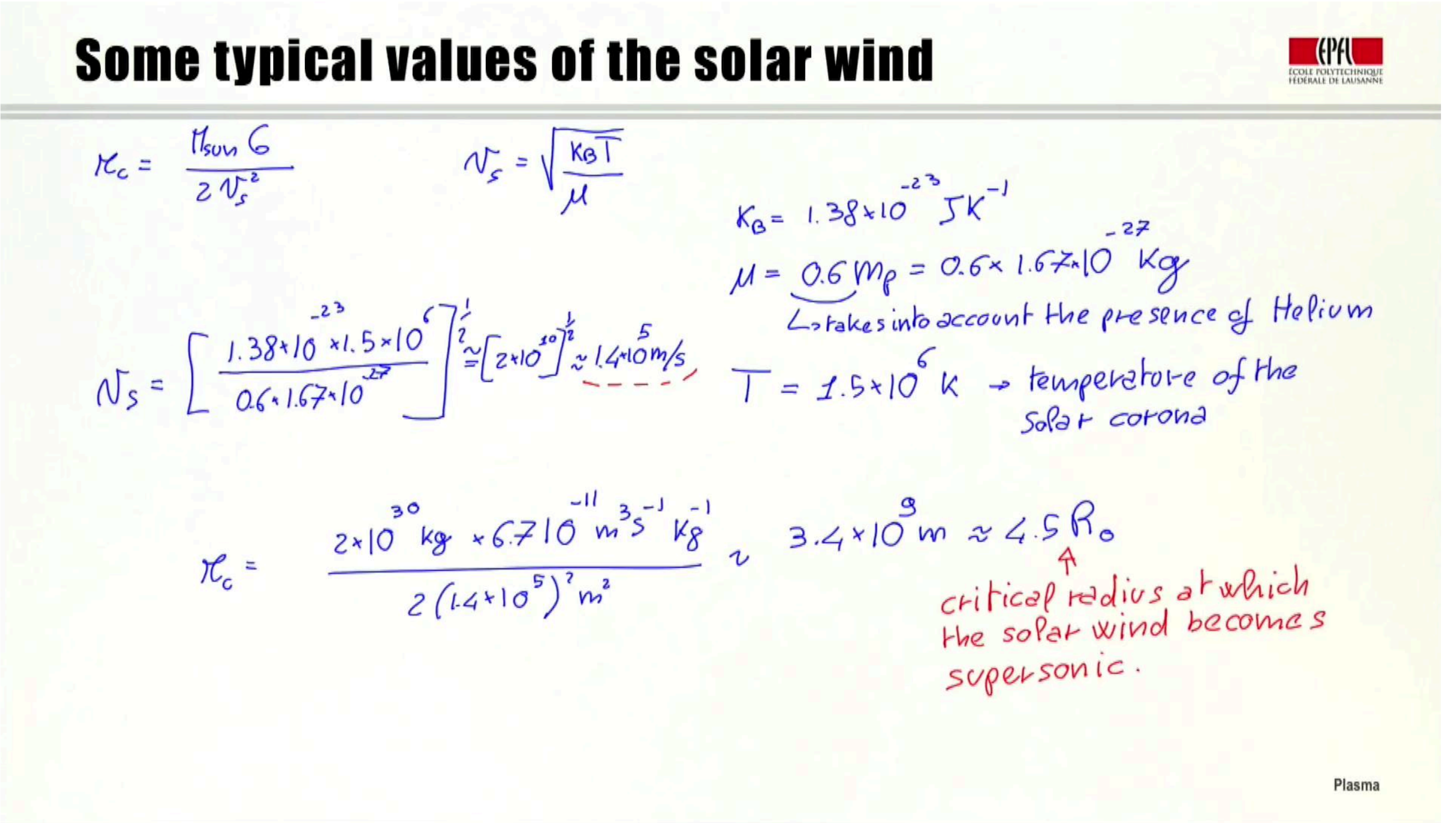


Now, if this maximum velocity is still smaller than the sound speed at that position, the derivative of the velocity with respect to the radius is equal to zero, which means that starting from the critical radius, the solar wind will start to decelerate. This solution represents a family of solutions that we call *subsonic breeze*. The third family of solution represents the *supersonic solar winds*. If, starting from a certain velocity, initial velocity, the solar wind accelerates in such a way that at the critical radius rC, the velocity of the wind corresponds to the sound speed, we obtain that the derivative of the velocity with respect to the radius will always be positive and this will result in a wind that accelerates continuously, giving rise to a supersonic wind which is represented by a family of solutions of which one example is shown here.

