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ANGULAR MOMENTUM TRANSPORT IN STELLAR INTERIORS

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Abstract. In this short article we review the advances that have been obtained in the global modelling of angular momentum transport in stellar interiors during the last years. First, we consider the couplings between differential rotation and the large-scale meridional circulation and shear-induced turbulence this induces. Then, we describe the state of the art of our understanding of transport mechanisms in presence of a fossil magnetic field. Next, we show how rotation and magnetic fields are now taken into account in the study of internal waves. Finally, we emphasize that it becomes necessary to get a complete picture of the interaction of stars with their environment.

Keywords: MHD, turbulence, stars: evolution, stars: rotation, stars: magnetic fields

1 Context

Stars are dynamical rotating and magnetic objects. So, rotation and magnetic fields modify their evolution as well as their interactions with their environment. For example, differential rotation induces "non-standard" mixing processes, which modify their life time, their late stages of evolution, their nucleosynthetic properties and the resulting chemical enrichment of the close interstellar medium. Since, more and more observational constraints are obtained thanks to asteroseismology, interferometry, and spectropolarimetry, it is thus necessary to construct stellar models that account for transport processes both on dynamical and secular time-scales. This short article addresses the most recent progresses that have been achieved for the modelling of secular exchanges of angular momentum in stellar interiors. Therefore, we focus on mechanisms acting in stellar radiation zones while the reader could refer to Brun (2011) for a review on dynamical time-scales and on convective regions.

2 Differential rotation and associated large-scale meridional circulation and shear-induced turbulence

The first processes that should be understood are the differential rotation and the associated large-scale meridional circulation and shear-induced turbulence. A global understanding of their couplings have been obtained in Decressin et al. (2009). First, viscous turbulent transport, stellar winds, and structural adjustments induce meridional currents. Then, these latters advect heat that leads to latitudinal gradients of temperature. Because of the associated baroclinic torque, a new differential rotation profile is built which can be understood looking at the so-called thermal-wind equation and the transport loop is closed. However, these three mechanisms, if applied to the Sun and low-mass stars, are unable to reproduce the angular velocity profile of the radiative core of the Sun and the light elements mixing (Turck-Chièze et al. 2010; Talon & Charbonnel 2005). Therefore, other processes such as magnetic fields or internal waves excited by penetrative convection or tides if there is a close companion must be studied.

3 Magnetic fields

The main admitted hypothesis for magnetic field origin in stellar radiation zones is the one of a fossil field. Fossil fields are thus believed to originate from the trapping of the interstellar magnetic field flux during star formation. If the initial field is a small-scale turbulent field, we have to understand and predict the topolgy of the resulting field after the birth of the radiative region, which impacts the angular momentum transport. As

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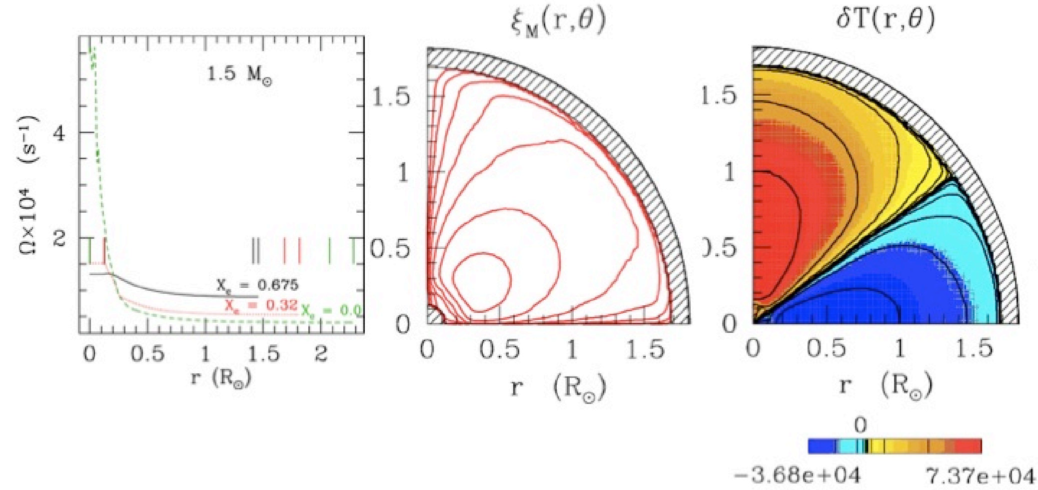

