

COSMIC MAGNETIC FIELDS

DETECTED ALMOST EVERYWHERE IN THE UNIVERSE, MAGNETISM IS ONE OF THE MOST POWERFUL, YET LEAST UNDERSTOOD, FORCES TO SHAPE ASTROPHYSICAL PHENOMENA

Magnetic fields are made up of lines of force occupying a region of space—a compass needle placed inside a magnetic field will point along the field line. The more bunched up the field lines, the stronger the field in that location. They can be produced by varying electric fields or by electric currents—bulk motions of charged particles such as electrons or protons. For example, the field lines around a straight current-carrying wire are circles (Fig. A). Conversely, a varying magnetic field can induce an electric field, leading to electric currents. This can be demonstrated by producing a current in a coil by moving a magnet (Fig. B).

Light, or for that matter, all electromagnetic radiation (microwave, radio, x-ray, etc.), is an eternal braid, so to speak, of electric and magnetic fields. A varying electric field gives rise to a varying magnetic field, which gives rise to a varying electric field, etc.... resulting in an electromagnetic wave propagating through space that can be detected by an eye or a telescope.

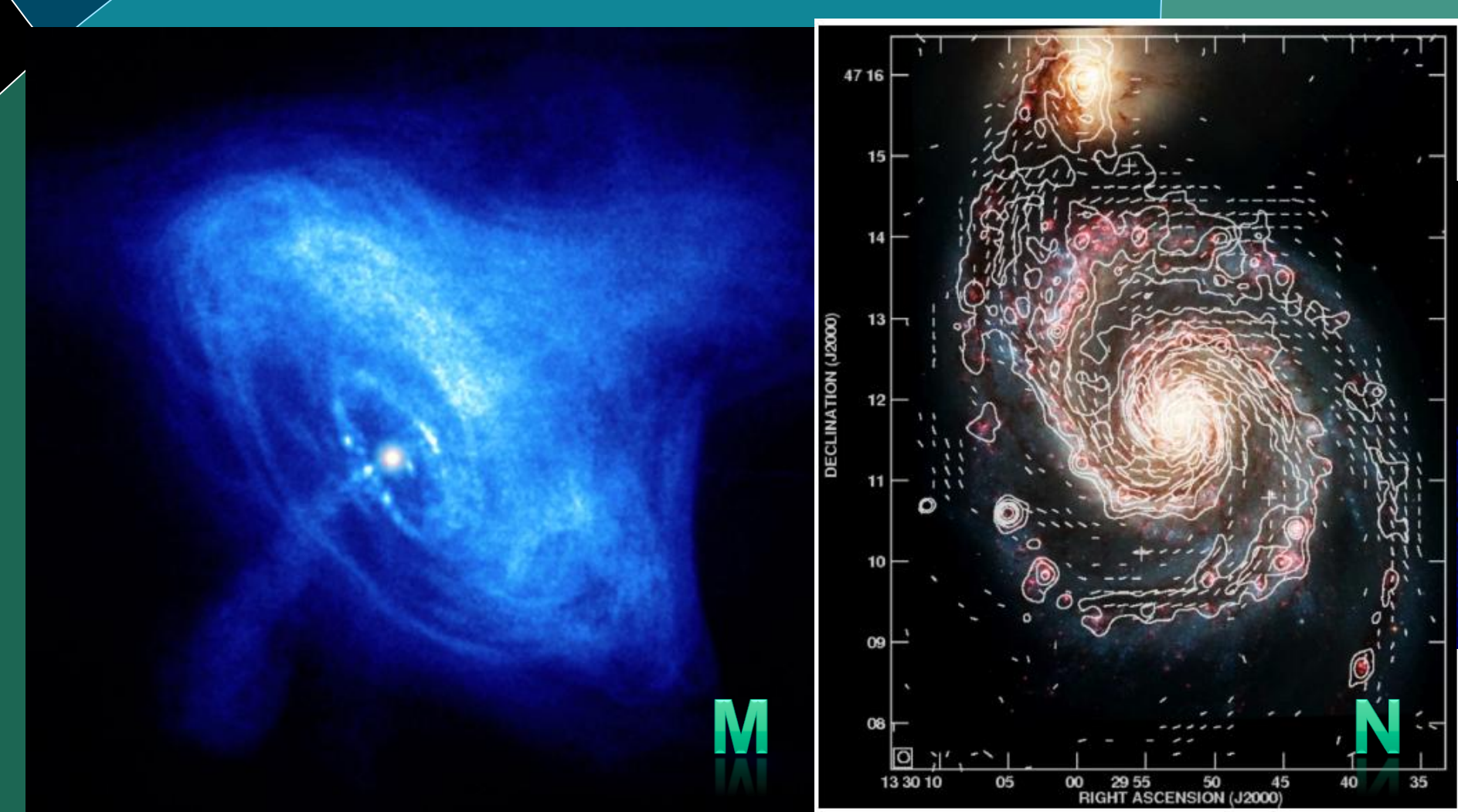
One difference between magnetic and electric fields is that magnetic field lines must form closed loops since there are no 'magnetic monopoles', i.e. free magnetic norths or souths.

