MAGNETO-CONVECTION

Magneto-convection

Convection is the process whereby energy is transported by bulk fluid motions. It is driven by buoyancy. Since there is approximate horizontal pressure balance (no large scale sideways motions), warm fluid is less dense and buoyant, while cool fluid is denser and is pulled down by gravity. In a stratified system (where there is a large difference in density between the top and bottom of the convecting layer) there is asymmetry between the upward and downward motions because of mass conservation. Density decreases with increasing height, so rising fluid must diverge and must turn over within a density scale height (the distance over which the density decreases by a factor of e=2.72). Similarly, descending fluid must converge. The divergence of rising fluid tends to smooth out any fluctuations and turbulence. The convergence of descending fluid tends to enhance fluctuations and turbulence.

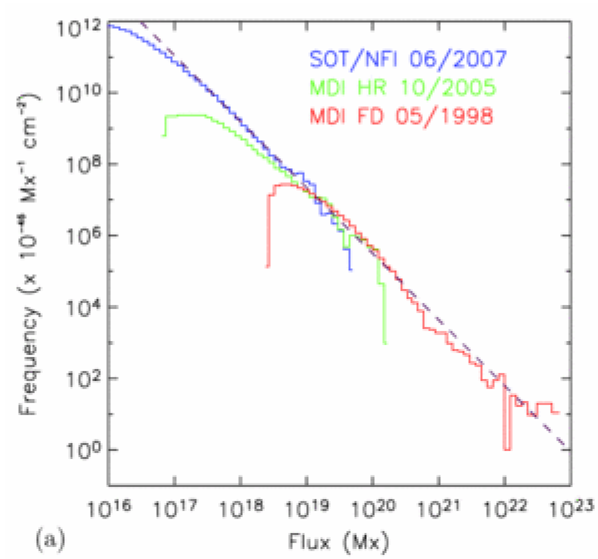

Figure 1: Histogram of magnetic features' fluxes is a power law (from Hinode and MDI; Parnelll et al. 2009; reproduced by permission of the AAS)

Magneto-convection is convection in an ionized plasma in the presence of magnetic fields. If the Lorentz force exerted by the magnetic field is weaker than the force exerted by the moving plasma (turbulent pressure), then the convective motions twist and stretch the magnetic field, which in a turbulent flow increases its strength (dynamo action). If the Lorentz forces are stronger than the turbulent pressure forces, then the magnetic field channels the plasma motions along the field direction and inhibits the convection. In a stratified medium, the diverging upflows sweep the magnetic field into the converging, turbulent downflow lanes (Weiss 1966; Hurlburt & Toomre 1988). When strong magnetic flux threads through a horizontal convective layer, it tends to get concentrated in strong patches, with convection proceeding relatively unencumbered outside the patches in a phenomenon known as flux separation (Tao et al. 1998).

Magneto-convection occurs in stars: near the surface of cool (low mass) stars, in the cores of large mass stars, surrounding nuclear burning shells in the late stages of stellar evolution, and in supernova explosions. Magneto-convection also occurs inaccretion disks during the formation of stars and planets and in accretion onto black holes and neutron stars. Magneto-convection occurs as well in the hot plasma in clusters of galaxies. See Stellar convection simulations, Hydromagnetic dynamo theory.

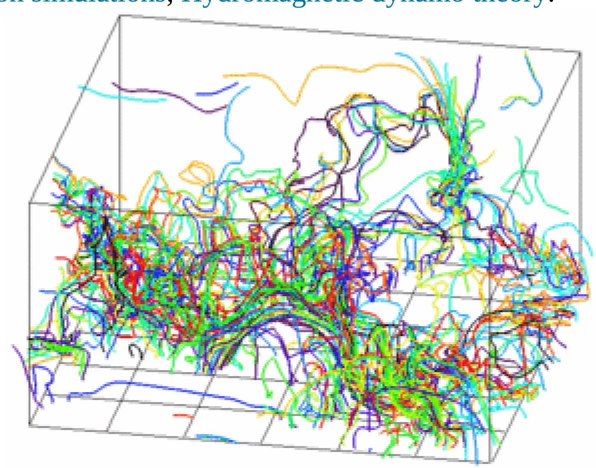

Figure 2: Magnetic field lines in solar surface magneto-convection simulation. Horizontal magnetic field was advected into the computational domain by upflows at the bottom boundary. Note the flux tube that formed in the upper right, which is connected in a complex way to the subsurface magnetic field (Stein & Nordlund 2006, reproduced by permission of the AAS)

