Dynamo theory

In geophysics, **dynamo theory** proposes a mechanism by which a celestial body such as the Earth or a star generates a magnetic field. The theory describes the process through which a rotating, convecting, and electrically conducting fluid can maintain a magnetic field over astronomical time scales.

History of theory

When William Gilbert published *de Magnete* in 1600, he concluded that the Earth is magnetic and proposed the first theory for the origin of this magnetism: permanent magnetism such as that found in lodestone. In 1919, Joseph Larmor proposed that a dynamo might be generating the field.[1] [2] However, even after he advanced his theory, some prominent scientists advanced alternate theories. Einstein, believed that there might be an asymmetry between the charges of the electron and proton so that the Earth's magnetic field would be produced by the entire Earth. The Nobel Prize winner Patrick Blackett did a series of experiments looking for a fundamental relation between angular momentum and magnetic moment, but found none.[3] [4]

Walter M. Elsasser, considered a "father" of the presently accepted dynamo theory as an explanation of the Earth's magnetism, proposed that this magnetic field resulted from electric currents induced in the fluid outer core of the Earth. He revealed the history of the Earth's magnetic field through pioneering the study of the magnetic orientation of minerals in rocks.

In order to maintain the magnetic field against ohmic decay (which would occur for the dipole field in 20,000 years) the outer core must be convecting. The convection is likely some combination of thermal and compositional convection. The mantle controls the rate at which heat is extracted from the core. Heat sources include gravitational energy released by the compression of the core, gravitational energy released by the rejection of light elements (probably sulfur, oxygen, or silicon) at the inner core boundary as it grows, latent heat of crystallization at the inner core boundary, and radioactivity of potassium, uranium and thorium.[5]

At the dawn of the 21st century, numerical modeling of the Earth's magnetic field has not been successfully demonstrated, but appears to be in reach. Initial models are focused on field generation by convection in the planet's fluid outer core. It was possible to show the generation of a strong, Earth-like field when the model assumed a uniform core-surface temperature and exceptionally high viscosities for the core fluid. Computations which incorporated more realistic parameter values yielded magnetic fields that were less Earth-like, but also point the way to model refinements which may ultimately lead to an accurate analytic model. Slight variations in the core-surface temperature, in the range of a few millikelvins, result in significant increases in convective flow and produce more realistic magnetic fields.[6] [7]

Formal definition

Dynamo theory describes the process through which a rotating, convecting, and electrically conducting fluid acts to maintain a magnetic field. This theory is used to explain the presence of anomalously long-lived magnetic fields in astrophysical bodies. The conductive fluid in the geodynamo is liquid iron in the outer core, and in the solar dynamo is ionized gas at the tachocline. Dynamo theory of astrophysical bodies uses magnetohydrodynamic equations to investigate how the fluid can continuously regenerate the magnetic field.

It was actually once believed that the dipole, which comprises much of the Earth's magnetic field and is misaligned along the rotation axis by 11.3 degrees, was caused by permanent magnetization of the materials in the earth. This means that dynamo theory was originally used to explain the Sun's magnetic field in its relationship with that of the Earth. However, this theory, which was initially proposed by Joseph Larmor in 1919, has been modified due to extensive studies of magnetic secular variation, paleomagnetism (including polarity reversals), seismology, and the solar system's abundance of elements. Also, the application of the theories of Carl Friedrich Gauss to magnetic observations showed that Earth's magnetic field had an internal, rather than external, origin.

There are three requisites for a dynamo to operate:

- An electrically conductive fluid medium
- Kinetic energy provided by planetary rotation
- An internal energy source to drive convective motions within the fluid.[8]

In the case of the Earth, the magnetic field is induced and constantly maintained by the convection of liquid iron in the outer core. A requirement for the induction of field is a rotating fluid. Rotation in the outer core is supplied by the Coriolis effect caused by the rotation of the Earth. The coriolis force tends to organize fluid motions and electric currents into columns (also see Taylor columns) aligned with the rotation axis. Induction or creation of magnetic field is described by the induction equation:

$$\frac{\partial \mathbf{B}}{\partial t} = \eta \nabla^2 \mathbf{B} + \nabla \times (\mathbf{u} \times \mathbf{B})$$

where $\mathbf{u}$ is velocity, $\mathbf{B}$ is magnetic field, t is time, and $\eta = 1/\sigma\mu$ is the magnetic diffusivity with σ electrical conductivity and μ permeability. The ratio of the second term on the right hand side to the first term gives the Magnetic Reynolds number, a dimensionless ratio of advection of magnetic field to diffusion.

Kinematic dynamo theory

In kinematic dynamo theory the velocity field is prescribed, instead of being a dynamic variable. This method cannot provide the time variable behavior of a fully nonlinear chaotic dynamo but is useful in studying how magnetic field strength varies with the flow structure and speed.

Using Maxwell's equations simultaneously with the curl of Ohm's Law, one can derive what is basically the linear eigenvalue equation for magnetic fields (**B**) which can be done when assuming that the magnetic field is independent from the velocity field. One arrives at a critical *magnetic Reynolds number* above which the flow strength is sufficient to amplify the imposed magnetic field, and below which it decays.

The most functional feature of kinematic dynamo theory is that it can be used to test whether a velocity field is or is not capable of dynamo action. By applying a certain velocity field to a small magnetic field, it can be determined through observation whether the magnetic field tends to grow or not in reaction to the applied flow. If the magnetic field does grow, then the system is either capable of dynamo action or is a dynamo, but if the magnetic field does not grow, then it is simply referred to as non-dynamo.

The membrane paradigm is a way of looking at black holes that allows for the material near their surfaces to be expressed in the language of dynamo theory.

