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PLANETARY MAGNETISM

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ABSTRACT

Magnetic fields are ubiquitous in the Universe because of the absence (or rarity) of free magnetic monopoles. However, the large scale concentration of magnetic flux in an essentially non-ferromagnetic body such as the Earth, requires a non-cosmogonical explanation. A regenerative process must exist because the magnetic diffusion time in the Earth is much less than the age of the Earth. The most popular explanation is the dynamo model in which convectional or precessional fluid motions in the core induce and sustain a magnetic field. Other mechanisms are possible in which, for example, thermoelectric effects are important. The advent of planetary probes has led to a dramatic increase in information on the magnetic fields of the five innermost planets. In particular, the recent flybys of Jupiter (by Pioneer 10) and Mercury (by Mariner 10) have yielded unexpected results. These observations are discussed and shown to be reconcilable with present theories of planetary magnetism and solar system chemistry. Some predictions are made for Saturn, Uranus and Neptune.

INTRODUCTION

One hundred years from now, the present decade will be looked upon as the beginning of an exciting new era in which Man first began to explore the environment of other planets in the solar system. Apart from the pure scientific knowledge that this exploration yields, there is hope that the understanding of our own environment will also be enhanced. One aspect of our environment that is as yet incompletely understood, is the geomagnetic field. In the past, theories of the geomagnetic field could be applied to only one body. Now, it is possible to test these theories on other bodies in the solar system.

The magnetic field of a planet is one of the few planetary properties that is externally measurable yet gives us information on the interior of the planet. If it is possible to deduce the interior composition of planets, then our knowledge of the chemistry of the solar system will be thereby enhanced. Since theories of planetary magnetism are strongly dependent on the assumed internal constitution, it should be possible to correlate models of planetary interiors with observed internal magnetic fields. Such a correlation is attempted here. We first discuss the existence of primordial fields and the need for regeneration. In subsequent sections, the various methods of regeneration are discussed, and their relevance for each planet considered.

PRIMORDIAL FIELDS

A turbulent era soon after the Big Bang could generate a magnetic field that reached energy equipartition with the kinetic energy of small scale motions.¹ This field persists because of the abundance of free electric charges and the apparent absence of free magnetic monopoles. It could account for almost all the magnetic field energy in the Universe. Subsequent gravitational contraction of a hot gas that can trap the field lines, leads to large localized concentrations of magnetic field. For example, the contraction from an interstellar medium in which the field is 10^{-5} gauss (the present field of our galaxy), would give fields as large as 10^6 gauss in a body like Jupiter. Indeed, Hoyle² invoked a large magnetic field in the primordial solar nebula, to explain the distribution of angular momentum in the solar system.

The reason that such initial fields might not persist is to be found in Ohm's law and Maxwell's equations which together give

$$\nabla^2 \vec{H} = \frac{4\pi\sigma}{c} \left[\frac{\partial \vec{H}}{\partial t} - \nabla \times (\vec{V} \times \vec{H}) \right] \quad (1)$$

where $\vec{H}$ is the magnetic field and $\vec{V}(\vec{r})$ the velocity of a medium of electrical conductivity σ . (Displacement currents are neglected). Consider a region with linear dimensions of order L , surrounded by an insulator (e.g. vacuum). If $\vec{V} = 0$ then equation (1) gives

$$\frac{H}{L^2} \sim \frac{4\pi\sigma}{c^2} \cdot \frac{H}{\tau} \quad (2)$$

where the field is assumed to change on a time scale of order τ and a distance scale of order L . Thus,

$$\tau \sim \frac{4\pi\sigma L^2}{c^2} \quad (3)$$

Unless the term involving $\vec{V}$ in equation (1) is significant, τ is a measure of the decay time of an initial field. Fluid flow is important if

$$G_m \equiv \frac{V\tau}{L} \gtrsim 1 \quad (4)$$

where V is a typical magnitude of $\vec{V}(\vec{r})$ and G_m is known as the magnetic Reynold's number.

The value of τ is typically only a fraction of a second for a laboratory sized object but it can be very large for an astronomical body. For the Sun,³ τ is about 2×10^9 years. A similar value has been estimated for the metallic core of Jupiter.⁴ It is possible that the present magnetic fields of the Sun and Jupiter are remnants of once large primordial fields. In contrast,⁵ the Earth has a decay time τ of about 10^3 or 10^4 years. Similar decay times apply to the other terrestrial planets. The Earth's magnetic field is consequently not primordial, neither can it be explained by ferromagnetism.⁶ A regenerative process must exist.

