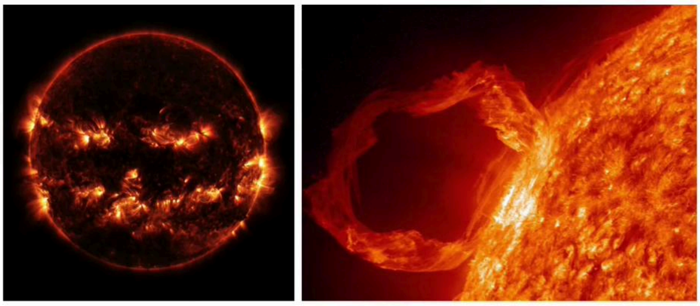


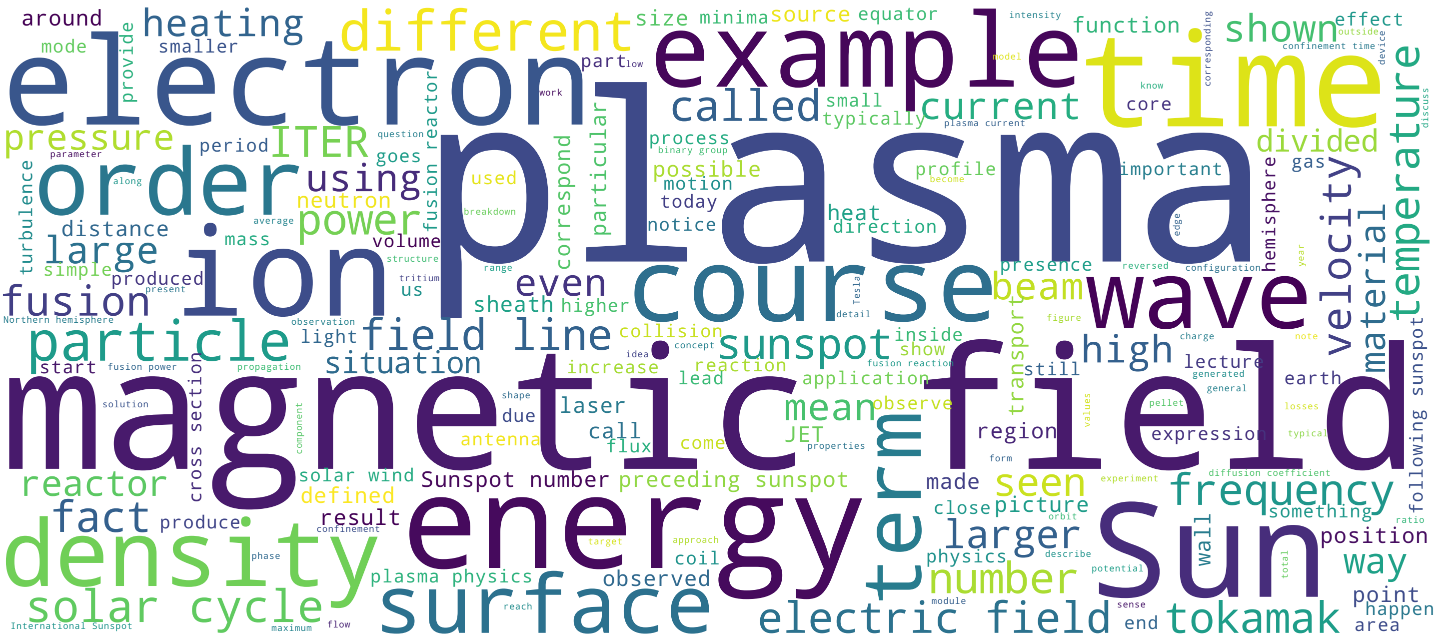
Courtesy of NASA

# The solar cycle and magnetic fields in the Sun

**Plasma Physics and Application to Fusion Energy, Astrophysics and Industry**

**Lecture 4b**


Ivo Furno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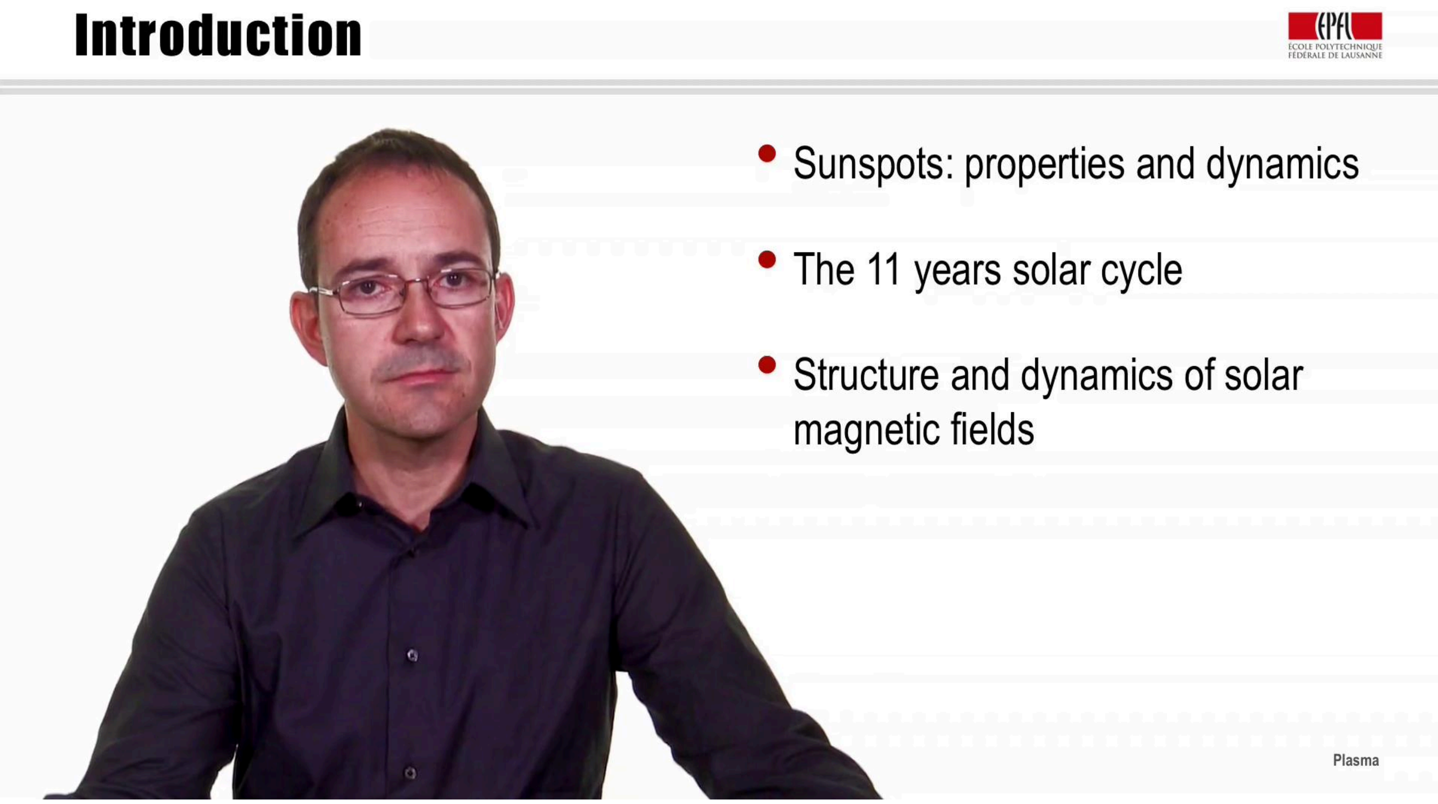


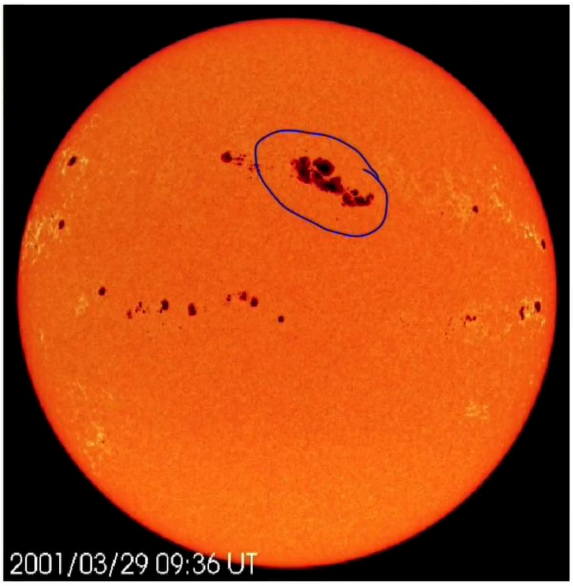

Welcome back to the course on Plasma Physics and Applications. The Sun is characterized by the presence of magnetic fields. The origins of these magnetic fields is a long-standing problem not only for our Sun, but for other astronomical bodies as well. Today we believe that the magnetic fields are generated by a hydrodynamic dynamo process which converts energy of the plasma flow into magnetic energy. In the course of this lecture I will detail the dynamics of the magnetic fields in the Sun. In particular, I will discuss the properties of the sunspots, the 11-years solar cycle, and the overall structure of the Sun's magnetic fields. This phenomenology is particularly important in solar physics since it can be directly extracted from observations and also because it provides experimental data the dynamo theory and the numerical simulation must reproduce in order to be successful.

Notes

Summary

0m 06s

## Sunspots: definition and an early history




Courtesy of SOHO (ESA & NASA)

- Sunspots: dark patches on the Sun where intense magnetic fields emerge from the interior through the surface.
