OCR
RECOGNISING ACHIEVEMENT

ADVANCED GCE **2865/01**

PHYSICS B (ADVANCING PHYSICS)

Advances in Physics

INSERT

TUESDAY 17 JUNE 2008 Afternoon

Time: 1 hour 30 minutes

CUP/T44680

INSTRUCTIONS TO CANDIDATES

- This insert contains the article required to answer the questions in Section A.

This document consists of **8** printed pages.

 [Turn over

The Magnetic Earth

Viking and Chinese seafarers

Sailing across expanses of open sea was a dangerous undertaking a thousand years ago. Viking explorers sailed across the Atlantic but usually followed the coast-lines of Norway, Iceland and Greenland, never travelling far from sight of land or of seabirds, such as gulls, that forage from the coast. Voyages were made in the warmer summer months, but navigation by the stars was difficult then. This was because the Sun never sets far enough below the horizon in summer at northerly latitudes for stars to be visible.

The medieval Icelandic sagas refer to the use of 'sunstones' to find the position of the Sun in the sky when it was below the horizon or covered by cloud. It has been suggested that sunstones were polarising crystals, such as the mineral calcite which was first found in Viking Iceland. The sky is blue because particles in the atmosphere scatter sunlight, with blue light scattered more than red. The same scattering partially polarizes the sunlight, and this is used by many insects, such as bees, in navigation. A Viking navigator viewing the sky through his sunstone would see a dark band stretching across the sky perpendicular to the direction of the Sun's rays. Providing that he knew the time of day, this would allow him to navigate, as the position of the Sun indicates the directions of north and south.

By this time, the Chinese had already developed magnetic compasses using iron or steel needles that had been touched by a 'lodestone', a naturally magnetic iron oxide mineral. These compasses came to Europe, probably on the over-land route called the Silk Road, some time during the twelfth century. Compasses would have been of limited use to the Vikings, travelling as they did close to the Earth's magnetic pole near Greenland, but for most Europeans the magnetic compass became an essential aid to navigation.

From Gilbert to Gauss

In the year 1600, not long before Kepler and Galileo published their first books on astronomy, Queen Elizabeth's physician William Gilbert published his studies of static electricity and magnetism in *De Magnete* (About Magnets). He was the first to distinguish between these two phenomena, but he was struck with the similar way in which these two forces act, and thought that they were fundamentally related. He was right, but it took 250 years before Faraday and Maxwell worked out the relationship.

For his experiments, he used a spherical lodestone ball, which he used as a model of the Earth. By moving a small compass around the surface of the sphere, he was able to model the way in which compasses behave, pointing to one part of the globe, and also tilting increasingly inwards as you approach the pole, as shown in his own diagram (Fig. 1).

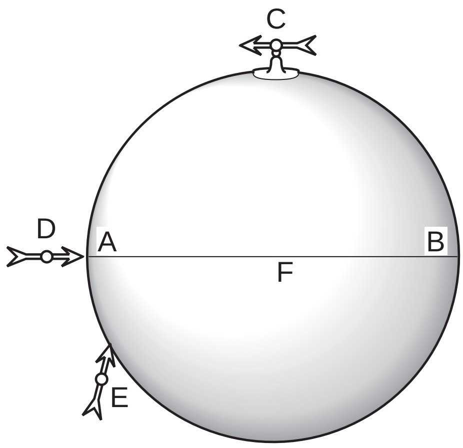


Fig. 1

Gilbert recognised the way in which the magnetic field of the Earth was aligned with its axis of rotation. In fact, he assumed that the rotation was caused by the magnetic field. However, he had difficulty in explaining why compasses veered away from geographic north, with the deviation being more noticeable as you approach what we now recognise to be the magnetic pole. He thought that the land masses of the continents were responsible; that as you sail towards America, it attracts the compass more, making it deviate to the west of geographic north. He ingeniously demonstrated this by etching a hole, to represent the Atlantic Ocean, into his magnetic sphere (Fig. 2). Near the centre of the 'ocean', or on the land masses at each side, the compass bearings converged on the pole, but as at **X** near the North American coast the compass deviates towards the nearby land mass.

