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Modelling transport processes in stellar radiative interiors

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Abstract. I report here on the different transport processes redistributing angular momentum and nuclides in stellar radiative interiors and on their modelling in stellar evolution codes.

1 Introduction

The CoRoT and *Kepler* missions have unexpectedly triggered a new era in our understanding of stellar evolution along with the huge step forward they have permitted in the domain of exoplanets. The many solar-type oscillations found in the targets of these missions have revealed the power of asteroseismology to study low-mass stars as they evolve beyond the main sequence turn-off, and bring new and strong constraints on the stratification of the stellar plasma and the distribution of angular momentum within stars for which such information was previously unreachable.
The observational constraints brought by ground-based photometry, spectroscopy and helioseismology already shed light on the importance of transport processes in shaping the surface and interiors of stars. The introduction of these processes in stellar evolution codes is now a clear necessity to be able to advance our understanding of stellar structure and evolution.
Physical processes transporting nuclides and angular momentum will be reviewed in the present paper, with an emphasis on their implementation in stellar evolution codes and on the comparison of the resulting models outcomes with observational constraints including asteroseismology.

2 Microscopic diffusion and double-diffusive instability

2.1 Atomic diffusion

The introduction of atomic diffusion in the standard stellar evolution model is a first improvement to the classical model in which the only regions undergoing any mixing are the convective regions [1].
Atomic diffusion is a very generic term to describe the transport of nuclides from first principles. In the multicomponent plasma of the stellar radiative regions, and in the absence of rotation or any other physical mechanisms likely to produce mixing, the chemical stratification is the result of a competition between gravitational settling, thermal diffusion and radiative levitation [2–4]. Gravitational settling and thermal diffusion dominate the atomic diffusion when the radiative flux is small and the radiative accelerations on heavy elements are slower than the gravity. This is the case of main sequence stars with spectral types later than mid-F (corresponding to $M \leq 1.2\ M_{\odot}$), in which atomic diffusion essentially leads to gravitational settling of elements heavier than hydrogen. In the case of the Sun, introducing these processes has considerably improved the agreement between the sound speed profile of solar models and that deduced from helioseismic inversion techniques [5–7]. Gravitational settling

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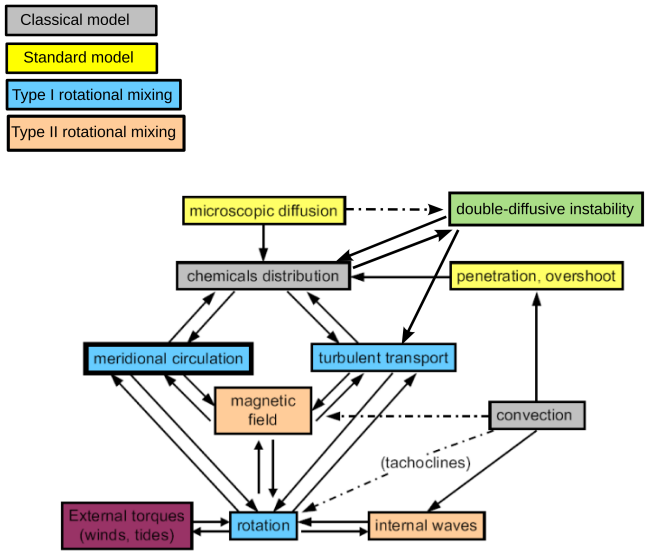

Fig. 1. Dynamical transport processes in stellar radiative zones: those regions are the seat of highly non-linear interactions between the differential rotation, the meridional circulation, the turbulence, the magnetic field, the internal waves, the winds and the atomic diffusion. *Adapted from [19]*

and thermal diffusion are routinely included in stellar evolution codes as either or both a velocity and a diffusion term in the equation for the evolution of nuclides according to the adopted formalism [2, 4]. A dedicated routine is even made available by A. Thoul [8] to compute all the relevant terms in the Burgers formalism.