- Earliest recording are from China over 2000 years ago.
- The first European observation in 1610 was made by Galileo Galilei with his telescope.

Plasma

The most striking manifestation of the solar activity are sunspots. They are dark patches on the sun where intense magnetic fields emerge from the interior through the surface. The earliest recording of sunspots are from China over 2,000 years ago. The first European observation was made by Galileo Galilei with his famous telescope in 1610. In this figure you can see a huge group of sunspots as observed by the SOHO satellite. On March 30, 2001, the area spanned by this sunspot group was larger than 13 times the entire surface of the earth. This group was the source of numerous flares and coronal mass ejections including the largest flare recorded in 25 years.

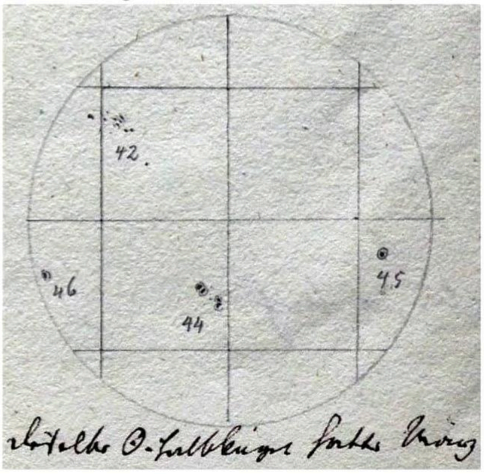
Notes

Summary

1m 04s

# Early and modern observations of Sunspots

Drawing of the Sun of 1847 Apr 14




- First observations of the solar cycle by the astronomer Samuel Heinrich Schwabe. He made drawings of sunspots from 1825–1867 and observed that the number of sunspots exhibits a ~10 year period.
- In 1848, Rudolph Wolf (Bern observatory and Zurich) started the modern daily observation of the Sun

$$R = k(10g + n)$$

correction factor for observer
individual sunspots
number of sunspot groups

- Solar Influences Data Analysis Center (SIDC) provides the International Sunspot number.