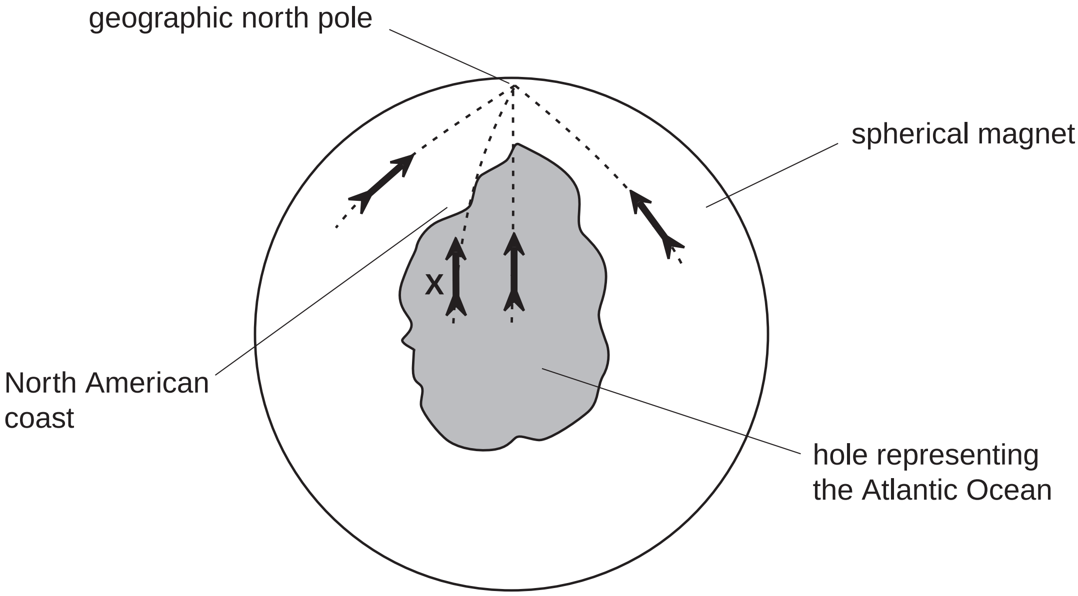


Fig. 2

Gilbert's essentially correct model of the Earth as a large magnet was refined over the following years. Careful observations showed that the difference between magnetic north and geographic north slowly changes with time. This led Edmond Halley to suggest that the interior of the Earth consisted of a series of separate layers, rather like an onion, each with its own magnetism, and which all rotated independently. Eventually the great mathematician Karl Friedrich Gauss, working with the physicist Wilhelm Weber, measured and analysed the three-dimensional magnetic field and deduced that it originated from somewhere inside the Earth.

The Internal Structure of the Earth

Halley's suggestion that the Earth was made of a series of layers was not based purely on the problems of identifying the Earth's poles: Halley was trying to explain Newton's deduction, using his gravitational law, that the mean density of the Earth was about double the density of rocks of the crust. The increase in pressure in the interior of the Earth does lead to an increase in density, but this is not nearly enough to account for the density doubling. The only reasonable explanation is that the Earth contains much denser material somewhere within it.

In 1936, more evidence came from the detection of different types of seismic waves. With sensitive seismometers, small earthquakes can be detected anywhere in the world, and the different sorts of waves distinguished on the seismometer trace by their amplitudes, times of arrival and the different components of vibration they produce.

There are two sorts of seismic waves which travel through the body of the Earth, and so give us information about its structure. These body waves are called Primary and Secondary, as the faster Primary waves arrive first at any seismograph. They are of interest here because there are regions on the Earth's surface where these waves are not observed, as shown (Fig. 3).