Solar magneto-convection has an indirect impact on the Earth. In the outer third of the Sun energy is transported by convection because the mean free path for photons becomes too short for them to transport much energy from the hot interior (where it is released by the fusion of hydrogen into helium) to the cool surface. The turbulent convective motions generate a magnetic field by dynamo action. The field emerges through the visible surface over a wide range of scales (from hundreds to tens of thousands of km). The convection induced motions of the field that threads through the surface up into the corona, heats the corona to millions of degrees and drives outward a wind of energetic electrons, protons and ions (the solar wind). These charged particles when they reach the Earth, interact with Earth's magnetic field. The magnetic field above the Sun's surface can store large amounts of magnetic energy. Occasionally, the field reconnects rapidly into a lower energy configuration and produces a burst of extremely high energy particles. These bursts cause disturbances in the outer atmosphere of the Earth, which can produce auroras, disrupt radio communication, and endanger astronauts and satellites. The effect of the solar wind on the Earth is a primary component of "space weather".

Equations

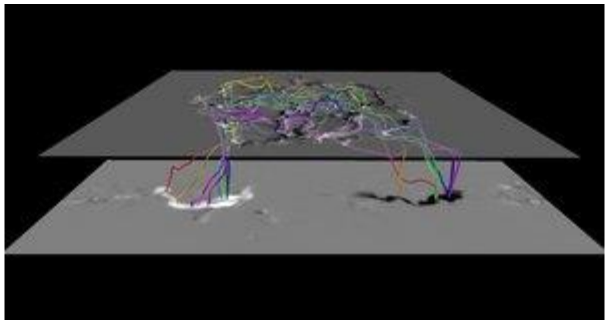

Figure 3: Magnetic field lines and vertical magnetic field strength (at the surface and 5 Mm below) for an emerging magnetic flux tube (Cheung et al. 2008)

To model magneto-convection, one solves the conservation equations for mass, momentum and energy (either total or internal or internal plus kinetic) plus the induction equation for the magnetic field (or the vector potential) and Ohm's law for the electric field. In general, one can use the MHD approximation, because charge neutrality is preserved except on very small length scales. It may be necessary in some cases to use a generalized Ohm's law, including the Hall term.

Numerical methods

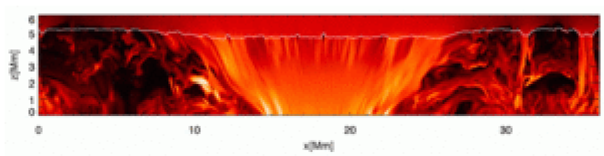

Figure 4: Magnetic field strength in simulated sunspot (Rempel, Schussler & Knolker 2009, reproduced by permission of the AAS)

To solve the partial differential equations describing magneto-convection on a computer it is necessary to either discretize the variables on a grid, or represent them in terms of some set of basis functions, or represent the fluid as individual particles. Discretizing the variables on a grid is called a finite difference or a finite volume method. Representing the variables in terms of basis functions is referred to as spectral or finite element methods. Representing the fluid as particles, with mass, momentum, energy and magnetic flux is called smooth particle dynamics. Once this is done, there are a finite number of variables (density, momentum, energy and magnetic field at each grid location or amplitude of each basis function or for each smooth particle) whose time derivatives must be calculated and then the variables advanced in time by some integration formula such as Runge-Kutta, starting from a chosen initial state.