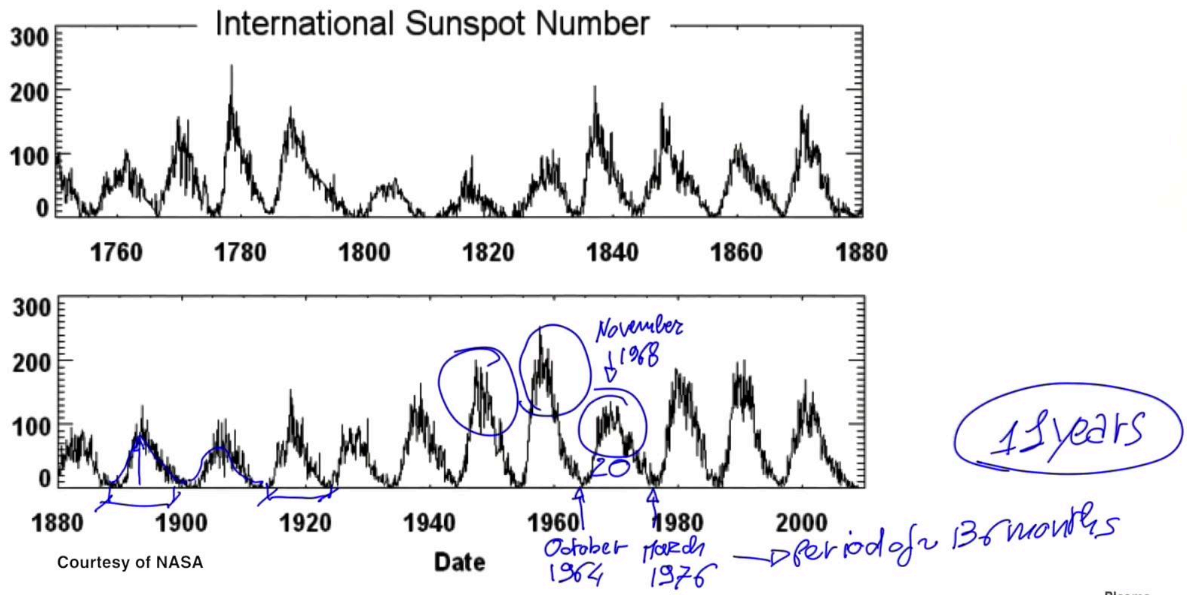
Plasma

The first observations of the solar cycle were made by the astronomer, Samuel Schwabe. He made an impressive number of drawings, approximately 10,000, of sunspots from 1825 to 1867. Using these drawings, he observed that the number of sunspots exhibits a period of approximately 10 years. It was in 1848 that the modern, daily observation of the sun started, with Rudolph Wolf at the Bern observatory in Switzerland and later in Zürich. Wolf noticed that it is much easier to identify sunspot groups than each individual sunspot on the Sun. He then defined a relative sunspot number, R = k (10g + n). Here k is a correction factor that takes into account that sunspots can be observed by different observers. g is the number of identified spot groups. and n identifies the number of individual sunspots. Wolf was the primary observer between 1848 and 1893 and had a personal correction factor of k = 1. He also extended the data back to 1749 using primary, indirect observer. The Swiss Federal Observatory continued the monitoring of the sunspot number through 1980, and then the Royal Observatory of Belgium took over as the primary observer and the International Sunspot number was defined by averaging all the numbers provided by many observers. Today, International Sunspot numbers are provided by the Solar Influences Data Analysis Center (SIDC).