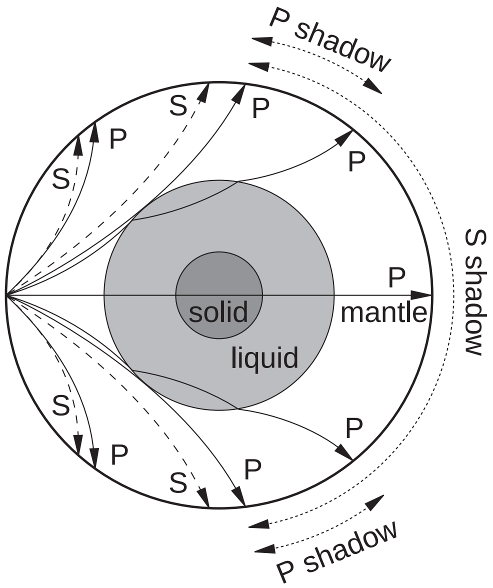


Fig. 3A
Sectional view of the Earth

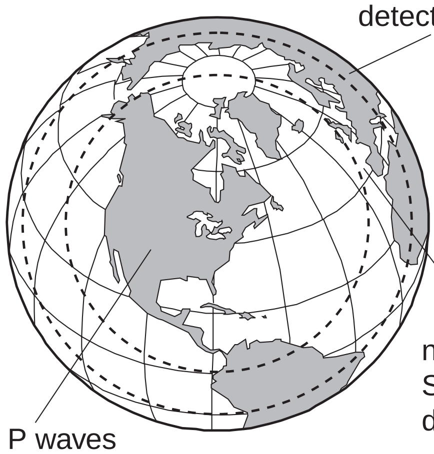


Fig. 3B
The P and S shadow zones produced by an earthquake in the Indian Ocean

Fig. 3

The Primary (P) waves are compression waves, whereas the Secondary (S) are transverse waves. Transverse mechanical waves propagate by setting up shear stresses in the medium through which they travel, which is only possible for a solid medium. The fact that S waves are undetectable on the other side of the Earth from the earthquake shows that the Earth's core is liquid. More detailed study of the paths taken by P waves through the core showed another boundary. The inner core is solid, surrounded by liquid, as shown in Fig. 3A.

Although P waves are detected in the centre of the S shadow, they are not detected in a region near the edge of the S shadow (Fig. 3). This is caused by refraction of the P waves at the boundary of the core, where the P waves slow down by a factor of about 1.7 times, indicating that the liquid core is substantially denser than the surrounding mantle. This is a confirmation of Newton and Halley's prediction of a denser material inside the Earth. Two things suggested that the material of the core is iron. The first is the fact that the known density of iron and the size of the core account for the large value of the Earth's mass. The second is that the Earth's magnetic field originates within the Earth itself.

With our modern understanding of cosmology and the formation of solar systems, this now seems self-evident. Iron, the most stable nucleus, is formed in large stars, then scattered through the Universe during the subsequent supernovas. As planets like Earth form, it is to be expected that the denser materials will sink to the centre of the molten mass, leading to an iron core.

Fig. 3A also shows refraction within the mantle and core regions, as indicated by the curved rays showing the paths taken by the waves. Both the stiffness and the density of the material increase with depth, due to the greater pressure, and the speed of waves depends in different ways on both of these factors.

The Geodynamo

The method by which the Earth's magnetic field is generated is now thought to be an example of a self-exciting dynamo. A simple explanation is shown in Fig. 4 below.