Fig. 1. Evolution of a rotating 1.5 $M_\odot$ star with a solar metallicity and an initial surface velocity of 100 km.s^{-1}. **Left:** the angular velocity profile is given for different stages of the evolution of the star on its main-sequence; X_c is the central fraction of mass in Hydrogen. **Middle:** Steam lines of the meridional circulation for $X_c = 0.32$; the red color indicates that the circulation is extracting angular momentum towards the surface where it is carried by the stellar wind. **Right:** Baroclinic temperature profile at the same stage. (Adapted from Decressin et al. (2009)).

described in Neiner, Alécian & Mathis and in Duez contributions in this proceeding, this problem is related to the turbulent MHD relaxation processes, in which a turbulent magnetic field is converted into a large-scale one due to a selective decay of the ideal MHD invariants. The case of high-beta stellar radiation zone plasmas has been studied both theoretically (Duez & Mathis 2010) and numerically (Braithwaite & Spruit 2004; Braithwaite & Nordlund 2006; Braithwaite 2008). Resulting non force-free relaxed states minimize the total energy for given magnetic helicity and fluid invariants due to the stable stratification of stellar radiation zones. Roughly axisymmetric dipolar twisted configurations are obtained if the initial magnetic energy is confined near the center (Braithwaite & Nordlund 2006; Duez & Mathis 2010) while one obtains non-axisymmetric fields in the case where this is distributed in the whole radiation zone (Braithwaite 2008). The field is then organized on large-scale, mixed (poloidal and toroidal), non force-free configurations, which are stable as it has been demonstrated by Braithwaite (2009) and Duez et al. (2010).

Once the initial non force-free magnetic configuration (axi or non-axisymmetric) has been established, this interacts with differential rotation. Then, two cases are possible as described by Spruit (1999). In the first case, if the field is strong, the rotation becomes uniform on magnetic surfaces due to Alfvén waves phase mixing, which damps the differential rotation; in the axisymmetric case this leads to the Ferraro's state where the angular velocity is frozen in the poloidal field lines and to a uniform rotation in the non-axisymmetric case (the oblique rotators case for example; see Moss 1992). In the second case, if the field is weak, it could first become axisymmetric if it is non-axisymmetric because of rotational smoothing and then, because of phase mixing, this leads to the Ferraro's state (Strugarek et al. 2011). This picture could be modified by magnetic instabilities, if during the first step of the phase mixing, the residual differential rotation on each magnetic surface is able to generate a strong toroidal component of the field that becomes unstable and if this instability becomes able to trigger a dynamo action through an α-effect; this question remains open (Zahn et al. 2007). Let us now take into account the meridional circulation. To understand its interaction with the other dynamical processes (the differential rotation and the shear induced turbulence) in presence of a fossil magnetic field, we shall adopt the picture of rotational transport as described in §2. and generalise it to the magnetic case. As in the purely hydrodynamical case, meridional circulation in radiation zones are driven by applied torques (internal like the Lorentz torque or external like those induced by stellar winds), structural adjustments during stellar evolution, and turbulent transport. In the case where all these sources vanish, the meridional circulation dies after an Eddington-Sweet time and the star settles in a baroclinic state described by the thermal wind equation. If we apply this picture to the case of radiation zones with a fossil magnetic field, we thus understand that the meridional circulation (if we consider a star without structural adjustments and external torques) will be mainly driven by the residual magnetic torque until the phase mixing leads the star to a torque-free state (see fig. 2). Then, the meridional circulation advection of angular momentum balances the residual Lorentz torque (see Mestel et al. 1988; Mathis

& Zahn 2005).

