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DYNAMICAL ASPECTS OF STELLAR PHYSICS

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Abstract. Several manifestations of the dynamics of stellar interiors are briefly presented, with emphasis on the most recent developments in their numerical simulation.

1 Introduction

For someone who contemplates the night sky, stars seem to behave as inert objects: their brightness does not change, except for a few of them, which are purposely called variable stars. But this is a false impression: in fact stars are extremely dynamic, as illustrated by the closest of all, our Sun. Observed through a telescope, its surface displays granules that have a lifetime of about 10 minutes. Moreover, a few dark spots are visible in general, which can be followed as they cross the disk. From their migration one can deduce the rotation of the Sun, and detect that the equator rotates faster than the regions of higher latitude. The number of spots varies with time, on a cycle of about 11 years, during which the location where they appear decreases in latitude. And when we observe the Sun in selected wavelengths, many more phenomena are revealed, such as eruptions, flares, coronal mass ejections, and these are also related with the activity cycle.

The physical processes causing this dynamical behavior have now been identified, in the Sun as well as in other stars: they are seated in the interior and the main players are thermal convection, the rotation and the magnetic field. Modeling their effects benefits greatly from the ever increasing computer resources, although it still encounters severe limitations when dealing with turbulent and highly stratified flows. We shall illustrate this here with some recent examples.

2 Thermal convection

The thermal energy which is released by the nuclear reactions in the core of stars is transported by radiation as long as the medium is transparent enough. Near the surface of solar-type stars, this is no longer the case, because the ions recombine in atoms and molecules, which increases the opacity; the temperature gradient then steepens until it becomes superadiabatic, leading to thermal convection. There, heat is transported by hot eddies moving upward and cold eddies mowing downward, and these are the motions observed as granulation at the surface of the Sun.

Surface convection is now being modeled in exquisite detail by high resolution 3-dimensional numerical simulations, where the transfer of radiation has been treated with care. The pioneers in this field were Stein and Nordlund (1998); Fig. 1 shows one of their early simulations, where the computational domain was chosen such as to accommodate 20 - 30 granules, with a resolution of $253 \times 253 \times 163$. The result is compared with pictures of the solar granulation - the agreement is excellent. Moreover, the spectral line profiles deduced from such simulations match perfectly those observed on the Sun, and they can be used to determine the surface abundance of various chemical elements (Asplund et al. 2004).

A complementary approach to model convection in solar-type stars is to treat globally the whole convection zone, except for the upper layers where the density contrast would be too high. But both sphericity and rotation are then taken in account. Figure 2 displays a simulation performed by Brun and Toomre (2002) with the ASH

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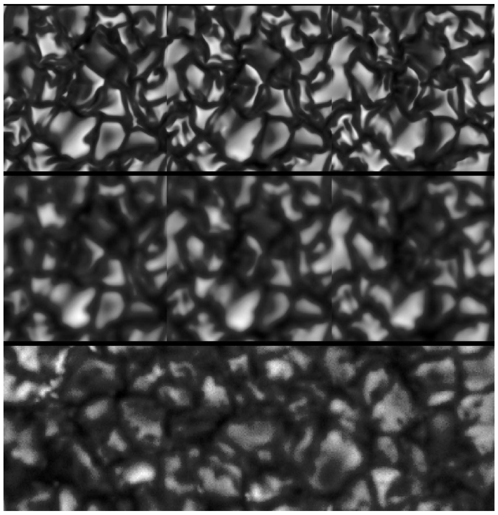

Fig. 1. Comparison of solar granulation as predicted by the numerical simulations performed by Stein & Nordlund (1998) (top row) and observed by the Swedish Solar Telescope in La Palma (bottom row). Each row presents 3 images at 1 minute intervals. In the middle row the computed image has been smoothed to account for the effect of atmospheric turbulence (courtesy ApJ).