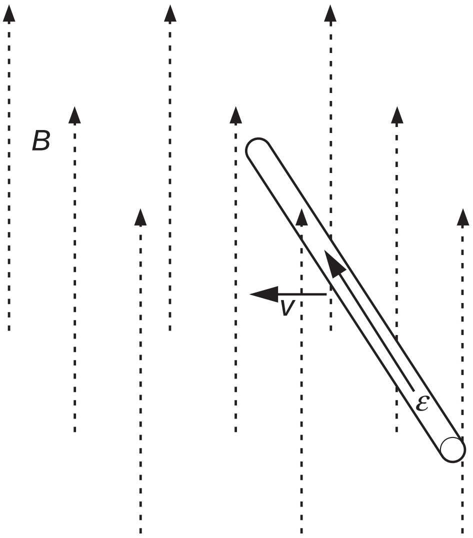


Fig. 4A

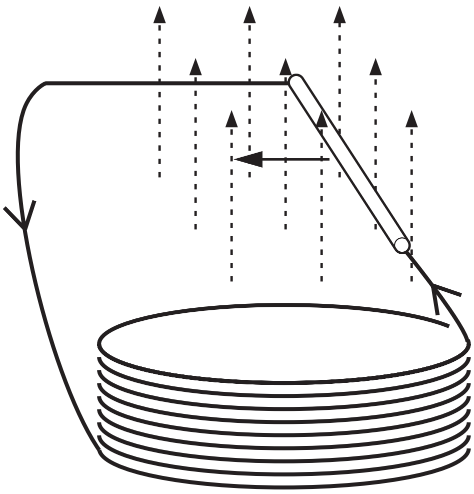


Fig. 4B

Fig. 4

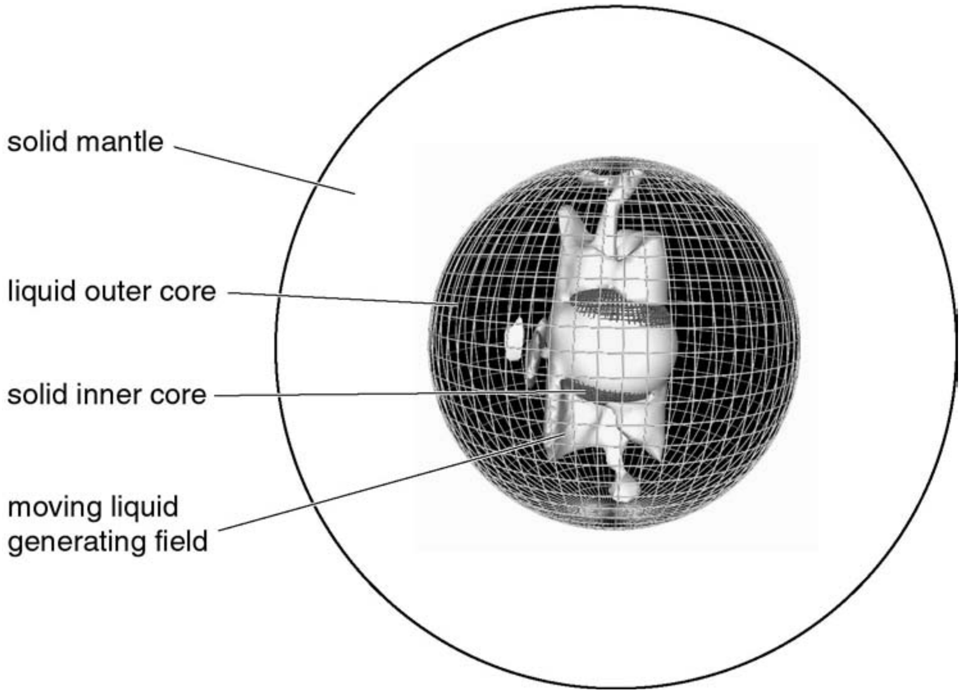
In a self-exciting dynamo, a conductor moves through a magnetic field *B*, which induces an emf ε as shown in Fig. 4A. The current produced passes through a coil, which generates a field in the direction of the original field, as in Fig. 4B. In this way, the field needed for the induction is produced by the induced current itself.

This procedure looks, at first glance, rather like a perpetual motion machine, which makes it impossible. However, the system does not contravene the law of conservation of energy, because the necessary work done is supplied by the force pushing the conductor through the magnetic field. In the case of the Earth, convection in the liquid core provides the necessary force as it pushes the molten iron around in loops, rising from the boundary with the solid inner core to the boundary with the mantle, and then returning.

The mechanism by which the heat is produced is not clear. One theory is that the liquid core is continuously solidifying onto the inner core. To melt any solid requires an input of energy, and so a solidifying liquid will release energy. However, the energy produced by this method over the known age of the Earth, when compared with the measured rate at which energy is emitted by the cooling Earth, is too small.

