The Structure and Evolution of Stars

Subjects: Astronomy & Astrophysics

Contributor: Dominic M. Bowman , Jennifer van Saders , Jorick S. Vink

Generally speaking, stars consist of three regimes: a core, an envelope, and an atmosphere from which the light emerges. Depending on the stellar mass and the evolutionary stage, cores and envelopes can be either radiative or convective. These regions define the (dominant) form of energy transport, but their physical definition and the interface between them represent a large source of uncertainty in stellar structure theory. Whilst stellar atmospheres are key messengers of astronomical information, they are also physical laboratories of radiation pressure leading to radiation-driven winds for high-mass stars and chemical mixing and transport phenomena such as radiative levitation in hot low-mass stars, which is where heavy elements with large cross-sections can gain momentum by absorbing photons from outflowing radiation.

stellar structure and evolution | convection | rotation | diffusion | magnetism | asteroseismology | radiation pressure

1. 1D Convection in Stellar Modelling

Convection is omnipresent in stars at some point in their evolution. For stars like the Sun, convection occurs in a thick envelope and thus is the dominant mixing and energy transport mechanism at the photosphere. Very low-mass stars, such as M dwarfs, are fully convective throughout their interior. Meanwhile, for compact stars, such as white dwarfs, conduction is an important energy transport mechanism. At the other end of the mass-scale in the upper part of the HR diagram, the hydrogen-burning cores of high-mass main-sequence stars are convective and their envelopes are radiative. During the main sequence, the envelopes of massive stars are dominated by radiation, but convection becomes increasingly more important in their envelopes as they evolve off the main sequence. This means that for all stars in the HR diagram the definition and numerical implementation of convection is important in calculating stellar structure models. However, convection is inherently a 3D process, but most state-of-the-art evolution models are 1D, with some being 2D (e.g., the ESTER code [1][2][3]). Consequently, the optimum 1D representation and numerical prescription for convection remains a topic of ongoing investigation.

Joyce and Tayar (2023) [4] provide a detailed overview of convection inside stars. Specifically, they focus on the numerical prescription known as Mixing Length Theory (MLT [5]) commonly used to define convective regions within stellar structure models and to parameterise convection in 1D. MLT for convection is a formalism analogous to having a mean free path of a fluid parcel in thermodynamics, and specifies the distance such a parcel travels before fully mixing with its surrounding fluid. However, the MLT formalism is only described in 1D which limits its application to 3D convective zones in stellar interiors (e.g., [6]).

There has been tremendous effort in calibrating MLT using observations, which has been hugely successful using helioseismology—the study of the Sun's interior from its resonant pulsation frequencies [7][8][9]. The study of the interior physics using pulsations in stars other than the Sun is called asteroseismology [8][10]. This field of stellar astrophysics has greatly expanded in recent years thanks to high-precision space photometry, such as from the Kepler mission [11][12]. It has provided tight constraints on the masses, radii, and ages of thousands of stars [13][14][15][16][17].

Asteroseismology combined with additional observables from spectroscopy and interferometry have also been able to provide constraints on MLT [18][19][20]. However, this remains a challenging endeavour that can only be achieved as of today for the brightest low-mass stars. A direct observational calibration of MLT for interior convection is currently beyond reach, but asteroseismology is able to provide constraints on this important physical ingredient of stellar structure.

2. Opacities and Atomic Diffusion

When radiation passes through a gas, photons are removed by scattering and absorption with the efficiency coefficient of these processes termed opacity. In reality, a star's opacity is a function of its chemical composition and the thermodynamic state of its constituent gas. Thus, opacity influences how stars are formed in the earliest phases of their lives, because of the interaction between photons and atoms, and also how stars evolve and end their lives. For example, diffusion processes, such as radiative levitation, depend on stellar opacity mix and transport chemical species within stellar interiors. Therefore, such processes are important contributors to uncertainties when inferring stellar ages and chemical abundances (see, e.g., [21][22]).