Observations

Magnetic fields emerge through the solar surface on a wide range of scales, from small bipoles in granules that emerge randomly all the time, to the large sunspots and active regions that follow an 11 year cycle from minimum to maximum to minimum again. Clumping each contiguous area of magnetic flux with a given sign of the vertical component, leads to a power law distribution of flux over the entire range (Fig. 1) (Parnell et al. 2009). The magnetic field is produced by dynamo action in which the convective motions twist and stretch the magnetic field lines increasing their strength. The large scale cyclical pattern is believed due to the meridional circulation and the large shear layer at the bottom of the convection zone. Smaller scale flux emergence appear independent of these large scale flows.

In the quiet Sun, most of the small scale flux emerges as bipoles, with first horizontal field appearing and then opposite polarity vertical field appearing at the ends of the horizontal field concentration (Jin, Wang & Zhou 2009). These vertical legs of the bipole loops get swept into the intergranular lanes by the diverging upflows in the granules. Sometimes emerging flux appears only has horizontal field without accompanying vertical field, possibly due to diffuse vertical components that are below the detection limit. The average horizontal field strength is at least 55 G and is 5 times larger than the average vertical field strength. Typical horizontal field strengths may be as large as a few hundred Gauss (in approximate dynamic equilibrium with the convection) and vertical field strengths occur up to 1 kG (Lites 2009).

In active regions, magnetic flux initially emerges as a *cloud* of very small mixed polarity bipolar flux elements, and flux with opposite polarity stream away from each other coalescing into larger unipolar concentrations. In the process, some flux interacts with opposing polarity elements and reconnection occurs.

Applications

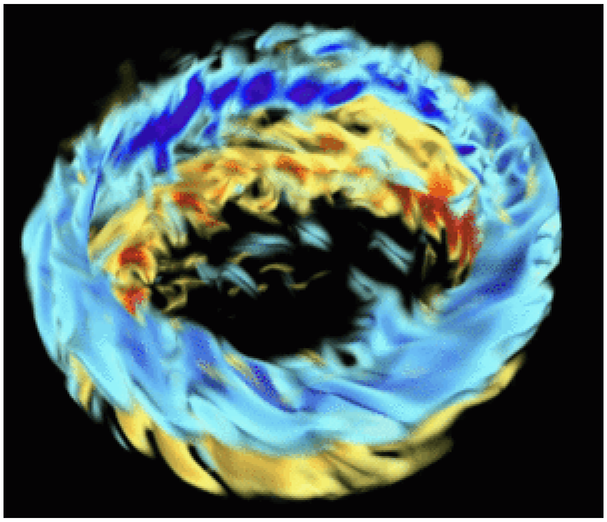

Figure 5: Magnetic field strength in simulation of solar like star rotating three times faster than the Sun. Note the formation of large scale field structures with opposite polarity above and below the equator (Brown, AAS, SPD, 6/2009)

Magneto-convection occurs in a wide range of astrophysical circumstances:

- cores of planets (Christensen, Schmitt & Rempel 2009; Chan et al. 2007),
- The surface of the Sun and other cool stars (Steiner et al. 1998; Brun, Miesch

& Toomre 2004; Voegler et al. 2005; Miesch 2005; Stein & Nordlund 2006, Jacoutot et al. 2008),

- sunspots (Schussler & Vogler 2006; Scharmer,Nordlund & Heinemann 2008; Rempel, Schussler & Knolker 2009)
- dynamos (Nordlund et al. 1992; Cattaneo 1999; Brun, Miesch & Toomre 2004;

Vogler & Schussler 2007; Browning et al. 2006)

- the cores of large mass stars (MacDonald & Mullan 2004),
- throughout very low mass stars (Browning 2008),
- outside nuclear burning shells in the advanced stages of a star's evolution

(Arnett et al. 2009),

- super-nova explosions (Scheck et al. 2008; Mikami et al. 2008),
- accretion disks during star and planet formation (Balbus

& Hawley 1991, 2000; Brandenburg et al. 1995; Hennebelle & Fromang 2008; Fromang & Nelson 2009),

- accretion disks around black holes and neutron stars (Noble, Krolik &

Hawley 2009),

- the gas in clusters of galaxies (Parrish, Quataert & Sharma 2009).

However, simulations of these phenomena do not yet always include magnetic fields.

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