Earth’s Magnetism

Objectives

After going through this lesson, the learners will be able to

- Conceptualize Earth’s magnetic field
- Express mathematically the magnitude of earth’s magnetic field
- Recognise elements of earth’s magnetic field
- Establish a relation between different elements of earth’s magnetic field
- Appreciate the importance of study of earth’s magnetic field

Content Outline

- Unit Syllabus
- Module wise distribution of unit syllabus
- Words you must know
- Introduction
- Earth’s magnetism
- Magnetic meridian
- Strength of earth’s magnetic field
- Magnetic declination
- Magnetic dip
- Horizontal component of earth’s magnetic field
- Some interesting facts
- Summary

Unit Syllabus

Unit –3: Magnetic Effects of Current and Magnetism

Chapter-4: Moving Charges and Magnetism

Concept of magnetic field, Oersted’s experiment

Biot - Savart law and its application to current carrying circular loop

Ampere’s law and its applications to infinitely long straight wire, Straight and toroidal solenoids, Force on a moving charge in uniform magnetic and electric fields, Cyclotron,

Force on a current-carrying conductor in a uniform magnetic field. Force between two parallel current-carrying conductors-definition of ampere. Torque experienced by a current loop in uniform magnetic field; moving coil galvanometer-its current sensitivity and conversion to ammeter and voltmeter.

Chapter-5: Magnetism and Matter

Current loop as a magnetic dipole and its magnetic dipole moment, Magnetic dipole moment of a revolving electron. Magnetic field intensity due to a magnetic dipole (bar magnet) along its axis and perpendicular to its axis. Torque on a magnetic dipole (bar magnet) in a uniform magnetic field; bar magnet as an equivalent solenoid, magnetic field lines; Earth's magnetic field and magnetic elements.

Para-, dia- and ferro- magnetic substances with examples. Electromagnets and factors affecting their strengths. Permanent magnets.

Module Wise Distribution of Unit Syllabus - 10 Modules

The above syllabus has been divided into 10 modules for better understanding

Module 1	● Introducing moving charges and magnetism ● Concept of Magnetic field and Oersted's Experiment ● Biot-Savart Law
Module 2	● Applications of Biot- Savart Law to current carrying circular loop, straight wire ● Current loop as a magnetic dipole and its magnetic moment ● Ampere's Law and its applications: straight wire, straight and toroidal solenoids.
Module 3	● Force on moving charges in uniform magnetic field and electric field.
Module 4	● Cyclotron
Module 5	● Force on a current carrying conductor in uniform magnetic field ● Force between two parallel current carrying conductors ● Definition of ampere
Module 6	● Torque experienced by a current loop in uniform magnetic field
Module 7	● Moving coil Galvanometer- its current sensitivity and conversion to ammeter and voltmeter

Module 8	• Magnetic field intensity due to a magnetic dipole (bar magnet) along its axis and perpendicular to its axis. • Torque on a magnetic dipole in a uniform magnetic field.
Module 9	• Dia, Para and ferro-magnetic substances with examples. Electromagnets and factors affecting their strengths, permanent magnets.
Module 10	• Earth's magnetic field and magnetic elements.

Module 10

Words You Must Know

- **Magnetic field:** The magnetic field at a point may be defined as the force acting on a unit charge moving with a unit velocity at right angle to the direction of the field.
- **S I unit of Magnetic field:** SI unit of magnetic field is tesla (T). The magnetic field is said to be one tesla if a charge of one coulomb moving with a speed of 1 m/s at right angles to the field experiences a force of one newton.
- **C G S unit of magnetic field:** CGS unit of magnetic field is gauss (G).
  $1T = 10^{-4}G$
- **Lorentz magnetic force:** The force acting on moving charge in a magnetic field is called Lorentz magnetic force. This force is maximum when the direction of motion of a charged particle is perpendicular to the direction of magnetic field.
- **Direction of force on current carrying conductor:** Direction of force acting on a current carrying conductor in magnetic field is given by the right hand thumb rule. The force is perpendicular to both the direction of magnetic field and the direction of current.
- **Maximum Force**: The force acting on the current carrying conductor in a magnetic field is maximum when the conductor is placed perpendicular to the direction of magnetic field.
- **Torque:** It is defined as the moment of force. It is given by cross product of distance of force from axis of rotation and the force.
- **Magnetic Moment:** M = NIA.
- **Torque on coil:** The torque acting on the coil in the magnetic field is maximum when the plane of coil is parallel to the magnetic field. The coil does not experience torque when the plane of the coil becomes perpendicular to the magnetic field.

