for airborne surveys is the diurnal variation, which generally has an amplitude of tens of nanotesla. Shorter time-period variations due to magnetic storms can be much larger (hundreds of nanotesla) and severe enough to prevent survey data collection. Data can also be degraded my micropulsations with short periods and amplitudes of several nanotesla. Monitoring of the Earth's field is an essential component of a survey in order to mitigate these time-varying effects. One or more base station magnetometers is used to track changes in the field during survey operations. When variations are unacceptably large, surveying is suspended and any flightlines recording during disturbed periods are reflown. The smoothly changing diurnal variation is removed from the data using tie-line leveling. Simply subtracting this variation from the measured data is not sufficient since diurnal changes may vary significantly over the survey area. Nonetheless, the recorded diurnal can be used as a guide in the leveling process. Tie-line leveling is based on the differences in the measured field at the intersection of flightlines and tie-lines. If the distance and hence the time taken to fly between these intersection points is small enough then it can be assumed that the diurnal varies approximately linearly and can be corrected for (Luyendyk, 1997).

Data display and interpretation

The final product resulting from an aeromagnetic survey is a set of leveled flightline data that are interpolated onto a regular grid of magnetic field intensity values covering the survey region. These values can be displayed in a variety of ways, the most common being a color map or image, where the magnetic field values, based on their magnitude, are assigned a specific color. Similarly, the values can be represented as a simple line contour map. Both kinds of representation can be used in a qualitative fashion to divide the survey area into subregions of high and low magnetizations. Since the data are available digitally, it is straightforward to use computer-based algorithms to modify and enhance the magnetic field image for the specific purpose of the survey. Transformation and filtering allows certain attributes of the data to be enhanced, such as the effects due to magnetic sources at shallow or deep levels, or occurring along a specified strike direction. More sophisticated methods may estimate the depths, locations, attitudes, and the magnetic properties of magnetic sources.

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Cross-references

Compass
Crustal Magnetic Field
Depth to Curie Temperature
IGRF, International Geomagnetic Reference Field
Magnetic Anomalies for Geology and Resources
Magnetic Anomalies, Modeling

AGRICOLA, GEORGIUS (1494–1555)

Agricola, which seems to have been the classical academic pen-name for Georg Bauer, was born at Glauchau, Germany, on March 24, 1494 as the son of a dyer and draper. He studied at Leipzig University and trained as a doctor, and became Town Physician to the Saxon mining community of Chemnitz. His significance derives from his great treatise on metal mining, *De Re Metallica* (1556), or "On Things of Metal." This sumptuously illustrated work was a masterly study of all aspects of mining, including geology, stratigraphy, pictures of mineshafts, machinery, smelting foundries, and even the diseases suffered by miners.

Book III of *De Re Metallica* contains a description and details of how to use the miner's compass which, by 1556, seems to have been a well-established technical aid to the industry. Agricola drew a parallel between the miner's and the mariner's compass, saying that the direction cards of both were divided into equidistant divisions in accordance with a system of "winds." Agricola's compass is divided into four quadrants, with each quadrant subdivided into six: 24 equidistant divisions around the circle. And just as a mariner named the "quarters" of his compass from the prevailing winds, such as "Septentrio" for north and "Auster" for south, so the miner likewise named his underground metal veins, depending on the directions in which they ran.

Agricola also tells us that when prospecting for ore, a mining engineer would use his compass to detect the veins of metal underground and use it to plot their direction and the likely location of their strata across the landscape.

Agricola, it was said, always enjoyed robust health and vigor. He served as Burgomaster of Chemnitz on several occasions and worked tirelessly for the sick during the Bubonic Plague epidemic that ravaged Saxony during 1552–1553. Then, on November 21, 1555, he suddenly died from a "four days" fever.