Notes

Summary

14m 48s

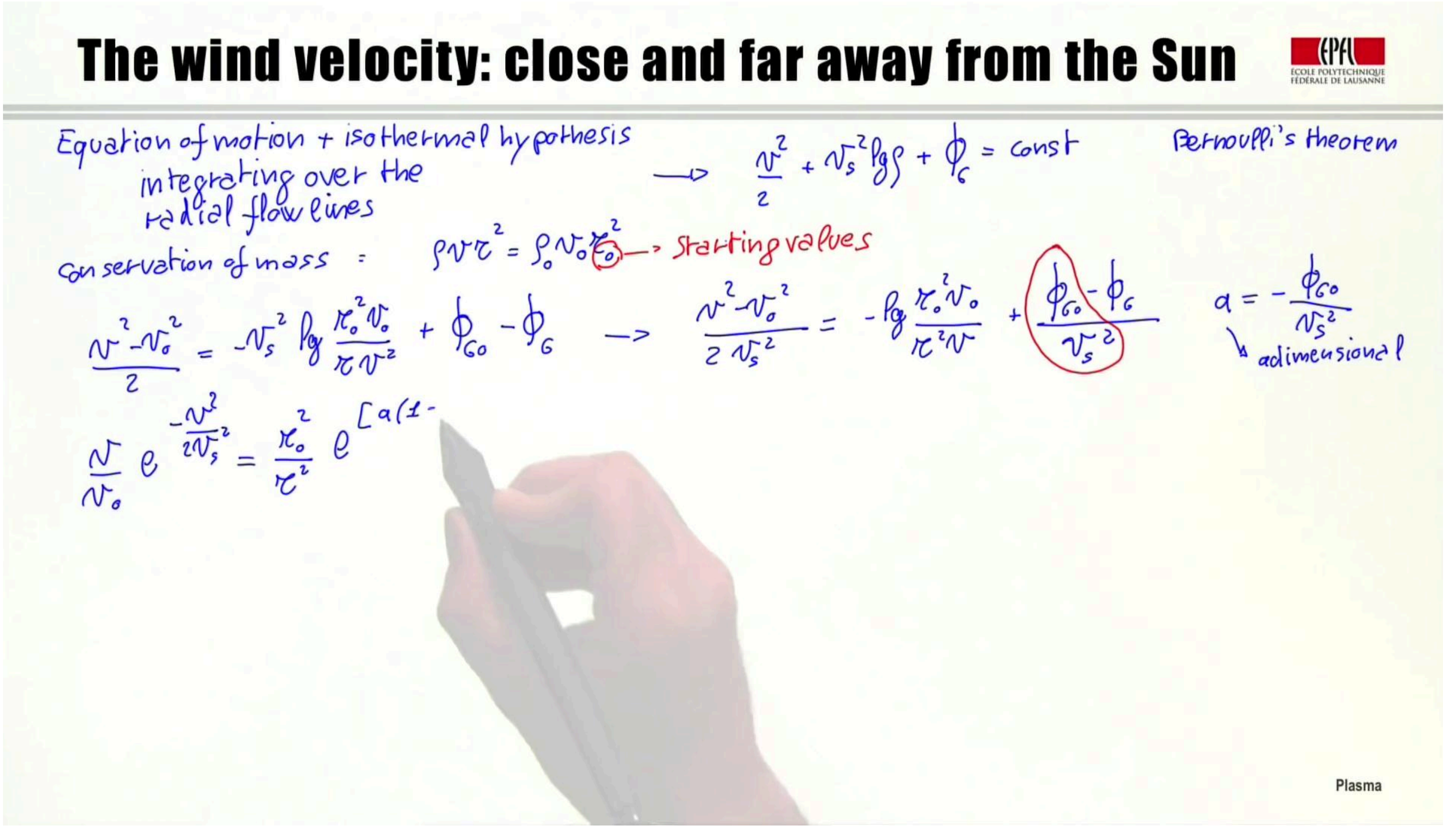


Let's now try to estimate some typical values for the solar wind. For example, let us estimate the critical radius. In order to do that, we need to know the sound speed vs which is defined as:,... where KB is the Boltzmann constant which has this value in Joules per Kelvin. μ is the average weight of individual particles which we express in kilograms and where we have used 0.6 instead of 0.5 to take into account the fact that the plasma has a small fraction of helium as we have seen in previous modules. We can assume a temperature of 1.5 x 10^6 K which is a typical temperature for the solar corona where the solar wind originates. Now we can plug these numbers into the formula and estimate the value of the sound speed. This results in a sound speed of approximately 1.4 x 10^5 m/s. We can now compute the value of the critical radius rC by plugging these numbers into this formula where we have to remember that the total mass of the Sun is approximately 2. x 10^{30} kg, times the value of the gravitational constant which is approximately 6.7 x 10^{-11} m^3 s^{-1} kg^{-1}, we obtain that the critical radius, rC is approximately 3.4 x 10^9 m, which corresponds to approximately 4.5 times the radius of the Sun. This is the critical radius at which the solar wind becomes supersonic.

