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Dynamos from large-scale flows versus α-effect

RAINER ARLT

Astrophysikalisches Institut Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany

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Abstract. The observation of certain longitudes on stars which show persistent activity requires non-axisymmetric dynamo solutions which coexist with the typical axisymmetric, oscillatory dynamo solutions known from mean-field α-dynamos. This study is an attempt of finding non-axisymmetric solutions arising from large-scale flows with meridional circulation and a differential rotation imitating the ones in stars.

Key words: stars: magnetic fields – magnetic fields – turbulence

1. Motivation

A variety of solar-type stars shows activity, in many cases much stronger than that on the Sun. Activity cycles have also been detected on some of these active stars. An interesting feature is the emergence of activity on persistent stellar longitudes. These active longitudes may be nearly constant over years. Additionally, the active longitude of a star can jump by about 180° within weeks, and the opposite longitude is then persistently active for a year or more. The behaviour is called the ‘flip-flop phenomenon’. Observational data indicate that even the Sun exhibits the phenomenon. We are referring to Berdyugina (2005) for a full review and all the references which cannot be given in appropriate detail here.

A typical axisymmetric solution preferred by mean-field dynamos in axisymmetric spherical shells with differential rotation thus cannot account for the entire observational evidence. The superposition of one or more non-axisymmetric modes has been proposed. Large-scale flows provide dynamo solutions which are not based on a mean-field assumption and which are naturally non-axisymmetric because of the Cowling theorem. This approach is different from the attempts by Korhonen & Elstner (2005) and Moss (2005) who sought non-axisymmetric solutions in the α-effect pool exclusively.

2. Model description

Amplification of magnetic fields by dynamo action can typically be achieved in two ways. One is the assumption of turbulence providing the generating flows for a dynamo. The flow is not resolved computationally but is expressed in terms of the α-effect. The other way makes no assumption on the action of the flow, but computes the induction from the flow directly. We will call these dynamos laminar dynamos. A variety of flows suitable for laminar dynamos have been found. An instructive collection and very simple new flows were published by Dudley & James (1989). Such flows are of particular interest as they provide dynamos for non-turbulent media and lead to non-axisymmetric modes. If the azimuthal structure is decomposed in $e^{im\phi}$ modes, it is the $m \geq 1$ modes we are looking for.

While the Dudley & James dynamos do work, they are based on combinations of differential rotation and meridional circulation which are physically not consistent. In stellar environments, a few propositions on the flows may apply: radiative angular-momentum transport can provide a decreasing angular velocity Ω with radius, the resulting meridional flow is from the equator to the pole at the surface (Dudley & James had opposite flow direction), a convection zone may provide a decreasing Ω with latitude, the resulting meridional flow is again from the equator to the pole at the surface.

The computations employ the induction equation

$$\frac{\partial \boldsymbol{B}}{\partial t} = C_\Omega \nabla \times (\boldsymbol{u} \times \boldsymbol{B}) + \nabla^2 \boldsymbol{B} \qquad (1)$$

for a spherical domain of radius $R = 1$, where $\boldsymbol{u}$ is the flow velocity and $\boldsymbol{B}$ is the magnetic field. The parameter C_Ω is the magnetic Reynolds number $C_\Omega = R^2\Omega/\eta$, where η is the magnetic diffusivity. The magnetic Reynolds number is varied to find the threshold for dynamo action. This is by no means sophisticated physics; the problem is simplified to the question whether flows supposed to be present in astrophysical objects are capable of driving a dynamo with no additional

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Correspondence to: rarlt@aip.de

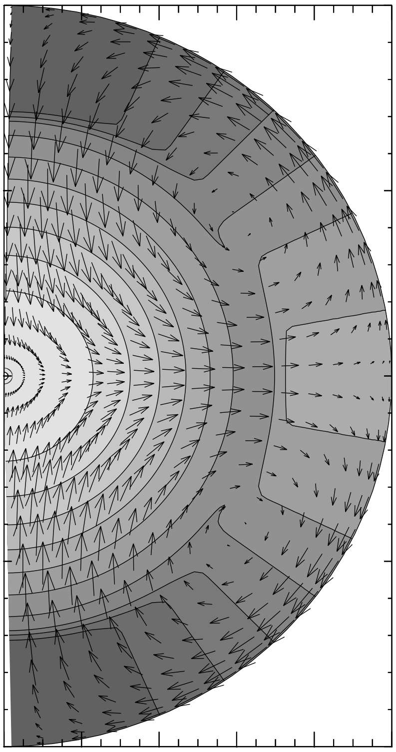

Fig. 1. Prescribed axisymmetric flow for a laminar dynamo. The arrows show the meridional circulation, the darker and lighter shades represent lower and higher angular velocity.

assumption of an α-effect. The spectral spherical MHD code by Hollerbach (2000) is applied for the integration of the induction equation. Its capabilities of integrating the momentum and temperature equation are not used here.