- **Relative permeability:** The ratio of permeability of the medium to the permeability of free space is called relative permeability. It has no unit.
- **Intensity of magnetization:** When a substance is placed in a magnetic field the net magnetic moment developed per unit volume is defined as the intensity of magnetisation (M).

  $M = m_{net} / V$, M is a vector quantity with dimensions $[L^{-1} A]$ and is measured in a unit of $A\ m^{-1}$.
- **Magnetising field:** The magnetic field that exists in vacuum and induces magnetization is called magnetizing field. Consider a long solenoid of n turns per unit length and carrying a current I. The magnetic field induced inside the solenoid is given by $B_0 = \mu_0 nI$. This field is called a magnetizing field.
- **Magnetizing field intensity:** The ability of a magnetizing field to magnetize a material is expressed by 'H' called Magnetizing field intensity. Its magnitude is defined as the number of ampere turns flowing round per unit length of the solenoid required to produce the given magnetizing field. Thus,

  $B_0 = \mu_0 nI = \mu_0 H$

  So, $H = nI$

  Dimension of H is $[L^{-1} A]$ and is measured in units of $A\ m^{-1}$.
- **Magnetic susceptibility:** It measures the ability of a substance to get magnetized when placed in a magnetic field. It is defined as the ratio of the intensity of magnetization 'M' to the magnetizing field intensity 'H'. It is represented by the symbol χ_m.

  $\chi_m = M/H$

  It has no unit.
- **Relation between relative permeability and magnetic susceptibility;**

  If the interior of the solenoid is filled with a material with non-zero magnetisation, the field inside the solenoid will be greater than B_0. The net magnetic field in the interior of the solenoid may be expressed as

  $B = B_0 + B_m$

  (where, B_m is the field contributed by the material core)

  $B_m \propto M$

  $B_m = \mu_0 M$ (where μ0 is the permeability of vacuum)

  Thus, the total magnetic field B is written as:

$B = \mu_0 (H + M)$

And $B = \mu H$

Therefore $\mu H = \mu_0 (H + M)$

$\mu = \mu_0 (1 + M/H)$

$\mu_r = (1 + \chi_m)$

- **Magnet:** Is a material or object that attracts iron pieces.
- **Magnetic field:** The three dimensional space where the magnetic effect of a magnet is experienced.
- **Magnetic field lines:** The pattern of iron filings permits us to plot the magnetic field lines.
- **Magnetic flux density:** The magnetic flux density (also called magnetic B field or just magnetic field, usually denoted B) is a vector field. The magnetic B field vector at a given point in space is specified by two properties: Its *direction*, which is along the orientation of a compass needle. Its *magnitude* (also called *strength*), which is proportional to how strongly the compass needle orients along that direction.

  In SI units, the strength of the magnetic B field is given in tesla.
- **Compass needle:** It functions as a pointer to "magnetic north", It comprises of a magnetic needle is mounted on a low-friction pivot point, when the compass is held level, the needle turns until, after a few seconds to allow oscillations to die out, it settles into its equilibrium orientation.

Introduction

Magnetic phenomena are universal in nature. Vast, distant galaxies, the tiny invisible atoms, men and beasts all are permeated through and through with a host of magnetic fields from a variety of sources. The earth's magnetism predates human evolution. The word magnet is derived from the name of an island in Greece called Magnesia where magnetic ore deposits were found, as early as 600 BC. Shepherds on this island complained that their wooden shoes (which had nails) at times stayed struck to the ground. Their iron-tipped rods were similarly affected. This attractive property of magnets made it difficult for them to move around. The directional property of magnets was also known since ancient times. A thin long piece of a magnet, when suspended freely, pointed in the north-south direction. A similar effect was observed when it was placed on a piece of cork which was then allowed to float in still water. The name lodestone (or loadstone) given to a naturally occurring ore of iron magnetite means leading stone. The technological exploitation of this property is generally credited to the Chinese.

Chinese texts dating 400 BC mention the use of magnetic needles for navigation on ships. Caravans crossing the Gobi desert also employed magnetic needles. A Chinese legend narrates the tale of the victory of the emperor Huang-ti about four thousand years ago, which he owed to his craftsmen. These craftsmen ‘engineers’ built a chariot on which they placed a magnetic figure with arms outstretched. The figure swiveled around so that the finger of the statuette on it always pointed south. With this chariot, Huang-ti’s troops were able to attack the enemy from the rear even in thick fog, and to defeat them.

