RISING FLUX TUBES IN A SPHERICAL CONVECTIVE SHELL

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Abstract. We discuss recent 3D MHD numerical simulations computed with the ASH code of the nonlinear dynamical evolution of magnetic flux tubes in a three-dimensional spherical convective zone, that maintains self consistently a solar like differential rotation and a large scale meridional circulation. We seek to understand the mechanism of emergence of strong toroidal fields from the base of the solar convection zone to the surface and their interactions with convection and its associated mean flows. We find that mainly two parameters influence the tubes during their rise through the convection zone: the degree of initial twist of the field lines and the initial strength of the magnetic field inside the tube.

1 The numerical model: embedding a flux tube in a turbulent convective zone

We use the ASH code (Anelastic Spherical Harmonic, see Brun, Miesch & Toomre 2004 for details) to solve the three-dimensional set of MHD equations in a rotating convective spherical shell. As shown in fig. 1, we introduce at t=0 a torus of magnetic field in thermal and pressure equilibrium with the surrounding medium at the base of a turbulent convective spherical shell and follow the nonlinear MHD evolution of the tube. Such initial conditions make the tube buoyant (due to the lower density present in the magnetized tube) and it begins to rise. We here discuss the influence of the presence of twist and of the amplitude of the field on the nonlinear evolution of the tube by considering three cases: an untwisted case (the initial field is exclusively oriented in the direction of the tube) and two twisted cases (a transverse field is present initially, with helicoidal field lines) for either a "weak field" case (the initial field amplitude $B0_\phi$ is $8.10^4 G$) or a "strong field" case ($B0_\phi \sim 3.10^5 G$).

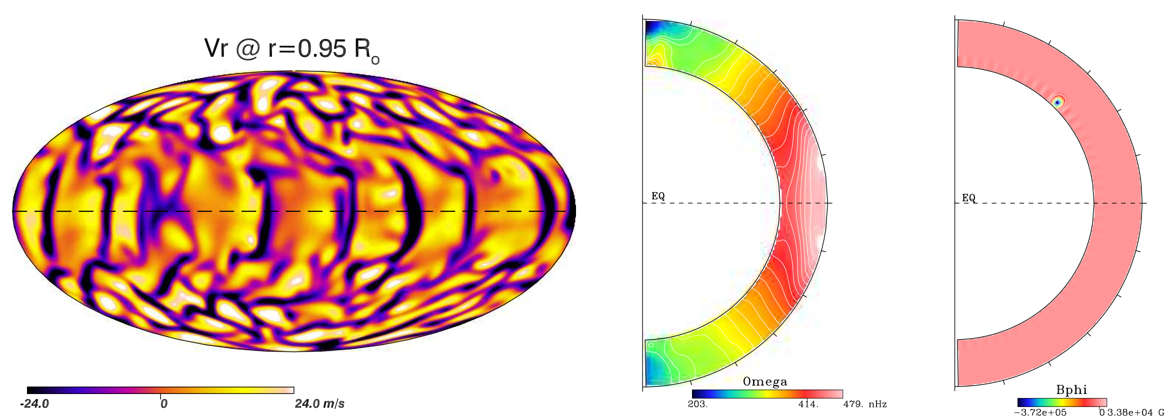

Fig. 1. Initial conditions for the flux tube model. On the left panel we show a snapshot of vertical velocity near the top of the shell (dark tone denotes downflows) in which we embedded the flux tube at a latitude of 45^o (as seen on the right panel showing an azimuthal average of B_ϕ). In the middle panel we show the solar-like differential rotation sustained by the convective flows (see Miesch, Brun & Toomre 2006 for details on case AB3).

2 Nonlinear Temporal and Spatial Evolution of the Flux Tube

Figure 2 shows the results of the 3D MHD evolution of a strong flux tube through the turbulent convection zone in the untwisted and in the twisted case. We clearly see in the untwisted case the formation of two counter vortices, splitting the tube in two parts as it rises. As shown in Emonet & Moreno-Insertis (1998), the splitting can be understood by considering the equation for the temporal evolution of the azimuthal vorticity:

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$$\rho\frac{D}{Dt}(\frac{\omega_\phi}{\rho}) = \nabla(\frac{\Delta\rho}{\rho}) \times g + \frac{\nabla \times F_{Lt}}{\rho} + \nabla(\frac{1}{\rho}) \times [-\nabla(\Delta p + \frac{B_l^2}{8\pi}) + F_{Lt}] \tag{2.1}$$