We try to find dynamo action from more suitable large-scale flows than the ones used by Dudley & James. A flow which was found to be able to excite dynamo action without an α-effect is shown in Figure 1. The meridional circulation has the same shape as the Dudley & James circulation, but with opposite flow direction. The gray contours show the profile of the angular velocity. The angular-velocity difference between equator and pole at the surface is 80%. Note that such a setup is one successful step on the road to real stellar configuration. We are not meaning to simulate a specific star here. A single meridional-flow cell extending over both the convection zone and the radiative interior is of course not what one would finally wish to get.

The critical Reynolds numbers for the modified large-scale flow are much higher than the ones required for the Dudley & James flow, but not unusual for stellar flows. Figure 2 shows the critical magnetic Reynolds numbers for modes which are symmetric and antisymmetric with respect to the equator. The horizontal axis is the amplitude of the meridional flow in fractions of the equatorial surface velocity. Note that there is only a 'window' of suitable meridional flow amplitudes which provide growing solutions for finite Rm. There is no dynamo for amplitudes larger than 0.23. The critical Reynolds numbers for weak circulation are much higher, but are usually finite in these Dudley-&-James-type dynamos. The meridional plane was decomposed in 80 Chebyshev and 160 Legendre polynomials for such runs at high magnetic Reynolds numbers.

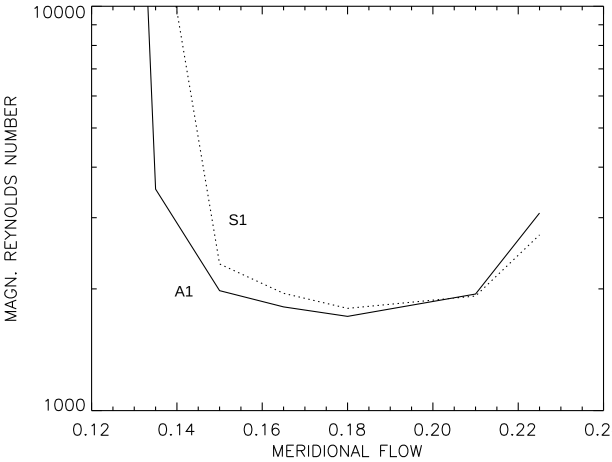

Fig. 2. Critical magnetic Reynolds numbers for the velocity field as in Figure 1. The meridional-flow amplitude is given in units of the equatorial velocity at the surface. A1 is the line for marginal dynamo growth for the $m = 1$ mode antisymmetric with respect to the equator. S1 is the corresponding line for the symmetric mode.

Dynamos based on the α-effect easily produce axisymmetric modes. The mean-field induction equation reads

$$\frac{\partial \boldsymbol{B}}{\partial t} = C_\Omega \nabla \times (\boldsymbol{u} \times \boldsymbol{B}) + C_\alpha \nabla \times (\hat{\alpha}\boldsymbol{B}) + \nabla^2 \boldsymbol{B} \qquad (2)$$

where α in our case is a simple scalar (isotropic α-effect) There is also $C_\alpha = R\alpha_0/\eta_\mathrm{T}$ as a free parameter controlling the strength of the α-effect, where η_T now is a turbulent magnetic diffusivity. The spatial distribution $\hat{\alpha}$ is normalized and is non-zero only in the 'convection zone' where it is $\sim \cos\theta$. If the differential rotation entering $\boldsymbol{u}$ is strong, also oscillatory solutions are excited. At a given $C_\Omega = 2000$, the critical C_α for pure differential rotation is 5.33. The full flow of Figure 1 with differential rotation and a meridional flow with an amplitude of 15% of the equatorial surface velocity requires a somewhat higher C_α of 9.40. The first unstable, axisymmetric solutions are symmetric with respect to the equator.

The example flow in Figure 1 with its imitated convection zone leads to the idea of combining a turbulent dynamo and a laminar dynamo from large-scale flows. Future work aims at this combination which is supposed to lead to a variety of non-linear interactions possibly being capable of explaining phenomena such as grand minima, active stellar longitudes, and the flip-flop phenomenon of these longitudes.

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