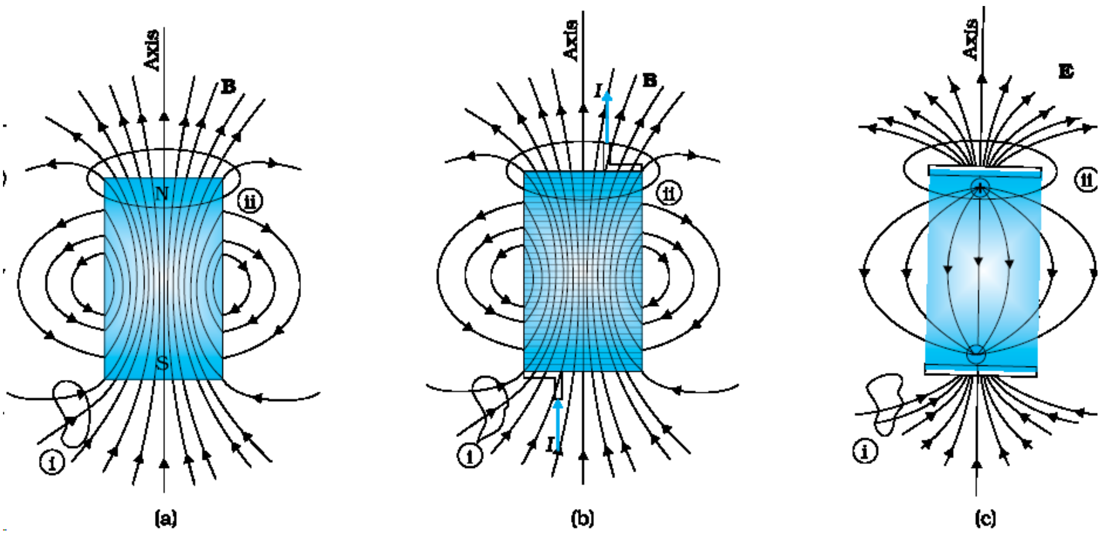
We have learnt that moving charges or electric currents produce magnetic fields. This discovery, which was made in the early part of the nineteenth century, is credited to Oersted’s, Ampere, Biot and Savart, among others.

Some of the commonly known ideas regarding magnetism are:

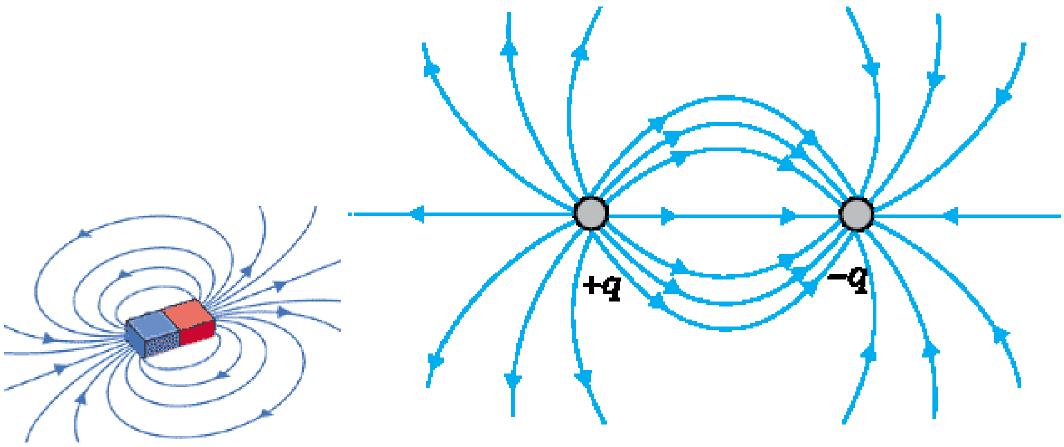
- The earth behaves as a magnet with the magnetic field pointing approximately from the geographic south to the north.
- When a bar magnet is freely suspended, it points in the north-south direction. The tip which points to the geographic north is called the North Pole and the tip which points to the geographic south is called the south pole of the magnet.
- There is a repulsive force when north poles (or south poles) of two magnets are brought close together. Conversely, there is an attractive force between the north pole of one magnet and the south pole of the other.
- We cannot isolate the north, or South Pole of a magnet. If a bar magnet is broken into two halves, we get two similar bar magnets with somewhat weaker properties. Unlike electric charges, isolated magnetic north and south poles known as magnetic monopoles do not exist.
- It is possible to make magnets out of iron and its alloys.