Opacity data are an important ingredient to essentially all forms of stellar structure modelling and all stars across the HR diagram, and remain a primary contributor to the uncertainty of the heavy element content of our own Sun [23]. Stellar evolution models typically include and thus implicitly depend on an opacity table with a chosen number of specific chemical elements as main contributors, and a fixed chemical mixture for heavy elements (e.g., C, N and O). The construction of precise and accurate opacity tables for use within stellar physics presents a herculean task within the atomic physics community [24][25][26][27], with which stellar astrophysics has great synergy.

Nuclear fusion, chemical mixing and atomic diffusion processes redistribute sources of opacity within a star, with the different processes taking place on different time scales. Since a full calculation of stellar opacity taking such processes into account is computationally expensive, especially for each time-step of a stellar evolution model, a common simplification is to calculate a mean opacity averaged across all wavelengths. A commonly used approach is to calculate the Rosseland mean opacity, which is a harmonic weighted average over all chemical species. Moreover, the full implementation of all atomic diffusion processes, which are inherently chemical–element specific, in evolutionary models can be computationally demanding, so not all of them are always included because of computation time arguments. Such a numerical simplification bears validity that depends on the type of star being studied.

Alecian and Deal (2023) [28] provide a detailed discussion of opacities and atomic diffusion inside stars. This includes a comparison of the different opacity tables available in the literature for stellar modelling, their domains of applicability, and impact on opacity profiles in the context of providing accurate stellar structure and evolution models.

3. Magnetism in High-Mass Stars

Despite its importance and impact on stellar structure, magnetic fields are an important, yet typically missing ingredient in evolution models. Observational constraints on the strength and geometry of magnetic fields, both at the surface and in the deep interiors, are generally lacking for the vast majority of stars.

For low-mass stars like the Sun, their large convective envelopes during the main sequence produce weak global magnetic fields, but strong local fields in the form of sunspots through a dynamo process. The reader is referred to literature reviews of stellar magnetism in low-mass stars [29][30][31].

On the other hand, the origin and consequences of magnetic fields in massive stars are less understood compared to low-mass stars. In the last couple of decades, there has been a large effort and major progress in detecting surface magnetic fields in early-type stars (i.e., spectral types O and B). Ground-based surveys using spectropolarimetry such as the Magnetism in Massive Stars (MiMeS) [32] and Binarity and Magnetic Interactions in various classes of Stars (BinaMIcS) [33] consortia established that large-scale magnetic fields with strengths ranging between approximately tens of Gauss and tens of kG, which are predominantly dipolar in topology, exist at the surface of about 10% of massive main-sequence stars. However, the origin of such strong and globally organised magnetic fields, whether they are of fossil origin (e.g., [29]) or are a result of stellar mergers (e.g., [34]), remains yet to be generally established. Nor is it known how such fields evolve throughout a star's lifetime, because a single surface measurement defines only one epoch during a star's evolution. What is clear, however, is that the presence of a (strong) magnetic field inside a massive star has a significant impact on its interior rotation and thus mixing profiles compared to a non-magnetic star. Thus, the evolution of magnetic massive stars significantly differ to non-magnetic stars (see [35][36][37]).

Of course, almost all constraints of magnetic fields for massive stars are limited to their surface properties (e.g., strength and geometry) when using spectropolarimetry. The most promising method to diagnose the interior magnetic field properties and their impact on stellar evolution arise from magneto-asteroseismology—the study of pulsations and their interaction with magnetic fields. First applications of this technique suggest that magnetic and non-magnetic massive stars have different interior mixing properties, with evidence for the presence of a magnetic field suppressing mixing in the near-core region of massive stars [38][39].

4. Multi-D Simulations of Core Convection

In addition to traditional observational techniques and comparison to evolution models, complementary synthetic observables predicted and inferred from numerical simulations are also extremely valuable when studying the physics of stellar structure.

