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Geomagnetic Field: Marvolous Environmental Entity

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Abstract

On the Earth's surface, a small, freely turning magnetic needle (e.g., a compass needle) aligns itself roughly with the north-south direction. Earth’s magnetic field is existing for at least 3.45 billion years. It is working as a shield around earth and protecting from the direct impact of solar radiation. The Earth’s magnetic field is created by the rotation of the Earth and Earth's core. It shields the Earth against harmful particles in space. The field is unstable and has changed often in the history of the Earth. As the Earth spins the two parts of the core move at different speeds and this is thought to generate the magnetic field around the Earth as though it had a large bar magnet inside it. The magnetic field creates magnetic poles that are near the geographical poles. A compass uses the geomagnetic field to find directions. Many migratory animals also use the field when they travel long distances each spring and fall. The magnetic poles will trade places during a magnetic reversal. Earth’s magnetic field is also termed as geomagnetic field. This geomagnetic field is extending from the interior of the earth to outside in the space. The range of magnitude of geomagnetic field on the surface of earth is about 25 to 65 microteslas or 0.25 to 0.65 Guass. In the space, geomagnetic field is meeting with the solar wind. The solar wind is nothing but, a stream of charged particles emanating from the Sun. Most of the solar winds are deflected as a result of geomagnetic field. If earth were without magnetic field, the stream of charged particles in the form of solar wind strip away the Ozone layer. Credit of presence of atmosphere suitable for life goes to the geomagnetic field. The universal definition of the geaomagnetic field is based exclusively on a mathematical model. If a line is drawn through the center of the Earth, parallel to the moment of the best-fitting magnetic dipole, the two positions where it intersects the Earth's surface are called the North and South geomagnetic poles. If the Earth's magnetic field were perfectly dipolar, the geomagnetic poles and magnetic dip poles would coincide and compasses would point towards them. However, the Earth's field has a significant non-dipolar contribution, so the poles do not coincide and compasses do not generally point at either. The geomagnetic field, provides animals with different sorts of information, which can be used for different purposes in navigation, as compasses and as maps. Sea turtles, salmon, and a few other animals use these magnetic cues to navigate during long-distance migrations. In the case of sea turtles, magnetic map information can be used either to guide a turtle toward a particular area or to help it assess its approximate location along a transoceanic migratory route.

Keywords: Magnetosphere; Magnetopause; Cosmic Rays; Heliosphere; Magnetoreception

INTRODUCTION

The magnetic field of the earth exert influence on holding appreciable atmosphere. Life on earth is only due to the atmosphere. The Earth's magnetic field serves to deflect most of the solar wind, whose charged particles would otherwise strip away the ozone layer that protects the Earth from harmful ultraviolet radiation (Shlermeler Quirin, 2005*)*. One stripping mechanism is for gas to be caught in bubbles of magnetic field, which are ripped off by solar winds. Calculations of the loss of carbon dioxide from the atmosphere of Mars, resulting from scavenging of ions by the solar wind, indicate that the dissipation of the magnetic field of Mars caused a near total loss of its atmosphere (Luhmann Johnson & Zhang, 1992). The study of past magnetic field of the Earth is known as paleomagnetism (McElhinny Michael and McFadden Phillip, 2000). The polarity of the Earth's magnetic field is recorded in igneous rocks, and reversals of the field are thus detectable as "stripes" centered on mid-ocean ridges where the sea floor is spreading, while the stability of the geomagnetic poles between reversals has allowed paleomagnetists to track the past motion of continents. Reversals also provide the basis for magnetostratigraphy, a way of dating rocks and sediments (Opdyke Neil and Channell James,1996). The field also magnetizes the crust, and magnetic anomalies can be used to search for deposits of metal ores (Mussett and Khan Aftab, 2000). Finlay*, et al* (2010) reported the magnitude of geomagnetic field on the surface of earth that is ranging from twenty five to sixty five microteslas (0.25 to 0.65 Gauss). Approximately, it is the field of a magnetic dipole currently tilted at an angle of about 11 degrees with respect to Earth's rotational axis, as if there were a bar magnet placed at that angle at the center of the Earth. The North geomagnetic pole, located near Greenland in the northern hemisphere, is actually the south pole of the Earth's magnetic field, and the South geomagnetic pole is the north pole. The magnetic field is generated by electric currents due to the motion of convection currents of molten iron in the Earth's outer core driven by heat escaping from the core, a natural process called a geodynamo. The North and South magnetic poles are usually located near the geographic poles. The North and South magnetic poles are able to move / spread / wander widely over geological time scales, but sufficiently slowly for ordinary compasses to remain useful for navigation. However, at irregular intervals averaging several hundred thousand years, the Earth's magnetic field reverses and the North and South Magnetic Poles relatively abruptly switch places. These reversals of the geomagnetic poles leave a record in rocks that are of value to paleomagnetists in calculating geomagnetic fields in the past. This type of document is going to serve a lot for the study of plate tectonics through motions of floors of ocean and continents. According to Finlay, et al (2010), magnetosphere is the region above the ionosphere that is defined by the extent of the Earth's magnetic field in space. Magnetosphere extends several tens of thousands of kilometers into space. This system is helping for protection of the Earth from the charged particles of the solar wind and cosmic rays. Otherwise, the charged particles from the Sun strip away the upper atmosphere, including the ozone layer that protects the Earth from harmful ultraviolet radiation. Protection of earth from Sun’s charged particles is prime concern for geomagnetic field. Astrobiology is reporting rapid shift of geomagnetic field and forecasting increase in earth exposure to the Sun’s radiation that may cause trillions of dollars in power and communications systems damage.