Allan Chapman

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ALFVÉN WAVES

Introduction and historical details

Alfvén waves are transverse magnetic tension waves that travel along magnetic field lines and can be excited in any electrically conducting fluid permeated by a magnetic field. *Hannes Alfvén (q.v.)* deduced their existence from the equations of electromagnetism and hydrodynamics (Alfvén, 1942). Experimental confirmation of his prediction was found seven years later in studies of waves in liquid mercury (Lundquist, 1949). Alfvén waves are now known to be an important mechanism for transporting energy and momentum in many geophysical and astrophysical hydromagnetic systems. They have been observed in Earth's magnetosphere (Voigt, 2002), in interplanetary plasmas (Tsurutani and Ho, 1999), and in the solar photosphere (Nakariakov *et al.*, 1999). The ubiquitous nature of Alfvén waves and their role in communicating the effects of changes in electric currents and magnetic fields has ensured that they remain the focus of increasingly detailed laboratory investigations (Gekelman, 1999). In the context of geomagnetism, it has been suggested that Alfvén waves could be a crucial aspect of the dynamics of Earth's liquid outer core and they have been proposed as the origin of *geomagnetic jerks* (*q.v.*) (Bloxham *et al.*, 2002). In this article a description is given of the Alfvén wave mechanism, the Alfvén wave equation is derived and the consequences of Alfvén waves for geomagnetic observations are discussed. Alternative introductory perspectives on Alfvén waves can be found in the books by Alfvén and Fälthammar (1963), Moffatt (1978), or Davidson (2001). More technical details concerning Alfvén waves in Earth's core can be found in the review article of Jault (2003).

The Alfvén wave mechanism

The restoring force responsible for Alfvén waves follows from two simple physical principles:

1. Lenz's law applied to conducting fluids: "Electrical currents induced by the motion of a conducting fluid through a magnetic field give rise to electromagnetic forces acting to oppose that fluid motion."
2. Newton's second law for fluids: "A force applied to a fluid will result in a change in the momentum of the fluid proportional to the magnitude of the force and in the same direction."

The oscillation underlying Alfvén waves is best understood via a simple thought experiment (Davidson, 2001). Imagine a uniform magnetic field permeating a perfectly conducting fluid, with a uniform flow initially normal to the magnetic field lines. The fluid flow will distort the magnetic field lines (see *Alfvén's theorem and the frozen flux approximation*) so they become curved as shown in Figure A1 (part (b)). The curvature of magnetic field lines produces a magnetic (Lorentz) force on the fluid, which opposes further curvature as predicted by Lenz's law. By Newton's second law, the Lorentz force changes the momentum of the fluid, pushing it (and consequently the magnetic field lines) in an attempt to minimize field line distortion and restore the system toward its equilibrium state. This restoring force provides the basis for transverse oscillations of magnetic fields in conducting fluids and therefore for Alfvén waves. As the curvature of the magnetic field lines increases, so does the strength of the restoring force. Eventually the Lorentz force becomes strong enough to reverse the direction of the fluid flow. Magnetic field lines are pushed back to their undistorted configuration and the Lorentz force associated with their curvature weakens until the field lines become straight again. The sequence of flow causing field line distortion and field line distortion exerting a force on the fluid now repeats, but with the initial flow (a consequence of fluid inertia) now in the opposite direction. In the absence of dissipation this cycle will continue indefinitely. Figure A1 shows one complete cycle resulting from the push and pull between inertial acceleration and acceleration due to the Lorentz force.

Consideration of typical scales of physical quantities involved in this inertial-magnetic (Alfvén) oscillation shows that the strength of the magnetic field will determine the frequency of Alfvén waves. Balancing inertial accelerations and accelerations caused by magnetic field curvature, we find that $U/T_A = B^2/L_A\rho\mu$ where U is a typical scale of the fluid velocity, T_A is the time scale of the inertial-magnetic (Alfvén) oscillation, L_A is the length scale associated with the oscillation, B is the scale of the magnetic field strength, ρ is the fluid density, and μ is the magnetic permeability of the medium. For highly electrically conducting fluids, magnetic field changes occur primarily through advection (see *Alfvén's theorem and the frozen flux approximation*) so we have the additional constraint that $B/T_A = UB/L_A$ or $U = L_A/T_A$. Consequently $L_A^2/T_A^2 = B^2/\rho\mu$ or $v_A = B/(\rho\mu)^{1/2}$. This is a characteristic velocity scale associated with Alfvén waves and is referred to as the Alfvén velocity. The Alfvén velocity will be derived in a more rigorous manner and its implications discussed further in the next section.

