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# Geomagnetic field of Earth and its relation to the liquid outer core

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**Abstract:** Magnetism is deeply related to the motion of the charged particles or more specifically the motion of electrons. The temperature condition together with the metallic composition of the core is favorable for the generation of free electrons. But the nature of the internal structure of the earth traps the electrons (with a very high velocity of random motion gained during the thermionic emission effect) within that system, resulting in the change of phase from solid to liquid by electron pressure (increasing the distance between Fe, Ni atoms beyond the critical point. In relation to the rotational motion of the earth, these free electrons originate the geomagnetic field perpendicular to the direction of that circular motion. The magnetosphere is the region of space, surrounding the Earth, that is controlled by Earth's magnetic field. The geomagnetic field of the magnetosphere, as an umbrella, shields us from the cosmic radiation. The earth's magnetic field in the liquid outer core acts as a window, offering one of the few glimpses of the inner workings of the Earth. Ancient records of the geomagnetic field can inform us about the geodynamics of the early period.
**Keywords:** Geomagnetic field, Phase diagram, Outer core, Critical electron pressure, work function, Thermionic emission.

## Introduction

In the case of metal, with increasing density the physical state of matter changes from gas to solid because the distance between molecules decreases with increasing density. According to the seismic investigation, the physical state of the outer core is liquid while the inner core is solid (Winter, 2010) and the rotation of the outer core is responsible for the generation of geomagnetic field. So, three basic questions appear: 1) Why does the outer core exist in the liquid phase? 2) Why is the rotation of the outer core responsible for the generation of the geomagnetic field? and 3) Is there any relation between these two facts? In reply to the second question, it is answered that in the pressure-temperature condition of the outer core, the Ni-Fe alloy exists in the liquid form (Lin, 2002) but another point of view is, if we increase the distance between the atoms of a solid forcefully by some other process without changing the P-T condition then phase will also change from solid to liquid and the P-T condition will change automatically. On the other hand, if magnetism exists somewhere then it is very definite that the motion of charged particles (either linear or rotational) also gets involved within that system. In this background, the following points will be discussed one by one:

- A model representing the process of changing phase from solid to liquid by electron pressure within a metallic body and generation of the magnetic field around that metallic body.
- The reason behind the existence of the outer core in the liquid phase comparing similarities between the interior of the earth and the previously mentioned model.
- Origin of the geomagnetic field in connection with the liquid phase of the outer core.

### Model representing the process of changing phase from solid to liquid by the appearance of electron cloud among atoms and generation of magnetic field.

With increasing energy, the electrons of an atom jump to the next higher energy level, and the distances of the electrons increase from the nucleus. If the atoms are significantly energized then the electron of the outer orbit becomes free from the atom. Consider a spherical metallic body that is surrounded by a thick layer of insulator having a very high melting temperature. If the atoms of that metallic body are significantly energized then the free electrons will occur at the surface of the metallic body.

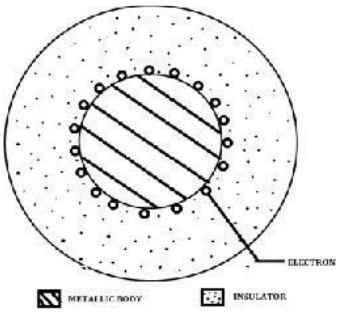


**Fig. 1.** Representing the blocking of free electrons at the surface of metal by thick layer of insulator.

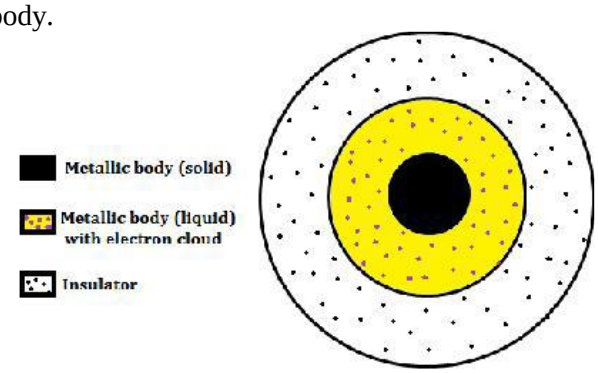


**Fig. 2.** Change of phase of the metallic body after reaching critical electron pressure.

 

