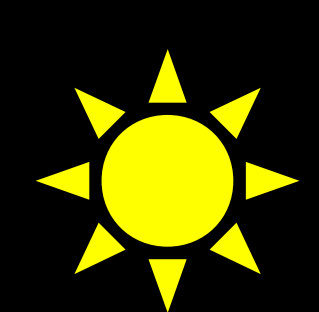
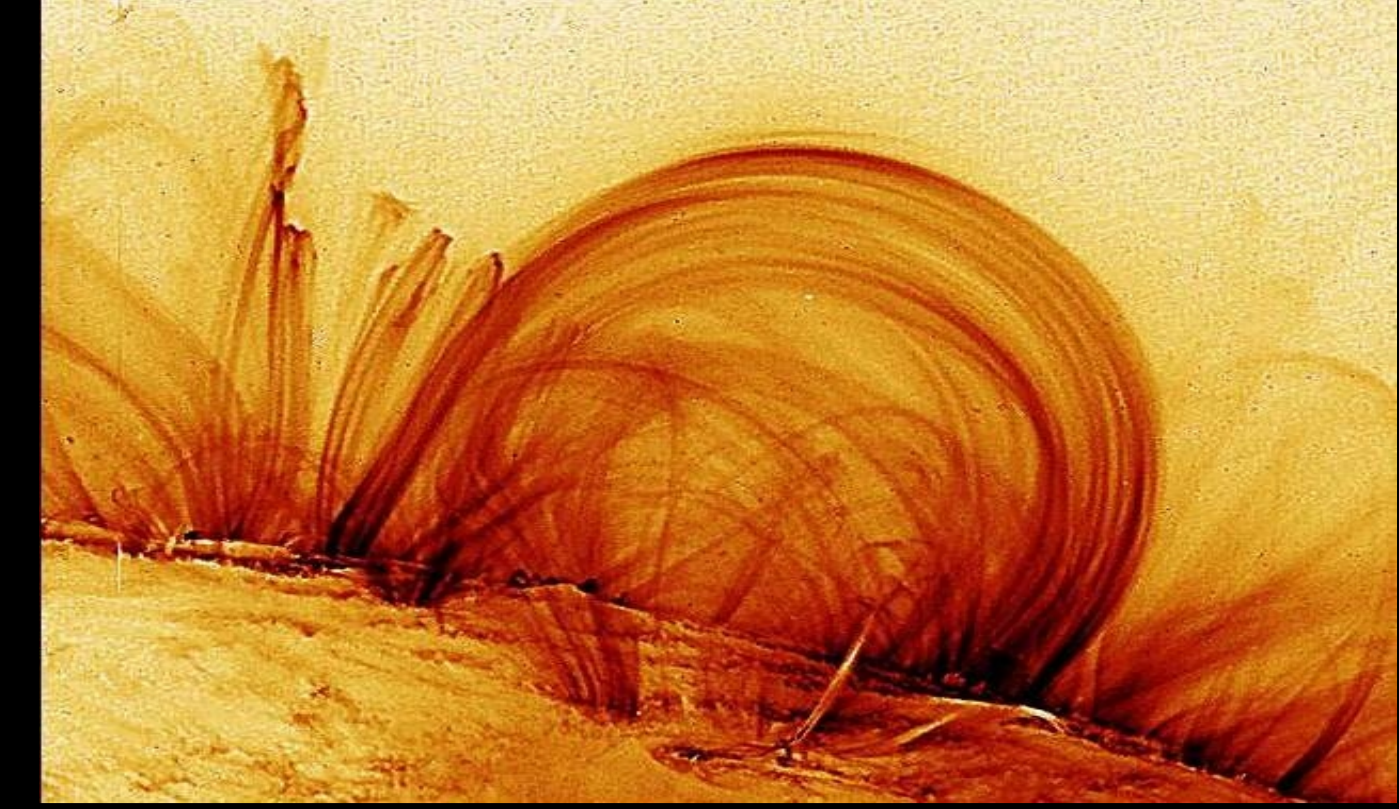
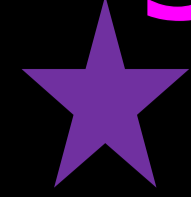


# Cosmic Magnetic Fields



## What are magnetic fields?

Electric and magnetic fields are regions of space in which electromagnetic forces can act. These two types of field always go hand in hand, but in astronomy magnetic fields are more important than electric fields.

Light (electromagnetic radiation) is an electromagnetic wave of oscillating electric and magnetic fields.

Electric and magnetic fields are made up of lines of force called "field lines"; the more bunched up the field lines, the stronger the field. A compass needle placed in a magnetic field points along the magnetic field line at its location.

Magnetic fields are associated with electric currents, for example:

- The magnetic field around a current-carrying wire is circular.
- Moving a permanent magnet inside a coil produces a current.