Physical intuition concerning Alfvén waves can be obtained through an analogy between the response of a magnetic field line distorted by fluid flow across it and the response of an elastic string when plucked. Both rely on tension as a restoring force, elastic tension in the case of the string and magnetic tension in the case of the magnetic field line and both result in transverse waves propagating in directions perpendicular to their displacement. When visualizing Alfvén waves it can be helpful to think of a fluid being endowed with a pseudoelastic nature by the presence of a magnetic field, and consequently supporting transverse waves. Nonuniform magnetic fields have similar consequences for Alfvén waves as nonuniform elasticity of solids has for elastic shear waves.

The Alfvén wave equation

To determine the properties of Alfvén waves in a quantitative manner, we employ the classical technique of deriving a wave equation and then proceed to find the relationship between frequency and wavelength necessary for plane waves to be solutions. Consider a uniform, steady, magnetic field $\boldsymbol{B_0}$ in an infinite, homogeneous, incompressible, electrically conducting fluid of density ρ, kinematic viscosity ν, and magnetic diffusivity $\eta = 1/\sigma\mu$ where σ is the electrical conductivity.

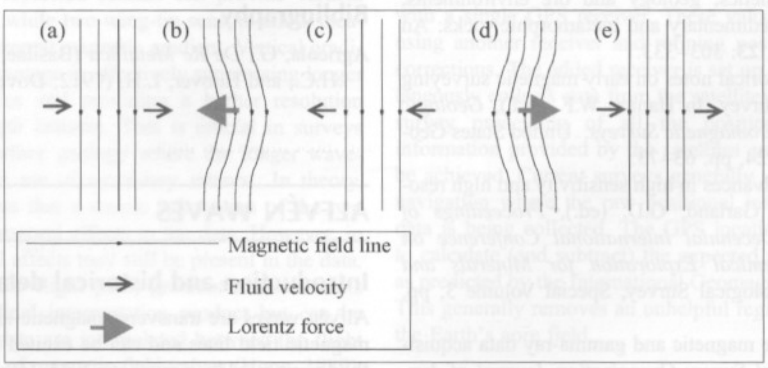

Figure A1 The Alfvén wave mechanism. In (a) an initial fluid velocity normal to the uniform field lines distorts them into the curved lines shown in (b) giving rise to a Lorentz force which retards and eventually reverses the fluid velocity, returning the field lines to their undisturbed position as shown in (c). The process of field line distortion is then reversed in (d) until the cycle is completed with the return to the initial configuration in (e).

We imagine that the fluid is perturbed by an infinitesimally small flow $\boldsymbol{u}$ inducing a perturbation magnetic field $\boldsymbol{b}$. Ignoring terms that are quadratic in small quantities, the equations describing Newton's second law for fluids and the evolution of the magnetic fields encompassing Lenz's law are

$$\underbrace{\frac{\partial \boldsymbol{u}}{\partial t}}_{\substack{\text{Inertial}\\ \text{acceleration}}} = \underbrace{-\frac{1}{\rho}\nabla p}_{\substack{\text{Combined mechanical}\\ \text{and magnetic}\\ \text{pressure gradient}}} + \underbrace{\frac{1}{\rho\mu}(\boldsymbol{B_0}\cdot\nabla)\boldsymbol{b}}_{\substack{\text{Lorentz acceleration}\\ \text{due to magnetic tension}}} + \underbrace{\nu\nabla^2\boldsymbol{u}}_{\substack{\text{Viscous}\\ \text{diffusion}}}, \qquad \text{(Eq. 1)}$$

$$\underbrace{\frac{\partial \boldsymbol{b}}{\partial t}}_{\substack{\text{Change in the}\\ \text{magnetic field}}} = \underbrace{(\boldsymbol{B_0}\cdot\nabla)\boldsymbol{u}}_{\substack{\text{Stretching of magnetic}\\ \text{field by fluid motion}}} + \underbrace{\eta\nabla^2\boldsymbol{b}}_{\substack{\text{Magnetic}\\ \text{diffusion}}} \qquad \text{(Eq. 2)}$$