Notes

Summary

1m 59s




Plasma

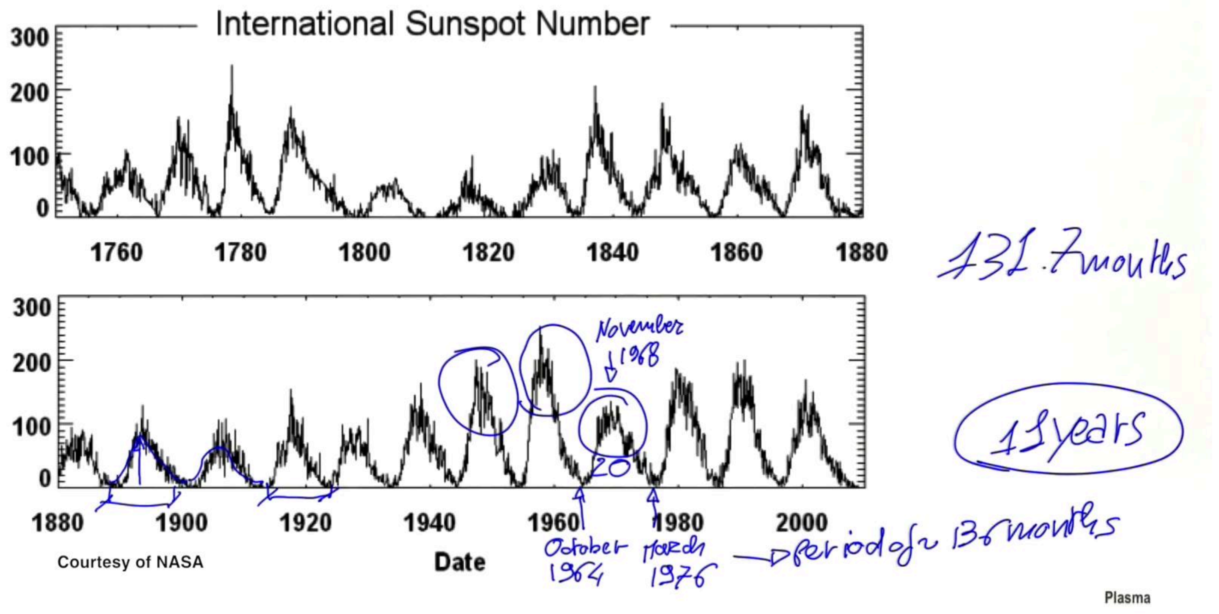
The International Sunspot number is the key indicator for solar activity. It provides very long-time series with many data available, to trace back solar activity. This plot illustrates the International Sunspot number during the different solar cycles. Sunspot numbers are usually given as daily numbers, monthly averages, yearly averages and smoothed numbers to get rid of the noise present in the data that you can also observe in this figure. Solar maxima and minima are identified in terms of these smoothed numbers. We can observe from this figure that the sunspot number varies in amplitude, time, shape, and also length. Each solar cycle is defined as the period between two minima of the International Sunspot number. For example, if we consider these two minima in October, 1964 and March, 1976, these two minima identify the solar cycle number 20. In this solar cycle, the maximum of activity was reached in November, 1968. The period of the sunspot cycle is defined as the time elapsed between these two minima of activity. For example, for the solar cycle 20, it was 136 months which corresponds approximately to 11 years.

Notes

Summary

4m 03s

# The 11 year solar cycle



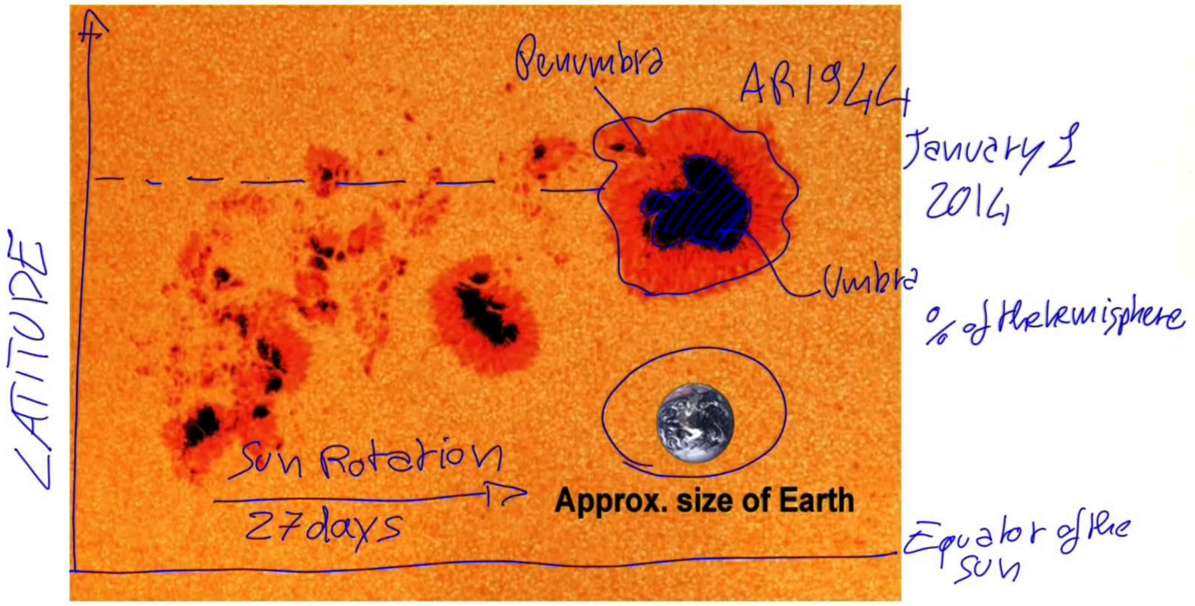

If we consider all the solar cycles and we take the average of the solar period, we obtain approximately 131.7 months, almost exactly 11 years. This is the so called 11-years solar cycle which is telling us that the sun goes through phases of maximum and minimum activity with an average period of approximately 11 years.

Notes

Summary

5m 40s

# A closer look at individual sunspot




Courtesy of NASA/SDO

Plasma

Let's now have a closer look at an individual sunspots. This is an example of an enormous sunspot which is labeled AR1944 which slipped into the view over the Sun late on January 1, 2014. You can see on this picture the projected approximate size of the earth which gives you an idea of the size of this sunspot. You can also observe that the sunspot has two distinct regions. One darker region, this dark region is called *umbra*, and one brighter region surrounding the umbra which is called *penumbra*. If we look at the umbra, we can define an area for this region. Conventionally, the area of the sunspot is given in terms of percentage that the sunspot occupies of the hemisphere of the Sun. If we assume that this line identifies the position of the equator of the Sun, we can also identify the position of the sunspot in terms of the latitude. Actually the area and the position on the surface of the sun of every single sunspot, or group of sunspots, has been recorded since 1847. The Sun rotates with a 27-days period. And the sunspot and groups of sunspots, move together with the Sun.