FIELD GENERATION

The most popular theory of field generation for planets is the dynamo mechanism. Before discussing that, we shall consider some of the other theories or explanations that have been proposed.

As we have already mentioned, ferromagnetism does not explain the Earth's dipole field. It could, however, be responsible for the much smaller fields of Mars and Mercury. Such planets might have had primordial dynamos when they were hotter, and then cooled off, leaving behind a permanent magnetic trace of their early history.⁷

In contrast, well known solid-state effects such as thermoelectricity and thermomagnetism offer ways of transforming thermal energy into magnetic field energy. As we have discussed elsewhere,⁸ thermomagnetic effects are unimportant unless the electron mean free path greatly exceeds the inter-atomic spacing in the interior of a planet. None of the planets is cold enough for this criterion to be adequately satisfied at present. However there is no similar constraint on theories involving thermoelectric effects.

In 1939, Elsasser⁹ proposed that the Earth's magnetic field could be maintained by electric currents driven by a thermoelectric e.m.f. In Elsasser's version, the thermocouple is obtained by assuming that the warm upward and cold downward streams of convecting fluid in the core have slightly different compositions. In a later version by Runcorn,¹⁰ the e.m.f. is at the core-mantle boundary. In both cases, Inglis¹¹ found that to produce an electric current adequate to explain the Earth's magnetic moment, the convection currents required

would transport more heat than the observed geothermal heat flux. For this reason, the theory is not favored.

Recently,⁸ a more successful application of Elsasser's idea has been made to Jupiter. Jupiter satisfies two of the criteria that are necessary for large thermoelectric currents. One is a large internal heat flux, recently confirmed by Pioneer 10.¹² The other is rapid rotation. This is required to ensure a preferential alignment of the fluid flows and current loops, which in turn ensures a net magnetic dipole moment.

The thermoelectric current depends on the product of the electrical conductivity and the relative thermopower. The thermocouple in Jupiter could be between helium-rich and helium-poor metallic hydrogen fluid regions (in which case, the conductivity is large and the thermopower small) or between metallic and molecular hydrogen (small conductivity but large thermopower). We favor the former because of the very low electrical conductivity that molecular hydrogen is expected to have. (However, recent calculations by this author indicate that molecular hydrogen may even be a semi-metal at pressures just below the first order phase transition to metallic hydrogen. This might favor a thermoelectric mechanism.) With our present incomplete knowledge of the interior of Jupiter, a detailed model would be premature.

Amongst other ideas that have been proposed to explain planetary magnetism are: gyromagnetic effects, rotating electric charge, induction by magnetic storms, Hall currents, the compression effect (the differential motion of electrons and ions in a gravitational field), and new physical laws. These have all been discussed elsewhere.⁸ The Hall effect is the only mechanism listed above that seems promising.

The mechanisms we have discussed so far share one feature: they all involve small perturbations on the dominant dynamic processes within a planet. Such mechanisms were worth considering only because the magnetic field energy in the Earth (for example) is much less than the thermal energy, or even the tidal energy that has been dissipated in a billion years. It seems that we should consider a more direct coupling between the magnetic field and the dynamic processes within a planet. This is the aim of the dynamo mechanism.

The existence of a homogeneous, planetary dynamo can be mathematically determined as follows: is there a velocity field $\vec{v}(\vec{r})$ that is a solution to the magnetohydrodynamic Navier-Stokes equation and to equation (1), such that the magnetic field does not decay with time? These are constraints on both the geometry of the velocity field and on the magnitude of a typical velocity.

We have already seen (equation (4)) that fluid flow is important if the magnetic Reynold's number exceeds unity. If the fluid flow is rapid enough, then the field does not have time to diffuse out of the fluid and is "frozen in" to the conductor. This is essential to all dynamo theories. This lower limit on the velocity is important since it limits dynamo action to a conducting fluid. Note, however, that the conductivity and fluid velocities required depend on the size of the planet. A very large planet does not require a large conductivity.

Cowling¹³ considered the geometric constraints on the velocity field and showed that a dynamo can not exist if the fluid flow is axisymmetric. For this reason it is difficult to construct a dynamo in a non-rotating planet. Furthermore, dynamo models inevitably involve large toroidal, as well as poloidal, fields.