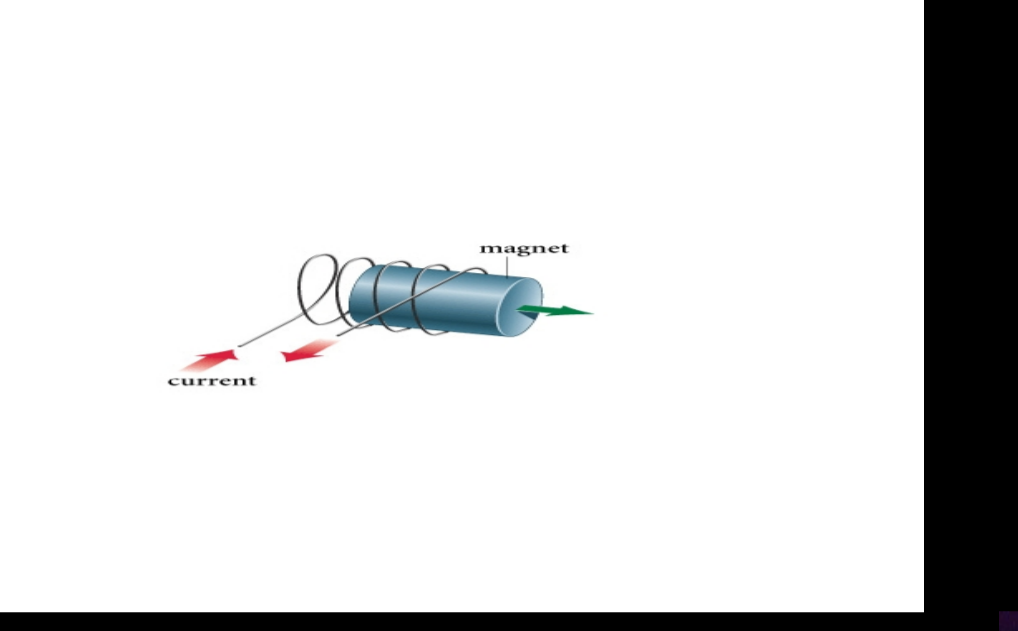
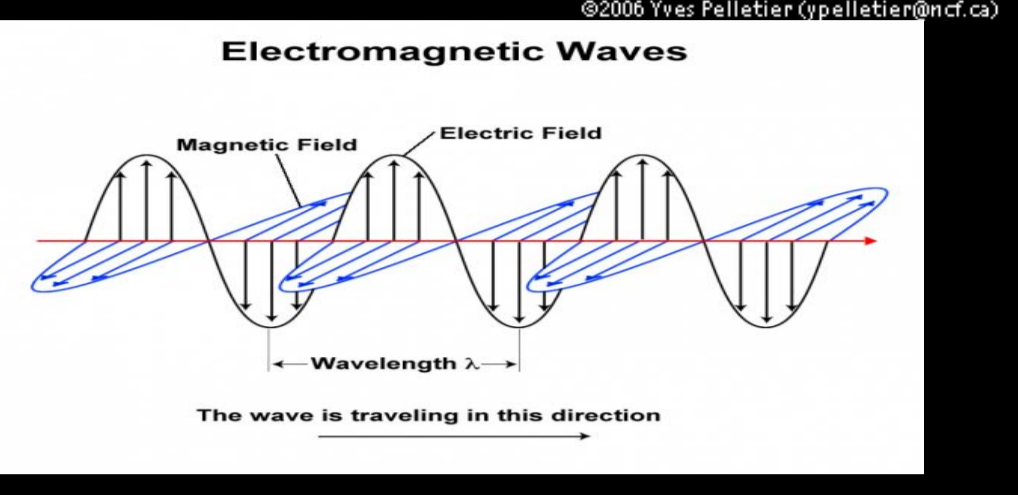