The magnetic Field Lines

The pattern of iron filings permits us to get a picture of the magnetic field lines. This is shown both for the bar-magnet and the current-carrying solenoid in figure.



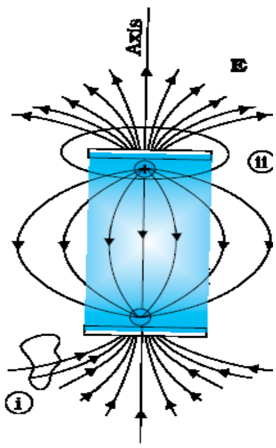
For comparison refer to Electric field lines of an electric dipole are also displayed in figure.



The magnetic field lines provide a visual and intuitive realisation of the magnetic field.

Properties of Magnetic Field Lines:

- The magnetic field lines of a magnet (or a solenoid) form continuous closed loops. This is unlike the electric dipole where these field lines begin from a positive charge and end on the negative charge or escape to infinity.
- The tangent to the field line at a given point represents the direction of the net field at that point.
- The larger the number of field lines crossing per unit area, the stronger is the magnitude of the magnetic field B. In B is larger around region (ii) than in region (i).



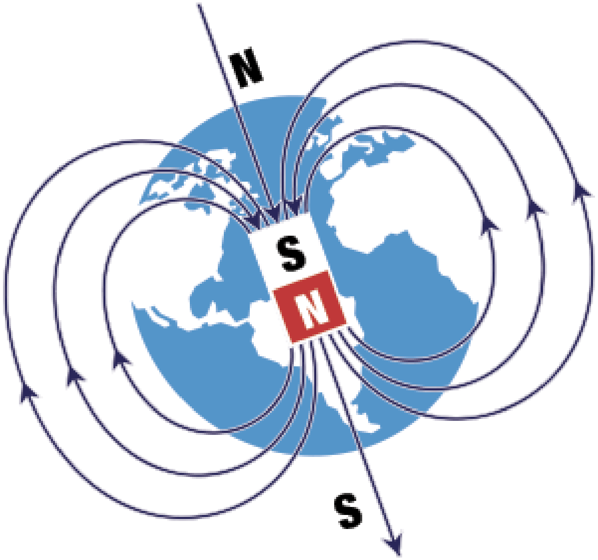
- The magnetic field lines do not intersect, for if they did, the direction of the magnetic field would not be unique at the point of intersection.
- The field lines can be plotted using a compass needle.

The Earth's Magnetism

We have referred to the magnetic field of the earth. The strength of the earth's magnetic field varies from place to place on the earth's surface. Its value is of the order of 10^{-5} T.

Cause of Earth's Magnetic Field

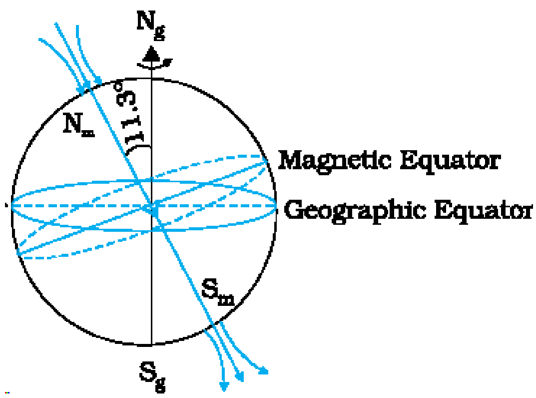
What causes the earth to have a magnetic field is not clear. Originally the magnetic field was thought of as arising from a giant bar magnet placed approximately along the axis of rotation of the earth and deep in the interior. However, this simplistic picture is certainly not correct.



The magnetic field is now thought to arise due to electrical currents produced by convective motion of metallic fluids (consisting mostly of molten iron and nickel) in the outer core of the earth. This is known as the dynamo effect.

The magnetic field lines of the earth resemble that of a (hypothetical) magnetic dipole located at the centre of the earth.

The axis of the dipole does not coincide with the axis of rotation of the earth but is presently titled by approximately 11.3º with respect to the later.