In addition to this qualitative constraint on the geometry of the velocity field, there is a quantitative constraint that expresses the requirement that the dissipation of electric currents be matched by production. In a laboratory dynamo, this requirement is met by attaining a certain angular velocity.¹⁴ The corresponding criterion for a planetary dynamo is similar but not as simple. It should be emphasized that this requirement is a kinematic one, and not just a question of whether sufficient energy is available to run the dynamo.

The existence of many suitable velocity fields for dynamo action is now well established,¹⁵ although no general existence proofs have been derived. We must now consider what mechanisms are available to sustain a suitable velocity field. Two are considered here: cyclonic convection and precession.

Thermal convection in a rotating planet leads to differential rotation of the fluid (cyclonic convection), and the resulting non-axisymmetric flow may sustain a dynamo. Parker¹⁶ has analyzed this in detail and finds that dynamo modes do exist provided the quantity $\omega\tau$ exceeds some critical value. (Here, ω is the angular velocity of the planet and τ is defined by equation (3)). The critical value of $\omega\tau$ depends on the details of the flow pattern and the heat flux transported. If, as Levy has suggested,¹⁷ the Earth only marginally satisfies this requirement, the critical value is $\omega\tau \sim 10^6$ or 10^7 .

So far, we have discussed only the kinematics of the dynamo. This discussion has been independent of the magnitude of the generated field. The magnitude is determined by the available energy source. For thermal convection, the energy source is the heat flux emanating from the deep interior of the planet. This heat flux drives a heat engine that maintains the fluid flow. The inherent inefficiency of such an engine ensures that the Ohmic dissipation of the dynamo is much less than the heat flux.

We now consider the precessional model proposed by Malkus.¹⁸ In the frame of reference in which a rotating, precessing planet is at rest, there is, in addition to the usual Coriolis force, a Poincare force per unit mass

$$\vec{F}_p = (\vec{\omega} \times \vec{\Omega}) \times \vec{r} \quad (5)$$

where $\vec{\omega}$ is the angular velocity vector, $\vec{\Omega}$ the precession vector and $\vec{r}$ a radius vector. The precession rate Ω depends on the dynamic ellipticity of the body and consequently on the density of the body. If the planet has a density discontinuity in the interior, then the material on either side of the discontinuity tends to precess at different rates. The resulting fluid flow may be adequate to maintain a dynamo.

For fully magnetoturbulent flow in the core, Malkus found that the condition for field regeneration is

$$K \equiv (\Delta\Omega\tau \sin i)/2 \geq 1 \quad (6)$$

where Δ is the fractional density discontinuity ($\Delta \sim \frac{1}{4}$ for the Earth) and i is the angle between $\vec{\Omega}$ and $\vec{\omega}$. This criterion is analogous to the condition on $\omega\tau$ that we discussed for the convective dynamo. If this criterion is satisfied then an estimate for the poloidal field is

$$H_p \approx (2K\rho c^2/\sigma)^{\frac{1}{2}} \text{ gauss} \quad (7)$$

where ρ is the density in g/cm³, and σ the electrical conductivity in esu(sec⁻¹). Applications of these formulae are made in the next section.

THE PLANETS

In the following discussion, some of the numerical details are omitted since they have appeared elsewhere. Mercury: The high mean density of Mercury (5.4 g/cm³) indicates a dense iron-rich core that occupies about 50% of the total volume. Even in the unlikely event that part of this core is still fluid, the smallness of the planet and its slow rotation do not favor a convective dynamo. A precessional dynamo is even less likely because of the almost complete absence of precession.¹⁹ Nevertheless, the recent fly-by of Mercury by Mariner 10 indicates a substantial magnetosphere.²⁰ The magnetic field could be intrinsic to the planet (in which case, it corresponds to a surface field of typically 0.02 gauss); or it could be induced by temporal or spatial variability in the local interplanetary field. If the field is intrinsic, then the most likely explanation is a ferromagnetic remnant of a primordial dynamo that existed when the planet was rotating faster and had a fluid core.

(A rotation rate comparable to the present Earth would be adequate.) Such a primordial state is not in conflict with our present understanding of the formation of the solar system. Indeed, the surface morphology indicates ancient lava flooding and volcanism.