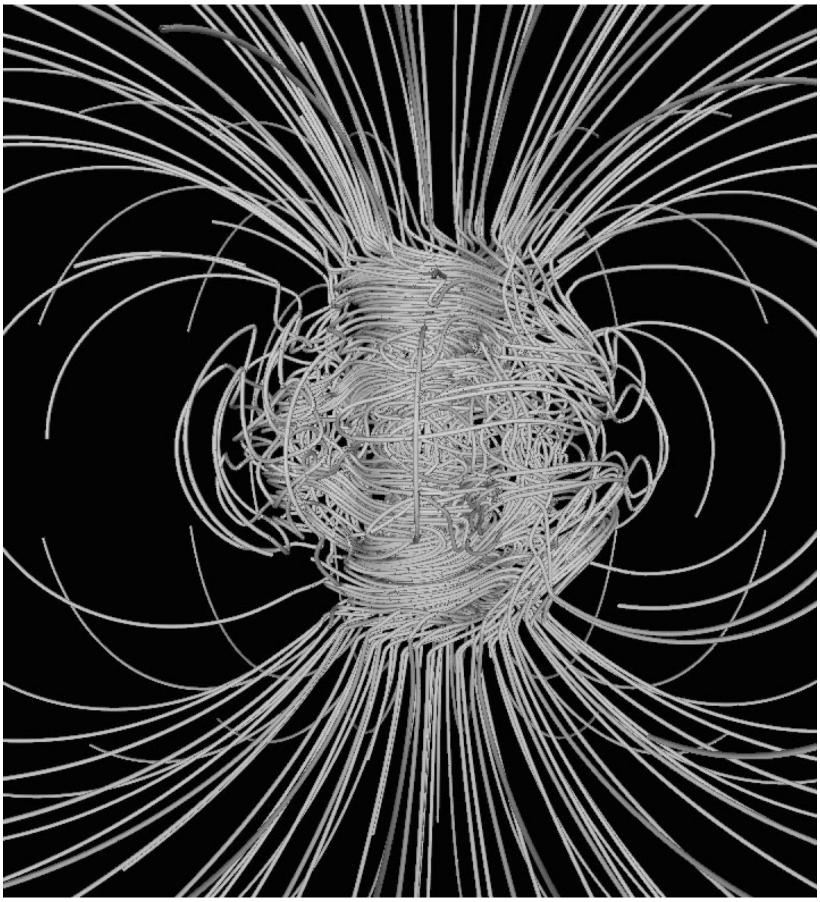
Another possible source is similar to that responsible for geothermal energy: the decay of radioactive nuclei. Isotopes of uranium and thorium are responsible for geothermal energy, but in the Earth's core it is now believed they are joined by potassium-40. This was prompted by the discovery that the proportion of potassium is far higher in meteorites than in the Earth's crust. If the missing potassium had dissolved in the iron core at an early stage of the Earth's formation, then the combination of uranium, thorium and potassium may be enough to supply the energy needed.

In reality, the interactions within the Earth are complex, and the most accurate analyses have been done by computer models. One such, created by Professors Gary Glatzmaier and Paul Roberts of the University of California, makes good predictions of the magnetic field we currently observe, including occasional reversals of the magnetic field direction.



The movement of molten iron in the outer core

Fig. 5A



The resultant magnetic field

Fig. 5B

The geodynamo theory above shows that there is a mechanism for keeping the Earth's field going, and the random fluctuations which will inevitably occur can clearly lead to the changes in the field – the reversal of direction, and the wanderings of the poles – which have been observed. But where did the magnetic field come from which started the process off? In a commercial self-exciting dynamo, this field is produced by the residual magnetic field present in the iron cores of the electromagnets. The hot conditions in the Earth's core would prevent any permanent magnetic field there, in much the same way as strong heating of a permanent magnet destroys its magnetism. Fortunately for this theory, any magnetic field present at the start, however small, would be enough to start the process off. In the Earth's case, the initial field could have been from the Sun.

END OF ARTICLE

Written with reference to *The Great Magnet, the Earth* by David P. Stern.
http://www.phy6.org/earthmag

Copyright Acknowledgements:

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