DISTINGUISHIN FEATURES OF GEOMAGNETIC FIELD:

1. The Earth’s geomagnetic field is created because of two things. The convective motions in the liquid conducting core inside the center of the Earth are important for making the magnetic field. When the convective motions occur with the electrical currents around the Earth, the magnetic field is created. The Earth’s rotation is what keeps the magnetic field up. The interaction between the convective motions and the electrical currents creates a dynamo effect.

2. The intensity of the magnetic field is greatest near the magnetic poles where it is vertical. The intensity of the field is weakest near the equator where it is horizontal. The magnetic field's intensity is measured in gauss.

3. The magnetic field has decreased in strength through recent years. In the past twenty-two years, the field has decreased its strength 1.7%, on average. In some areas of the field, the strength has decreased up to 10%. The fast strength decrease of the field is a sign that the magnetic field might be reversing. The reversal might happen in the next few thousand years. It has been shown that the movement of the magnetic poles is related to the decreasing strength of the magnetic field.

4. A geomagnetic reversal is when the north magnetic pole and south magnetic pole trade places. This has happened a few times in the history of the Earth. The magnetic reversal happens after the strength of the field reaches zero. When the strength begins to increase again, it will increase in the opposite direction, causing a reversal of the magnetic poles. The time it takes the magnetic field to undergo a reversal is unknown, but can last up to ten thousand years. The Earth's magnetic reversals are recorded in rocks, especially in basalt. Scientists believed that the last geomagnetic reversal occurred 780,000 years ago.

MEASUREMENTS OF GEOMAGNETIC FIELD:

Merrill (1996) tried for establishment of method of representation of geomagnetic field. Accordingly, at any place on earth, the geomagnetic field is represented by three dimensional vector. Ideal procedure for measurement of direction of geomagnetic field is to use a compass. This will determine the direction of magnetic North. Its angle relative to true North is the declination (D) or variation. Facing magnetic North, the angle the field makes with the horizontal is the inclination (I) or magnetic dip. The intensity (F) of the field is proportional to the force it exerts on a magnet. Another common representation is in X (North), Y (East) and Z (Down) coordinates.

According to Temple Robert (2006), human being is using compasses for finding the direction since the 11th century A.D. and for navigation since the 12th century. It is assumed that, the declination of geomagnetic field is slowly shifting with the time. This process is too slow. Therefore, a simple compass remains useful for navigation. The animals are also using the technology of "Magnetoreception for Navigation". The unicellular organisms like bacteria and multicellular animals like birds are utilizing the geomagnetic navigation.

INTENSITY OF GEOMAGNETIC FIELDS:

The Guass (G) unit is used to mention the geomagnetic field. But generally, the unit of "Nanoteslas" (nT) is used for reporting the geomagnetic field. One unit of Guass correspond to 100,000 Nanoteslas (1 G = 100,000 nT). National Geophysical Data Center is referring the nanoteslas as a gamma (γ). According to Palm Eric (2011), the tesla is the SI unit of the magnetic field, B. The Earth's field ranges between approximately 25,000 and 65,000 nT (0.25–0.65 G). By comparison, a strong refrigerator magnet has a field of about 10,000,000 nanoteslas (100 G).

Chulliat, *et al* (2015), narrated the "World Magnetic Model for 2015-2020". Accordingly, map of intensity contours is called as "Isodynamic Chart". According to this "World Magnetic Model", "Intensity of geomagnetic field tends to Tendency of intensity of geomagnetic field tends to decrease from the poles to the equator". The South Atlantic Anomaly over South America deserve minimum intensity of geomagnetic field. There are maxima over northern Canada, Siberia, and the coast of Antarctica south of Australia.