Magnetic Meridian

In this way of looking at it, the magnetic poles are located where the magnetic field lines due to the dipole enter or leave the earth. The location of the north magnetic pole is at latitude of 79.74º N and a longitude of 71.8º W, a place somewhere in north Canada. The magnetic south pole is at 79.74º S, 108.22º E in Antarctica. The pole near the geographic north pole of the earth is called the south magnetic pole. Likewise, the pole near the geographic South Pole is called the north magnetic pole

There is some confusion in the nomenclature of the poles. If one looks at the magnetic field lines of the earth, one sees that unlike in the case of a bar magnet, the field lines go into the earth at the north pole (Nm) and come out from the south pole (Sm). The convention arose because the magnetic north was the direction to which the north pole of a magnetic needle pointed; the north pole of a magnet was so named as it was the north seeking pole. Thus, in reality, the north magnetic pole behaves like the south pole of a bar magnet inside the earth and vice versa. The plane passing through a freely suspended magnetic needle pivoted to move in the horizontal plane about a vertical axis.

Strength of Earth's Magnetic Field

How strong is Earth's magnet?

Let us consider the earth's magnetic field at the equator is approximately 0.4 G. Estimate the earth's dipole moment.

Solution

The equatorial magnetic field is:

$$B_E = -\frac{\mu_0 m}{4\pi r^3}$$

We are given that $B_E \sim 0.4$ G $= 4 \times 10^{-5}$ T.

For r, we take the radius of the earth 6.4×10^6 m.

Hence,

$= 4 \times 10^2 \times (6.4 \times 10^6)^3$ $(\mu_0/4\pi = 10^{-7})$

$= 1.05 \times 10^{23}$ A m^2

This is close to the value 8×10^{22}A m^2 quoted in geomagnetic texts.

The equatorial magnetic field is, 0 3 4 E m B r μ = π

We are given that BE ~ 0.4 G = 4 × 10^{-5} T.

For r, we take the radius of the earth 6.4×10^6 m.

Hence,

$$m = \frac{4\times10^{-5}\times\left(6.4\times10^{6}\right)^{3}}{\frac{\mu_0}{4\pi}}$$

$= 4 \times 10^2 \times (0.4 \times 10^6)^3$ $(\mu_0/4\pi = 10^{-7})$

$= 1.05\times10^{23}$ A m^2

This is close to the value 8×10^{22} Am^2 quoted in geomagnetic texts.

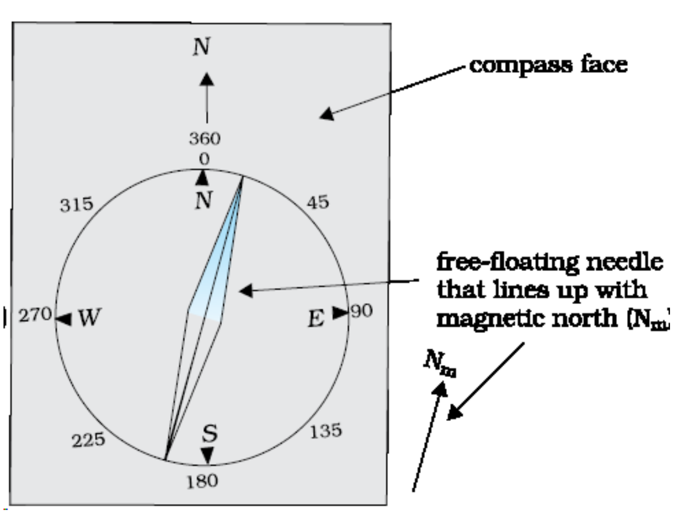
Magnetic Declination

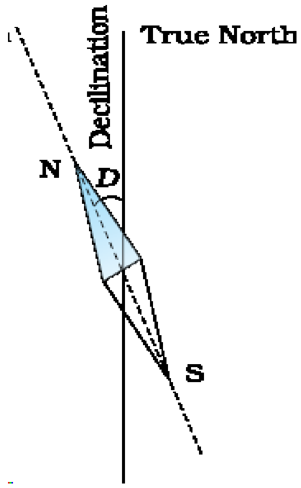
Consider a point on the earth's surface. At such a point, the direction of the longitude circle determines the geographic north-south direction, the line of longitude towards the North Pole being the direction of true north. The vertical plane containing the longitude circle and the axis of rotation of the earth is called the geographic meridian.

In a similar way, one can define the magnetic meridian of a place as the vertical plane which passes through the imaginary line joining the magnetic north and the south poles. This plane would intersect the surface of the earth in a longitude-like circle.

A magnetic needle, which is free to swing horizontally, would then lie in the magnetic meridian and the north pole of the needle would point towards the North Pole. Since the line joining the magnetic poles is titled with respect to the geographic axis of the earth,

The magnetic meridian at a point makes an angle with the geographic meridian.