Notes

Summary

6m 09s

# Sunspot dynamics: an example from SOHO

Courtesy of NASA/SOHO

Plasma

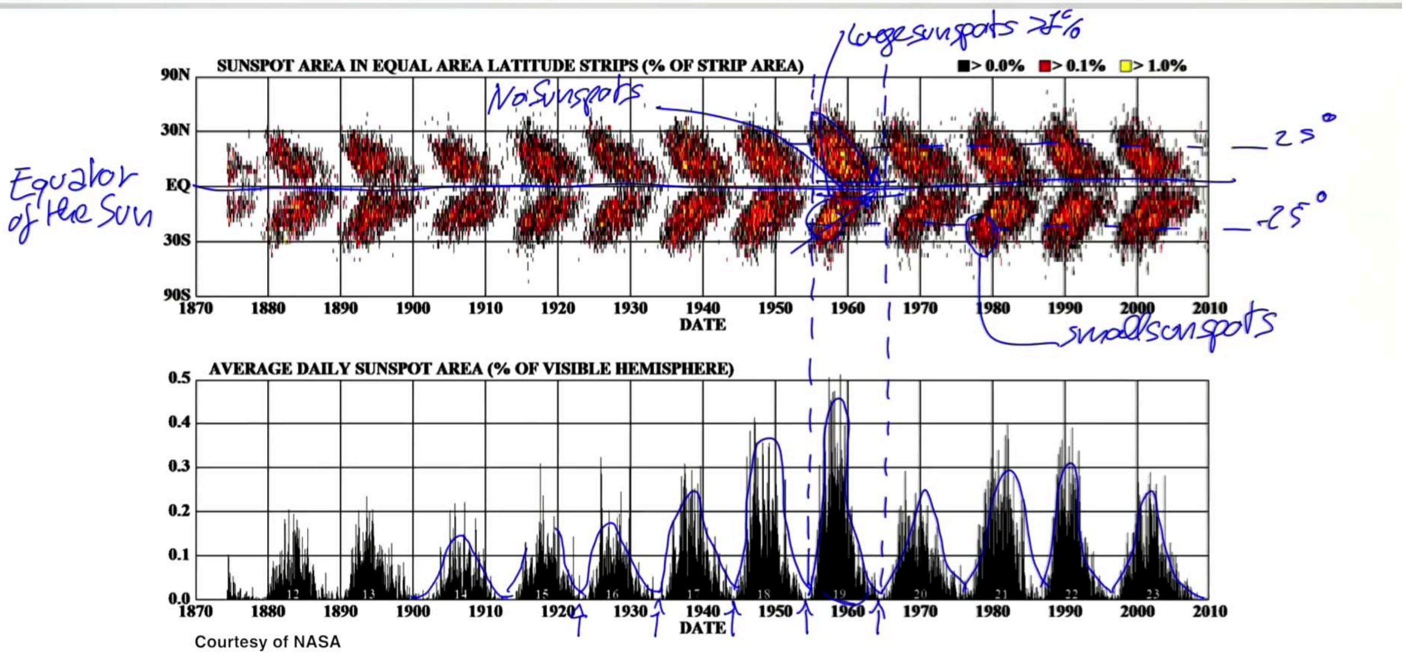
The sunspot rotation is shown in this movie that was recorded by the SOHO satellite in 2001. During the rotation, the sunspots exhibit the dynamics and they change their position on the sun surface, their shape and their size.