Nonlinear dynamo theory

The kinematic approximation becomes invalid when the magnetic field becomes strong enough to affect the fluid motions. In that case the velocity field becomes affected by the Lorentz force, and so the induction equation is no longer linear in the magnetic field. In most cases this leads to a quenching of the amplitude of the dynamo. Such dynamos are sometimes also referred to as hydromagnetic dynamos [9]. Virtually all dynamos in astrophysics and geophysics are hydromagnetic dynamos.

Numerical models are used to simulate fully nonlinear dynamos. A minimum of 5 equations are needed. They are as follows. The induction equation, see above. Maxwell's equation:

$$\nabla \cdot \mathbf{B} = 0$$

The (sometimes) Boussinesq conservation of mass:

$$\nabla \cdot \mathbf{u} = 0$$

The (sometimes) Boussinesq conservation of momentum, also known as the Navier-Stokes equation:

$$\frac{D\mathbf{u}}{Dt} = -\nabla p + \nu\nabla^2\mathbf{u} + \rho^{'}\mathbf{g} + 2\mathbf{\Omega}\times\mathbf{u} + \mathbf{\Omega}\times\mathbf{\Omega}\times\mathbf{R} + \mathbf{J}\times\mathbf{B}$$

where ν is the kinematic viscosity, $\rho^{'}$ is the density perturbation that provides buoyancy (for thermal convection $\rho^{'} = \alpha\Delta T$, Ω is the rotation rate of the Earth, and $\mathbf{J}$ is the electrical current density.

Finally, a transport equation, usually of heat (sometimes of light element concentration):

$$\frac{\partial T}{\partial t} = \kappa\nabla^2 T + \epsilon$$

where T is temperature, $\kappa = k/\rho c_p$ is the thermal diffusivity with k thermal conductivity, c_p heat capacity, and ρ density, and ϵ is an optional heat source. Often the pressure is the dynamic pressure, with the hydrostatic pressure and centripetal potential removed. These equations are then non-dimensionalized, introducing the non-dimensional parameters,

$$Ra = \frac{g\alpha T D^3}{\nu\kappa}, E = \frac{\nu}{\Omega D^2}, Pr = \frac{\nu}{\kappa}, Pm = \frac{\nu}{\eta}$$

where *Ra* is the Rayleigh number, *E* the Ekman number, *Pr* and *Pm* the Prandtl and magnetic Prandtl number. Magnetic field scaling is often in Elsasser number units $B = \rho\Omega/\sigma$.

References

[1] Larmor, J. (1919). "How could a rotating body such as the Sun become a magnet?". *Reports of the British Association* **87**: 159–160.

[2] Larmor, J. (1919). "Possible rotational origin of magnetic fields of sun and earth". *Electrical Review* **85**: 412ff. Reprinted in *Engineering*, vol. 108, pages 461ff (3 October 1919).

[3] Nye, Mary Jo (1 March 1999). "Temptations of theory, strategies of evidence: P. M. S. Blackett and the earth's magnetism, 1947–52". *The British Journal for the History of Science* **32** (1): 69–92. doi:10.1017/S0007087498003495.

[4] Merrill, McElhinny & McFadden 1996, page 17 claim that in 1905, shortly after composing his special relativity paper, Albert Einstein described the origin of the Earth's magnetic field as being one of the great unsolved problems facing modern physicists. However, they do not provide details on where he made this statement.

[5] Sanders, Robert (2003-12-10). "Radioactive potassium may be major heat source in Earth's core" (http://www.berkeley.edu/news/media/releases/2003/12/10_heat.shtml). UC Berkeley News. . Retrieved 2007-02-28.

[6] Sakuraba, Ataru; Paul H. Roberts (4 October 2009). "Generation of a strong magnetic field using uniform heat flux at the surface of the core". *Nature Geoscience* (Nature Publishing Group) **2** (11): 802–805. Bibcode 2009NatGe...2..802S. doi:10.1038/ngeo643.

[7] Buffett, Bruce (2009). "Geodynamo: A matter of boundaries". *Nature Geoscience* (Nature Publishing Group) **2** (2): 741–742. Bibcode 2009NatGe...2..741B. doi:10.1038/ngeo673.

[8] E. Pallé (2010). *The Earth as a Distant Planet: A Rosetta Stone for the Search of Earth-Like Worlds (Astronomy and Astrophysics Library)* (http://books.google.com/books?id=qLuVCJtRTV0C&pg=PA316&dq=the+dynamo+theory+holds+that#v=onepage&q=the dynamo theory holds that&f=false). Berlin: Springer. pp. 316–317. ISBN 1-4419-1683-0. . Retrieved 17 july 2010.

[9] http://www.scholarpedia.org/article/Hydromagnetic_Dynamo_Theory

- Demorest, Paul (21 May 2001). "Dynamo Theory and Earth's magnetic Field (term paper)" (http://setiathome.berkeley.edu/~pauld/etc/210BPaper.pdf) (pdf). Retrieved 14 October 2011.
- Fitzpatrick, Richard (18 May 2002). "MHD Dynamo Theory" (http://farside.ph.utexas.edu/teaching/plasma/lectures/node70.html). *Plasma Physics*. University of Texas at Austin. Retrieved 14 October 2011.
- Merrill, Ronald T.; McElhinny, Michael W.; McFadden, Phillip L. (1996). *The magnetic field of the earth: Paleomagnetism, the core, and the deep mantle*. Academic Press. ISBN 978-0124912465.
- Stern, David P.. "Chapter 12: The dynamo process" (http://www.phy6.org/earthmag/dynamos.htm). *The Great Magnet, the Earth*. Retrieved 14 October 2011.
- Stern, David P.. "Chapter 13: Dynamo in the Earth's Core" (http://www.phy6.org/earthmag/dynamos2.htm). *The Great Magnet, the Earth*. Retrieved 14 October 2011.

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