ELECTROMAGNETISM

Magnetic fields in permanent magnets owe their presence to the alignment of the intrinsic spins of electrons—a quantum phenomenon.

The theory of relativity teaches us that electric and magnetic fields are really just two sides of the same coin—observers moving at different speeds will measure differing amounts of electric and magnetic field, though they will agree about fundamental laws like conservation of energy.

Magnetic fields exhibit pressure—field lines resist being squeezed together. They also exhibit tension as they resist being stretched, just like, e.g. a guitar string. In plasmas—gases made up of freely moving positive and negative charges—many electromagnetic effects are important. Provided that a certain set of conditions about the plasma is satisfied, it can be treated using magnetohydrodynamics (MHD), the theory of magnetized fluids.



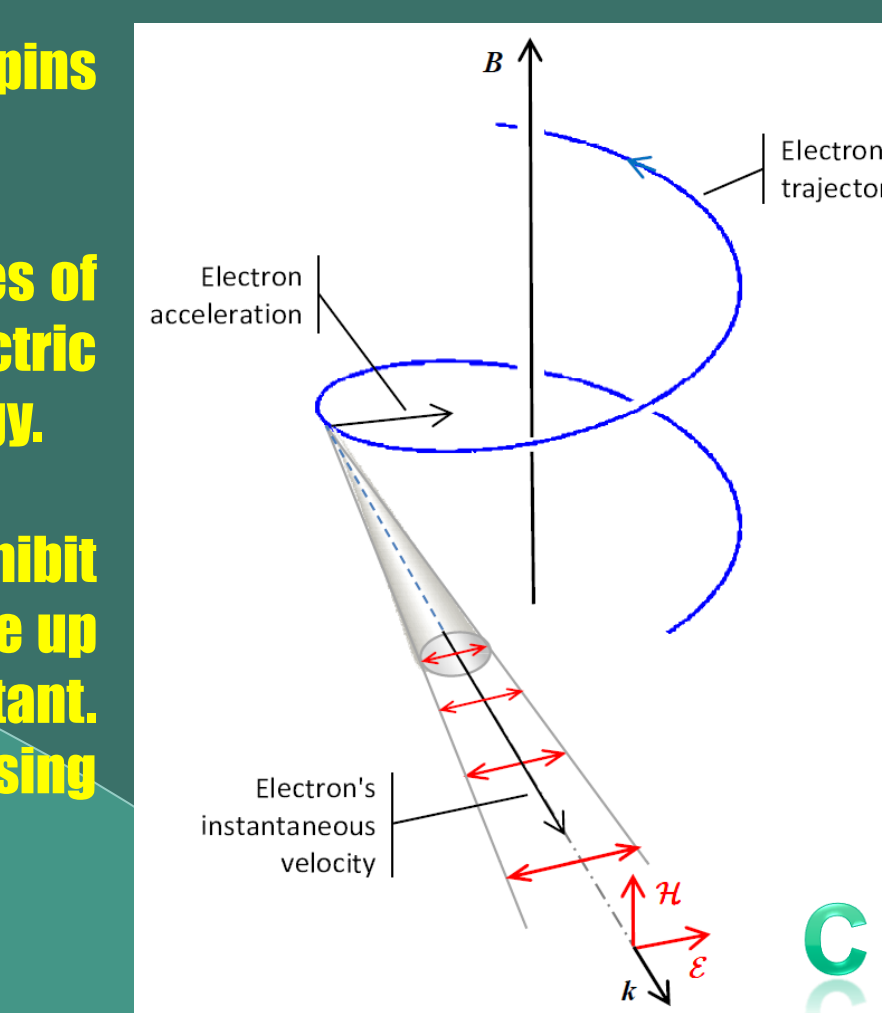
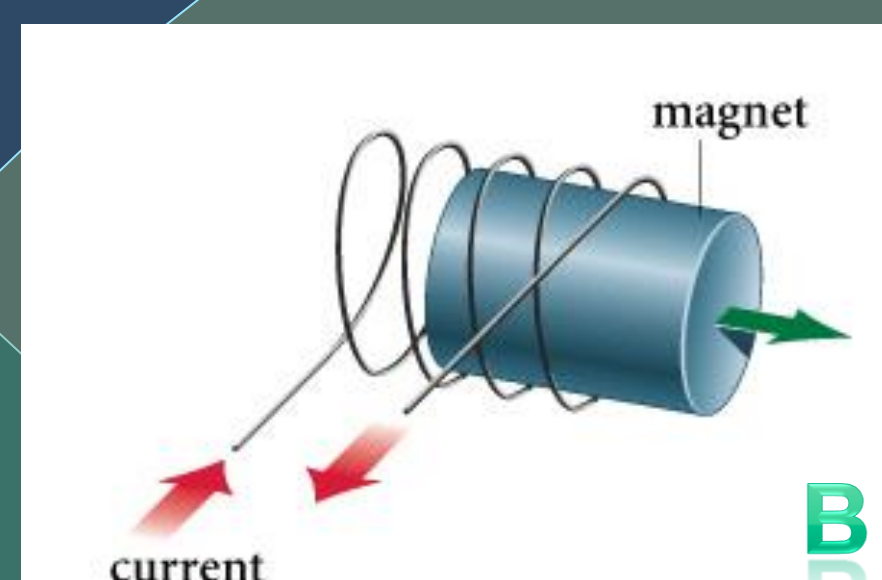
Most of the large bodies in the solar system have magnetic fields, the largest (after sunspots) being that of Jupiter (its aurora is shown in Fig. I). Though it is about the same size as Earth, Venus does not have a dynamo-generated field. Mars once did, but it has since died out.