Notes

Summary

8m 01s

# The butterfly diagram



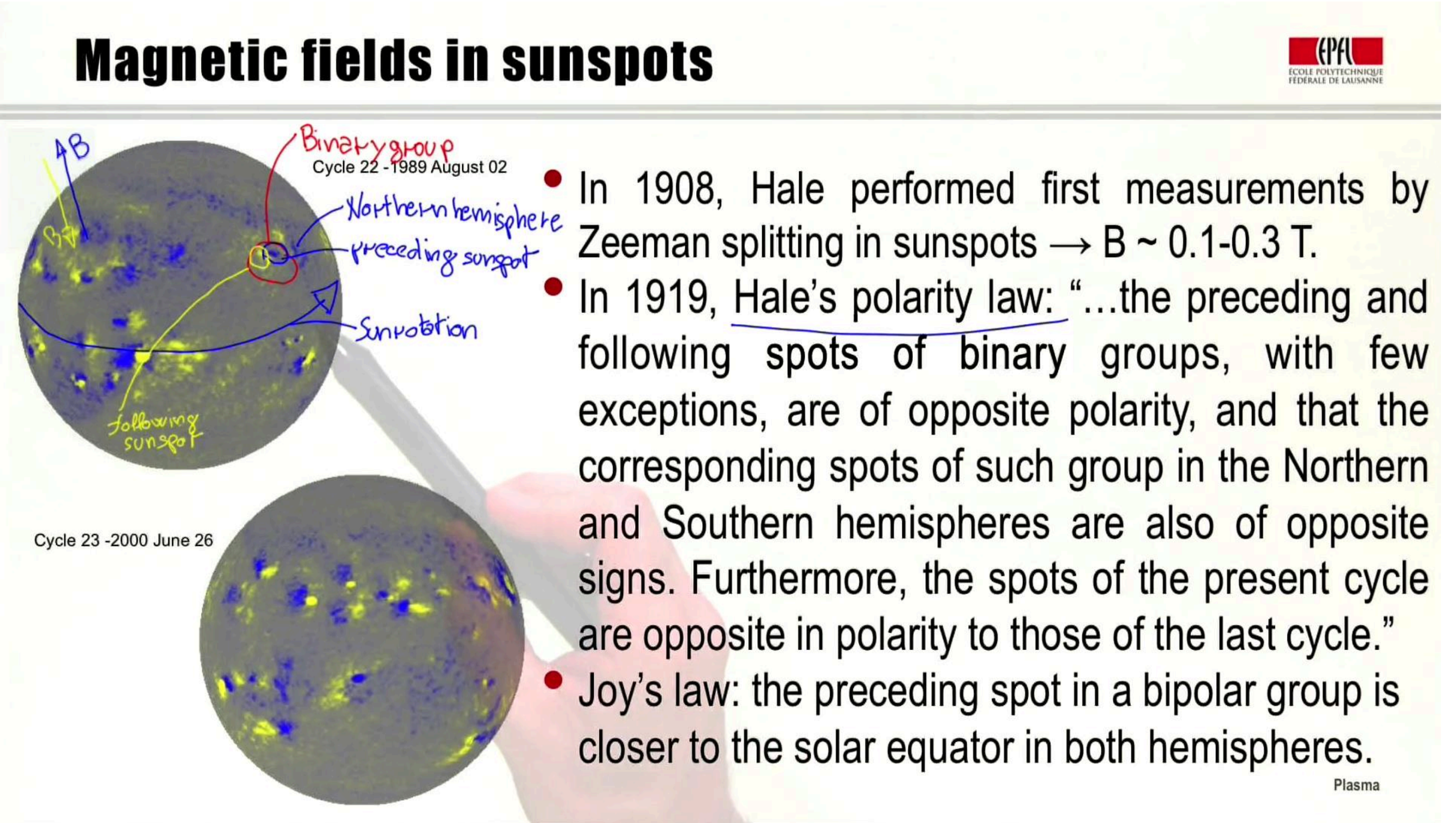

Plasma

The position of the sunspots in terms of their latitude has been recorded and a clear trend emerged. This plot shows the distribution of the sunspot area as a function of the latitude of the sun during each cycle. The yellow color indicates large sunspots that have an area which is larger than 1% of the hemisphere where the sunspot is located. Dark colors identify sunspots that are smaller. The bottom plot shows the sunspot area and allows us to identify each individual solar cycle by looking at the minima. In this figure, the central line identifies the equator of the Sun. If we look for example at the solar cycle number 19, we can see that at the beginning of the cycle the sunspots appear in two bands on either side of the Sun's equator for latitudes that are slightly larger than 25-30 degrees. As the cycle progresses the range of latitudes increases and the central latitude drifts towards smaller values. However, you should note that the corridor near the equator is always free from sunspots. This behavior is referred to as *Spörer's law of zones* and it was famously illustrated by Maunder in 1904, in his Butterfly Diagram.

Notes

Summary

8m 23s



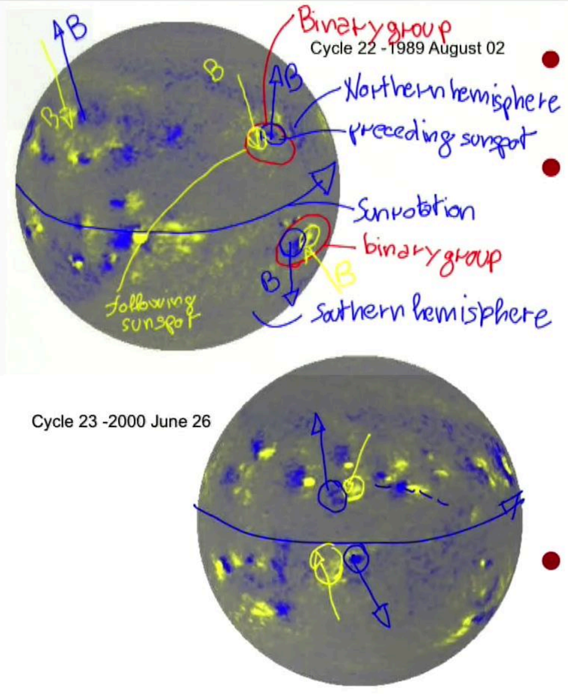

Let's now come to the first observation of magnetic fields in the Sun. They were first observed by Hale in 1908. He used spectral observation on a number of spectral liness emitted from sunspots, and he noted that in some lines it was possible to detect Zeeman's splitting that could only be due to the presence of strong magnetic fields. Typical magnetic fields that he measured on large sunspots were of the order of 0.3 Tesla. About 10 years later, he made observations that resulted in what is now called the *Hale's polarity law*. Hale's polarity law is illustrated in this picture which shows a magnetogram from the cycle 22 on August 2, 1989. The blue color identifies magnetic field lines that are pointing away from the Sun. The yellow color identifies magnetic fields that are entering into the Sun. The Sun rotates in this direction, and if we consider the Northern hemisphere, we can clearly identify binary groups of sunspots. For example, in this particular binary group, we can see in blue a preceding sunspot, and in yellow a following sunspot. They are defined as preceding or following with respect to the rotation of the sun indicated here.

Notes

Summary

10m 02s

# Magnetic fields in sunspots




- In 1908, Hale performed first measurements by Zeeman splitting in sunspots → B ~ 0.1-0.3 T.
- In 1919, Hale's polarity law: "...the preceding and following spots of binary groups, with few exceptions, are of opposite polarity, and that the corresponding spots of such group in the Northern and Southern hemispheres are also of opposite signs. Furthermore, the spots of the present cycle are opposite in polarity to those of the last cycle."
- Joy's law: the preceding spot in a bipolar group is closer to the solar equator in both hemispheres.