Taking the curl ($\nabla\times$) of equation 1, we obtain an equation describing how the fluid vorticity $\xi = \nabla\times\boldsymbol{u}$ evolves

$$\frac{\partial\xi}{\partial t} = \frac{1}{\rho\mu}(\boldsymbol{B_0}\cdot\nabla)(\nabla\times\boldsymbol{b}) + \nu\nabla^2\xi. \qquad \text{(Eq. 3)}$$

$\nabla\times$ equation 2 gives

$$\nabla\times\frac{\partial\boldsymbol{b}}{\partial t} = (\boldsymbol{B_0}\cdot\nabla)\xi + \eta\nabla^2(\nabla\times\boldsymbol{b}). \qquad \text{(Eq. 4)}$$

To find the wave equation, we take a further time derivative of equation 3 so that

$$\frac{\partial^2\xi}{\partial t^2} = \frac{1}{\rho\mu}(\boldsymbol{B_0}\cdot\nabla)\left(\nabla\times\frac{\partial\boldsymbol{b}}{\partial t}\right) + \nu\left(\nabla^2\frac{\partial\xi}{\partial t}\right), \qquad \text{(Eq. 5)}$$

and then eliminate $\boldsymbol{b}$ using an expression for $\frac{1}{\rho\mu}(\boldsymbol{B_0}\cdot\nabla)(\nabla\times\partial\boldsymbol{b}/\partial t)$ in terms of ξ obtained by operating with $\frac{1}{\rho\mu}(\boldsymbol{B_0}\cdot\nabla)$ on (4) and substituting for $\frac{1}{\rho\mu}(\boldsymbol{B_0}\cdot\nabla)(\nabla\times\boldsymbol{b})$ from equation 3 which gives

$$\frac{1}{\rho\mu}(\boldsymbol{B_0}\cdot\nabla)\left(\nabla\times\frac{\partial\boldsymbol{b}}{\partial t}\right) = \frac{1}{\rho\mu}(\boldsymbol{B_0}\cdot\nabla)^2\xi - \nu\eta\nabla^4\xi + (\nu+\eta)\nabla^2\left(\frac{\partial\xi}{\partial t}\right), \qquad \text{(Eq. 6)}$$

which when substituted into equation 5 leaves the Alfvén wave equation

$$\frac{\partial^2\xi}{\partial t^2} = \frac{1}{\rho\mu}(\boldsymbol{B_0}\cdot\nabla)^2\xi - \nu\eta\nabla^4\xi + (\nu+\eta)\nabla^2\left(\frac{\partial\xi}{\partial t}\right). \qquad \text{(Eq. 7)}$$

The first term on the right hand side is the restoring force which arises from the stretching of magnetic field lines. The second term is the correction to the restoring force caused by the presence of viscous and ohmic diffusion, while the final term expresses the dissipation of energy from the system due to these finite diffusivities.

Dispersion relation and properties of Alfvén waves

Substituting a simple plane wave solution of the form $\xi = Re\{\hat{\xi}e^{i(\boldsymbol{k}\cdot\boldsymbol{r}-\omega t)}\}$ where $\boldsymbol{k} = k_x\hat{x} + k_y\hat{y} + k_z\hat{z}$ and $\boldsymbol{r} = x\hat{x} + y\hat{y} + z\hat{z}$ into the Alfvén wave equation 7, we find that valid solutions are possible provided that

$$\omega^2 = \left(\frac{B_0^2(\boldsymbol{k}\cdot\hat{\boldsymbol{B}}_{\boldsymbol{0}})^2}{\rho\mu} - \nu\eta k^4\right) - i(\nu+\eta)k^2\omega. \qquad \text{(Eq. 8)}$$

where $\hat{\boldsymbol{B}}_{\boldsymbol{0}} = \boldsymbol{B_0}/|\boldsymbol{B_0}|$.