Most stars have magnetic cycles, and many are more active magnetically than our sun. Although most stars are 'point sources' for even the most powerful telescopes, methods exist to obtain information about their rotation and about 'starspots' (akin to sunspots) on their surfaces. Stars are often idealized as non-rotating, non-magnetic bodies, but much interesting physics is being discovered as scientists devise new models to include these effects.

Accretion discs are disc-shaped volumes of gas in the process of accreting—that is, falling—onto a central object. They are found around stars in the process of formation as well as around compact objects (white dwarfs, neutron stars and black holes). As it accretes, the gas must radiate away energy and transfer angular momentum outward. The magneto-rotational instability (MRI), which requires the presence of a magnetic field, is probably the correct explanation for how these things happen. Some of the inflowing gas actually gets directed into powerful outflows along the spin axis of the central object. Magnetic fields play a key role in producing and shaping these 'jets'.

Neutron stars, composed mostly of neutrons, 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. A Chandra x-ray image of the Crab pulsar and its surroundings is shown in Fig. M. Another type of neutron star, called a magnetar, can have fields that are hundreds of times stronger still. Such a star probably owes its power output to the decay of its magnetic field.

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 about 1/1,00,000 times that of Earth. This field can roughly be divided into two constituents. One constituent is coherent on a scale of tens of thousands of light years, comparable to the size of the galaxy, while the other constituent is more randomly oriented. Magnetic fields in nearby galaxies can also be mapped using synchrotron emission, and display a variety of interesting features (e.g. the whirlpool galaxy M51, in Fig. N). On an even larger scale, magnetic fields can be found in the intracluster medium—that is, in the space between galaxies within a cluster of galaxies.