The free electrons of a metallic body can be removed from the surface by gaining work function (NCERT, Part-II) served by the heat energy of the metallic body (thermionic emission). But in this case, the metallic body is covered by a thick layer of insulator hence the electrons cannot be removed from the surface and start to accumulate on that surface (Fig. 1). After gaining the work function the random motion of the electrons increases much higher. The increased random motions of electrons create electron pressure when they start to appear among the atoms on the surface zone of that metallic body. If such free electron formation continues over a long period of time, the electron pressure will also increase the distances among the atoms after reaching up to a minimum amount (Critical electron pressure) which is needed to increase the distances among the atoms significantly at a level where the atoms of the metallic body is unable to retain the metallic bond. As a result, the outermost layer of the metallic body will start to change in phase from solid to liquid (Fig. 2). If this process continues then the thickness of the molten area will also increase with time towards the center and the boundary between the molten phase and solid phase of the metal is marked by a narrow zone which represents the presence of critical electron pressure. Below that zone, the electron pressure is less than the critical electron pressure and the phase of the metal will be solid. Hence, the density or viscosity of the liquid increases towards the inner part. Now consider another situation which is the above-discussed system starts to rotate around a vertical axis. So, a magnetic field (Fig. 3) will be generated perpendicular to the direction of rotation because the molten portion of the metallic ball contains free electrons and any electron generates a magnetic field when it is in motion (either liner or rotational). This process of generation of magnetism is similar to the generation of magnetism in solenoids (NCERT, part-I) but remember that in the case of the earth, the rotational motion is restricted to a circular plane but in solenoids, they move ultimately towards the N pole through circular motion.

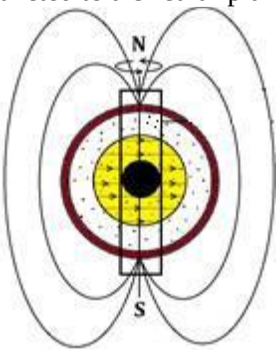


**Fig. 3.** Rotating liquid metal producing magnetic field.

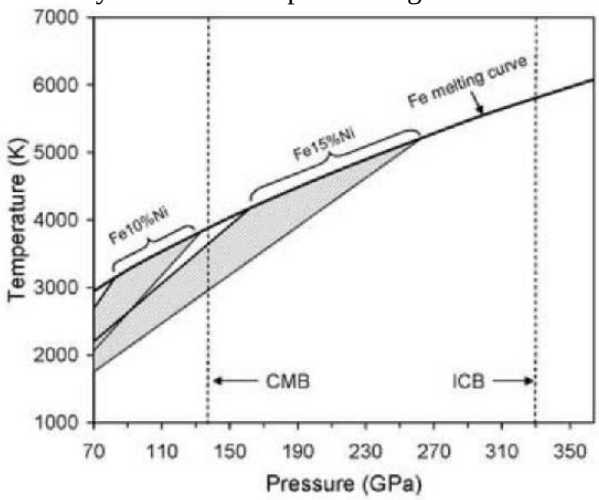


**Fig. 4.** Extrapolation of our Fe15%Ni and previously reported Fe10%Ni (Lin et al., 2002) results to core conditions.

## Interior of the Earth

**Table 1.** Representing the thickness, density, and composition of different parts of the earth's interior (Robertson, 1966)

| Divisions | Thickness | Density | | Composition |
|---|---|---|---|---|
| | | Top | Bottom | |
| Crust | 30 | 2.2 | 2.9 | Silicates |
| Upper Mantle | 2870 | 3.4 | 4.4 | Silicates |
| Lower Mantle | | 4.4 | 5.6 | Magnesium and silicon oxides |
| Outer core | 2245 | 9.9 | 12.2 | Iron and nickel alloy |
| Inner core | 1225 | 12.8 | 13.1 | Iron and nickel alloy |

The interior of the earth can be described in more detail, but here it is emphasized that information is useful to describe the relation between the geomagnetic field and the existence of the outer core in phase. From Table 1, it can be noticed that the density increases with depth (Robertson, 1966), and the core (conductor) is surrounded by the thick mantel (insulator). So, the internal structure of the earth contains the same condition as described

in the previous model which is spherical metallic substance covered by insulator. On the other hand the energy condition of the core is significant enough to generate free electrons from the Ni-Fe atoms.

**Application of the phase diagram**

The most acceptable reason for the existence of a liquid outer core is that if we plot the P-T (pressure-temperature) condition of the outer core it lies on the area of the liquid phase in the phase diagram of Fe- Ni system (Fig. 4). But, if we change the phase of the Ni-Fe alloy from solid to liquid by some other process except changing temperature or pressure of the system, the P-T condition will be automatically changed. So, it is difficult to know whether the changing phase (by some other process) is responsible for the generation of the P-T condition or the P-T condition is responsible for the change in phase. But both events are interrelated.