Concerning radiative levitation, it becomes important in early F, A and late-B stars, all spectral types well known for harbouring numerous classes of chemical peculiar stars. Its treatment is complex and scarcely implemented in stellar evolution codes because it requires the costly computation of the radiative accelerations based on monochromatic opacities, which were not made publicly available until recently. The simplified formalism proposed by [9, 10] and the access to monochromatic opacities via the OP opacity project [11] should facilitate a wider implementation of radiative accelerations in stellar evolution codes. The models of Am-Fm and other chemically peculiar hot stars obtained with the self-consistent treatment of all the processes constituting atomic diffusion strongly improves the agreement between models and observations [12–14, 21, 16–18, 20]. It also points towards the necessity to add a competing process to atomic diffusion in these stars in order to reduce its effect, the nature of which (turbulent mixing or transport by winds) remains unclear from observational constraints [18].

2.2 Double-diffusive convection or "Thermohaline" mixing"

The double-diffusive convection, also referred to as thermohaline mixing in analogy with the phenomenon observed in the oceans, develops in the astrophysical context in regions of stable entropy stratification ($\nabla - \nabla_{ad} < 0$) and unstable nuclides stratification ($\nabla_{\mu} > 0$). The mean molecular gradient is generally negative in stellar regions (due to nucleosynthesis), but it is inverted in regions with heavy elements accumulations due to radiative levitation (A-type stars [21]), or in regions where the ^{2}He(^{3}He, 2p)^{4}He reaction occurs [22].

The exact form of this dynamical instability is not fully assessed, and it seems to change from fingers to staircases according to numerical simulations [23, 24]. Different prescriptions exists to for the diffusion coefficient associated to the double-diffusive instability [25, 26]. When using the formalism of [25], with a large aspect ratio for the fingers associated to the thermohaline instability, [27] have

shown that this mixing could account for the surface variations of the light elements abundances (Li, C, N) observed in 98% of red giant branch stars. This result has been challenged by other works on the actual mixing efficiency (directly related to the fingers aspect ratio in case of a fingering form for the instability), and is still a matter of debate [28,29,23]. The actual efficiency of this instability in transporting nucleides is not fully set and will require further (numerical) investigations in the near future.

3 Type I rotational mixing

In addition to the physical processes described in Sect.2, transport of nuclides also occurs via the turbulence generated by hydrodynamical instabilities arising in differentially rotating stellar radiative interiors. The turbulence, together with the large-scale meridional circulation that is known to develop in the radiative interior of rotating stars, will also transport angular momentum, and the combination of these processes is referred to as ”Type I rotational mixing”. It was first invoked as the possible extra-mixing source required in stellar evolution models in order to explain a series of abundance anomalies across the HR diagram [30].

3.1 Hydrodynamical instabilities

In a differentially rotating stellar radiation zone, the baroclinic (isobars and iso-density surfaces do not coincide) stratification may lead to a series of instabilities that may transport nuclides and angular momentum when becoming turbulent. The Solberg-Høiland instability [31] is a dynamical baroclinic instability controlled by the Rayleigh-Taylor instability criterion in regions with decreasing specific angular momentum gradient. It is associated to axisymmetric perturbations of a fluid undergoing cylindrical rotation. In case of non-cylindrical rotation, other varieties of baroclinic instabilities may develop and act on secular timescales (GSF instability [32,33], ABCD instability). the associated stability criteria can be build as modifications of the Solberg-Høiland stability criterion [34]. The diffusion coefficients used to model these baroclinic instabilities are derived from linear analysis, and may thus not be correct to describe a turbulent transport. They are implemented in codes using the Endal & Sofia [35,36] formalism for the transport of angular momentum (see [37]).
The shear instability develops in differentially rotating fluids according to the Richardson criterion [34]. The horizontal shear instability develops along isobars where no restoring forces exist. It acts on dynamical timescales and leads to large horizontal shear turbulent viscosity ν_h. The vertical shear develops in the direction of entropy stratification. It is controlled by an instability criterion [38,39] and leads to a vertical shear turbulent viscosity $\nu_v << \nu_h$. This dichotomy ensures shellular rotation, a regime for which [40] derived prescriptions for the turbulent viscosities ν_v and ν_h using a non-linear approach.The shear is the only source of turbulence considered in the model of Zahn for the type I rotational mixing, which is implemented in several stellar evolution codes [41–43]. The choice of the prescriptions for ν_v and ν_h can strongly affect the models outcomes [44] but is poorly constrained by observations. It can only be tested by numerical simulations, a work that [45] have undertaken with promising results.