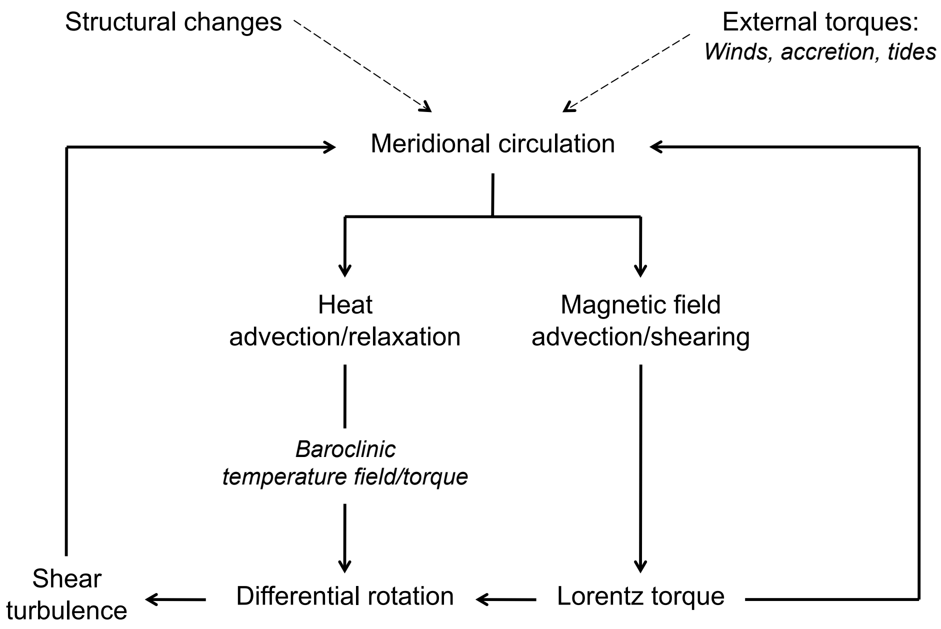

Fig. 2. Transport loop in stellar radiation zones in presence of large-scale magnetic fields.

4 Internal waves

The last transport mechanism that should be studied is the action of internal waves propagating in stably stratified radiation zones and which are excited by turbulent convective flows at the radiation/convection borders. Indeed, these transport angular momentum (of same sign of the energy flux for prograde waves and of the opposite one for retrograde waves), which is deposited where waves are dissipated because of diffusion processes or where these reach their critical layers where their frequency is proportional to the local angular velocity (see Alvan & Mathis in this proceeding). Then, if differential rotation is initially present, a net flux of angular momentum is transported because of the Doppler effect that affects the respective diffusive damping rates acting on pro- and retrograde waves. This transport, combined with the strong horizontal shear-induced turbulence is therefore seen as a candidate to explain the observed quasi uniform rotation rate of the solar radiative core as well as the mixing in low-mass stars (Talon & Charbonnel 2005). However, progresses should be obtained in the description of waves excitation by turbulent convection and on the impact of rotation and magnetic fields on waves structure, dissipation and associated transport of angular momentum.

This is the reason why the modification of their structure and dissipation by the (differential) rotation has been studied with taking into account the Coriolis acceleration (Mathis et al. 2008; Mathis 2009). Then, depending on the ratio between excited frequencies (σ_c) and the inertial frequency (2Ω, where Ω is the angular velocity), waves are propagating at all latitudes in the super-inertial regime ($\sigma_c > 2\Omega$) while these are trapped in an equatorial belt below a given critical latitude in the sub-inertial one ($\sigma_c < 2\Omega$) (see fig. 3 in the general case of a given differential rotation). This thus modifies the transmission of the energy coming from turbulent convective flows which may be thus reduced in this latter. Moreover, the thermal diffusion is enhanced and waves are thus damped close to their excitation region. This leads, combined with the equatorial trapping, to a weaker efficiency of the angular momentum transport as soon as the ratio $\sigma_c/2\Omega$ diminishes.