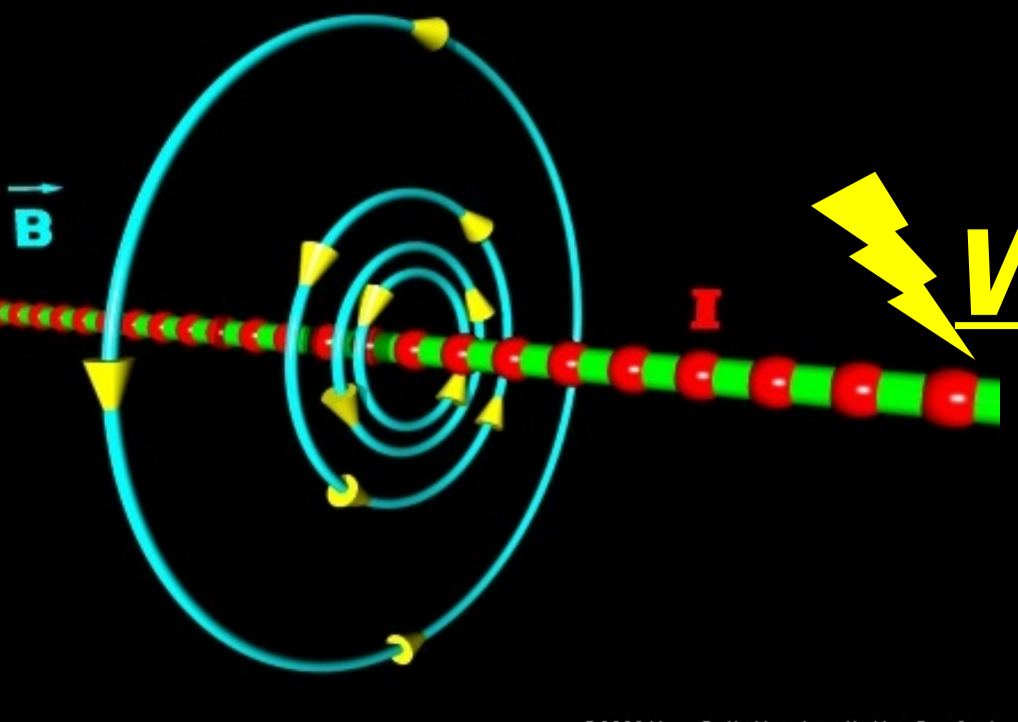
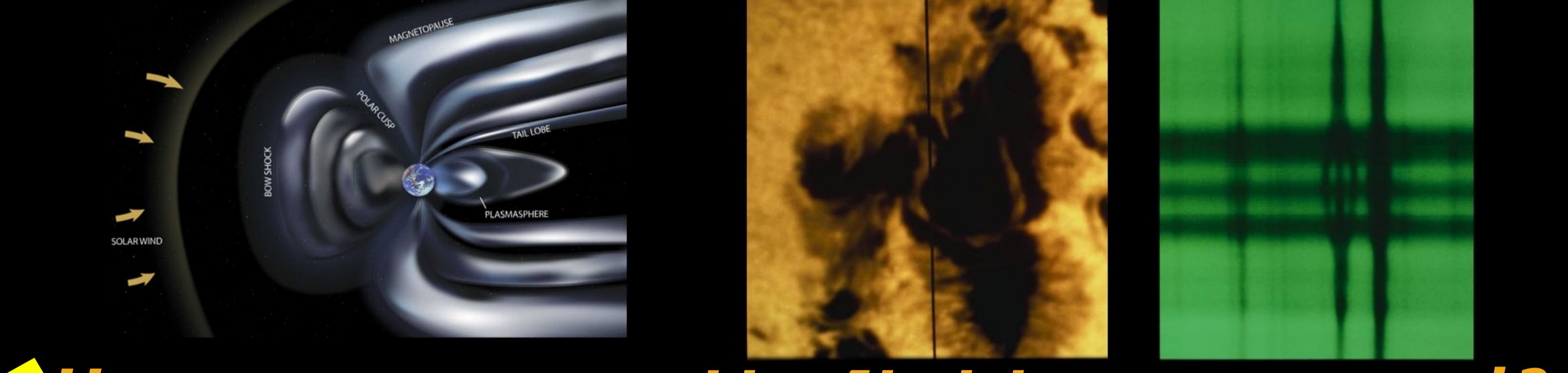
## Earth's magnetic field