Plasma

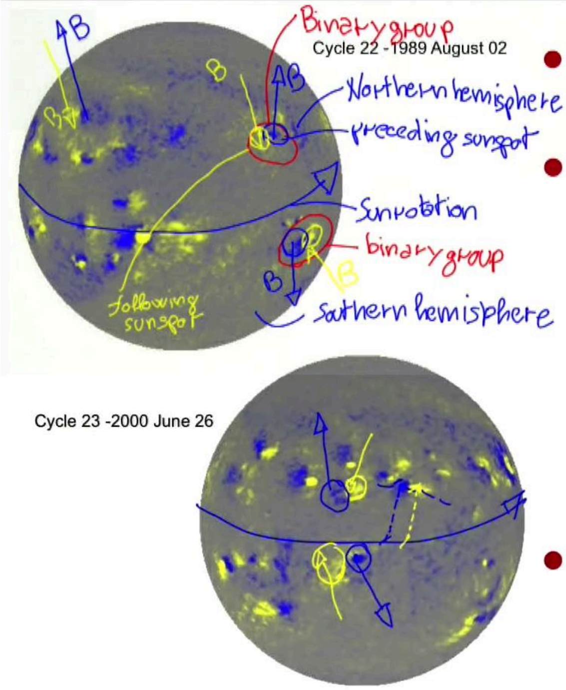
The Hale's polarity law for this particular cycle tells us that in the Northern hemisphere the magnetic field in the preceding sunspot is pointing away from the Sun while it's pointing towards the Sun in the following sunspot. We can now look at the Southern hemisphere and identify the corresponding binary group of sunspots shown here in red. The polarity of the magnetic field is now reversed with respect to the Northern hemisphere in the sense, that the magnetic field in the preceding sunspot points towards the Sun while the following sunspot has a magnetic field that points away from the Sun. This illustrates Hale's polarity law that was formulated in 1919. If we now look at the following cycle, the cycle number 23, we see here a magnetogram that was registered on June 26, 2000, the polarity of the sunspot is now reversed with respect to the previous cycle. In the sense that in the Northern hemisphere now the preceding sunspot has a magnetic field that points inward while in the Southern hemisphere, the preceding sunspot has a magnetic field that points outward. In the same year, Joy, made the following observation that the preceding spot in a binary group is closer to the solar equator in both hemispheres.

Notes

Summary

11m 37s

# Magnetic fields in sunspots




- In 1908, Hale performed first measurements by Zeeman splitting in sunspots → B ~ 0.1-0.3 T.
- In 1919, Hale's polarity law: "...the preceding and following **spots of binary** groups, with few exceptions, are of opposite polarity, and that the corresponding spots of such group in the Northern and Southern hemispheres are also of opposite signs. Furthermore, the spots of the present cycle are opposite in polarity to those of the last cycle."
- Joy's law: the preceding spot in a bipolar group is closer to the solar equator in both hemispheres.

Plasma

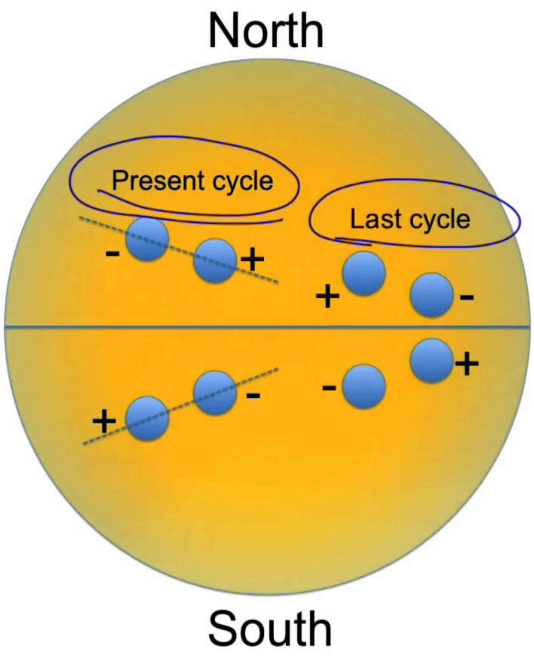
This can be observed by looking at the following binary group of sunspots where we can observe that the distance of the leading sunspots in yellow, is slightly smaller than the distance of the following sunspot.

