SF2A 2006
D. Barret, F. Casoli, T. Contini, G. Lagache, A. Lecavelier, and L. Pagani (eds)

DYNAMICAL PROCESSES IN STELLAR RADIATION ZONES: SECULAR MAGNETOHYDRODYNAMICS OF ROTATING STARS

S. Mathis[1,2,3], T. Decressin[1], A. Palacios[3], L. Siess[4], C. Charbonnel[1,5], S. Turck-Chièze[3] and J.-P. Zahn[2]

Abstract. With the imminent launch of COROT and the preparation of new helioseismology instruments such as GOLF-NG (cf. DynaMICS project), we need a coherent picture of the evolution of rotating stars from their birth to their death. We describe here the modeling of the macroscopic transport of angular momentum and matter in stellar interiors that we have undertaken to achieve this goal. First, we recall the dynamical processes that are driving this transport in rotating stars and the theoretical advances we have accomplished. Then, we present our new results of numerical simulations which allow us to follow in 2D the secular hydrodynamics of rotating stars, assuming that anisotropic turbulence enforces a shellular rotation law. Finally, we show how this work is leading to a dynamical vision of the Hertzsprung-Russel diagram in support of asteroseismology and helioseismology.

1 Dynamics of stellar radiation zones and differential rotation

Rotation, and more precisely differential rotation, has a major impact on the internal dynamics of stellar radiation zones. First, it induces a large-scale meridional circulation, which results from the interplay of the perturbing forces (centrifugal and Lorentz force) and from their impact on the thermal balance (cf. Zahn 1992, Maeder & Zahn 1998, Mathis & Zahn 2005). Next, differential rotation generates hydrodynamical turbulence through various instabilities: shear instabilities, baroclinic and multidiffusive instabilities. This turbulence acts to reduce its cause, namely the gradients of angular velocity, and therefore it is modeled as a diffusive process (cf. Mathis et al. 2004, Maeder 2003). Then, rotation interacts with fossil magnetic fields, leading to a secular torque exerted by the Lorentz force and to a turbulence induced by magnetohydrodynamical instabilities (Tayler instability, multidiffusive magnetic instability) (cf. Charbonneau & Mac Gregor 1993, Mathis & Zahn 2005, Spruit 2002, Menou et al. 2004, Maeder & Meynet 2004, Brun & Zahn 2006). Furthermore, rotation has a strong effect on the internal waves that are excited at the borders with convective zones. Those waves propagate inside the radiation zones, and they extract or deposit angular momentum where they are damped, leading to a modification of the angular velocity profile and of the associated mixing (cf. Talon & Charbonnel 2005 and references therein). Finally, rotation shapes the stellar wind and influences the mass loss (cf. Maeder 1999). In close binary systems, where the companion may be another star as well as a planet, there are transfers of angular momentum between the star, its companion and the orbit due to the dissipation acting on flows induced by the tidal potential (cf. Zahn 1977). The tidal torque thus modifies the internal rotation of each component, and hence the macroscopic transport.

To conclude, all the processes with which rotation interacts transport angular momentum and matter, and this modifies the internal angular velocity, the chemical composition and the nucleosynthesis. Therefore, rotation (differential rotation) has imperatively to be taken into account if one seeks a coherent picture of the internal dynamics and the evolution of the stars.

[1] Observatoire de Genève; 51, Chemin des Maillettes, CH-1290 Versoix, Switzerland
[2] LUTH, Observatoire de Paris, 5 place Jules Janssen, 92195 Meudon Cedex, France
[3] DSM/DAPNIA/Service d'Astrophysique, CEA/Saclay, 91191 Gif-sur-Yvette Cedex, France; AIM - Unité Mixte de Recherche CEA, CNRS, Université Paris VII - UMR 7158
[4] Institut d'Astronomie et d'Astrophysique, Université Libre de Bruxelles, Campus de la Plaine, Boulevard du Triomphe, CP 226, 1050 Bruxelles, Belgium
[5] LATT, Observatoire Midi-Pyrénées, 14 Avenue Edouard Belin, 31400 Toulouse, France