Not only is Earth's magnetic field useful for navigation but it protects us from the "solar wind" of charged particles streaming from the sun as well as from energetic charged particles known as "cosmic rays".

Earth's field has roughly a dipole geometry, like a bar magnet, though this geometry is distorted by the solar wind.

Some particles from the sun manage to follow the magnetic field lines down to the polar regions. There they can collide with atoms of nitrogen and oxygen in the upper atmosphere, leading to beautiful displays of light known as "aurora".

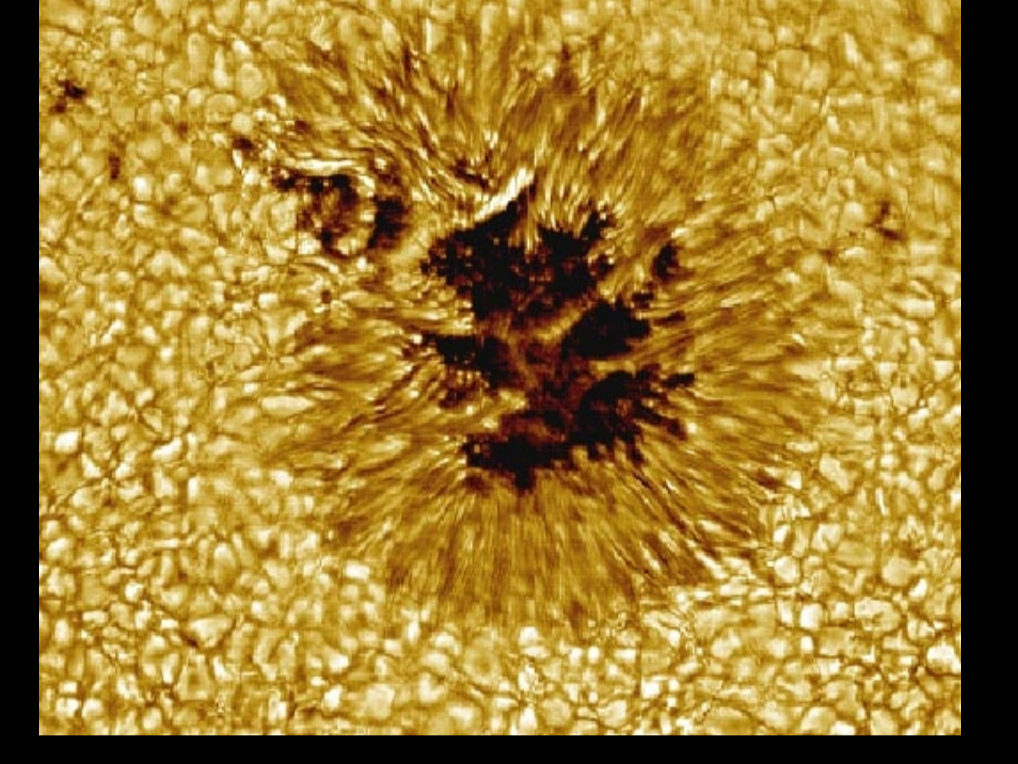
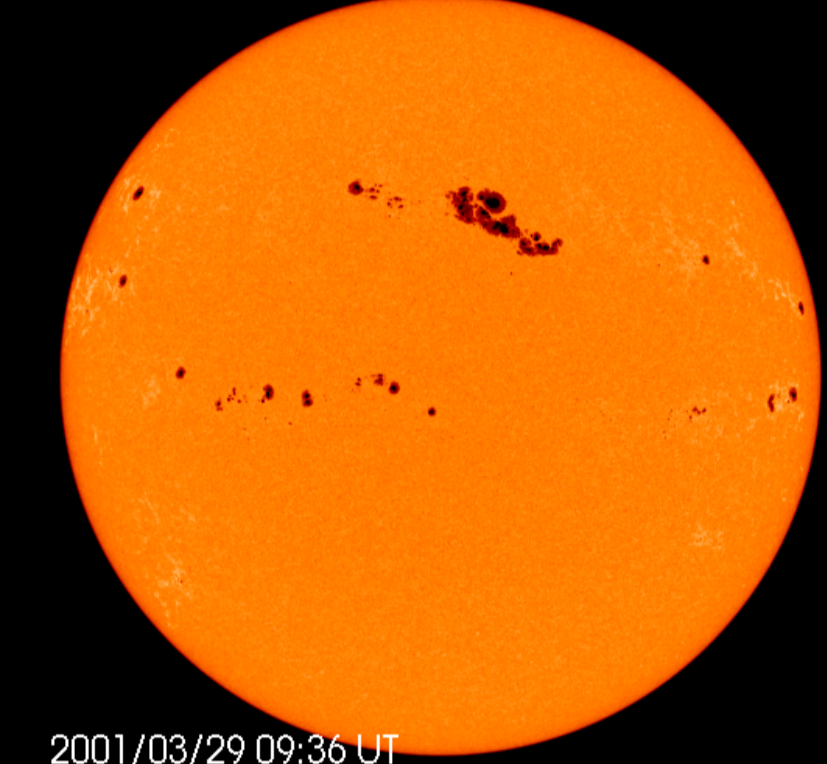
Earth's field is known to reverse itself—the magnetic poles more or less trade places—every 3,000,000 years on average, though the timing is actually quite erratic (the last reversal occurred some 7.80.000 years ago).



## Why are magnetic fields important?

Most of the regular matter in the universe is in the plasma state, which means it is a gas of freely moving positive and negative charges. As far as we know, wherever there are plasmas, there are currents and magnetic fields.

- ∅ In the laboratory, magnetic fields decay (disappear) very quickly without an electric current to preserve them.
- ∅ Because of the great size of astrophysical objects, it takes much longer for a magnetic field to decay by "diffusing" out of them.
- ∅ Thus, the field lines behave as though they are "frozen in" the gas like hairs stuck in a child's play-dough.
- ∅ A long life is one reason magnetic fields are found all over the universe.
- When clouds of plasma get compressed, stretched, sheared, twisted or mixed, so do the magnetic fields inside them. This can lead to many important effects, for example:
  - ∅ Magnetic field lines resist being squeezed together, and this "magnetic pressure" helps to support astrophysical bodies against gravity. This effect can limit the tendency of gas clouds to collapse in on themselves and form stars.
  - ∅ Field lines also resist being stretched, just like guitar strings. This "magnetic tension" can help to transfer momentum and energy between gas particles joined by a field line. Particles in the inner part of an "accretion disk", for example, can lose enough of their orbital energy to be able to accrete, or fall down onto, the central star or black hole.