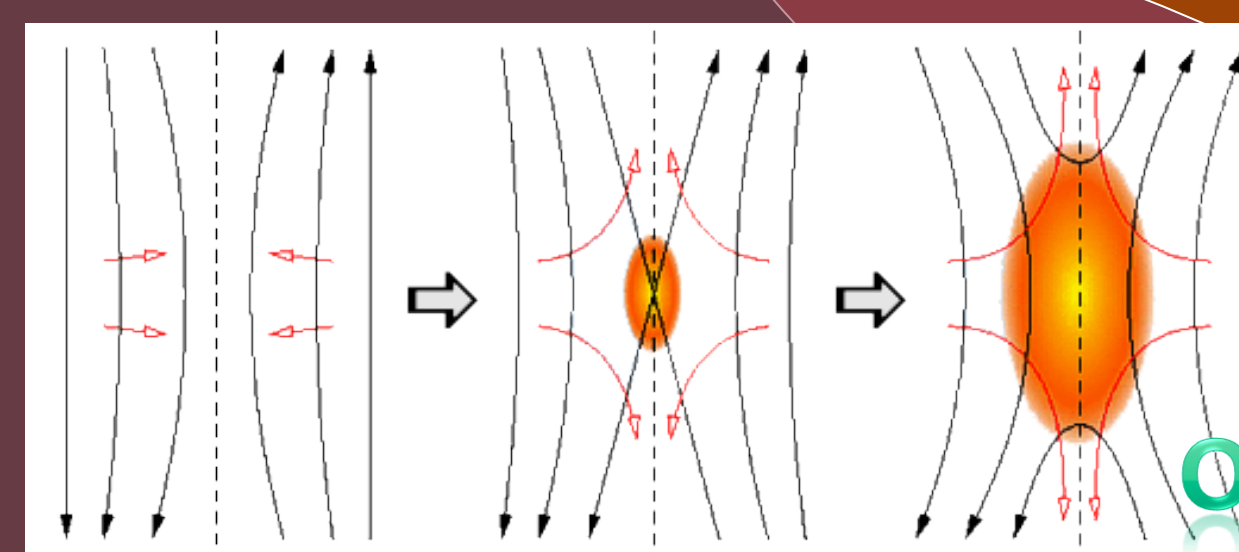
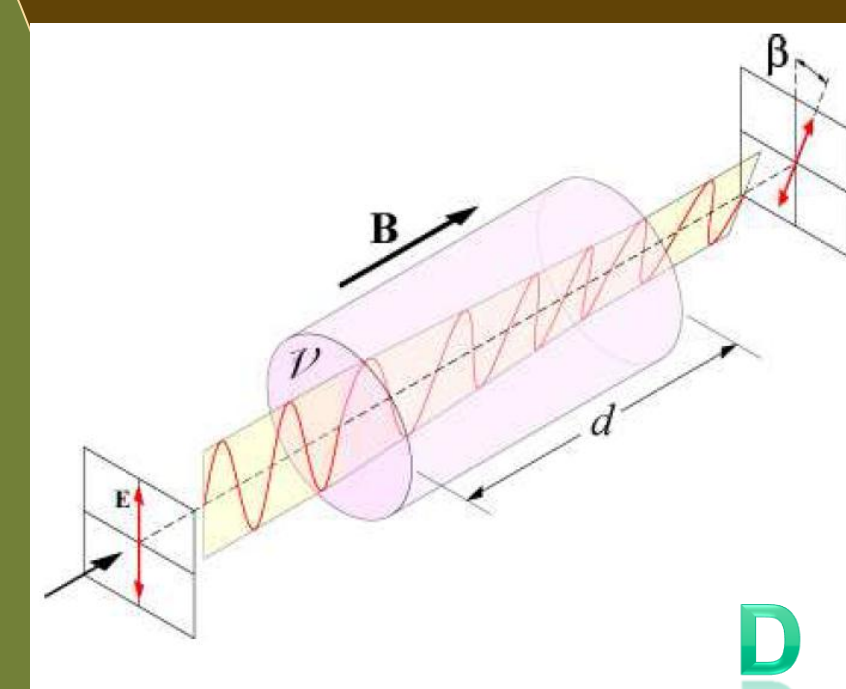


The oldest and most direct of these is to take advantage of a quantum phenomenon known as the Zeeman effect. Normally, the energies of the different electronic configurations of an atom do not depend on its orientation. However, the presence of a magnetic field introduces a preferred direction, with the result that certain energy levels are split into sublevels. Moreover, the energy difference between the levels 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. However, this occurs in addition to Doppler broadening, caused by relative motions of the atoms within the source. Since the Doppler broadening tends to be the larger of the two effects, measuring magnetic fields in this way requires very high sensitivity, and is usually possible only within our own galaxy.

DETECTION

Another way of detecting magnetic fields is by observing synchrotron radiation, which is the radio emission that is beamed by relativistic electrons (electrons moving close to the speed of light) following helical (spiral) paths about magnetic field lines (Fig. C). If the density of relativistic electrons can be estimated, then the strength of the component of the magnetic field in the plane of the sky, integrated from source to observer, can be obtained. The electric field of this radiation is oriented parallel to the instantaneous path of the emitting electrons, resulting in a fraction of the observed emission being 'polarized'. By measuring the orientation of this polarized component, we can map out the orientation of field lines in the plane of the sky. Thus, synchrotron can give us the field strength as well as orientation for the component of the field that is perpendicular to our line of sight.

To get the component of the magnetic field along our line of sight, the phenomenon of Faraday rotation can be utilized. The plane of polarization of polarized radio emission slowly rotates as the radiation makes its way through a magnetized medium (an example of birefringence—see Fig. D). The amount of rotation is proportional to the product of the electron density and line-of-sight component of the magnetic field, integrated from source to observer, and also to the square of the wavelength of emitted radiation. By measuring the polarization angle at various wavelengths, and given an estimate of the electron density, the line-of-sight component of the field can be determined. Moreover, the sense of rotation of the polarization plane tells us in which direction the field points along our line of sight.