3.2 Meridional circulation

The meridional circulation is a large scale flow that develops in radiative regions of rotating stars. Assuming strong anisotropic shear turbulence that ensures shellular rotation, the heat equation must be complemented by an horizontal heat flux that creates a thermal imbalance. This imbalance is compensated by the advection of entropy, introducing here the meridional circulation (see [40,46] for complete description). Meridional circulation transports both angular momentum and nuclides. This flow is of advective nature and appears as such in the angular momentum evolution equation as derived by [40, 46]. Using the formalism of [35,36], the meridional circulation is treated as a diffusive process for the angular momentum evolution. As shown by [47], it acts as a diffusive process on the nuclides evolution.

3.3 External torques

In low-mass stars, the angular velocity profile (hence the mixing) is strongly influenced by the external torques exerted at the stellar surface via the stellar winds and the star-disk-interaction (see [48] for a recent review). During the T-Tauri phase, when the star-disk interaction is the strongest, its is generally assumed that the surface angular velocity is assumed to be constant over the entire disk lifetime. This is referred to as "disk-locking" and reveals the difficulty to properly account for complex 3-D processes [49–51] in 1-D and is supported by observations [52]. For the subsequent evolution to the TAMS, the torque exerted on the stellar surface by the (weak) stellar winds can be described analytically [53–56] and is introduced as a boundary condition to the angular momentum transport equation. Additional angular momentum losses directly related to the amount of mass lost are also taken into account during the entire evolution of stars.

Type I rotational mixing successfully applies to (fast rotating) early-type stars [42,41]. When moving to late-type stars, models including it predict fast rotating cores [57] and strong lithium depletion due to mixing correlated with the angular momentum loss. These predictions are not supported by observations [58–60]. This points out to additional missing processes that would mainly transport angular momentum and have an indirect impact on the transport of nuclides through the modification of the angular velocity profile.
In the case of late-type stars, it is thus necessary to apply the so-called type II rotational mixing (see Fig. 1).

4 Type II rotational mixing

4.1 Internal Gravity Waves

Contrary to hydrodynamical instabilities or to meridional circulation which are *rotation-driven* transport processes, internal gravity waves (hereafter IGW) exist and propagate in stellar interiors even in the absence of rotation. Rotation however affects their damping and propagation, making IGW important vectors for the transport of angular momentum.
Fluid displacements generated by convective motions[1] in the surrounding stable and stratified radiative regions lead to the oscillation of the fluid elements displaced, thus yielding the propagation of IGW. Gravity and buoyancy are the restoring forces for these waves, which means that a favoured direction of propagation exists. Propagating vertically and horizontally in the fluid, IGW transport energy and angular momentum in stratified media. They are prone to radiative damping by thermal diffusivity and viscosity in co-rotation resonance (see [62]), and deposit the angular momentum they carry at the location where they are damped. Angular momentum deposition can be positive or negative depending on their nature in terms of prograde or retrogade (azimuthal number $m > 0$ or < 0 respectively). In differentially rotating regions, the damping differs for prograde an retrograde waves, leading to a local net variation of the angular momentum where the waves dissipate.
The actual efficiency of IGW on the angular momentum redistribution strongly depends on the physical conditions at the edge of the convective regions, which in turn depend on the surface temperature of the star. For instance, the IGW angular momentum luminosity is reduced for shallow convective envelopes at the base of which the thermal diffusivity is large, leading to an efficient damping very close to the convective edge (see [63]).
The first results obtained with this type II rotational mixing are very encouraging to explain the rotation profile and lithium abundance of low-mass stars [61]. However, the introduction of the transport of angular momentum by IGW in stellar evolution codes is still marginal due to the complexity of its implementation and to the incomplete description of their excitation process. When accounted for, they appear in the angular momentum evolution equation as a wave luminosity (see also [62–64]).