**Reason for the existence of outer core in the liquid phase**

From the interior of the earth, it can be considered that the core is made up of Ni-Fe alloy the physical state of the inner core is solid and the outer core is liquid (Winter, 2010). Let's assume that at the beginning, the earth has no magnetic field and the entire core is in a solid state which is surrounded by a solid mantel. At that condition, the core can be considered as a solid spherical metallic ball. Considering the energy condition of the core, it is clear that the core will generate free electrons from the outer orbit of Ni and Fe atoms through thermionic emission. These free electrons will occur at the surface of that metallic spherical core because free charges always occur at the surface of the metal. Although the energy condition is able to serve the work function of the electrons to come out from the surface of the metallic core but, the insulator mantel blocks them. As a result, the electrons begin to accumulate at the surface initially but with time they start to accumulate among the Fe-Ni atoms of the solid core in the form of electron clouds resulting in the increase of distance between them. So, a spherical zone of the outermost part metallic core changes its phase from solid to liquid (Fig. 5) because electron pressure increases the distances among the atoms. With time the zone increases in thickness towards the inner part. This liquid zone is known as the outer core which contains clouds of free electrons among the Ni-Fe atoms.

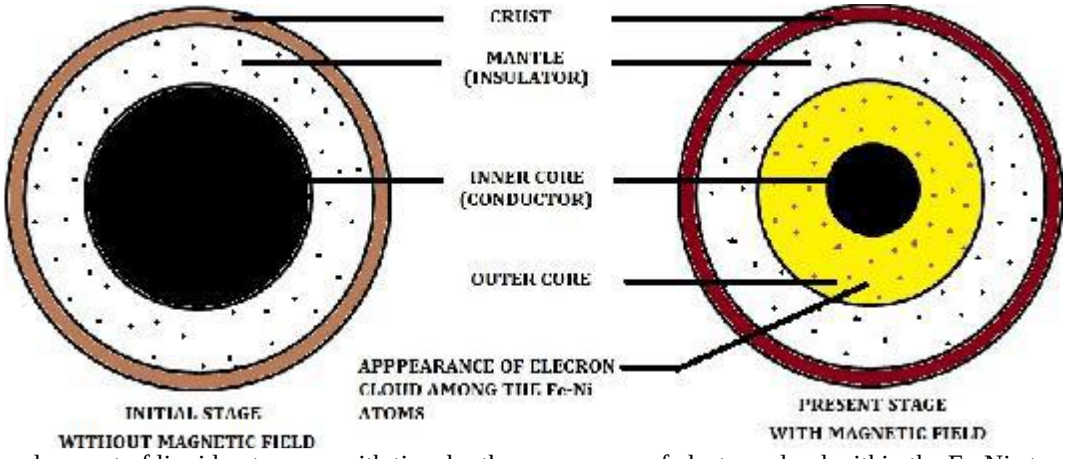


**Fig. 5.** Development of liquid outer core with time by the appearance of electron cloud within the Fe-Ni atoms.

**Relation Between seismic data and the proposed model**

According to the above described phenomenon, the distances among the atoms are maximum at the outer core-Mantel boundary and minimum (Fig. 6) at the level of the earth's interior with critical electron pressure (Minimum amount of electron pressure to change the phase of the Ni-Fe alloy from solid to liquid). That level is known as the Lehman discontinuity (Outer core – inner core boundary). Electron pressure below the critical value is not able to change the phase of metal from solid to liquid. So, the viscosity (or density of the liquid phase) of the outer core increases from the outer core – mantel boundary towards the Lehman discontinuity, or fluidity increases from Lehman discontinuity towards the outer core–mantel boundary. This data is evidenced by the moment of P wave seismic velocity within the outer core (Fig. 7). If the nature of the curve within the outer core can be observed then it can be noticed that after a sudden decrease at the outer core – mantel (Gutenberg discontinuity) boundary the velocity of the P- wave increases towards the outer-core- inner core boundary (Lehman discontinuity). The sudden decrease of P-wave (along Gutenberg discontinuity) is due to the change in phase between the lower mantel and outer core after that the gradual increase of P-wave velocity

within the outer core is due to increase in viscosity (or density) of the liquid phase towards the zone of critical electron pressure ( Lehman discontinuity). Then the velocity increases abruptly due to a change in phase from liquid to solid in the Lehman discontinuity.