Equation 8 is the dispersion relation, which specifies the relationship between the angular frequency ω and the wavenumber k of Alfvén waves. It is a complex quadratic equation in ω, so we can use the well known formula to find explicit solutions for ω, which are

$$\omega = \frac{-i(\nu+\eta)k^2}{2} \pm \sqrt{\frac{B_0^2(\boldsymbol{k}\cdot\hat{\boldsymbol{B}}_{\boldsymbol{0}})^2}{\rho\mu} - \frac{(\nu-\eta)^2k^4}{4}}. \qquad \text{(Eq. 9)}$$

In an idealized medium with $\nu = \eta = 0$ there is no dissipation and the dispersion relation simplifies to

$$\omega = \pm v_A(\boldsymbol{k}\cdot\hat{\boldsymbol{B}}_{\boldsymbol{0}}), \qquad \text{(Eq. 10)}$$

where v_A is the Alfvén velocity

$$v_A = \frac{B_0}{(\rho\mu)^{1/2}}. \qquad \text{(Eq. 11)}$$

This derivation illustrates that the Alfvén velocity is the speed at which an Alfvén wave propagates along magnetic field lines. Alfvén waves are nondispersive because their angular frequency is independent of $|k|$ and the phase velocity and the group velocity (at which energy and information are transported by the wave) are equal. Alfvén waves are however anisotropic, with their properties dependent on the angle between the applied magnetic field and the wave propagation direction.

An idea of Alfvén wave speeds in Earth's core can be obtained by inserting into equation 11 the seismologically determined density of the outer core fluid $\rho = 1\times10^4$ kg, the magnetic permeability for a metal above its Curie temperature $\mu = 4\pi\times10^{-7}$ T^2 mkg^{-1}s^2 and a plausible value for the strength of the magnetic field in the core (which we take to be the typical amplitude of the radial field strength observed at the core surface $B_0 = 5\times10^{-4}$ T) giving an Alfvén velocity of $v_A = 0.004$ m s^{-1} or 140 km yr^{-1}. The time taken for such a wave to travel a distance of order of the core radius is around 25 years. It should also be noted that Alfvén waves in the magnetosphere (where they also play an important role in dynamics) travel much faster because the density of the electrically conducting is very much smaller.

Considering Alfvén waves in Earth's core, Ohmic dissipation is expected to dominate viscous dissipation but for large scale waves will still be a small effect so that $\nu k^2 \ll \eta k^2 \ll v_A^2$. Given this assumption the dispersion relation reduces to

$$\omega = \frac{-i\eta k^2}{2} \pm v_A(\boldsymbol{k}\cdot\hat{\boldsymbol{B}}_{\boldsymbol{0}}) \qquad \text{(Eq. 12)}$$

and the wave solutions have the form of simple Alfvén waves, damped on the Ohmic diffusion timescale of $T_{ohm} = 2/\eta k^2$

$$\xi = Re\left\{\hat{\xi}e^{i(\boldsymbol{k}\cdot\boldsymbol{r}\pm v_A(\boldsymbol{k}\cdot\hat{\boldsymbol{B}}_{\boldsymbol{0}})t)e^{-t/T_{ohm}}}\right\} \qquad \text{(Eq. 13)}$$

Smaller scale waves are rapidly damped out by Ohmic diffusion, while large scale waves will be the longer lived, so we expect these to have the most important impact on both dynamics of the core and the observable magnetic field.

Observations of Alfvén waves and their relevance to geomagnetism

The theory of Alfvén waves outlined above is attractive in its simplicity, but can we really expect such waves to be present in Earth's core? In the outer core, rotation will have a strong influence on the fluid dynamics (see *Proudmann-Taylor theorem*). Alfvén waves cannot exist when the Coriolis force plays an important role in the force balance; in this case, more complex wave motions arise (see *Magnetohydrodynamic waves*). In addition convection is occurring (see *Core convection*)

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and gives rise to a dynamo generated magnetic field (see *Geodynamo*), which is both time dependent and spatially nonuniform, while the boundary conditions imposed by the mantle are heterogeneous—these factors combine to produce a formidably complex system.