[1] Two main excitation mechanisms are identified : bulk Reynolds stresses in the convective zones and convective overshooting in stably stratified regions.

4.2 Magnetic fields

Magnetic fields in stars are either fossil or generated by dynamo processes. Their nature and impact on the mixing and angular velocity profile in radiative regions remains unclear. A dynamo field generated in the convection envelope as it is the case for the Sun, is not likely to penetrate into the radiative zone [65]. A fossil field, like that possibly acting in Ap/Bp stars, could enforce uniform rotation and suppress hydrodynamical instabilities [66]. The field itself could also become unstable and generate a dynamo in the radiative stellar interiors as proposed by [67, 68], but this is debated based on the work by [69]. Finally, the magnetic field should introduce an additional torque through the Lorentz couple that should be included in the angular momentum equation [70]. When their impact is introduced in stellar evolution codes, it is done using the so-called Tayler-Spruit instability [37, 39]. This approach leads to very efficient flattening out of the angular velocity profile in solar models [71].

5 Conclusion

Transport processes in stellar radiative zones impact both the structure and the evolution of stars to a level that is fully reached by observations. They thus need to be implemented in stellar evolution codes. A great effort has been made to develop formalisms adapted to the 1-D treatment of the stellar structure problem within the secular evolution framework in the past two decades. Our understanding of early-type stars has been clearly improved by the implementation of type I rotational mixing in stellar evolution codes, as well as by the self-consistent treatment of the radiative levitation process.
On the other hand, many indicators, and in particular asteroseismic data, indicate that type II rotational mixing is at play in their radiative bulk. This type of mixing needs however to be investigated in much more detail and the exact interplay of all the physical processes at play in these objects and presented in Fig. 1 is still to be assessed. This should be achieved by the combined efforts on the simulation and theoretical side to provide accurate prescriptions to be implemented in stellar evolution codes, and on the observational side in particular through asteroseismology.

References

1. Bahcall J. N., Pinsonneault M. H., RvMP **64**, (1992) 885
2. Montmerle T., Michaud G., ApJS **31**, (1976) 489
3. Paquette C., Pelletier C., Fontaine G., Michaud G., 1986, ApJS **61**,(1986) 177
4. Burgers, J.M. Flow Equations for Composite Gases (New York: Academic Press, 1969)
5. Christensen-Dalsgaard J., et al., Science **272**, (1996) 1286
6. Richard O., Vauclair S., Charbonnel C., Dziembowski W. A., A&A **312**, (1996) 1000
7. Brun A. S., Turck-Chièze S., Morel P., ApJ **506**, (1998) 913
8. Thoul, A.A., Bahcall, J.N. and Loeb, A., ApJ **421**, (1994), 828
9. Alecian G., LeBlanc F., MNRAS **332**, (2002) 891
10. LeBlanc F., Alecian G., MNRAS **352**, (2004) 1329
11. Seaton M. J., MNRAS **362**, (2005) L1
12. Richard O., Michaud G., Richer J., ApJ **558**, (2001) 377
13. Gebran M., Monier R., Richard O., A&A **479**, (2008) 189
14. Michaud G., Richer J., Richard O., ApJ **675**, (2008) 1223
15. Théado S., Vauclair S., Alecian G., LeBlanc F., ApJ **704**, (2009) 1262
16. Vick M., Michaud G., Richer J., Richard O., A&A **521**, (2010) A62
17. Michaud G., Richer J., Richard O., A&A **529**, (2011) A60
18. Michaud G., Richer J., Vick M., A&A **534**, (2011) A18
19. Mathis S., Decressin T., Palacios A. et al., AN **328**, (2007) 1062
20. Théado S., Alecian G., LeBlanc F., Vauclair S., A&A **546**, (2012) A100
21. Théado, S., Vauclair, S., Alecian, G., & LeBlanc, F., ApJ **704**, (2009) 1262
22. Charbonnel C., Zahn J.-P., A&A **467**, (2007) L15