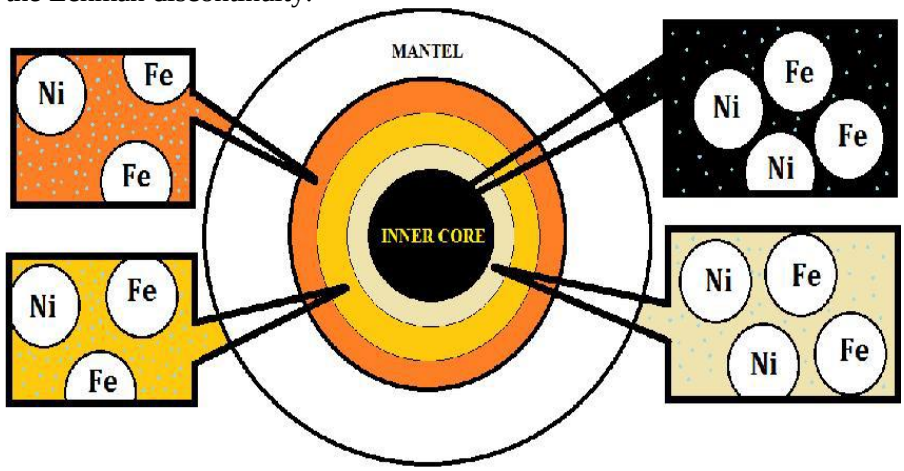


**Fig. 6.** Possible arrangement of Ni-Fe atoms together with the free electrons representing increasing distances among the atoms with increasing distance from the inner core.

**Origin of the Earth's geomagnetic field**

The earth rotates around its axis anti-clockwise, if someone observes it from the North Pole. So the liquid outer core also rotates around that axis in the same manner. If we observe the cross sections of the earth (Fig. 8) then we can clearly understand that the earth's axis acts as a solid pillar and the electrons move in a circular path around this pillar. This structure is very similar to the structure of a solenoid but here the motion of electrons follows a series of parallel circular paths rather than helical paths. Hence a magnetic field will originate perpendicular to the circular path or parallel to the axis of the earth which is known as a geomagnetic field.

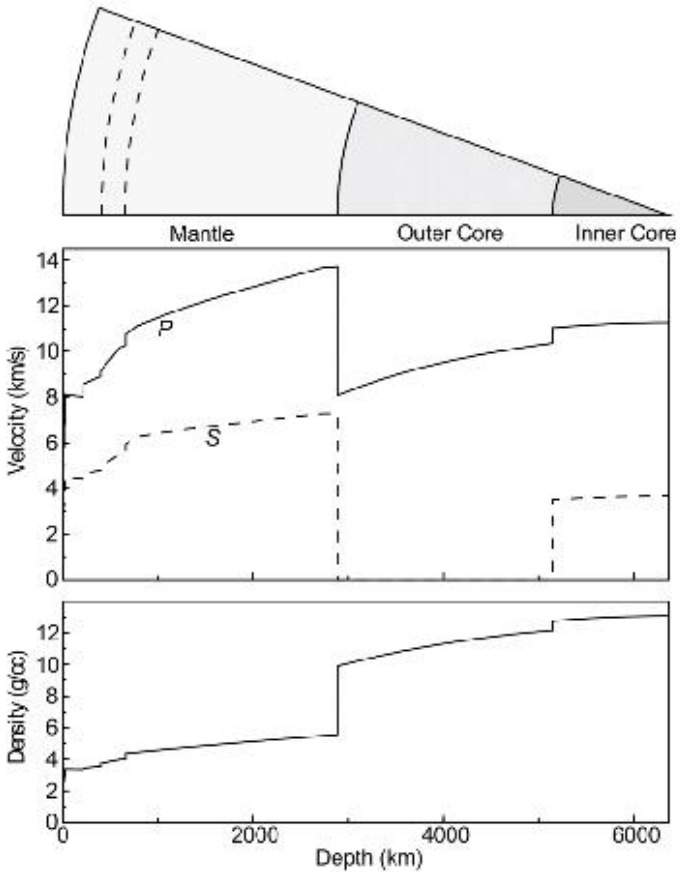


**Fig. 7.** Earth's P-wave velocity, S-wave velocity, and density profiles as a function of depth. Values are from the Dziewonski and Anderson (1981). Preliminary Reference Earth Model (Shear, 2009; Gill, 2015).