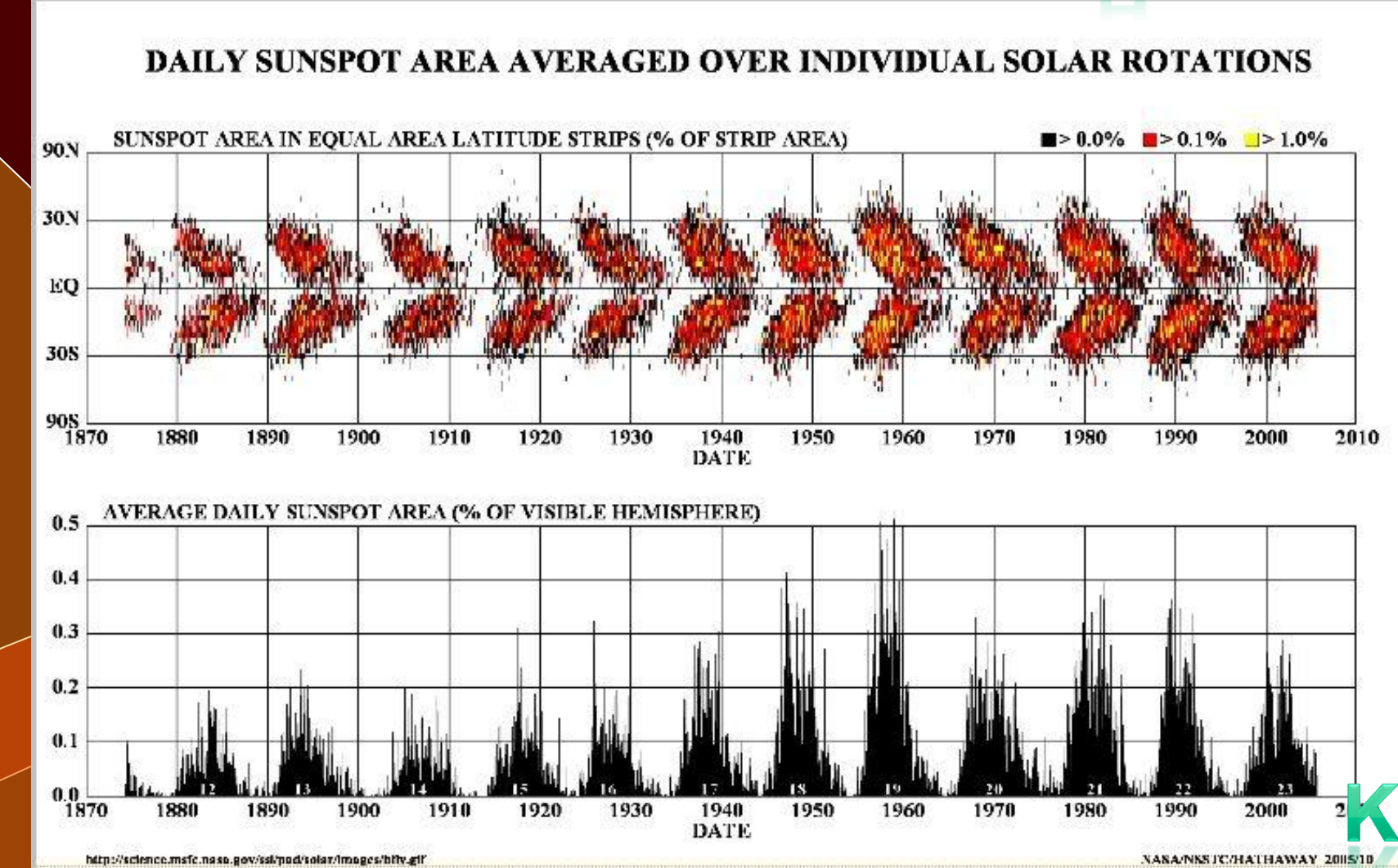
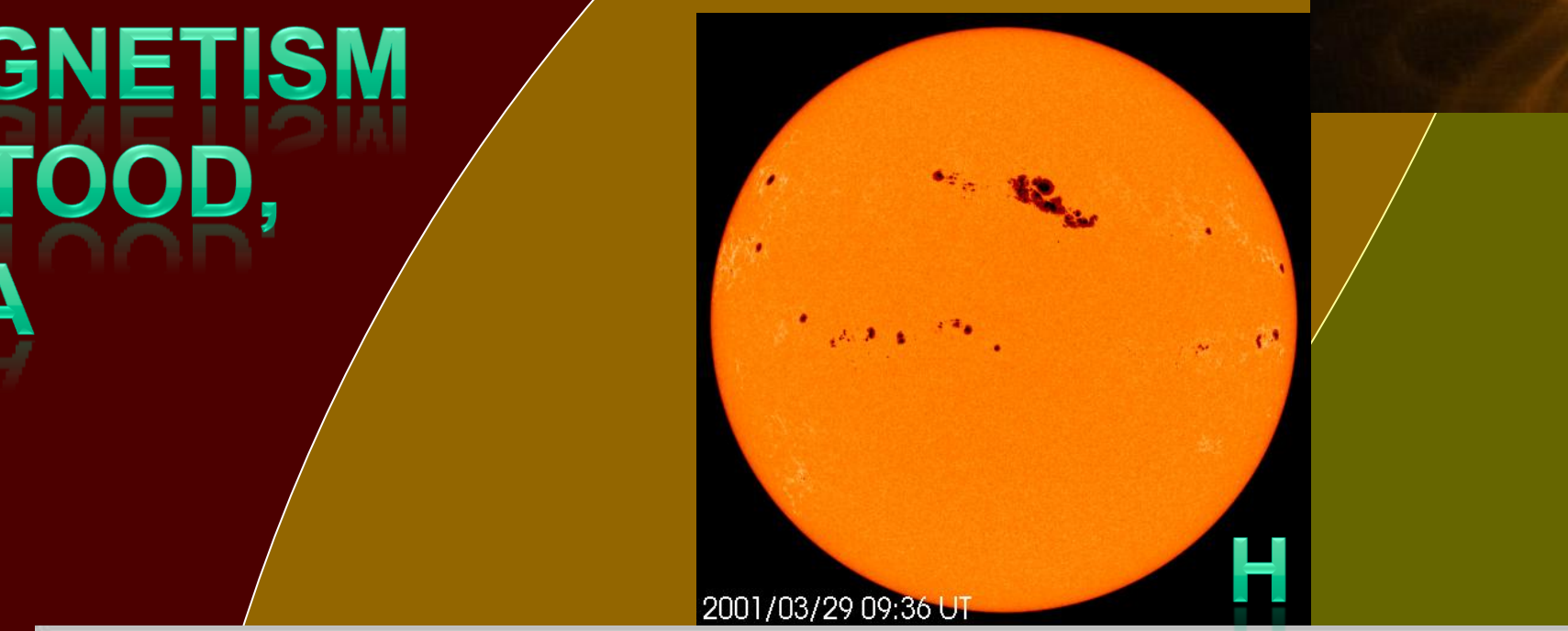