F_{Lt} represents the projection of the Lorentz force on the meridional plane. The rhs of the equation is dominated by the first two terms. If we consider the formation of vorticity in the main body of the tube in the right half, the first term in the rhs is related to the gravitational torque, and produces positive vorticity because it points outwards. On the contrary the second term linked to magnetic tension of the field lines, produces negative vorticity, that tends to counteract the effect of the gravitational torque and thus the deformation of the field lines while the tube is rising. If we do not have any twist (Fig. $2a, b$), the projection of the Lorentz force vanishes, leading to the apparition of two vortices. In the twisted case, with a sufficient amount of twist, the magnetic tension prevents vorticity to be created in the main body of the tube, the tube remains coherent during its rise (Fig. $2c$), with the maximum field amplitude still concentrated in the center of the tube (as also observed in cartesian geometry simulations, Fan et al. 2003). Note that in this case the maximum amplitude of the azimuthal vorticity and B_ϕ are not at the same location, contrary to the untwisted case. The presence of strong vorticity at the boundary layer of the twisted case as seen in Fig$2d$ comes from the fact that the gravitational and magnetic vorticity sources reinforce one another instead of counteracting each other.

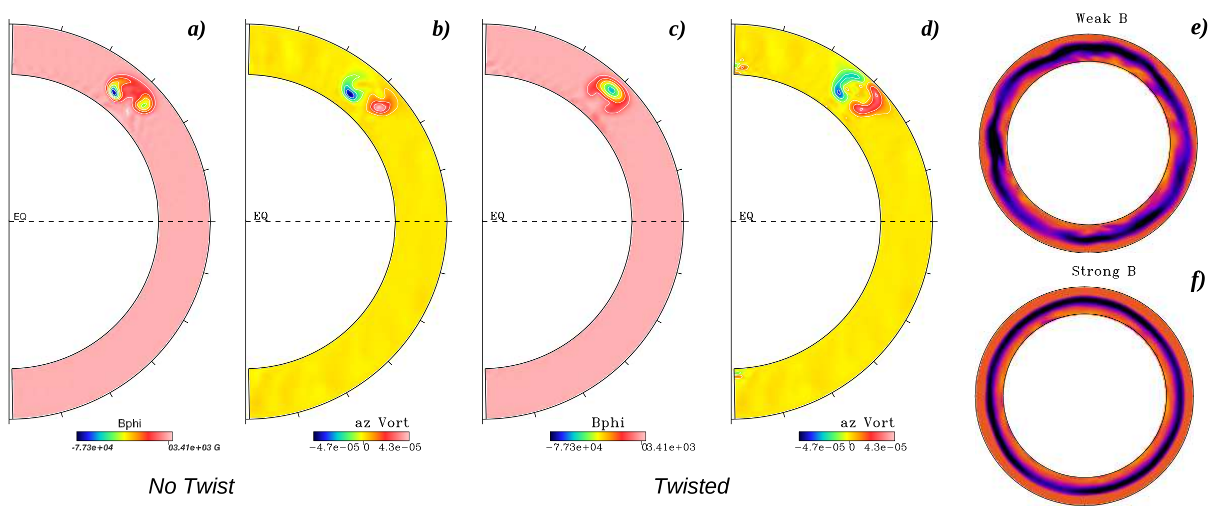

Fig. 2. Shown are snapshots of B_ϕ and the azimutal vorticity for the untwisted case (panels a & b) and for the twisted case (panels c & d), averaged over longitude, after 3.5 days of evolution. The field amplitude is expressed in Gauss and the vorticity amplitude in s^{-1}. Panels e) and f) are latitudinal cuts at 45^o of $B_\phi(r,\phi)$ after respectively 9.5 & 2.5 days. Note the irregular shape of the weak tube due to the strong influence of the convection on its evolution.

Another significant parameter which influences the behaviour of the flux tube during its rise is the initial amplitude of the magnetic field. In Fig. $2e, f$ we show planar cut at constant latitude of B_ϕ. We note the rapid radial rise toward the surface of the strong twisted flux tube case which seems to be insensitive to convection, evolving as if it was in a stably stratified zone. On the contrary, in the weaker field case the tube is highly deformed by convection during its slower rise (the weaker field resulting on a weaker buoyancy). We note the formation of "Ω-loops", that could lead to flux emergence at specific longitudes as seen with active regions instead of emerging at all longitudes like in the strong field case. These results are encouraging and we now wish to assess the influence of the latitude, magnetic diffusivity and mean flows on the tube's evolution.

References

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Fan, Y., Abbett, W.P. & Fisher G.H. 2003, ApJ, 582, 1206; Miesch, M., Brun, A.S. & Toomre, J. 2006, ApJ, 641, 618