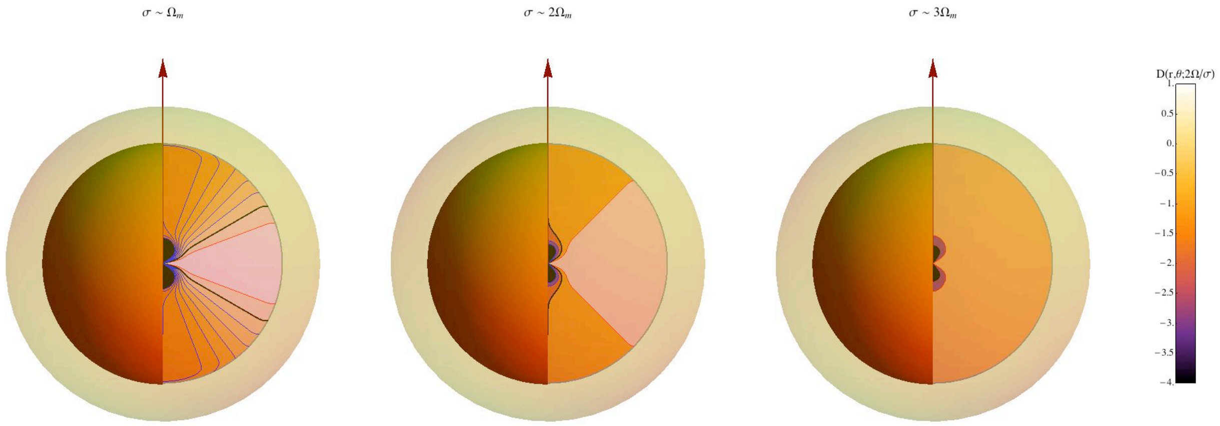

Fig. 3. We consider here a solar-twin star with an external convective envelope and a radiative core. The rotation profile in this latter is flat (i.e. $\Omega = \Omega_m$) for $r \in [0.2R, 0.7R]$, where R is the stellar radius. In the central region, Ω increases until $\Omega = 5\Omega_m$ in the center. Finally, at the radiation/convection border we choose the same differential rotation that in the Solar tachocline. Regions with reds contours correspond to those where waves are propagative while polar and central regions with blue contours correspond to "dead" zones for waves propagation. We choose three frequencies ($\sigma = \{\Omega_m, 2\Omega_m, 3\Omega_m\}$) that shows that for frequency below $2\Omega_m$ equatorial trapping phenomena appear. The black line corresponds to the critical surface (the critical latitude in the case of uniform rotation) at the level of which the wave propagation regime changes. The central region is always a non-propagative region because of the central rapid rotation. D is a function of σ, Ω, and the gradients of Ω. Its definition is given in Mathis (2009).

Then, the bottom of convective envelopes in solar-type stars as well as the top of convective cores in massive stars are the seat of dynamo action. For example, the tachoclines are believed to be the place of the large-scale toroidal magnetic field storage (Browning et al. 2006). Moreover, as it has been discussed in §3., stellar radiation zones may host fossil magnetic fields. We thus have to also account for the magnetic field action on internal waves dynamics, which become Magneto-Gravito-Inertial waves because of the three restoring forces: i.e. the buoyancy force, the Coriolis acceleration, and the Lorentz force. The first studies have been devoted to the case of waves dynamics with an axisymmetric toroidal field (Mathis & de Brye 2011). In this case, waves become vertically trapped as soon as $1 - m^2\,\omega_{\rm A}^2/\sigma_c^2 < 0$, where we introduce the Alfvén frequency $\omega_{\rm A}$ and the wave azimuthal order m. Moreover, waves are submitted to the same equatorial trapping phenomenon that in the hydrodynamical case of gravito-inertial waves. The main difference in the magnetic case is that this trapping due to the combined action of the Coriolis acceleration and the Lorentz force is different for pro- and retrograde waves because of this latter. Then, the horizontal trapping of prograde waves is stronger than those of retrograde waves. Finally, waves thermal diffusion become stronger as soon as magnetic field amplitude increases. The efficiency of the induced transport of angular momentum is thus a function of the rotation and of the magnetic field amplitude as shown in fig. 4. This decreases as soon as vertical and horizontal trappings modifies waves dynamics, with a net bias in favor of retrograde waves.