Fig.1: Schematic illustration of Earth's magnetic field (https://www.astrobio.net/also-in-news/earth-more-sun-exposed-with-rapid-magnetic-field-reversals/ NASA-Credit/ The University of Edinburgh)

INCLINATION AND DECLINATION OF GEOMAGNETIC FIELD:

The inclination is given by an angle that can assume values between -90° (up) to 90° (down). In the northern hemisphere, the field points downwards. It is straight down at the North Magnetic Pole and rotates upwards as the latitude decreases until it is horizontal (0°) at the magnetic equator. It continues to rotate upwards until it is straight up at the South Magnetic Pole. Inclination can be measured with a dip circle. Declination is positive for an eastward deviation of the field relative to true north. It can be estimated by comparing the magnetic north/south heading on a compass with the direction of a celestial pole. Maps typically include information on the declination as an angle or a small diagram showing the relationship between magnetic north and true north. Information on declination for a region can be represented by a chart with isogonic lines (contour lines with each line representing a fixed declination).

GEOGRAPHICAL VARIATIONS OF GEOMAGNETIC FIELD:

According to National Geophysical Data Center (2013), just near the surface of the Earth, geomagnetic field can be closely approximated through the field of a magnetic dipole positioned at the center of the Earth and tilted at an angle of about 11° with respect to the rotational axis of the Earth. Casselman Anne (2008) already postulated that, dipole is roughly equivalent to a powerful bar magnet, with its south pole pointing towards the geomagnetic North Pole. This may seem surprising, but the north pole of a magnet is so defined because, if allowed to rotate freely, it points roughly northward (in the geographic sense). Since the north pole of a magnet attracts the south poles of other magnets and repels the north poles, it must be attracted to the south pole of Earth's magnet. The dipolar field accounts for 80–90% of the field in most locations (Merrill, 1996).

Historically, the north and south poles of a magnet were first defined by the Earth's magnetic field, not vice versa, since one of the first uses for a magnet was as a compass needle. A magnet's North pole is defined as the pole that is attracted by the Earth's North Magnetic Pole when the magnet is suspended so it can turn freely. Since opposite poles attract, the North Magnetic Pole of the Earth is really the south pole of its magnetic field (the place where the field is directed downward into the Earth) (Emiliani Cesare,1992; Manners Joy, 2000; Serway Raymond and Chris Vuille, 2006; Nave Carl, 2010).

Campbell Wallace (1996) predicted local and global methods or ways to define the positions of magnetic poles. The local definition of position of magnetic poles is the point where the magnetic field is vertical (*Woods Hole Oceanographic Institution*, 2013). This can be determined by measuring the inclination. The inclination of the Earth's field is 90° (downwards) at the North Magnetic Pole and -90° (upwards) at the South Magnetic Pole. The two poles wander independently of each other and are not directly opposite each other on the globe. They can migrate rapidly: movements of up to 40 kilometres (25 mi) per year have been observed for the North Magnetic Pole. Over the last 180 years, the North Magnetic Pole has been migrating northwestward, from Cape Adelaide in the Boothia Peninsula in 1831 to 600 kilometres (370 mi) from Resolute Bay in 2001 (*Phillips Tony, 2003).* The magnetic equator is the line where the inclination is zero (the magnetic field is horizontal). The global definition of the geomagnetic field is based on a mathematical model. If a line is drawn through the center of the Earth, parallel to the moment of the best-fitting magnetic dipole, the two positions where it intersects the Earth's surface are called the North and South geomagnetic poles. If the Earth's magnetic field were perfectly dipolar, the geomagnetic poles and magnetic dip poles would coincide and compasses would point towards them. However, the Earth's field has a significant non-dipolar contribution, so the poles do not coincide and compasses do not generally point at either.

CONCEPT OF MAGNETOSPHERE

On the surface of earth, the geomagnetic field predominantly dipolar. It is distorted further out by the solar wind. Solar wind in real form is a stream of charged particles arising from the corona of Sun are accelerating to a speed of 200 to 1000 kilometres per second. The solar winds carry with them a magnetic field, the interplanetary magnetic field (IMF) (Merril, 2010).

The fundamental effect of solar wind is exerts a pressure. There is possibility of distortion of surface of earth through the pressure of solar winds. This possibility is prevented by the opposing pressure created through the geomagnetic field. The space around the earth with geomagnetic field may be called as magnetosphere. The term magnetopause is used for the area where the pressure of solar winds and geomagnetic field are balancing. The magnetopause may be called as the boundary of the magnetosphere. Parks, George K. (1991) postulated that, the magnetosphere is asymmetric, with the sunward side being about 10 Earth radii out but the other side stretching out in a magneto tail that extends beyond 200 Earth radii. Sunward of the magnetopause is the bow shock. The solar winds experiences “Slowing Abruptly” at this point of bow shock.