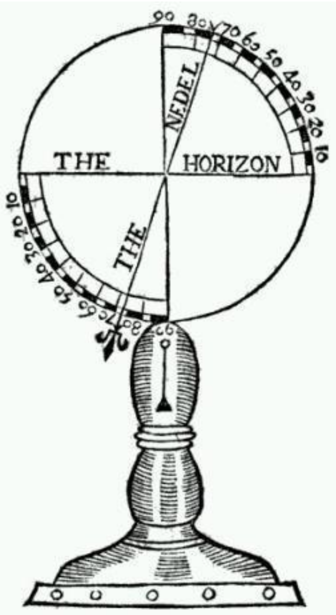


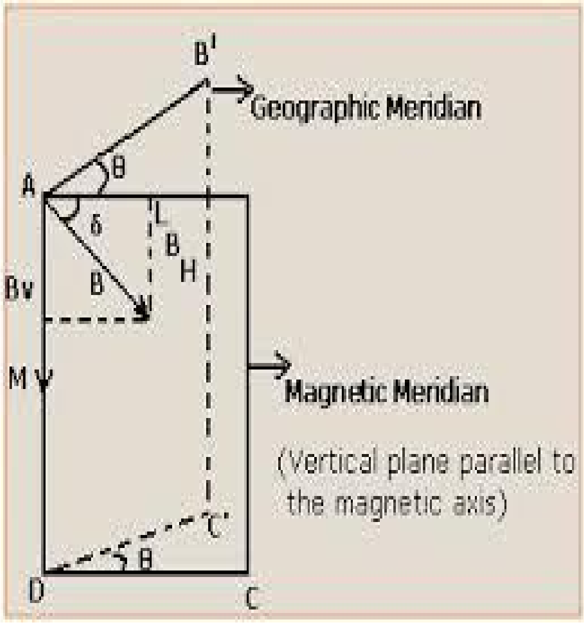
This, then, is **the angle between the true geographic north and the north shown by a compass needle**. This angle is called **the magnetic declination or simply declination**.

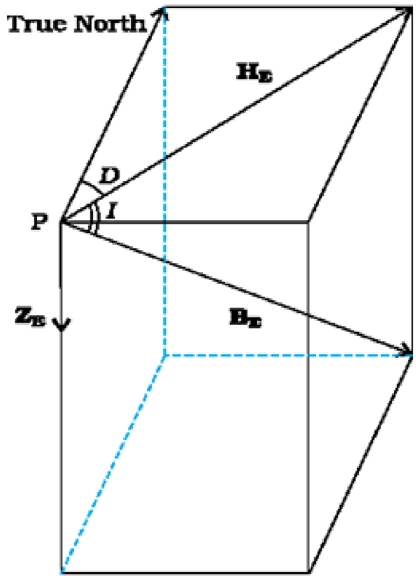
The declination is **greater at higher latitudes** and **smaller near the equator**. The declination in India is small, it being 0º41′ E at Delhi and 0º58′ W at Mumbai.

Angle of Dip

There is one more quantity of interest. If a magnetic needle is perfectly balanced about a horizontal axis so that it can swing in a plane of the magnetic meridian, the needle would make an angle with the horizontal.







This is known as the angle of dip (also known as inclination).

Thus, dip is the angle that the total magnetic field BE of the earth makes with the surface of the earth.

Horizontal Component of Earth's Magnetic field

Figure shows the magnetic meridian plane at a point P on the surface of the earth. The plane is a section through the earth. The total magnetic field at P can be resolved into a horizontal component H_E and a vertical component Z_E.

The angle that B_E makes with H_E is the angle of dip

In most of the northern hemisphere, the north pole of the dip needle tilts downwards. Likewise in most of the southern hemisphere, the south pole of the dip needle tilts downwards.

To describe the magnetic field of the earth at a point on its surface

We need to specify three quantities, viz.

- The declination D.
- The angle of dip or the inclination I.
- The horizontal component of the earth's field HE.

These are known as the elements of the earth's magnetic field.

What happens to compass needles at the poles?

A compass needle consists of a magnetic needle which floats on a pivotal point. When the compass is held level, it points along the direction of the horizontal component of the earth's magnetic field at the location. Thus, the compass needle would stay along the magnetic meridian of the place. In some places on the earth there are deposits of magnetic minerals which cause the compass needle to deviate from the magnetic meridian. Knowing the magnetic declination at a place allows us to correct the compass to determine the direction of true north.