ASTROPHYSICS

Why magnetic fields and not electric fields? It turns out that in astrophysical phenomena, the electric field in the rest frame of the plasma is usually negligibly small. This is not really surprising since one would expect a large electric field to be quickly neutralized by the redistribution of charged particles. In any case, the electric field can be determined from knowledge of the magnetic field.

In the laboratory, without externally generated electrical currents to preserve it, a magnetic field inside a plasma decays away in a fraction of a second; as the magnetic pressure causes the field lines to spread apart, the field 'diffuses' out of the plasma. The reason magnetic fields are prevalent inside astrophysical plasmas is largely a matter of scale. The larger the plasma, the longer it takes for the field to diffuse out—in astrophysical objects, the decay time is so long that the field is essentially 'frozen in' the gas. Whichever way the plasma flows, the field lines move with it, always threading the same surface of fluid. This 'flux freezing' is often a reasonable approximation that helps to simplify the physics, and allows one to visualize the field lines as being confined to stretchable 'flux tubes'.

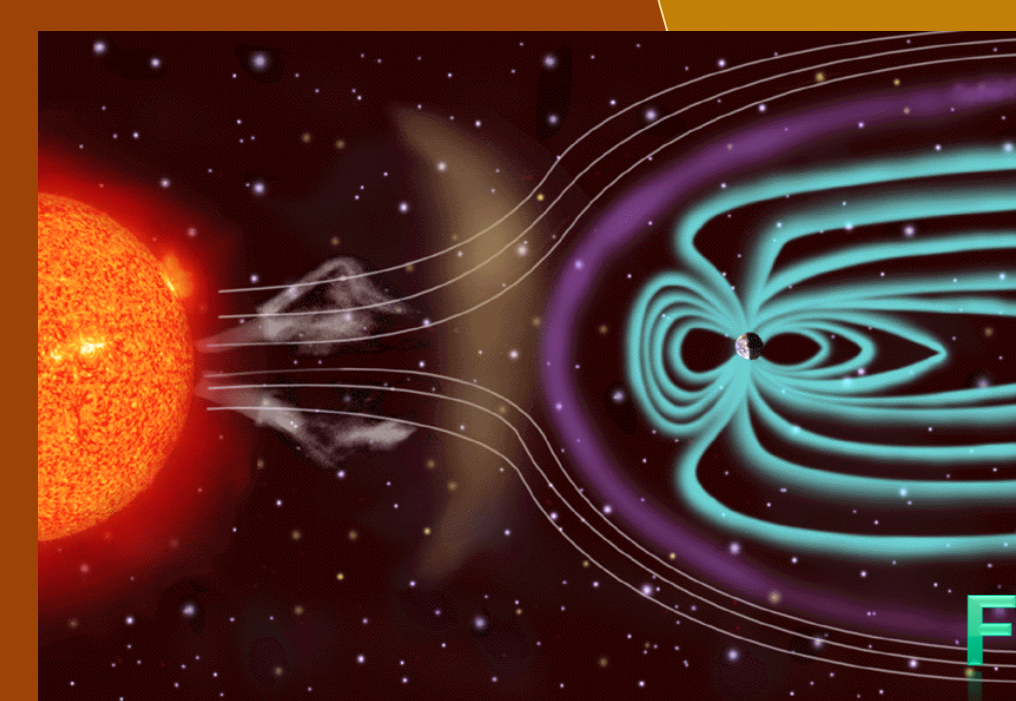
Magnetic 'reconnection' is a sudden reconfiguration of the field topology that occurs when field lines of opposite polarity come so close together that they merge (Fig. O). This leads to a conversion of magnetic energy into other forms of energy, such as kinetic energy in turbulence and in outflows. This is known to happen in the sun, for instance, where it helps to explain the emission of solar flares.