According to Darrouzet, et al (2013), inside the magnetosphere is the plasmasphere. This plasmasphere is a donut-shaped region containing low-energy charged particles, or plasma. This region begins at a height of 60 km, extends up to 3 or 4 Earth radii, and includes the ionosphere. Parks George K. (1991) predicted possibility of rotation of “Plasmasphere” along with the earth. Darrouzet, et al (2013) proposed “Van Allen Radiation Belts”. The Van Allen Radiation Belts are in the form of two concentric tire-shaped regions with high-energy ions (energies from 0.1 to 10 million electron volts (MeV)). The inner belt of “Van Allen Radiation Belts”is 1–2 Earth radii out while the outer belt is at 4–7 Earth radii. Darrouzet, et al (2013) extending the view through postulation of partial overlapping of plasmasphere and Van Allen belts. They are varying greatly with solar activity.

The cosmic rays are also high energy charged particles and are mostly from outside the Solar System. According to NASA (2004), many cosmic rays are kept out of the solar system through the action of magnetic field around the Sun (Heliosphere). The significance of geomagnetic field lies in deflecting the cosmic rays. By contrast, astronauts on the Moon risk exposure to radiation. Anyone who had been on the Moon's surface during a particularly violent solar eruption in 2005 would have received a lethal dose.

Some of the charged particles do get into the magnetosphere. These spiral around field lines, bouncing back and forth between the poles several times per second. In addition, positive ions slowly drift westward and negative ions drift eastward, giving rise to a ring current. This current reduces the magnetic field at the Earth's surface.[24] Particles that penetrate the ionosphere and collide with the atoms there give rise to the lights of the aurorae and also emit X-rays (*Parks* George,1991). Space weather is nothing but the varying conditions in the magnetosphere. Space weather is controlled by the solar activity. If the solar wind is weak, the magnetosphere expands; while if it is strong, it compresses the magnetosphere and more of it gets in. Periods of particularly intense activity, called geomagnetic storms, can occur when a coronal mass ejection erupts above the Sun and sends a shock wave through the Solar System. Such a wave can take just two days to reach the Earth. Geomagnetic storms can cause a lot of disruption; the "Halloween" storm of 2003 damaged more than a third of NASA's satellites. The largest documented storm occurred in 1859. It induced currents strong enough to short out telegraph lines, and aurorae [a natural electrical phenomenon characterized by the appearance of streamers of reddish or greenish light in the sky, especially near the northern or southern magnetic pole. The effect is caused by the interaction of charged particles from the sun with atoms in the upper atmosphere. In northern and southern regions it is respectively called aurora borealis or Northern Lights and aurora australis or Southern Lights] were reported as far south as Hawaii (Odenwald Sten, 2010).