23. Denissenkov P. A., Merryfield W. J., ApJ **727**, (2011) L8
24. Traxler A., Garaud P., Stellmach S., ApJ **728**, (2011) L29
25. Ulrich R. K., ApJ **172**, (1972) 165
26. Brown, J. M., Garaud, P., & Stellmach, S., ApJ **768**, (2013) 34
27. Lagarde, N., Charbonnel, C., Decressin, T., & Hagelberg, J., A&A **536**, (2011) A28
28. Denissenkov P. A., ApJ **723**, (2010) 563
29. Cantiello M., Langer N., A&A **521**, (2010) A9
30. Palacios, A., Evry Schatzman School 2012 (EAS Publications Series, Volume 62, 2013), 227-287
31. Wasiutynski, J., Astrophysica Norvegica **4**, (1946) 1
32. Goldreich, P. & Schubert, G., ApJ **150**, (1967) 571
33. Fricke, K. , ZAp **68**, (1968) 317
34. Talon S., IAUS **215**, (2004) 336
35. Endal A. S., Sofia S., ApJ **210**, (1976) 184
36. Endal A. S., Sofia S., ApJ **220**, (1978) 279
37. Heger A., Langer N., Woosley S. E., 2000, ApJ **528**, (2000) 368
38. Talon S., Zahn J.-P., A&A **317**, (1997) 749
39. Maeder A., Meynet G., A&A **411**, (2003) 543
40. Zahn J.-P., A&A **265**, (1992) 115
41. Palacios A., Talon S., Charbonnel C., Forestini M., A&A **399**, 603
42. Maeder A., Meynet G., ARA&A **38**, (2000) 143
43. Marques J. P., et al., A&A **549**, (2013) AA74
44. Meynet G., Ekstrom S., Maeder A., Eggenberger P., Saio H., Chomienne V., Haemmerlé L., LNP **865**, (2013) 3
45. Prat V., Lignières F., A&A **566**, (2014) A110
46. Maeder A., Zahn J.-P., A&A **334**, (1998) 1000
47. Chaboyer B., Zahn J.-P., A&A **253**, (1992) 173
48. Bouvier, J., Matt, S. P., Mohanty, S., et al., *Protostars and Planets VI*, (UAP, Arizona, 2014), 22 pages, *in press*
49. Zanni C., Ferreira J., A&A **550**, (2013) A99
50. Romanova M. M., Ustyugova G. V., Koldoba A. V., Lovelace R. V. E., MNRAS **399**, (2009) 1802
51. Romanova M. M., Long M., Lamb F. K., Kulkarni A. K., Donati J.-F., MNRAS **411**, (2011) 915
52. Gallet F., Bouvier J., A&A **556**, (2013) A36
53. Skumanich A., ApJ **171**, (1972) 565
54. Kawaler S. D., ApJ **333**, (1988) 236
55. Reiners A., Mohanty S., ApJ **746**, (2012) 43
56. Matt S. P., MacGregor K. B., Pinsonneault M. H., Greene T. P.,ApJ **754**, (2012) 26
57. Palacios A., Charbonnel C., Talon S., Siess L., A&A **453**, (2006) 261
58. García, R. A., Salabert, D., Ballot, J., et al. JPCS **271**, (2011)
59. Beck, P. G., Montalban, J., Kallinger, T., et al. Nature **481**, (2012) 55
60. Mosser, B., Goupil, M. J., Belkacem, K., et al. A&A **548**, (2012) A10
61. Charbonnel C., Talon S., Science **309**, (2005) 2189
62. Zahn J.-P., Talon S., Matias J., A&A **322**, (1997) 320
63. Talon S., Charbonnel C., A&A **482**, (2008) 597
64. Charbonnel C., Decressin T., Amard L., Palacios A., Talon S., A&A **554**, (2013) AA40
65. Garaud P., MNRAS **304**, (1999) 583
66. Charbonnel C., Zahn J.-P., IAUS **252**, (2008) 245
67. Spruit H. C., A&A **349**, (1999) 189
68. Spruit H. C., A&A **381**, (2002) 923
69. Zahn J.-P., Brun A. S., Mathis S., A&A **474**, (2007) 145
70. Mathis S., Zahn J.-P., A&A **440**, (2005) 653
71. Eggenberger P., Maeder A., Meynet G., A&A **440**, (2005) L9