Notes

Summary

16m 08s

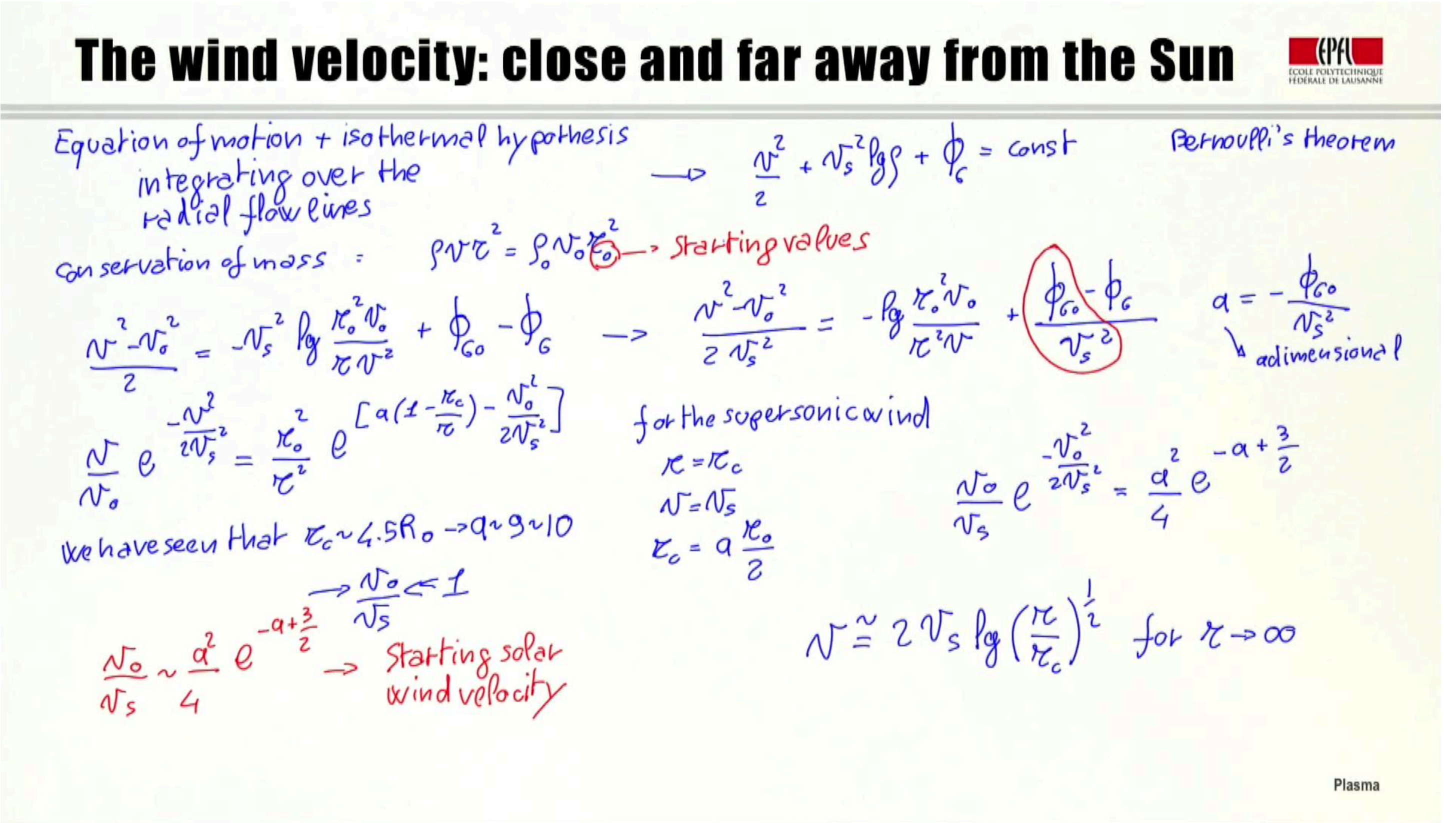


Now using these values, let's see how we can estimate the wind velocity close to where the solar wind originates and very far away from the Sun. Using the equation of motion and the isothermal hypothesis, we can integrate along flow lines and obtain that the square of the velocity divided by two plus the sound speed square times the logarithm of the density plus the gravitational energy is a constant of the motion. These equation is nothing else than a version of *Bernoulli's Theorem*, that you may use in very different fields. Let's now use the conservation of mass in spherical geometry that states that the product of the density times the velocity times the square of the radius is constant. The suffix 0 here indicates the starting values. If we now use the conservation of mass and we plug it into this equation and we integrate between the starting point and radius r, we obtain the following: Where ΦG0 is the gravitational energy at the starting point and ΦG is the gravitational energy at the position r. Dividing by the sound speed, we have:... Let's now define the following quantity a and note that a is dimensionless. Now using this definition and after some algebra, we obtain:...

Notes

Summary

18m 25s



Now this equation allows us to determine the initial speed of the solar wind provided that we know the velocity v of the solar wind at a certain distance r. For the supersonic wind, we have seen that the supersonic wind becomes supersonic at the critical radius rC and if we use the definition of a, we can obtain:... If we now plug these values into this formula, we obtain:... Which determines the initial velocity of the solar wind as a function of the sound speed. We have seen that the critical radius rC is approximately 4.5 times the solar radius. This results in a parameter a which is of the order of 10. If we now look for a solution where a is of the order of 10 in this formula, this in turn implies that the initial solar wind velocity divided by the sound speed is much smaller than 1. Therefore, we can obtain the final result which provides the value of the starting solar wind velocity. If we now plug this result into the original Bernoulli's theorem, we obtain the value of the velocity far away from the Sun. I will not go into the details of the algebra but I will recall the main formulas here.