The sun has a dipole magnetic field. Sunspots (Fig. H & I) are regions on the surface of the sun that have a higher magnetic field than their surroundings (and over 1000 times stronger than that of Earth). They also have a lower temperature, which makes them visible as dark patches in a photograph. They come in pairs of opposite polarity. Astronomers have been recording information about sunspots for centuries—data that is useful even today! Sunspots are formed when buoyant magnetic flux tubes rise through the surface, creating coronal loops. At each 'footprint' where a coronal loop intersects the surface, one member of the sunspot pair is formed (Fig. J).

SUN

Certain properties of the sun, such as sunspot number, x-ray luminosity and flaring, are correlated with each other, and vary quite regularly with an 11 year period on average. During one such period, the concentration of sunspots migrates from higher latitudes toward the equator—this can be represented graphically by a 'butterfly diagram' (Fig. K). In fact, the magnetic field reverses itself after each half-cycle, so a full cycle lasts about 22 years.



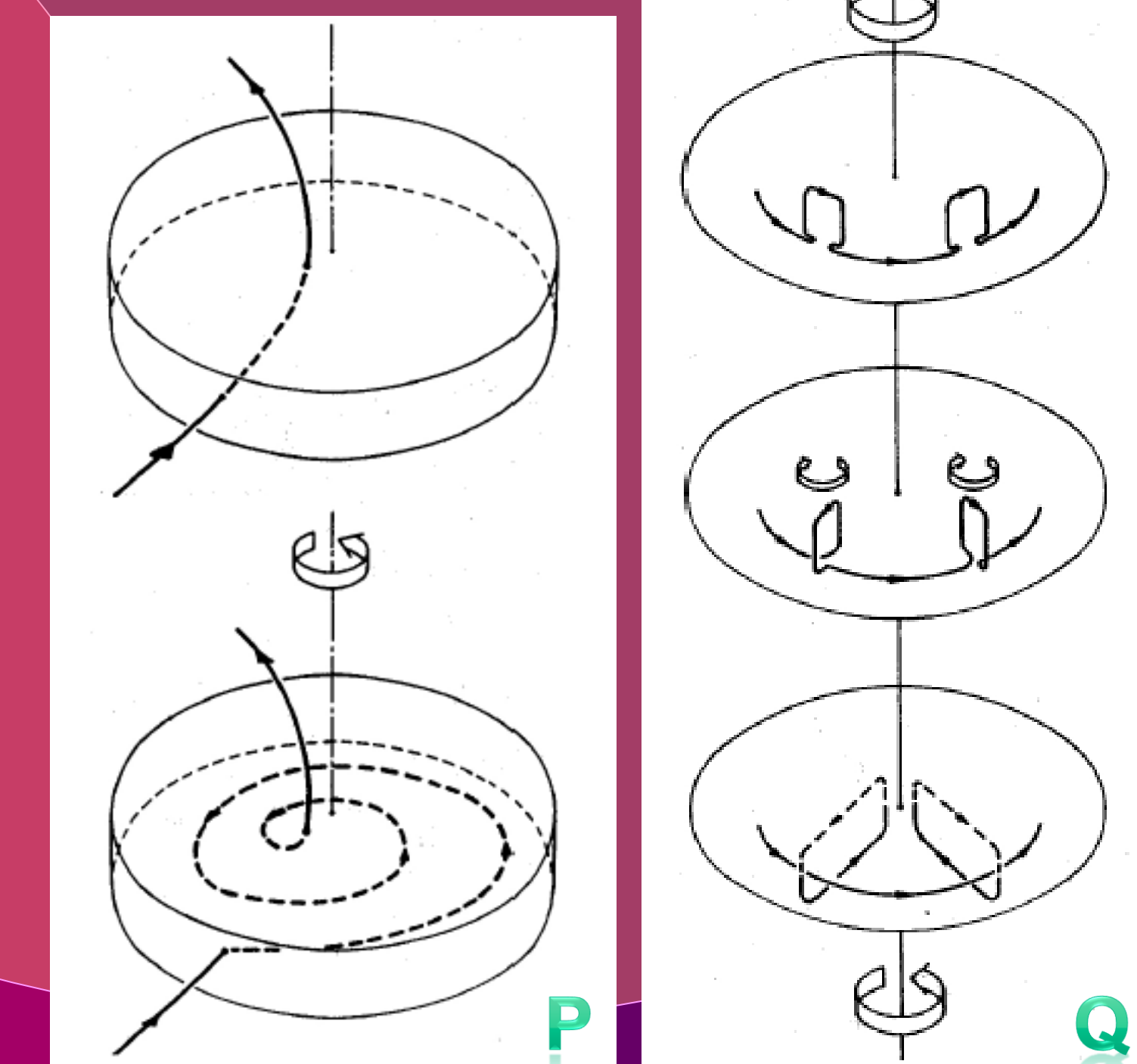
Not only is Earth's magnetic field useful for navigation but it protects us from the wind of charged particles streaming from the sun as well as from energetic charged particles known as cosmic rays.