5 Coupling the star with its environment

As it has been emphasized in previous sections, applied torques on stars modify internal transport processes; for example these generate large-scale meridional circulations. Therefore, one must get a coherent physical modeling of the interaction of the star with its environment when treating its rotational evolution. First, stellar winds must be carefully studied as a function of the stars rotation rate and their magnetic field topology and amplitude (see for example Pinto et al. 2011). Furthermore, if stars host a planetary system, the coupling with the proplanetary disk (Matt & Pudritz 2005) as well as tidal interactions should be taken into account. For this latters, the equilibrium tide associated to the hydrostatic adjustment of the star to the tidal excitation leads to a net torque applied on the external convective envelopes of solar-type stars (Zahn 1966), while internal waves are excited by the tidal potential at the radiation/convection borders and are able to transport angular momentum in the same way that those excited by the turbulent penetrative convection (this is the dynamical tide; see Zahn 1975).

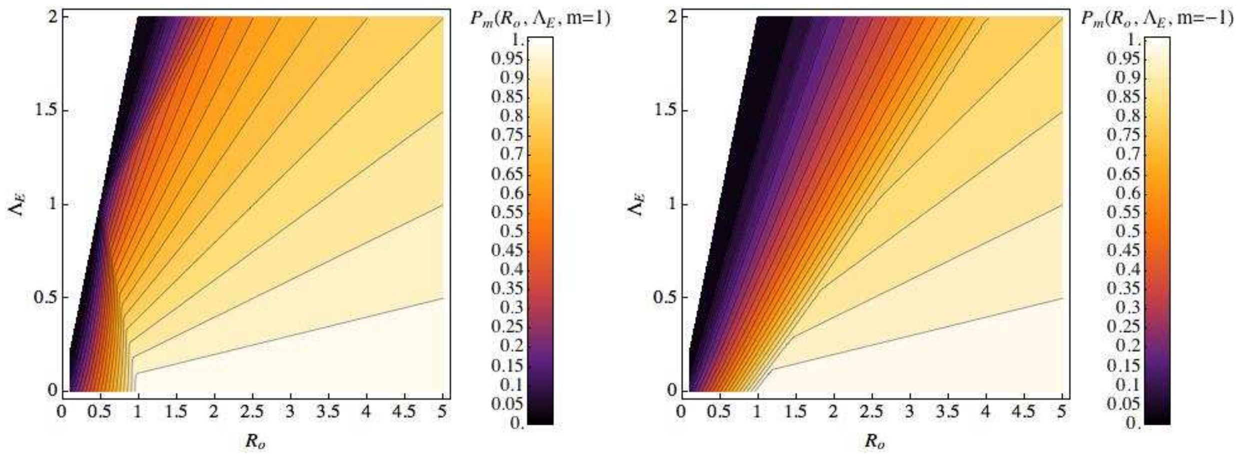

Fig. 4. Efficiency of the transmission of energy coming from convective regions to internal waves as a function of their Rossby and Elsasser numbers ($R_o = \frac{\sigma_c}{2\Omega}$, $\Lambda_{\rm E} = \frac{\omega_{\rm A}^2}{\sigma_c \Omega}$) for a given couple of retrograde ($m = 1$) and prograde ($m = -1$) waves.

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