2 Theoretical and numerical contributions

First we improved the description of the rotational transport of type I, where angular momentum and chemicals are both transported by the same processes, namely the meridional circulation and the hydrodynamical turbulence due to shear instabilities. We generalized its former modeling to treat simultaneously the bulk of radiation zones and their interfaces with convective zones, the tachoclines (Mathis & Zahn 2004), and we have implemented a new prescription for the horizontal turbulent transport which is inspired by laboratory experiments (Mathis et al. 2004). However, even with these improvements, that type of mixing leads to results that are in conflict with the observed properties of solar-type stars (such as the quasi uniform internal rotation of the Sun). In these stars angular momentum is thus carried by another physical process than the chemicals, and the two candidates that have been proposed to accomplish this are a fossil magnetic field (cf. Gough & McIntyre 1998) or the internal waves emitted at the base of the convection zone (cf. Talon & Charbonnel 2005). To describe that rotational transport of type II, as we call this scenario, we have expanded our formalism to include in a consistent way the effect of an axisymmetric magnetic field (Mathis & Zahn 2005), and we are presently introducing the effect of the Coriolis force in the modeling of internal waves (cf. Mathis & Zahn 2006a). Finally, we are completing a coherent treatment of the tidal processes (cf. Mathis & Zahn 2006b), which will enable us to compute the evolution of close binary systems.

In parallel, we have undertaken the numerical implementation of these theoretical results in existing stellar evolution codes. The first step has been completed, namely the implementation of the rotational transport of type I in the case where the horizontal turbulence enforces the angular velocity to be constant on a isobars (shellular rotation), and evolutionary sequences have been computed for moderately massive stars with the dynamical stellar evolution code STAREVOL (the reader is referred to Siess et al. 2000, Palacios et al. 2003, Palacios et al. 2006 for a detailed description). Moreover, diagnostic tools have been developed to identify the dominant physical processes in the angular momentum transport, the meridional circulation and chemicals mixing. Work is now in progress to implement the differential rotation in latitude and the transport by magnetic field and gravito-inertial waves. This will lead to an hydrodynamical (and then to a MHD) vision of stellar evolution which is required for the interpretation of helio and asteroseismic data.

References

Brun, A.-S., Zahn, J.-P. 2006, A&A, 457, 665

Charbonneau, P., MacGregor, K. B. 1993, ApJ, 417, 762

Decressin, T., Mathis, S., Palacios, A., Siess, L., Charbonnel, C., Turck-Chièze, S., Zahn, J.-P., *Secular hydrodynamics of rotating stars*, in prep. for A&A

Gough, D. O., McIntyre, M. E. 1998, Nature, 394, 755

Maeder, A., Zahn, J.-P. 1998, A&A, 334, 1000

Maeder, A. 1999, A&A, 347, 185

Maeder, A. 2003, A&A, 399, 263

Maeder, A., Meynet, G. 2004, A&A, 422, 225

Mathis, S., Zahn, J.-P. 2004, A&A, 425, 229

Mathis, S., Palacios, A., Zahn, J.-P. 2004, A&A, 425, 243

Mathis, S., Zahn, J.-P. 2005, A&A, 440, 653

Mathis, S., Zahn, J.-P., *Transport and mixing in the radiation zones of rotating stars III. Gravito-inertial waves*, in prep. for A&A

Mathis, S., Zahn, J.-P., *The dynamical tide in a differentially rotating star*, in prep. for A&A

Menou, K., Balbus, S. A., Spruit, H. C. 2004, ApJ, 607, 564

Palacios, A., Charbonnel, C., Talon, S., Siess, L. 2006, A&A, 453, 261

Spruit, H. C. 1999, A&A, 349, 189

Spruit, H. C. 2002, A&A, 381, 923

Talon, S., Charbonnel, C. 2005, A&A, 440, 981

Zahn, J.-P. 1977, A&A, 57, 383

Zahn, J.-P. 1992, A&A, 265, 115