Notes

Summary

20m 36s

The Sun mass loss rate due to the solar wind

$$v_0 \cong v_s \frac{d^2}{4} e^{-d+\frac{3}{2}} \qquad d \sim 9 \rightarrow v_0 \sim 0.011\, v_s$$

$$M' [kg\, s^{-1}] = 4\pi \rho_0 v_0 r_0^2 \sim 4\pi \times 0.011 \times v_s \times R_\odot^2 \times \rho_0 \sim 1.58 \times 10^9\, kg\, s^{-1} \rightarrow$$ 1.5 millions tons of plasma are emitted in the solar wind per second

plasma density in the solar corona $\sim 10^{14} m_p$

$$1\, AU \cong 214\, R_\odot \sim 48\, r_c$$

$$v = 2 v_s \left[\lg\left(\frac{r}{r_c}\right)\right]^{\frac{1}{2}} \sim 4 v_s \sim 5.6\; 10^5\, m/s$$

Plasma

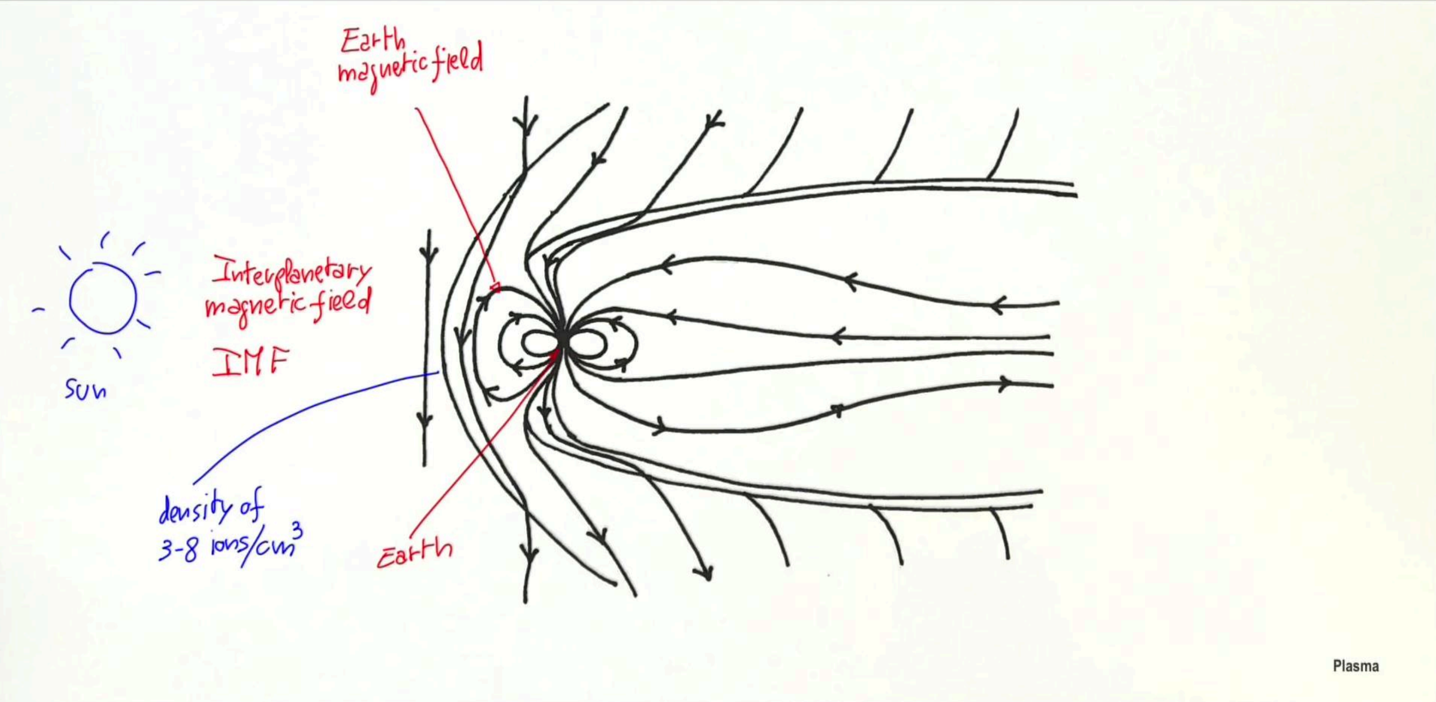
Now, using these results, let's plug in some numbers and let's compute the Sun mass loss rate [M' = dM/dt] due to the solar wind. First of all, let's compute the starting velocity for the supersonic wind. We find out that the starting supersonic solar wind velocity is approximately 1 hundredth of the sound speed in the solar corona. We can then compute the mass loss rate in the following way:... Where ρ_0 is the plasma density in the solar corona, which we approximate as 10^{14} times the mass of the proton. By plugging in these numbers, we obtain that approximately 1.5 million tons of plasma are emitted in the solar wind per second, which is almost negligible with respect to the total mass of the Sun. We can also estimate the solar wind speed at the position of the earth, recalling that one astronomical unit is approximately 214 times the radius of the Sun, which in our units will be 50 times the critical radius. If we plug the numbers into the previous formula, we obtain:... Which results in a solar wind speed at the distance of the earth of approximately 560 km/s, which is a number which compares pretty well with the experimental measurement.