So what happens if we take our compass to the magnetic pole?

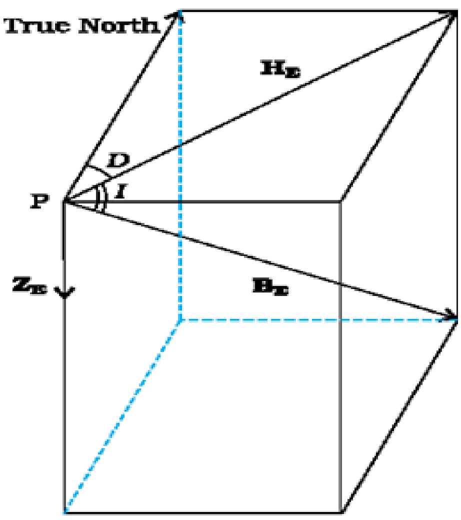
At the poles, the magnetic field lines are converging or diverging vertically so that the horizontal component is negligible. If the needle is only capable of moving in a horizontal plane, it can point along any direction, rendering it useless as a direction finder.

But what if we have a dip needle which is a compass pivoted to move in a vertical plane containing the magnetic field of the earth.

The needle of the compass then shows the angle which the magnetic field makes with the vertical. At the magnetic poles such a needle will point straight down. Angle of the dip will be 90^0.

Example

In the magnetic meridian of a certain place, the horizontal component of the earth's magnetic field is 0.26 G and the dip angle is 60º. What is the magnetic field of the earth at this location?



Solution

It is given that H_E = 0.26 G from the figure.

We have……

$$cos60^0 = \frac{H_E}{B_E}$$

$$B_E = \frac{H_E}{cos60^0}$$

$$= \frac{0.26}{(1/2)} = 0.52\ G$$

Some Interesting Facts - Earth's Magnetic Field

- **A Point of View Wikipedia**

It must not be assumed that there is a giant bar magnet deep inside the earth which is causing the earth's magnetic field. Although there are large deposits of iron inside the earth, it is highly unlikely that a large solid block of iron stretches from the magnetic north pole to the magnetic South Pole. The earth's core is very hot and molten, and the ions of iron and nickel are responsible for earth's magnetism. This hypothesis seems very probable. The Moon, which has no molten core, has no magnetic field; Venus has a slower rate of rotation, and a weaker magnetic field, while Jupiter, which has the fastest rotation rate among planets, has a fairly strong magnetic field. However, the precise mode of these circulating currents and the energy needed to sustain them are not very well understood. These are several open questions which form an important area of continuing research.

The variation of the earth's magnetic field with position is also an interesting area of study. Charged particles emitted by the sun flow towards the earth and beyond, in a stream called the solar wind. Their motion is affected by the earth's magnetic field, and in turn, they affect the pattern of the earth's magnetic field.

The pattern of magnetic field near the poles is quite different from that in other regions of the earth. The variation of earth's magnetic field with time is no less fascinating. There are short term variations taking place over centuries and long term variations taking place over a period of a million years. In a span of 240 years from 1580 to 1820 AD, over which records are available, the magnetic declination at London has been found to change by 3.5°, suggesting that the magnetic poles inside the earth change position with time.

On the scale of a million years, the earth's magnetic field has been found to reverse its direction. Basalt contains iron, and basalt is emitted during volcanic activity. The little iron magnets inside it align themselves parallel to the magnetic field at that place as the basalt cools and solidifies. Geological studies of basalt containing such pieces of magnetized region have provided evidence for the change of direction of earth's magnetic field, several times in the past.

- **Mapping India's Magnetic Field**

Because of its practical application in prospecting, communication, and navigation, the magnetic field of the earth is mapped by most nations with accuracy comparable to geographical mapping. In India over a dozen observatories exist, extending from Trivandrum (now Thiruvananthapuram) in the south to Gulmarg in the north.

These observatories work under the aegis of the Indian Institute of Geomagnetism (IIG), in Colaba, Mumbai. The IIG grew out of the Colaba and Alibag observatories and was formally established in 1971. The IIG monitors (via its nation-wide observatories), the geomagnetic fields and fluctuations on land, and under the ocean and in space. Its services are used by the Oil and Natural Gas Corporation Ltd. (ONGC), the National Institute of Oceanography (NIO) and the Indian Space Research Organization (ISRO). It is a part of the world-wide network which ceaselessly updates the geomagnetic data. Now India has a permanent station called Gangotri.