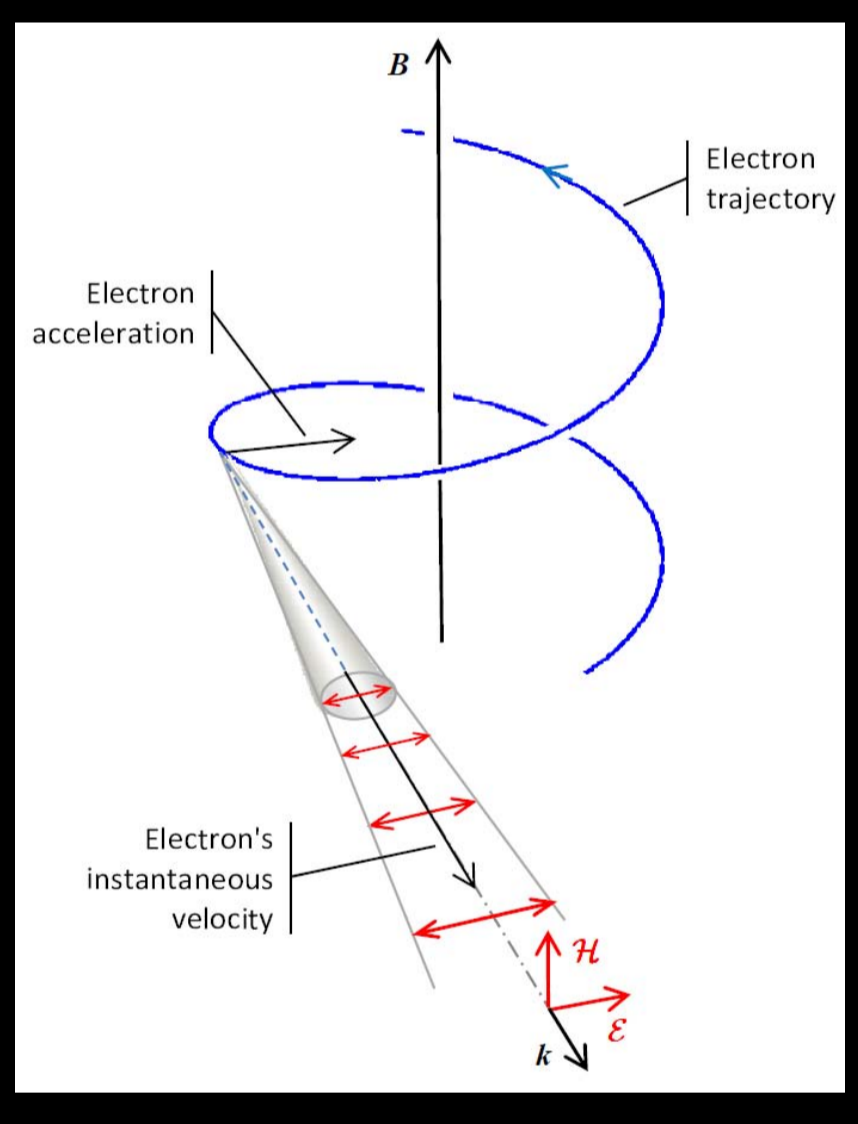


## Sun's magnetic field

The sun, like the earth, has roughly a dipole-shaped magnetic field. But the field is especially strong in regions on the surface called sunspots (over 1000 times stronger than Earth's field).

- ∅ Sunspots have a lower temperature, which makes them visible as dark patches in a photograph.
- ∅ They come in pairs with the magnetic field of each member of the pair having opposite directions.
- ∅ Astronomers have been recording information about sunspots for centuries—data that is useful even today!
- ∅ A sunspot pair is formed when a buoyant magnetic "flux tube" rises through the solar surface, creating a "coronal loop". Each "footprint" where a coronal loop intersects the surface corresponds to a sunspot.

## How are magnetic fields measured?



In parts of the solar system accessible to spacecraft, it is possible to measure magnetic fields directly with onboard magnetometers. Otherwise, various other methods can be used:

### The Zeeman effect

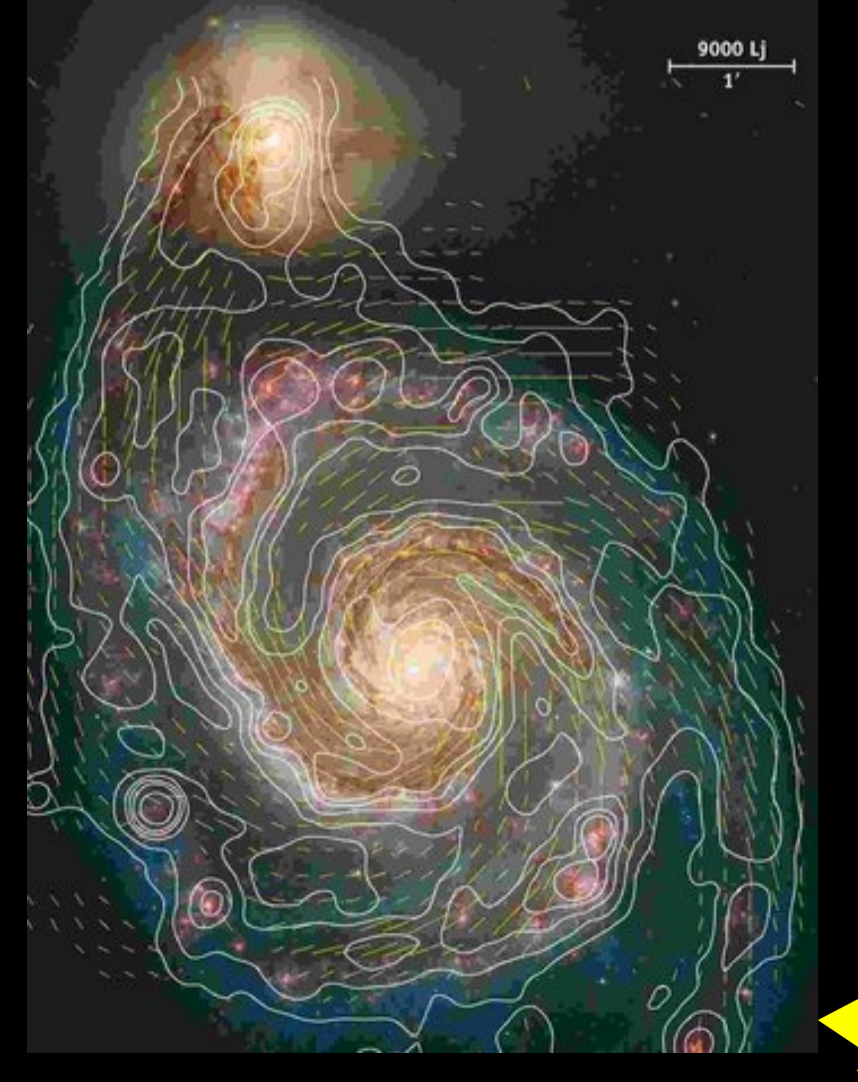
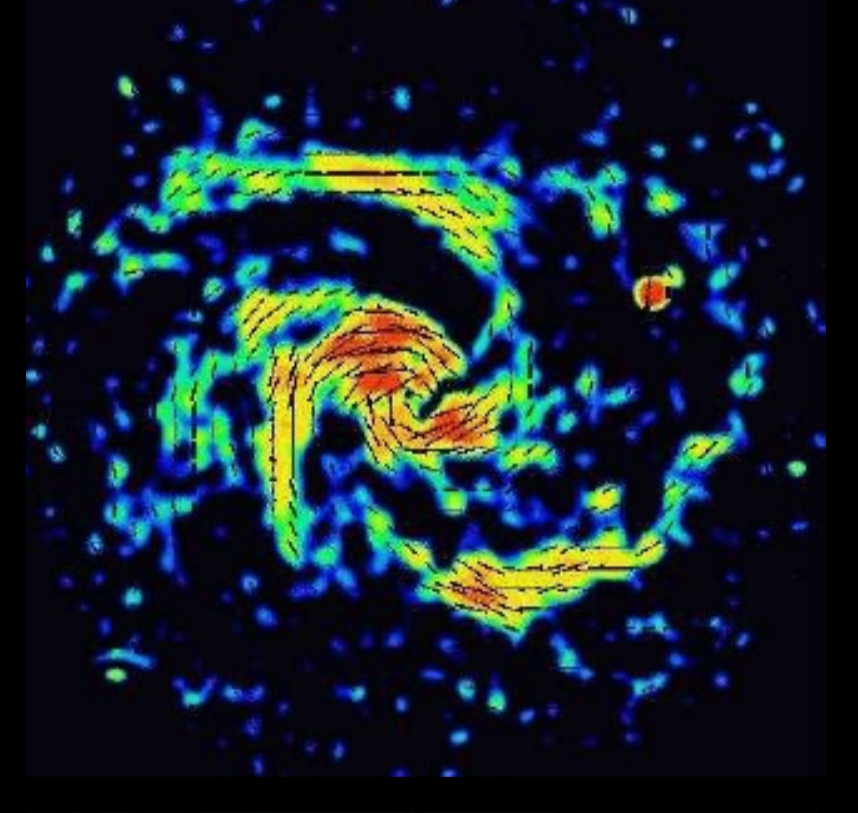
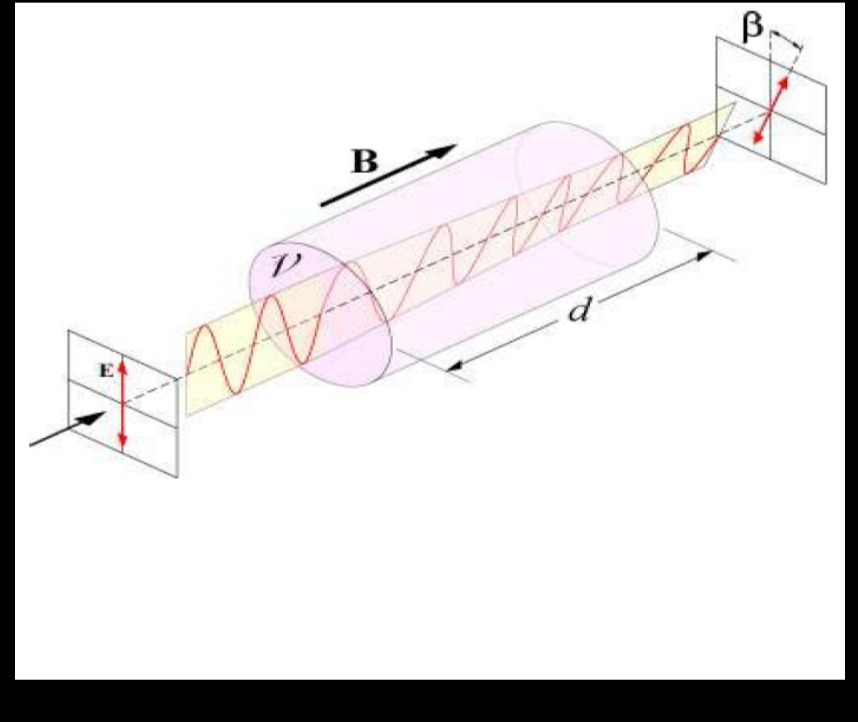
- ∅ The energies of the different electronic configurations of an atom do not normally depend on its orientation. However, the presence of a magnetic field introduces a preferred direction, with one result being that certain energy levels of the atom are split into sublevels.
- ∅ The difference in energy between these sublevels is proportional to the strength of the magnetic field—if this energy separation can be measured, then the field strength can be deduced. In practice, this is done by measuring the broadening of an emission line in the spectrum of a source.
- ∅ Measuring magnetic fields using the Zeeman effect requires high "sensitivity" of the measuring device, and is usually possible only within our own galaxy.