Venus: The important difference between the Earth and its sister planet is that the angular velocity of Venus is over two orders of magnitude smaller. Since Venus does not undergo significant precession, the dynamo mechanisms that we discussed do not work. It is not surprising that Mariner 10 and other planetary probes have detected no magnetosphere. (An upper bound to the surface field of Venus is 10^{-4} gauss.) Since Venus is the nearest thing we have to a non-rotating planet in our solar system, it is appropriate to mention that there is but one theory of planetary magnetism regeneration that requires no rotation: Hall currents.

Earth: The geomagnetic field has been extensively studied and is most easily explained by the dynamo mechanism. Such features as the secular variation and prehistoric reversals have been qualitatively explained by the dynamo model, although the reversals are not fully understood. More controversial is the energy source for the dynamo. The Ohmic dissipation of the Earth's dynamo is about 4×10^{17} erg/sec.⁸ If we suppose that cyclonic convection drives the dynamo then the geothermal heat flux of 3×10^{20} erg/sec would seem to be adequate. However, most of this heat is generated by radioactivity in the Earth's crust and is not available in the core. Furthermore, a convective engine is at most 4% efficient in transforming heat flux, through fluid motion, into Ohmic dissipation. It follows that unless more than about 5% of the Earth's heat flux originates from the core, a convective engine cannot run the Earth's dynamo. It has been suggested that the required heat flux could be supplied by radioactive ^{40}K in the core²¹ or the release of latent heat as the inner solid core grows.²²

The precession model has no similar problem. Malkus¹⁸ finds that the critical parameter K exceeds unity and that the dipole field (from equation (7)) is about 7 gauss, roughly the value expected in the Earth's core. The precessional model seems to be very satisfactory for the Earth.

Mars: The rotation and precession of Mars are comparable to the Earth's. However, Mars is a much smaller planet and only a small fraction of it (if any) is fluid.²³ If the conditions on Earth are kinematically marginal for a convective dynamo then they are certainly unfavorable for Mars. The precessional model is also in difficulty unless the conductivity in the deep interior of Mars is much greater than for the Earth. Our present understanding of solar system chemistry would not support that. It is not surprising that the observed magnetic field of Mars is only 10^{-4} gauss. This could be a ferromagnetic remnant of a primordial field or primordial dynamo.

Jupiter: The largest planet in our solar system also has the greatest range of possible explanations for its observed intrinsic field.²⁴ As we have already mentioned, the field could be primordial or a consequence of thermoelectric currents. It could also be easily driven by thermal convection because of the large heat flux¹² and rapid rotation. Indeed, there is enough energy within Jupiter to drive many smaller dynamos simultaneously. In this sense, Jupiter should be compared with the Sun rather than the Earth. However, there are not likely to be "Jovian spots" in analogy to Sun spots, since the outer layers of Jupiter are electrically insulating. The Jovian dynamo is expected to be confined to the highly conducting metallic hydrogen core.

The massive satellites of Jupiter lie almost exactly in the equatorial plane, and produce no precessional torques. However, the Sun causes precession that is sufficient to maintain a magnetic field.⁸

Thus, Jupiter may have both precessional and convective dynamos.

Saturn: Recent models for the interior of Saturn²⁵ indicate that Saturn is very similar to Jupiter. Not only is the deep interior expected to be metallic hydrogen, but the temperature is expected to exceed the melting point. Both precessional and convective dynamos can be maintained without difficulty. Radio observations of Saturn indicate no synchrotron radiation, in contrast to Jupiter which is a strong radio source. However, the radiation belts may be at a very large radial distance from the planet, so as not to intersect with the rings. Luthy²⁶ has estimated that Saturn could have an intrinsic field of even twenty gauss and yet produce synchrotron radiation that is unobservable at Earth. When Pioneer 11 passes Saturn in 1979, it is likely to find a substantial intrinsic field.

Uranus: Unlike Jupiter and Saturn, Uranus does not seem to be endowed with a large internal heat flux.²⁷ The satellites of Uranus lie in the equatorial plane and the precessional torque of the Sun is too small to drive a precessional dynamo. It seems unlikely that Uranus has a large magnetic field.

Neptune: In contrast to Uranus, Neptune has a massive satellite Triton for which the angle between ω and Ω is about 160° . If conducting fluid is present, Neptune is likely to have a precessional dynamo.

Pluto: The outermost planet is almost certainly too small and too cold to have a dynamo.

CONCLUSION

We have found no conflict between the predictions of the dynamo theory and the observations of the planets. It is hoped that more detailed information on internal planetary fields in the future will lead to independent tests of interior models of planets.

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