**Geomagnetism, its significance and applications**

The magnetosphere is the region of space surrounding the Earth where the dominant magnetic field is that of the planet Earth, rather than the magnetic field of interplanetary space. The magnetosphere is formed by the interaction of the solar wind with Earth's magnetic field. Earth's magnetic field extends up to 3200 km which can dispel the solar wind and save Earth from disaster. It protects us from solar flares and cosmic particle radiation, harmful gamma rays of the sun. Geomagnetism is one of the fundamental interactions in the universe which provides the study of magnetic fields near the Earth's surface. Geomagnetism has increased our knowledge related to geological processes and the earth's interior. This field of study in geomorphology is credited to William Gilbert. Geomagnetism is the study of the dynamics of the Earth's magnetic field, which is produced in the outer core. The Earth's magnetic field is predominantly a geo-axial dipole, with north and south magnetic poles located near the geographic poles. Earth's magnetic field is known to have wandered and flipped in the geologic past. This wandering has generally been quite slow, around 9 km a year, allowing scientists to easily keep track of its position. But since the turn of the century, this speed has increased to 50 km a year. The earth acts as a dipole magnet where the geomagnetic south pole is near the earth's geographic north and vice versa. Some movements of Earth's geological past are known to have witnessed the disappearance of magnetic fields. These phases also coincide with some of the major extinctions on Earth. The geomagnetic field acts both as an umbrella, shielding us from cosmic radiation, and as a window, offering one of the few glimpses of the inner workings of the Earth. Ancient records of the geomagnetic field can inform us about the geodynamics of the early Earth and changes in boundary conditions through time. It also provides the basis for navigation with a compass. Geomagnetism has applications in mapping, mineral exploration, and weather. Real-time and historic geomagnetic field measurements help to thwart damage to satellites, prevent corrosion of pipelines, and protect power grids and communication systems.

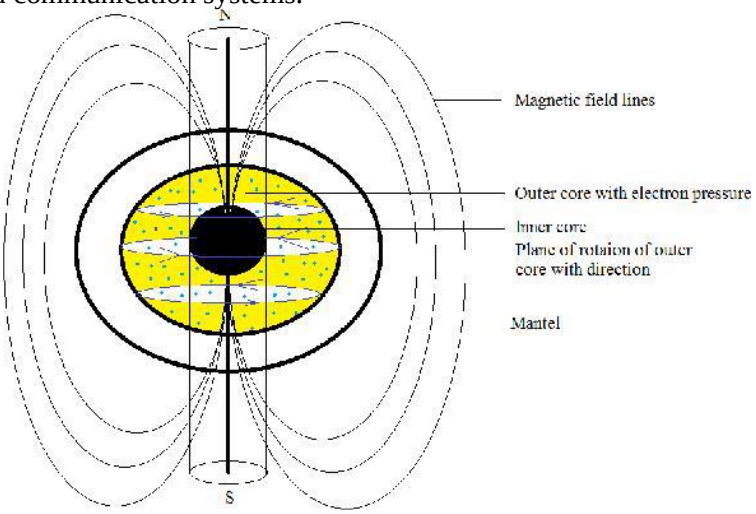


**Fig. 8.** Rotating outer core generates magnetic field (Mcpherron, 2023).

## Conclusion

- The liquid phase of the outer core of the Earth is due to the electron pressure which is created due to the forceful appearance of the randomly moving free electrons among the Ni, and Fe atoms.
- The electron pressure is maximum at the outer core–mantel boundary and decreases towards the outer core-inner core boundary. Critical electron pressure is a minimum amount of electron pressure that is responsible for changing the phase of the Ni-Fe alloy from solid to liquid. The line joining the zones of critical electron pressure around the inner core marks the Lehman discontinuity, below this zone the amount of electron pressure is less than the critical electron pressure, and as a result below this zone, the Ni-Fe alloy appears in the solid phase.
- The rotation of the earth moves the outer core together with the electrons in a circular path with a common axis of rotation. As a result, a geomagnetic field is generated perpendicular to the axis of rotation.
- If the motion of free electrons exists in any planet or star, there will be a magnetic field. The planets other than Earth: Jupiter, Saturn, Uranus, and Neptune also get their magnetism in the same process. The condition is applicable to the sun too. In the case of the sun the electrons of outer orbits of atoms

like H, He becomes free due to the highly energized condition but there is no solid cover to resist the motion of those electrons. As a result, the electrons together with ionized elements produce solar wind.

- The intensity of the magnetic field of planets is controlled by two major parameters, which are (i) The number of free electrons present within the system and (ii) The rotational speed of the planets around its own axis. This is the reason why planets with higher rotational speed (Jupiter, Saturn, Uranus, Neptune) have much stronger magnetic fields than the Earth. For example, Jupiter is the largest planet in the solar system with the highest rotational speed and it owns the strongest magnetic field.
- Venus has a similar internal structure to the Earth, but its rotational speed is not significant enough to produce an effective and recognizable magnetic field.
- Earth's dipolar geomagnetic field protects our planet from harmful cosmic radiation by deflecting all of the ionizing charged particles that come from the sun. In addition, it offers to look into the inner workings of the Earth.

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