### Synchrotron radiation

- ∅ This is the radio emission that is beamed by electrons spiraling around magnetic field lines at close to the speed of light.
- ∅ If the density of relativistic electrons can be estimated, then measuring the intensity of synchrotron radiation can give us the strength of the component of the magnetic field in the plane of the sky.
- ∅ This emission can also be "polarized" which means that it can be oriented along an axis. With this extra information, it is possible to determine the direction of the magnetic field lines (but with 180 degree ambiguity).

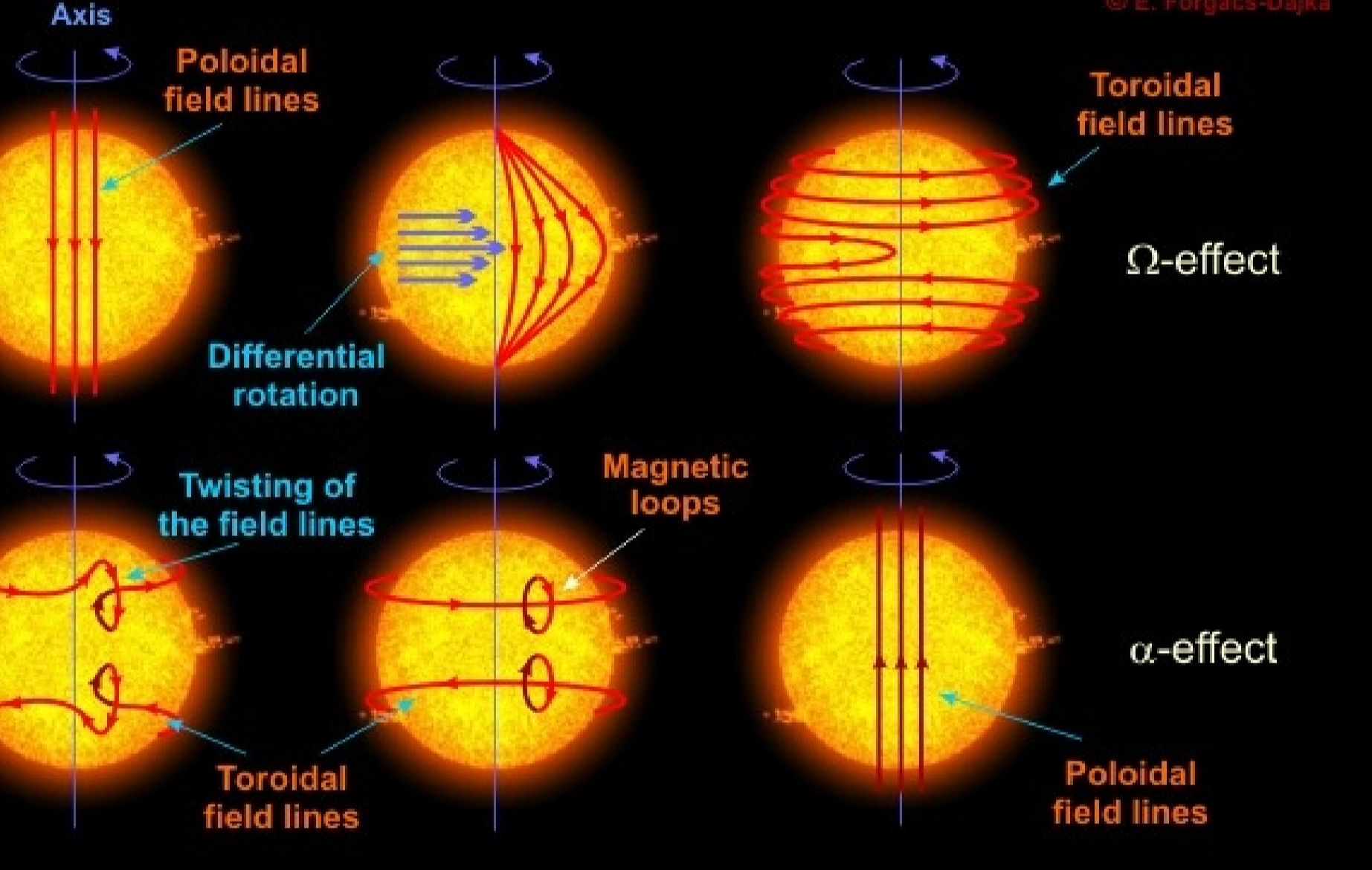
### Faraday rotation

- ∅ This can be used to get the component of the magnetic field along the line of sight from the Earth to the source.
- ∅ The polarization angle of the radio emission slowly rotates as the radiation makes its way through a magnetized medium.
- ∅ The amount of rotation is proportional to the line-of-sight component of the magnetic field and to the square of the wavelength of the radiation, so by measuring the polarization angle at different wavelengths, we can determine the strength and direction of this component of the magnetic field.



## Reconnection

Magnetic "reconnection" is a sudden reconfiguration of the field topology that happens when field lines pointing in opposite directions come so close together that they merge. This leads to a conversion of magnetic energy into other forms of energy, such as kinetic energy of turbulence and outflows, as well as heat. This is known to happen in the sun, for instance, where it helps to explain solar flares.



## Where are they found?

**Planets:** Most of the large bodies in the solar system have magnetic fields, the largest (after sunspots) being that of Jupiter. Though it is about the same size as Earth, Venus does not have a dynamo-generated field. Mars once had one, but no longer does.

**Stars:** Most stars have magnetic cycles, and many are more active magnetically than our sun. Although most stars cannot be resolved even by the largest telescopes due to their great distances, astronomers can still learn a great deal about them through indirect means. For example, we know that many stars have "starspots", like sunspots on the sun.

**Astrophysical jets:** When gas accretes, or falls, onto a central object such as a star or black hole, some of the inflowing plasma actually gets thrown back out. Sometimes, powerful "jets" of ejected material are formed along the spin axis of the central object. Magnetic fields play a key role in producing and shaping these outflows.

**Neutron stars:** Composed mostly of neutrons, these are compact remnants of supernova explosions, and have the largest magnetic fields in the universe. A radio pulsar is a type of neutron star that has a surface field around a trillion times stronger than that of Earth. Another type of neutron star, called a magnetar, can have fields that are hundreds of times stronger still. These fields are so large that they are the source of powerful explosions on the star that emit copious amounts of x-rays and gamma-rays.

**The interstellar medium:** The interstellar medium of our galaxy, comprised of gas and dust which fills the space between the stars, is known to have a magnetic field whose strength is only about 1/1,00,000 times that of Earth. This field can roughly be divided into two parts. One part is coherent on a scale of tens of thousands of light years, comparable to the size of the galaxy, while the other part is more randomly oriented. Magnetic fields in the interstellar media of nearby galaxies can be mapped using synchrotron emission and Faraday rotation. On an even larger scale, magnetic fields can be found in the diffuse gas in between galaxies that are grouped together and form a galaxy cluster.

## Dynamos

A plasma is in constant movement, both in terms of its average motion (e.g. rotation inside a disk) as well as its turbulent random motion. If the field lines are stretched and twisted in certain ways by these motions, the magnetic field can become enhanced with time. This process, whereby kinetic energy of the plasma is converted to magnetic energy, is known as an astrophysical "dynamo". Most of the magnetic fields in the universe, like those in the Sun and Earth, owe their existence to dynamos. Dynamos can grow a magnetic field exponentially with time, but initially they require a small "seed" field on which to operate. Astrophysicists have developed models to explain how these seeds come to be.