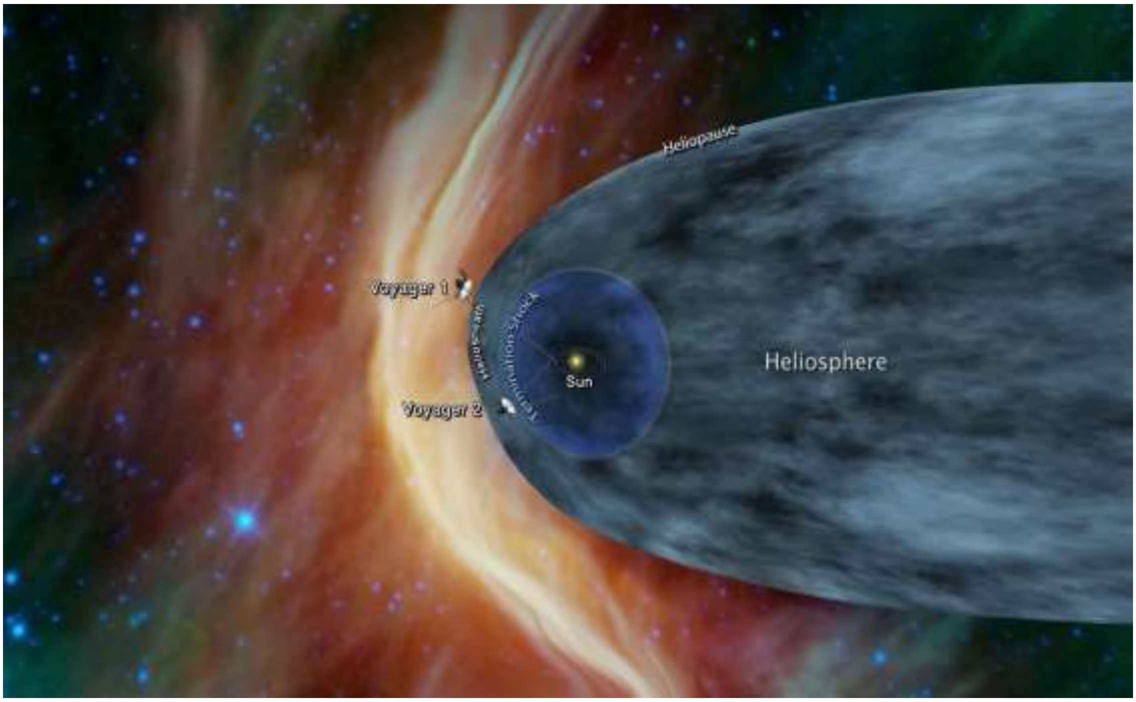

Fig. 2: Diagram of the heliosphere as it travels through the interstellar medium (Heliosheath: the outer region of the heliosphere; the solar wind is compressed and turbulent; Heliopause: the boundary between solar wind and interstellar wind where they are in equilibrium).

INTERPLANETARY MAGNETIC FIELD (IMF):

The interplanetary magnetic field (IMF), now more commonly referred to as the heliospheric magnetic field (HMF), (Owens Mathew, 2013) is the component of the solar magnetic field which is dragged out from the solar corona by the solar wind flow to fill the Solar System. The coronal and solar wind plasmas are highly electrically conductive, meaning the magnetic field lines and the plasma flows are effectively "frozen" together and the magnetic field cannot diffuse through the plasma on time scales of interest. In the solar corona, the magnetic pressure greatly exceeds the plasma pressure and thus the plasma is primarily structured and confined by the magnetic field. With increasing altitude through the corona, solar wind acceleration results in the flow momentum exceeding the restraining magnetic tension force and the coronal magnetic field is dragged out by the solar wind to form the HMF.

The dynamic pressure of the wind dominates over the magnetic pressure through most of the Solar System (or heliosphere), so that the magnetic field is pulled into an Archimedean spiral pattern (the Parker spiral) by the combination of the outward motion and the Sun's rotation (Parker, 1958). In near-Earth space, the IMF nominally makes an angle of approximately 45° to the Earth-Sun line, though this angle varies with solar wind speed. The angle of the IMF to the radial direction reduces with helio-latitude, as the speed of the photospheric foot point is reduced. Depending on the polarity of the photospheric foot point, the heliospheric magnetic field spirals inward or outward; the magnetic field follows the same shape of spiral in the northern and southern parts of the heliosphere, but with opposite field direction. These two magnetic domains are separated by a two current sheet (an electric current that is confined to a curved plane). This heliospheric current sheet has a shape similar to a twirled ballerina skirt, and changes in shape through the solar cycle as the Sun's magnetic field reverses about every 11 years.

The heliosphere is the bubble-like region of space dominated by the Sun, which extends far beyond the orbit of Pluto. Plasma "blown" out from the Sun, known as the solar wind, creates and maintains this bubble against the outside pressure of the interstellar medium, the hydrogen and helium gas that permeates the Milky Way Galaxy. The solar wind flows outward from the Sun until encountering the termination shock, where motion slows abruptly. The Voyager spacecraft have explored the outer reaches of the heliosphere, passing through the shock and entering the heliosheath, a transitional region which is in turn bounded by the outermost edge of the heliosphere, called the heliopause. The shape of the heliosphere is controlled by the interstellar medium through which it is traveling, as well as the Sun and is not perfectly spherical (NASA, 2007). The limited data available and unexplored nature of these structures have resulted in many theories (Matson, 2013). The word "heliosphere" is said to have been coined by Alexander J. Dessler, who is credited with first use of the word in the scientific literature (Alexander J. Dessler, 1967). On September 12, 2013, NASA announced that Voyager 1 left the heliopause on August 25, 2012, when it measured a sudden increase in plasma density of about forty times (NASA, 2013). Because the heliopause marks one boundary between the Sun's solar wind and the rest of the galaxy, a spacecraft such as Voyager 1 which has departed the heliosphere, can be said to have reached interstellar space.

RESPONSE OF ANIMALS TO THE GEOMAGNETIC FIELD

Response of animals to the geomagnetic field may be called as magnetoreception. The idea that animals perceive Earth's magnetic field was once dismissed as impossible by physicists and biologists alike. Earth's field is much too weak for an organism to detect, the argument went, and there are no possible biological mechanisms capable of converting magnetic-field information into electrical signals used by the nervous system. Over time, however, evidence accumulated that animals do indeed perceive magnetic fields. It is now clear that diverse animals, ranging from invertebrates such as molluscs and insects to vertebrates such as sea turtles and birds, exploit information in Earth's field to guide their movements over distances both large and small. What has remained mysterious is exactly how they do this. Determining how the magnetic sense functions is an exciting frontier of sensory physiology. For sensory systems such as vision, hearing, and smell, the cells and structures involved in perceiving relevant sensory stimuli have been largely identified, and the basic way in which the sense operates is understood. In contrast, the cells that function as receptors for the magnetic sense have not been identified with certainty in any animal. Even the basic principles around which magnetic sensitivity is organized remain a matter of debate. Earth's magnetic field, also known as the geomagnetic field, provides animals with different sorts of information, which can be used for different purposes in navigation, as *compasses* and as *maps*. Sea turtles, salmon, and a few other animals use these magnetic cues to navigate during long-distance migrations. In the case of sea turtles, magnetic map information can be used either to guide a turtle toward a particular area or to help it assess its approximate location along a transoceanic migratory route. In effect, sea turtles have a low-resolution biological equivalent of a global positioning system, but one that is based on geomagnetic information instead of on satellite signals.