- **Animals and Earth's Magnetic Field**

Magneto reception (also Magnetoception) is a sense which allows an organism to detect a magnetic field to perceive direction, altitude or location.

This sensory modality is used by a range of animals for orientation and navigation,[1] and as a method for animals to develop regional maps. For the purpose of navigation, magneto reception deals with the detection of the Earth's magnetic field.

Magneto reception is present in bacteria, arthropods, molluscs and members of all major taxonomic groups of vertebrates.

Humans are not thought to have a magnetic sense, but there is a chemical (a cryptochrome) in the eye which could serve this function.

Magneto Tactic Bacteria

An unequivocal demonstration of the use of magnetic fields for orientation within an organism has been in a class of bacteria known as magneto tactic bacteria. These bacteria demonstrate a behavioural phenomenon known as magneto taxis, in which the bacterium orients itself and migrates in the direction along the Earth's magnetic field lines. The bacteria contain magnetosomes, which are nanometer-sized particles of magnetite or iron sulphide enclosed within the bacterial cells. They act as a magnetic dipole, giving the bacteria their permanent-magnet characteristics.

Sharks, Stingray's Fish

Another less general type of magnetic sensing mechanism in animals that has been thoroughly described is the inductive sensing methods used by sharks, stingrays. These species possess a unique electro receptive organ. Which can detect a slight variation in electric potential? These organs are made up of mucus-filled canals that connect from the skin's pores to small sacs within the animal's flesh that are also filled with mucus. They are capable of detecting DC currents and have been proposed to be used in the sensing of the weak electric fields of prey and predators.

These organs could also possibly sense magnetic fields, by means of Faraday's law: as a conductor moves through a magnetic field an electric potential is generated. In this case the conductor is the animal moving through a magnetic field, and the potential induced depends on the time varying rate of flux through the conductor.

Worms appear to use the magnetic field to orient during vertical soil migrations that change in sign depending on their satiation state (with hungry worms burrowing down and satiated worms burrowing up. Fruit flies respond to magnetic fields.

Magneto reception is well documented in honey bees, ants and termites. In ants and bees, this is used to orient and navigate in areas around their nests and within their migratory paths.

For example, through the use of magneto reception, the Brazilian stingless bee is able to distinguish differences in altitude, location, and directionality using the thousands of hair-like particles on its antenna.

Pigeons

Pigeons can use magnetic fields as part of their complex navigation system.

Domestic Hens

They have iron mineral deposits in the dendrites in the upper beak and are capable of magneto reception, because hens use directional information from the magnetic field of the earth to orient in relatively small areas, the ability of hens to orient in or to move in and out of buildings.

Mammals

Several mammals, including the big brown bat can use magnetic fields for orientation. Work with mice, mole-rats and bats has shown that some mammals are capable of magneto reception. This indicates that when wood mice are displaced, they use magnetic fields to orient themselves if there are no other cues available.

Red foxes may use magnetoreception when predating small rodents. When foxes perform their high-jumps onto small prey like mice and voles, they tend to jump in a north-eastern compass direction. In addition, successful attacks are "tightly clustered" to the north.

One study has found that when domestic dogs are off the leash and the Earth's magnetic field is calm, they prefer to urinate and defecate with their bodies aligned on a north-south axis.

There is also evidence for magneto reception in large mammals. Resting and grazing cattle as well as roe deer and red deer tend to align their body axes in the geomagnetic north-south direction. Because wind, sunshine, and slope could be excluded as common ubiquitous factors in this study, alignment toward the vector of the magnetic field provided the most likely explanation for the observed behaviour.

Humans "are not believed to have a magnetic sense", but humans do have a crypto chrome in the retina which has a light-dependent magnetosensitivity.

Summary

We have learnt:

- A freely suspended Small magnetic needle aligns in a particular direction.
- The above gives evidence that earth behaves like a magnetic dipole.
- The magnetic flux lines resemble that due to an electric dipole.
- The pole near the geographic north is called the north pole of the magnetic needle.
- This should be the south pole of the earth's magnet.
- The magnitude of the field on the earth's surface $\approx 4 \times 10^{-5}$ T.
- Three quantities are needed to specify the magnetic field of the earth on
    - the horizontal component
    - the magnetic declination
    - the magnetic dip
- These are known as the elements of the earth's magnetic field
- Many species are sensitive to earth's magnetism.