Notes

Summary

22m 35s

The magnetosphere

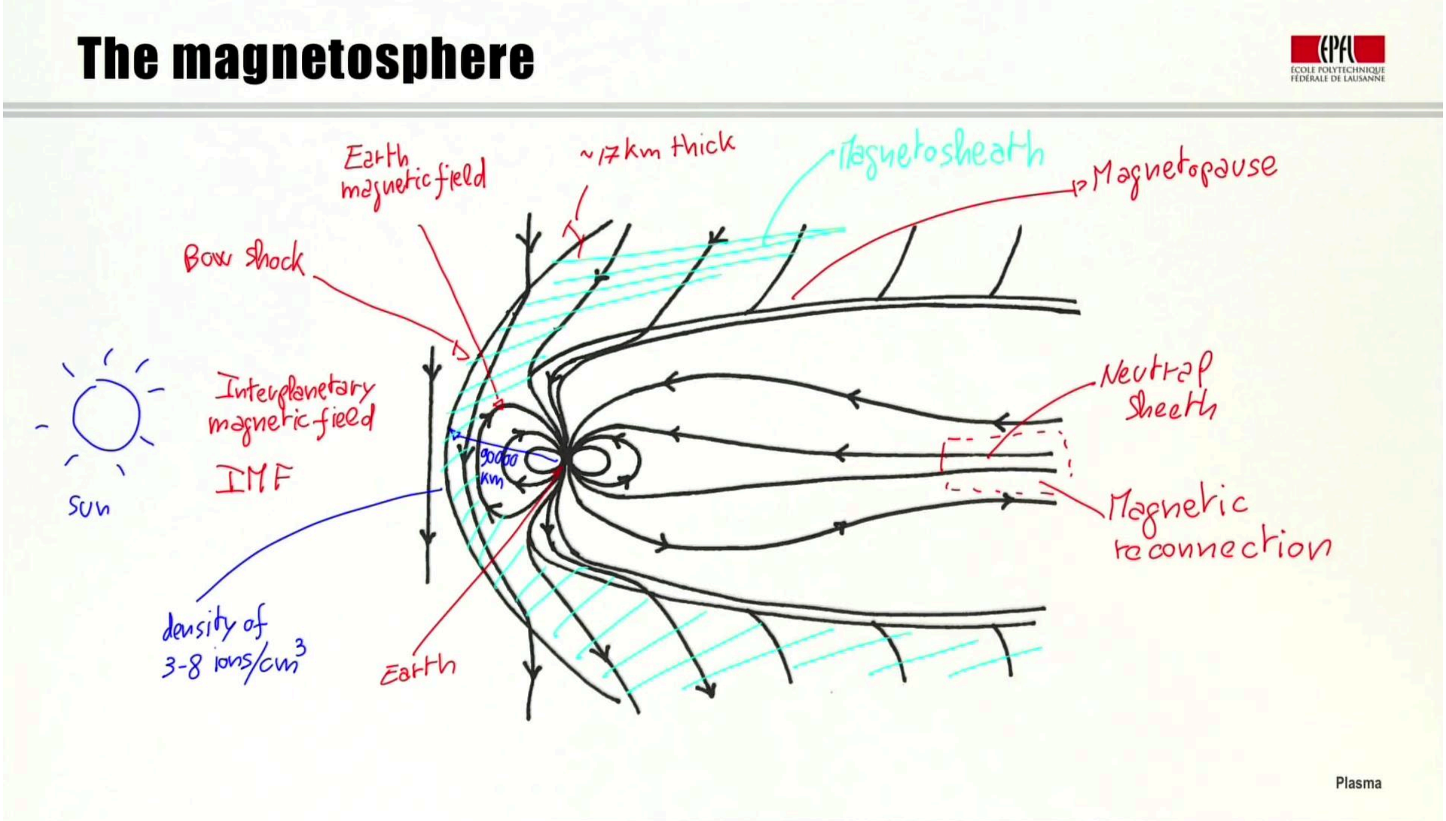


Now, moving at about 500 km/s, the solar wind needs about 4 or 5 days to reach Earth, and many more months to reach the outermost planets. As the solar wind leaves the corona, due to the large magnetic Reynolds number, It picks up the local magnetic field, which is the field associated with sunspots and Sun's magnetic poles, and drags it into the space. The dragging of the magnetic field by the plasma is a result of the frozen flux theorem that you have seen in module 3G. The dragged magnetic field forms the interplanetary magnetic field [IMF] The interplanetary magnetic field is quite weak. At the earth's orbit it's about 1 over 10,000 times the field at the Earth's surface. However, it exerts an extraordinary influence on the Earth's magnetosphere. The magnetic field of the Earth provides an effective obstacle to the solar wind plasma. When it reaches the Earth's orbit, the solar wind is quite rarified between 3 and 8 ions per cubic centimeter. The Earth's magnetic field keeps the ions, keeps the plasma out of the Earth by carving its own cavity in the solar wind. This region is called the magnetosphere although it is not spherical.