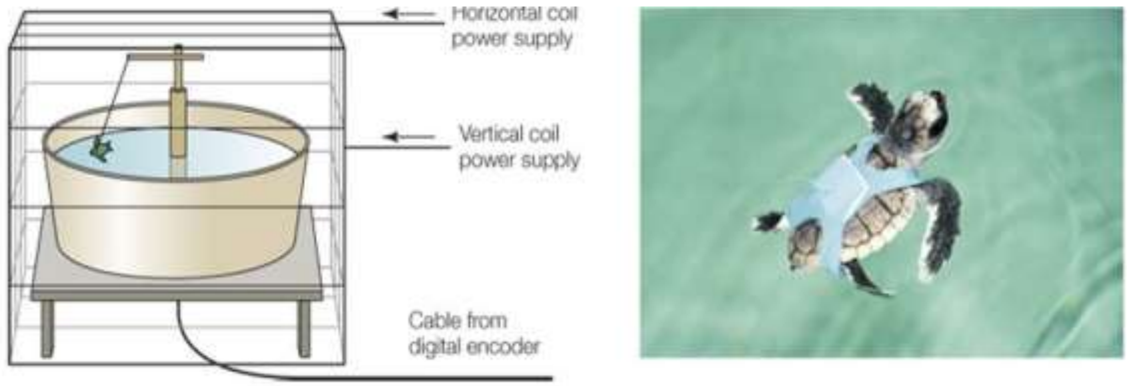

Fig.3: Experimental setup used in magnetic navigation experiments with sea turtles. Hatchling loggerhead turtles were placed in a soft cloth harness and tethered in a circular pool of water surrounded by a magnetic coil system (boxlike structure), which could be used to reproduce the exact magnetic fields that exist in different parts of the ocean. Turtles swam in different directions when exposed to magnetic fields that exist at different locations along the migratory route, demonstrating that they can use Earth's field to assess their geographic position in the ocean (Lohmann et al. 2001; Putman et al., 2011; Lohmann et al. 2012).

POSSIBLE MECHANISM OF MAGNETORECEPTION

Exactly how animals perceive magnetic fields is not known. There are several reasons why locating magnetoreceptors has proven to be unusually difficult. First, magnetic fields are unlike other sensory stimuli in that they pass unimpeded through biological tissue. Receptors for senses such as olfaction and vision must make contact with the external environment, but magnetoreceptors might plausibly be located almost anywhere inside an animal's body. Second, magnetoreceptors might be tiny and dispersed throughout a large volume of tissue. Third, the transduction process might occur as a set of chemical reactions, in which case no obvious organ or structure devoted to this sensory system necessarily exists. If you imagine trying to find a small number of submicroscopic structures, possibly located inside cells scattered anywhere within an animal's body, then you can begin to appreciate the challenge.

Several mechanisms have been proposed that might underlie magnetic-field detection. Most recent research, however, has focused on three main ideas: electromagnetic induction, magnetite, and chemical magnetoreception.

ELECTROMAGNETIC INDUCTION (EMI)

If a small bar composed of an electrically conductive material moves steadily through a magnetic field in any direction except parallel to the field lines, positively and negatively charged particles migrate to opposite sides of the bar. This results in a constant voltage, which in turn depends on the speed and direction of the bar's motion relative to the magnetic field. If the moving bar is in a conductive medium that is stationary relative to the field, an electrical circuit is formed and current flows through the medium and the bar.

This same principle of electromagnetic induction might explain how elasmobranch fish (sharks, rays, and skates) perceive magnetism. The bodies of these animals are conductive. In addition, the fish have sensitive electroreceptors called ampullae of Lorenzini. These receptors are so sensitive to weak electrical changes that they might detect the voltage drop of induced currents that arise as the fish swim through Earth's field. Whether elasmobranchs actually detect magnetic fields in this way, however, is not known.

