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The convective origin of hemispherical dynamos

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Abstract

The hemispherical magnetization of the Martian crust suggests, that Mars once must have had an internal magnetic field. To investigate the reason for the dichotomy we explore the possibility for a hemispherical dynamo action [4] using the numerical dynamo model MagIC [5]. Since Mars may still not have developed a solid inner core and therefore no compositional convection has been activated we model a dynamo purely driven by secular cooling. At the outer boundary of the spherical shell dynamo region a heat flux condition is used. Additionally, we impose a sinusoidal north/south variations with a relative amplitude g to mimic non-homogeneous core mantle boundary (CMB) heat flux due to low-degree mantle convection [2] or giant impacts [3].

1. EAA convection

The convection favors an equatorial antisymmetric and axisymmetric (EAA) mode. This EAA mode is promoted by the CMB heatflux variation, but also emerges naturally when the Rayleigh number is high enough [1]. It consists of two thermal wind cells, a prograde cell in the northern hemisphere and a dominantly retrograde cell in the southern hemisphere. A large meridional circulation cell transports heat from the northern hemisphere, which remains hot, to the cooler southern. Plume like convection is only present in the south where the CMB heat flux is higher. The convection pattern is drastically different from the more classical columnar convection (see figure 1). The relative heat flux perturbation amplitude g is varied up to three times the mean superadiabatic heat flux [4]. Starting from columnar convective and dipolar magnetic field, a relative perturbation amplitude of around $g = 50\%$ is sufficient to yield a dominant EAA mode. At moderate anomalies of around $g = 30\% \ldots 60\%$ Lorentz force induced oscillations between dominantly columnar and dominantly EAA convection appear.

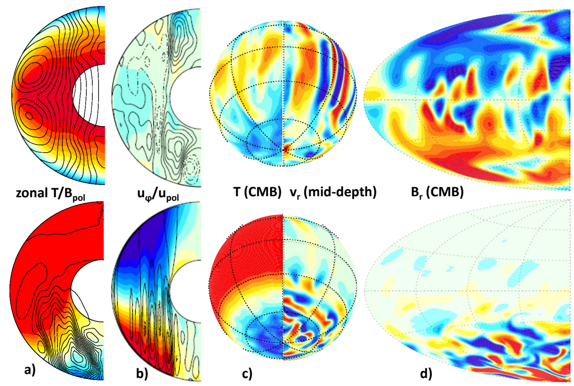

Figure 1: (From left to right) a) zonal averaged temperature with poloidal magnetic field as contours, b) azimuthal flow with meridional circulation as contours, c) CMB temperature in the left halves and radial velocity at mid-depth in the right halves and d) the radial magnetic field at the CMB of columnar (upper row) and EAA convective (lower row) mode. The columnar convection shows strong equatorial symmetry, whereas in the EAA mode axisymmetry is dominant.

2. The convective origin of hemispherical dynamos

In the columnar regime, which is present in the unperturbed system with $g = 0$, poloidal and toroidal magnetic fields are produced by helical motions in the individual columns by a α-mechanism. The stronger the CMb heat flux perturbation, the more dominant the EAA mode becomes and the more vanish the columnar structure of the convection. Then both magntic field contributions decrease simultaneously. But, in the EAA convection toroidal field is mainly induced in an ω-mechanism associated to shear region between the strong thermal wind cells. Poloidal field production is then confined to the southern plumes and much less efficient. Consequently, the outer boundary field

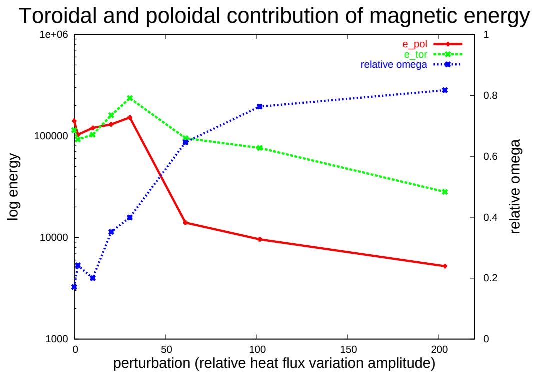

Figure 2: Toroidal (green) and (poloidal) magnetic field as a function of the heat flux perturbation amplitude. Both field contributions are of equal amplitude in the unperturbed reference case, but the toroidal dominates the poloidal by factor of 10 in the case of dominant EAA convection at higher CMB heat flux anomalies. In blue the relative ω-effect (induced by shearing) dominates the toroidal induction in the case if dominant EAA convection.

is dominated by small scale patches in the southern hemisphere. The dynamo character therefore changes from an α^2-type in columnar convection to an $\alpha\omega$-type in the EAA convection (see figure 2).

The Lorentz force tends to suppress columnar convection and therefore makes the flow more axisymmetric and also increases the relative importance of the EAA contribution (see figure 3). Since the absolute field strength is lower in EAA than in columnar convection, the Lorentz force decreases and the columnar mode once more gains in strength. These counteracting effects lead to the oscillations found at moderate perturbations.

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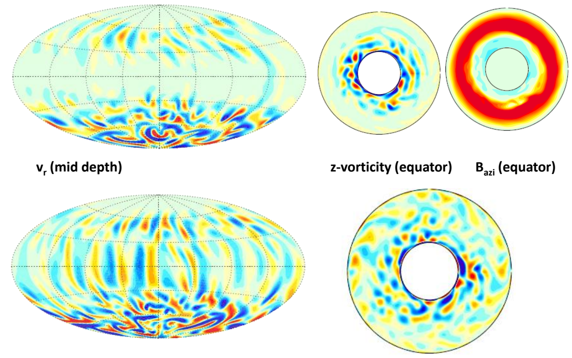

Figure 3: In the magnetic case (upper row), the convective columns (z-vorticity) are weakened due to the action of the Lorentz force (azimuthal magnetic field her), whereas in the non-magnetic case (lower row) the columns are present throughout the whole shell.

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