Notes

Summary

24m 29s

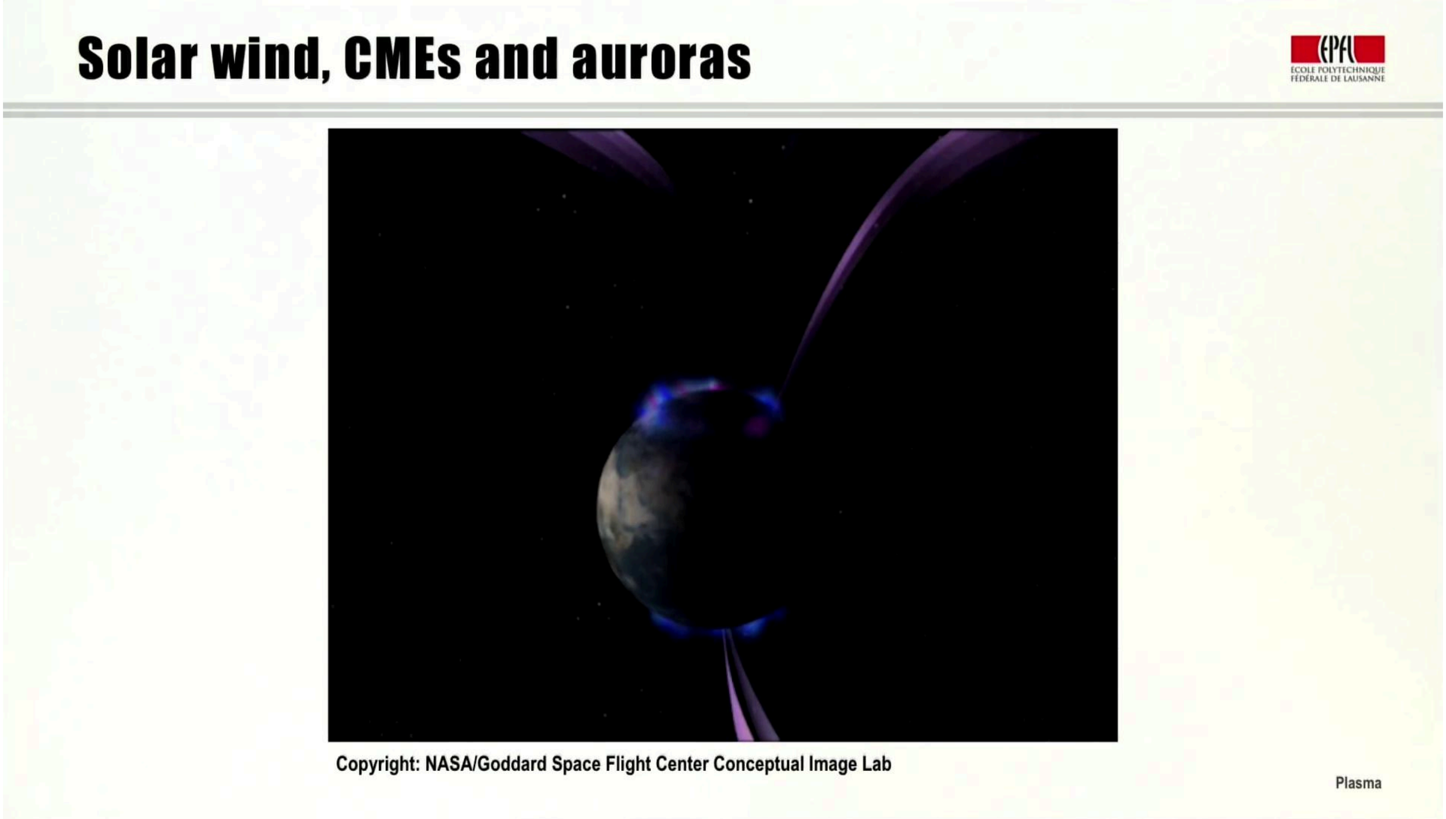


When it reaches the Earth's magnetic field, the solar wind, as we have seen, is usually supersonic and the magnetic field of the Earth creates a magnetic obstacle which creates a shock front where the plasma becomes subsonic. This region is called *bow shock region*. The bow shock region is approximately 17 kilometers thick, and it is located at a distance of approximately 90,000 kilometers from earth. Most of the solar wind plasma is heated and slows down at the bow shock and detours around the earth. Some plasma of the solar wind penetrates inside the magnetic field of the earth and forms the so called *magnetosheath*. The magnetosheath exerts a pressure on the Earth's magnetic field. The region where the pressure of the magnetic field equals the pressure of the magnetosheath, this is called *the magnetopause*. By dragging the magnetic field lines of the Earth's magnetic field with it, the solar wind deforms the magnetic field lines and creates a neutral sheath where the magnetic field lines are opposite directed. As we have seen in previous modules where opposite directed magnetic field lines come together, magnetic reconnection can take place if the magnetic field lines are pushed together strongly enough.

Notes

Summary

26m 18s



One of the most important perturbations to the solar wind are coronal mass ejections or in short, CME's. During a coronal mass ejection, the Sun can eject 10^{12} up to 10^{13} kg of plasma moving at speeds of approximately 1,000 km/s. These are strong perturbations to the solar wind which can have profound consequences on earth. By pushing together the magnetic field lines at the neutral sheath, reconnection can occur and plasmas and electrons can be accelerated and reach down earth, creating one of the most spectacular events on earth, which is the *aurora borealis*.

Notes

Summary

28m 13s

Summary

This was the last module in Applications of Plasmas in Astrophysics. You have learned that distant astrophysical objects, like the Sun, can have a profound influence on our environment. An example is how the solar wind shapes the magnetosphere around the earth. Throughout the five modules, I have pointed out the importance of three major players in the dynamics of the universe: nuclear fusions, plasmas, and magnetic fields. The complex interaction of all of these elements through dynamo and magnetic reconnection, shapes our world. Plasma physics is of fundamental importance to advance the understanding of the universe we live in.

Notes

Summary

29m 09s