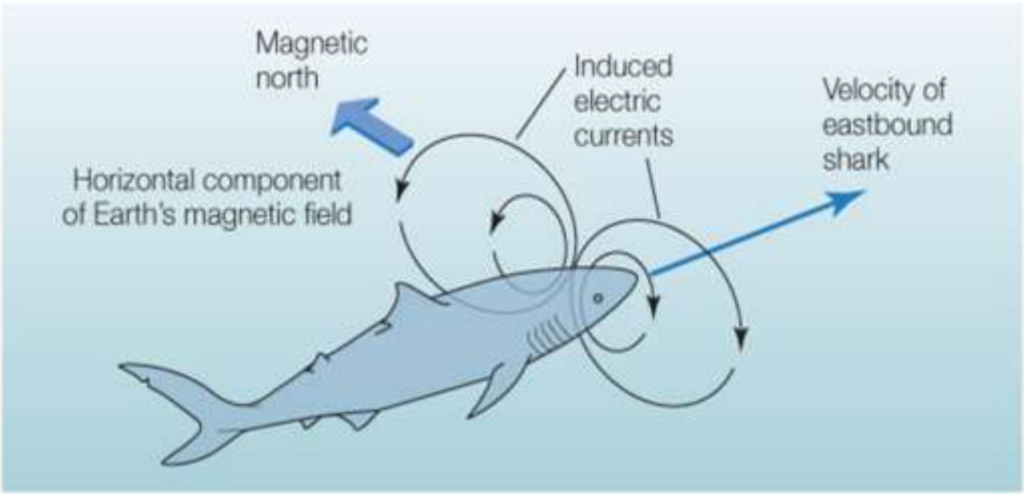

Fig.4: Possible mechanism for a magnetic compass based on electromagnetic induction As a shark swims through Earth's magnetic field, it induces weak electric currents to flow through the surrounding seawater. The induced current depends partly on the heading of the shark relative to the magnetic field. In effect, the shark uses its electric sense to infer its magnetic heading. (After Kalmijn 1978).

Although using electromagnetic induction for magnetoreception may be plausible for elasmobranchs, it has two significant requirements: The animal must have sensitive electroreceptors, and the animal must live in an electrically conductive environment. Unlike water, air does not conduct electricity, so this mechanism appears unlikely for terrestrial animals. In addition, many aquatic animals such as sea turtles appear to lack electroreceptors, implying that another mechanism must be used.

MAGNETITE

A second hypothesis is that crystals of the mineral magnetite (Fe_3O_4) provide the physical basis for magnetoreception. The idea was inspired partly by the discovery that some bacteria produce magnetite crystals; as a result, the bacteria are physically rotated into alignment with magnetic field lines and can move along them. Magnetite has been detected in diverse animals known to perceive magnetic fields, but particularly detailed studies have been done with fish and birds.

In trout, magnetite has been found in the nose and appears to be closely associated with a nerve that responds to magnetic stimuli. Magnetite isolated from fish and other animals has mainly been in the form of single-domain crystals similar to those in bacteria. Single-domain crystals are tiny (about 50 nanometers [nm] in diameter), and each is a permanent magnet that will align with Earth's magnetic field if permitted to rotate freely.

Such crystals might provide the basis for a magnetic sense in several different ways. For example, magnetite crystals might activate secondary receptors (such as hair cells, stretch receptors, or mechanoreceptors) as the particles try to align with the geomagnetic field. Alternatively, if magnetite crystals are located within cells and are connected to ion channels by cytoskeletal filaments, then the rotation of intracellular magnetite crystals might open ion channels directly, thus allowing ions to flow across the cell membrane to produce electrical signals used in communication by the nerve cells.