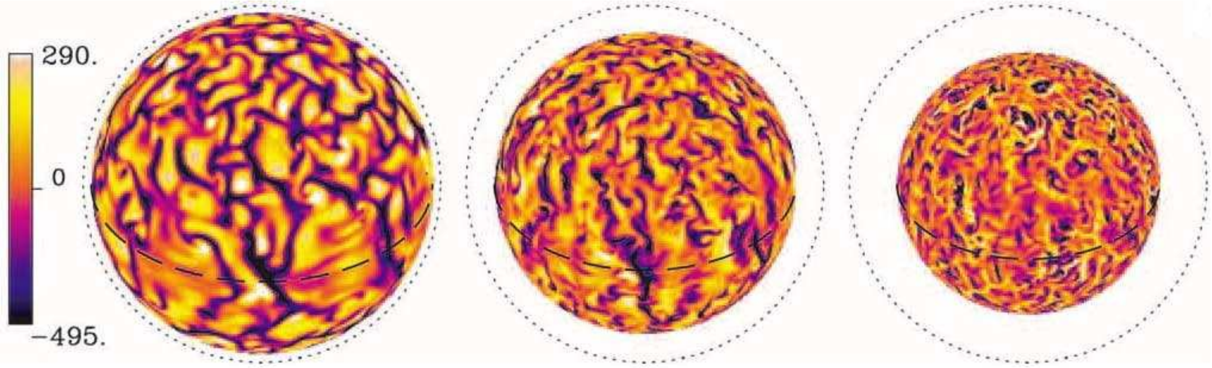

Fig. 2. Numerical simulation of solar convection, performed by Brun & Toomre (2002); the figure displays the pattern of the vertical velocity at different depths (0.95, 0.84 and 0.73 $R_\odot$). The upflows are in bright orange and the downflows in dark purple tones; the dashed circle indicates the position of the surface (courtesy ApJ).

code (for anelastic spherical harmonics) which has been specially designed to run on massive parallel computers; the resolution is $192 \times 512 \times 1024$. The main results of such simulations are that the strongest downflow lanes extend over the whole convection zone and that the equator is rotating faster than the higher latitudes, as observed on the Sun. Also, the large banana cells, that were present in earlier low resolution simulations, no longer show up here, because the level of turbulence could be substantially increased. For a recent account on global solar convection, see Miesch et al. (2008).

3 Towards a consistent model for the solar dynamo

According to the widely accepted paradigm (Parker 1955), the solar dynamo consists of two steps. In the Ω-step, the poloidal (meridian) field is sheared through the differential rotation into a toroidal (azimuthal) component. In the α-step, that toroidal field is twisted back into a poloidal field by the convective motions, that are rendered 'helical' by the Coriolis force. In Parker's original view, both mechanisms were supposed to operate in the convection zone, but since the discovery of the tachocline through acoustic sounding, it became plausible that the Ω-step takes place in that thin shear layer, which connects the differential rotation of the

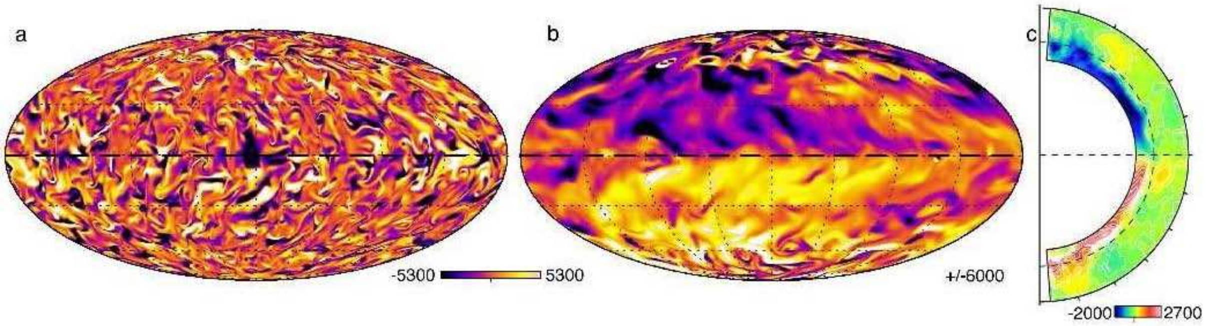

Fig. 3. Dynamo action in the solar convection zone: the Ω mechanism. Mollweide projections at one instant of the azimuthal field in the middle of the convection zone (**a**: 0.84 $R_\odot$) and in the underlying radiative region (**b**: 0.67 $R_\odot$). Panel **c**: meridional view of the azimuthal field averaged in time and longitude (Browning et al. 2007; courtesy ApJ).

convection zone, above, with the uniform rotation of the radiative interior.