Braginsky (1970) recognized that, despite all these complications, a special class of Alfvén waves is likely to be the mechanism by which angular momentum is redistributed on short (decadal) timescales in Earth's core. He showed that when Coriolis forces are balanced by pressure forces, Alfvén waves involving only the component of the magnetic field normal to the rotation axis can exist. The fluid motions in this case consist of motions of cylindrical surfaces aligned with the rotation axis, with the Alfvén waves propagating along field lines threading these cylinders and being associated with east-west oscillations of the cylinders. Similarities to torsional motions familiar from classical mechanics led Braginsky to christen these geophysically important Alfvén waves torsional oscillations (see *Oscillations, torsional*). Although the simple Alfvén wave model captures the essence of torsional oscillations and leads to a correct order of magnitude estimate of their periods, coupling to the mantle and the non-axisymmetry of the background magnetic field should be taken into account and lead to modifications of the dispersion relation given in equation 9. A detailed discussion of such refinements can be found in Jault (2003).

The last 15 years have seen a rapid accumulation of evidence suggesting that Alfvén waves in the form of torsional oscillations are indeed present in Earth's core. The transfer of angular momentum between the mantle and torsional oscillations in the outer core is capable of explaining decadal changes in the rotation rate of Earth (see *Length of day variations, decadal*). Furthermore, core flows determined from the inversion of global magnetic and secular variation data show oscillations in time of axisymmetric, equatorially symmetric flows which can be accounted for by a small number of spherical harmonic modes with periodic time dependence (Zatman and Bloxham, 1997). The superposition of such modes can produce abrupt changes in the second time derivative of the magnetic field observed at Earth's surface, similar to geomagnetic jerks (Bloxham *et al.*, 2002). Interpreting axisymmetric, equatorially symmetric core motions with a periodic time dependence as the signature of torsional oscillations leads to the suggestion that geomagnetic jerks are caused by Alfvén waves in Earth's core. Further evidence for the wave-like nature of the redistribution of zonally averaged angular momentum derived from core flow inversions has been found by Hide *et al.* (2000), with disturbances propagating from the equator towards the poles. The mechanism exciting torsional oscillations in Earth's core is presently unknown, though one suggestion is that the time dependent, nonaxisymmetric magnetic field could give rise to a suitable fluctuating Lorentz torque on geostrophic cylinders (Dumberry and Bloxham, 2003).

Future progress in interpreting and understanding Alfvén waves in Earth's core will require the incorporation of more complete dynamical models of torsional oscillations (see, for example, Buffett and Mound, 2005) into the inversion of geomagnetic observations for core motions.

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Cross-references

Alfvén's Theorem and the Frozen Flux Approximation
Alfvén, Hannes Olof Gösta (1908–1995)
Core Convection
Geodynamo
Length of Day Variations, Decadal
Magnetohydrodynamic Waves
Oscillations, Torsional
Proudman-Taylor Theorem

ALFVÉN, HANNES OLOF GÖSTA (1908–1995)

Hannes Alfvén is best known in geomagnetism for the "frozen flux" theorem that bears his name and for the discovery of magnetohydrodynamic waves. He started research in the physics department at the University of Uppsala, where he studied radiation in triodes. His early work on electronics and instrumentation was sound grounding for his later discoveries in cosmic physics. When his book *Cosmical Electrodynamics* (Alfvén, 1950) was published, the author was referred to by one of the reviewers—*T.G. Cowling* (*q.v.*)—as "an electrical engineer in Stockholm." All of Hannes Alfvén's scientific work reveals a profound physical insight and an intuition that allowed him to derive results of great generality from specific problems.

Hannes Alfvén is most widely known for his discovery (Alfvén, 1942) of a new kind of waves now generally referred to as *Alfvén waves* (*q.v.*). These are a transverse mode of magnetohydrodynamic waves, and propagate with the Alfvén velocity, $B/(\mu_0\rho)^{1/2}$. In the Earth's core they occur as torsional oscillations as well as other Alfvén-type modes that are altered by the Coriolis force and have quite a different character (see *Magnetohydrodynamic waves*). Before Alfvén, electromagnetic theory and hydrodynamics were well developed but as separate