Earth's field has a dipole geometry, like a bar magnet (Fig. E), though this gets distorted by the solar wind (see artist's impression in Fig. F). Some particles from the sun manage to follow the magnetic field lines down to the polar regions, where they can collide with atoms of nitrogen and oxygen in the upper atmosphere, leading to beautiful displays of light known as 'aurora' (Fig. G).

Earth's field is known to reverse itself—the poles more or less trade places—every 3,00,000 years on average, though the timing is actually quite erratic (the last reversal occurred some 7,80,000 years ago).



EARTH



DYNAMO

A dynamo is a device that converts kinetic energy into magnetic energy via the generation of electric currents. A bicycle light operated by pedalling makes use of the dynamo effect, and incorporates permanent magnets in its design. Permanent magnets are not necessary if the magnetic field produced by the dynamo is strong enough to sustain the dynamo action—astrophysical dynamos have this self-sustaining property. Another important distinction between technology-based and astrophysical dynamos is that in the latter, electric currents are not restricted to residing in conducting wires, but can flow freely within the plasma.

Left to itself, Earth's magnetic field would decay away in about 3,00,000 years. Since our planet's magnetic field is known to have existed for much longer than this, it must be continuously re-grown by some mechanism. This argument cannot be used for the solar or galactic magnetic fields, whose decay times are longer than the ages of the objects they occupy. However, many observations, such as the reversal of the sun's field every 11 years or the spiral structure of galactic magnetic fields, are best explained by dynamo models.

One example of a dynamo mechanism that is believed to operate in stars and galaxies is the α - Ω turbulent dynamo. This mechanism converts kinetic energy of turbulence and rotation into magnetic energy. In a spiral galaxy, such a dynamo may operate in the following way. 1) The rotation of the galaxy, with a rate that decreases with distance from the galaxy's centre, winds up the poloidal (longitudinal) component of the field, bringing the field lines closer together and so amplifying the toroidal (equatorial) component of the field (this is the Ω effect—Fig. P). 2) Consider a parcel of fluid as it moves toward or away from the galactic midplane due to turbulent motions. Because ambient pressure decreases away from the midplane, the parcel expands if it is moving away from, or contracts if it is moving toward, the midplane. 3) Since the galaxy is rotating, the Coriolis force causes the rising or falling fluid parcel to start spinning, so that fluid elements inside it trace out helical paths. Magnetic field lines frozen in the fluid get twisted, producing loops of poloidal field. 5) Turbulence acts to merge these loops together to produce a large-scale poloidal field. (Steps 2-5 comprise the α effect—Fig. Q) Step (1) can then operate again, completing the cycle. Successive repetitions of the cycle lead to exponential growth of the magnetic field.

Magnetic fields are very common in the universe, but having no magnetic field is also a perfectly good solution to the equations of physics. Dynamos can grow a field exponentially with time, but initially they require a small 'seed field' on which to operate. Astrophysicists have developed models to explain how these seed fields come to be.