Notes

Summary

13m 26s

# Hale's and Joy's laws illustrated



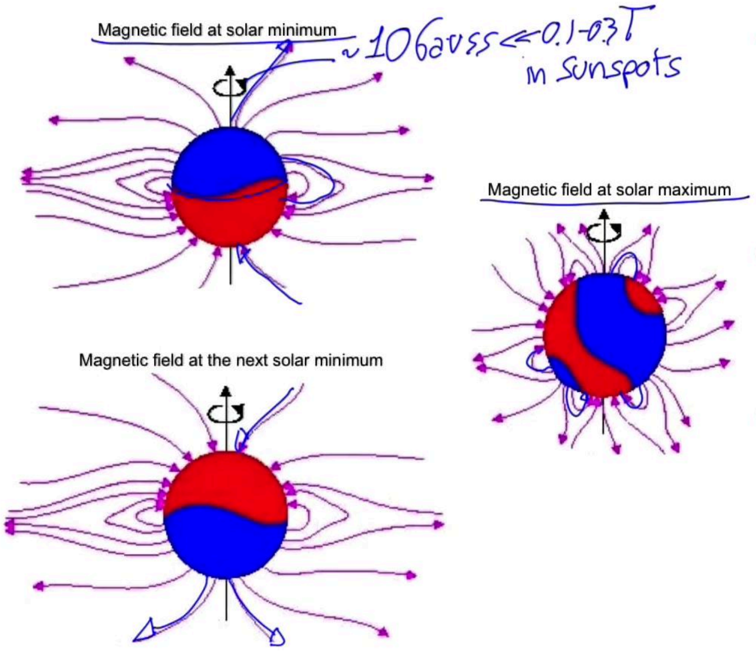

So for example in this sketch here, if we look at the preceding sunspot in the Northern hemisphere, and the corresponding preceding sunspot in the Southern hemisphere, their magnetic fields are pointing in opposite directions. Similarly, following sunspots have opposite polarities in the two hemispheres. Joy's law states, that the preceding sunspot in a bipolar group is closer to the solar equator in both hemispheres. This is shown here, where the distance of the preceding sunspot from the equator, is indicated by dp, and it is smaller than the distance of the following sunspot indicated by df. The same is true for both hemispheres. If we now look at the solar cycle before the one that we have just considered, we notice that the polarity seen by bipolar groups of sunspots reverses between the two solar cycles. This observation taken together with the Maunder Butterfly Diagram means that higher latitude bipolar groups emerging as the new cycle begins have opposite ordering of polarities to the last bipolar group of the previous cycle. These laws are and have remained important observational building blocks of theories of the solar cycles.

Notes

Summary

13m 44s

# The Sun global magnetic field structure




- In 1955, the magnetogram was invented. It became possible to measure much weaker magnetic fields near the poles of the Sun.
- The polar field is of the order of 10G and it reverses as well at the time of a solar maximum activity.
- Polar fields are at their peak near sunspot minimum. The magnetic field structure is close to a dipole.

Plasma

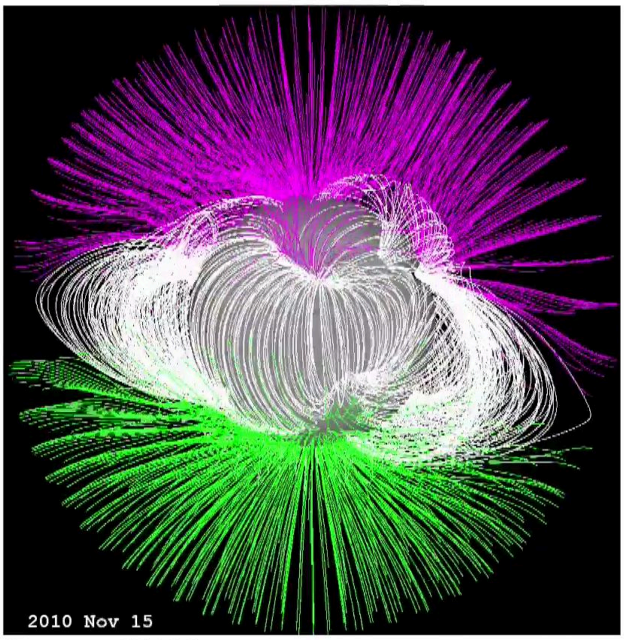
In 1955, the magnetogram was invented by Babcock. It became thus possible to measure magnetic fields much weaker than those that were observed previously in solar sunspots near the poles of the Sun. Typical polar fields are of the order of 10 Gauss. These polar fields are much smaller than those observed in sunspots that are of the order of 0.1-0.3 Tesla. At the time of minimum activity, which is shown in this picture here, the magnetic field of the sun is close to a dipole with magnetic field lines that for example, exit the North Pole and enter the South Pole for a specific solar cycle. Near the equator the field lines are closed and connect approximately one hemisphere to the other. During the evolution of a solar cycle, the magnetic field changes dynamically. During maximum activity, at the solar maximum which is shown in this picture here, the magnetic field is multipolar with intense magnetic fields that connect neighboring sunspots. Going through the following period of minimum activity the magnetic field is again close to a dipole but now with a reverse polarity, with magnetic fields that now exit the South Pole and enter the North Pole. Over this period, the overall configuration of the Sun's magnetic field has reversed its polarity.

Notes

Summary

15m 18s

# Solar magnetic field from 1997 to 2013



Courtesy of NASA

Plasma

The magnetic field reversal in the sun is shown by this movie that shows the evolution of the Sun's magnetic field from 1997 to 2013. The magnetic field in this animation is reconstructed using a model that takes as inputs the solar magnetogram as the source surface of the magnetic field at each time. The model then builds the field structure from the photosphere out to approximately two solar radii. The white magnetic field lines are magnetic field lines that are closed. They move up and then return to the solar surface. The green and violet lines represent field lines that are open. Green lines represent positive magnetic polarity, and violet lines represent negative polarity. These field lines do not connect back to the sun but with more distant magnetic fields in space. You should note that the polarity of the magnetic field is reversed from the beginning of a solar period to the end of the same solar period.

Notes

Summary

16m 57s

# Summary


In this module we have learned that the Sun is an extremely dynamic object. On its surface, sunspots with intense magnetic fields form and die with a period of approximately 11 years and following precise empirical laws. Over an entire solar cycle the magnetic field reverses its polarity. These experimental observations are particularly important since they provide hints at possible mechanisms behind the generation of magnetic fields. Any proposed mechanism should be able to reproduce these observations. In the next module we will describe how the hydrodynamic dynamo process can be at the origin of solar magnetic fields.

Notes

Summary

18m 02s