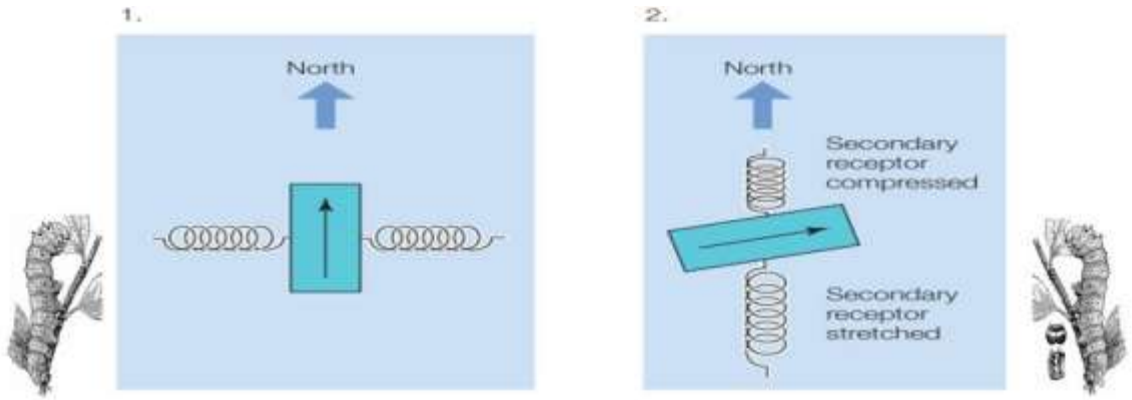

Fig.5: A hypothetical magnetite-based magnetoreceptor. The green rectangle indicates a chain of single-domain magnetite crystals that forms a biological compass needle. The coils represent secondary receptors (stretch receptors) attached to the compass needle. The compass needle always attempts to rotate into alignment with Earth's magnetic field but is constrained by the secondary receptors and has a limited range of motion. (1) When the animal is oriented in such a way that the compass needle is aligned toward the north, no force is exerted on either of the secondary receptors. (2) When the animal is oriented so that the compass needle is aligned in any other direction, one of the secondary receptors is stretched, eliciting action potentials, while the other is compressed. A few such receptor units, arranged orthogonally, could hypothetically provide the basis for a magnetic compass.

CHEMICAL MAGNETORECEPTION

Another hypothesis is that magnetoreception involves a set of unusual biochemical reactions that are influenced by Earth's magnetic field. The hypothesized reactions involve pairs of free radicals (molecules with unpaired electrons) as fleeting intermediates. For this reason, the idea is sometimes called the *radical pairs hypothesis*.

The details of these chemical reactions are highly complex, but the putative process begins with an electron transfer from a donor molecule, A, to an acceptor molecule, B. This leaves each molecule with an unpaired electron; the two unpaired electrons have spins that are either opposite (singlet state) or parallel (triplet state). For a brief instant, the spin of each unpaired electron *precesses*, which means the axis of rotation changes in a way that can be likened to a spinning top wobbling around a vertical axis as it slows down. Precession of electron spins is caused by interactions with the local magnetic environment, which in turn depends on the combined magnetic fields generated by the spins and orbital motions of unpaired electrons and magnetic nuclei, plus the orientation and strength of any external field. Because the two unpaired electrons of molecules A and B encounter slightly different magnetic forces, they precess at different rates.

After a brief period of time, the electron that was transferred returns to the donor, a process known as *backtransfer*. Depending on the time that elapsed before backtransfer and the rates of precession for the two electrons, the original singlet or triplet state of the donor might be preserved or altered. For example, if backtransfer occurs quickly, then the electron spins will have precessed little and are likely to remain in their original opposite or parallel state, resulting in no change to molecules A and B. Alternatively, in a longer reaction, differences in the precession rates of the two unpaired electrons can change the original spin relationship, in which case A is chemically altered. This, in turn, can influence subsequent reactions or the chemical products that ultimately result. In sum, because an ambient magnetic field can influence the precession of electron spins under some circumstances, magnetic fields can influence some chemical reactions.

Where these reactions occur in animals, if indeed they do, is not known. An interesting clue, however, is that many of the best-known radical pair reactions begin with electron transfers that are induced by the absorption of light. This has led to the suggestion that chemical magnetoreceptors might also be photoreceptors. Recent attention has focused on cryptochromes, which are blue-sensitive photoreceptive proteins known to exist in numerous animals. Some researchers think that cryptochromes have the right chemical properties to function as magnetoreceptors.

The most direct evidence for cryptochrome involvement has come from experiments with the fruit fly *Drosophila*, in which flies were trained to enter one arm of a simple maze on the basis of magnetic-field conditions. Mutant flies lacking genes for cryptochrome were unable to perform this task, but magnetic sensitivity was restored when cryptochrome genes were inserted into the flies. Further research will be needed to determine whether the principles discovered in flies are applicable to other organisms.

CONCLUSION Geomagnetism is the study of the dynamics of the Earth's magnetic field, which is produced in the inner core. The Earth's magnetic field is predominantly a geo-axial dipole, with north and south magnetic poles located near the geographic poles that undergo periodic reversals and excursions. The geomagnetic field can affect radical-pair reaction yields as governed by the stochastic Liouville equation depicted in the thinking bubble of the bird. These effects result in a modulation of visual information. The changes of visual modulation patterns with different orientations of the bird can explain the magnetic compass orientation observed in behavioral experiments. The use of magnetite has been shown in magnetotactic bacteria that are rotated by a magnetic field because of the torque exerted on their magnetite particles. Elasmobranch fish have a special sensory organ to perceive electric fields with high accuracy and can use this organ also to detect magnetic fields. The magnetic compass is light-dependent. The magnetic compass in birds requires the presence of short wavelength (blue/green) light in order to work properly. If only red light is present, birds are no longer able to orient. Such behavior points to the involvement of photoreceptors rather than magnets in magnetoreception.

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