Recent simulations by Browning et al. (2006) seem to confirm that expectation. A seed field grows to finite amplitude, where it is maintained for high enough magnetic Reynolds number (Rm=$v\ell/\eta$ where v is the rms velocity, ℓ the size of the convective eddies and η the magnetic diffusivity). As shown in Fig. 3, in the convection zone the longitudinal field is turbulent and not structured on large scale; once it is pumped down, by penetrating plumes, into the stable layer below (i.e. the tachocline), it is sheared into a well organized toroidal field. The calculations were run with a resolution of $98 \times 512 \times 1024$. In this simulation the α-effect, which closes the dynamo loop, is operating in the bulk of the convection zone.

4 Rotation induced mixing in stellar radiation zones

Until recently, stellar radiation zones were deemed as being motionless, except for their rotation. But now a new picture emerges, where these zones are the seat of slow flows, that are turbulent in spite of their low velocity because their characteristic scale is so large (of the order of the radius of the star). For instance a large scale circulation arises in the immediate vicinity of a differentially rotating convection zone, in the tachocline we have encountered above (Spiegel & Zahn 1992). A similar circulation occurs also in the bulk of the radiation zone, whenever angular momentum requires to be transported from one depth to the other. For instance, when a star looses angular momentum through a wind, that angular momentum is extracted from the deep interior by a large scale flow (Zahn 1992; Maeder & Zahn 1998; Mathis & Zahn 2004). That transport shapes the angular velocity profile, rendering it non uniform, and the shear of the differential rotation becomes unstable and generates turbulence. This turbulence produces mixing, and modifies the evolution of the star by carrying hydrogen rich material into the nuclear core.

These transport processes can be easily implemented in a stellar evolution code if one assumes that the turbulence generated by the shear is able to reduce the differential rotation in latitude to a point where the star can be considered in ‘shellular’ rotation, with the angular velocity depending only on depth. Then the problem reduces to one dimension, but with the transport of angular momentum keeping its advective character.

This rotation driven circulation explains well why on the surface of massive stars some chemical elements are observed (such as nitrogen) that have been synthesized in the core (Talon et al. 1997; Maeder & Meynet 2000). It also predicts that solar-type stars should have a fast rotating central region, but it is the contrary that is observed, through helioseismology. This means that another, more powerful process is responsible for the transport of angular momentum in these stars, and is able to render their rotation uniform.

5 Angular momentum transport in stellar radiation zones: magnetic stresses or internal gravity waves?

One candidate for this transport is the magnetic field, which can easily render the rotation uniform along the field lines of the poloidal field. However such a field, which can only be of fossil origin, will eventually connect with the convection zone above, and it should imprint the differential rotation of that zone on the radiative interior, which is not observed. Our simulations (Brun & Zahn 2006) seem to confirm that, although the results may depend somewhat on the boundary conditions applied on the top of the radiation zone (see Garaud & Garaud 2008).

Internal gravity waves are another candidate: these are waves whose restoring force is buoyancy, in a stably stratified medium. Some are excited at the edge of a convection zone and travel into the adjacent radiative region. They transport angular momentum, which they deposit at the location where they are dissipated through radiative damping, as was first pointed out by Press (1981).

Preliminary calculations by Talon et al. (2002) showed that low frequency gravity waves could indeed extract the angular momentum from the core of late-type stars, and render their rotation quasi uniform. This transport was then implemented in stellar evolution codes, together with the rotational mixing described above, and it led to results that agree very well with the observations, such as the lithium depletion in solar-type stars, both of populations I and II (Charbonnel & Talon 2005). The main weaknesses of this modeling is that it depends on the energy spectrum one assumes for these waves and that the picture given above can be modified by the Coriolis acceleration for low-frequency waves, but we should be able soon to study them with numerical simulations of penetrative convection.

6 Perspectives

Great progress has been recently achieved in understanding the dynamical behavior of stellar interiors, thanks to numerical simulations, as we have seen in those few examples. But such simulations must be validated by observational constraints, and these are provided presently by a score of instruments, ground based or in space. To mention only a few, of the most recent ones: while the mini-satellites MOST and CoRoT are probing the interior of stars through asteroseismology, the spectropolarimeters ESPaDOnS (CFHT Hawaii) and NARVAL (Pic du Midi) are mapping the magnetic field at their surface. Both to be launched in 2009, the next asteroseismic mission will be Kepler, and SDO (Solar Dynamics Observatory) promises to be as successful as SoHO, which started operating in 1995 and is still providing first rate data. No doubt, understanding the dynamical aspects of stellar physics has a bright future!

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