The long time scales associated with nuclear burning processes prohibit numerical simulations of convection covering the duration of stellar evolution. However, simulations studying dynamical processes comparable to hydrostatic timescales are much more feasible. Therefore, simulations of relatively rapid processes such as convection and pulsations, which are perturbations to the equilibrium structure, yield prescriptions for stellar structure that can be implemented into 1D stellar evolution models. Moreover, evolution models necessarily take time steps that are orders of magnitude larger than the typical time scales of convection in most stars, and thus seek to include only the time-averaged net effects of dynamical processes such as convection, mixing and wave generation. Numerical simulations are a unique method for testing the validity of assumptions in stellar evolution models, and provide improved prescriptions where needed (see, e.g., [40][41][42][43]).

Lecoanet and Edelmann (2023) [44] explore the literature of multidimensional simulations of core convection in main-sequence stars. In addition to providing a firm mathematical grounding in the physics, they also discuss and elucidate the differences and similarities in various numerical setups and their implications for the resultant synthetic observables. Given their importance for mixing and angular momentum transport within stellar interiors, the generation and propagation of waves excited by turbulent convection in the core of massive stars is discussed in detail.

5. Convective Boundary Mixing in Main-Sequence Stars

In addition to an incomplete theory of convection and how to implement it in 1D evolutionary models, the specific issue of the amount and shape of the mixing profile at the boundary of convective and radiative zones remains a primary unresolved uncertainty in stellar structure theory (e.g., [42][45]). This problem, known as convective boundary mixing (CBM), cannot be derived from first principles and encompasses several possible physical scenarios. One mechanism is convective penetration in which the dynamics of convective motions significantly extend into an overlying radiative zone causing an extended convection zone [46][47][48][49]. Additionally, mixing at the convective–radiative boundary can give rise to increased chemical entrainment, which alters the chemical composition in the zone just beyond the convective boundary in the radiative zone.

There are two main techniques that have made significant strides in our understanding of CBM: (i) hydrodynamical simulations and (ii) observations. For the former, the ability to vary parameters within different numerical setups allows one to study the fundamental physics of convection, and moreover the physics of the boundary layer of convective and radiative regions. This then allows physical prescriptions from multi-dimensional numerical simulations to be implemented in 1D evolution models (see, e.g., [42][48]).

In terms of observational constraints, the comparison of various observables to theoretical predictions from (evolution) models reveal discrepancies in the physics of convection and thus also CBM. For example, spectroscopy, binary modelling and asteroseismology have all independently highlighted not only the importance of

CBM in stellar structure and evolution, but also have been able to quantify, to differing levels of precision, the shape of the mixing profile of the CBM region [50][51][52].

6. Radiation-Dominated Envelopes of Massive Stars

While convection is relevant in most stars, the uncertainties in energy transport are not nearly as large as for the outer layers of the most massive stars. In standard 1D stellar evolution models, stars close to the Eddington limit, which is the maximum luminosity a star can have such that outward radiation balances the force of gravity acting inward, stellar models develop rather peculiar structures.

Jiang (2023) [53] discusses the state-of-the art for 3D radiation-dominated envelopes. In reality, the envelopes and stellar winds probably interact with one another, either by winds removing the inflated layer [54], or by other wind–envelope interactions, which may play a role in the S Doradus variability of Luminous Blue Variables [55].

References

1. Espinosa Lara, F.; Rieutord, M. Gravity darkening in rotating stars. Astron. Astrophys. 2011, 533, A43.
2. Espinosa Lara, F.; Rieutord, M. Self-consistent 2D models of fast-rotating early-type stars. Astron. Astrophys. 2013, 552, A35.
3. Rieutord, M.; Espinosa Lara, F.; Putigny, B. An algorithm for computing the 2D structure of fast rotating stars. J. Comput. Phys. 2016, 318, 277–304.
4. Joyce, M.; Tayar, J. A Review of the Mixing Length Theory of Convection in 1D Stellar Modeling. Galaxies 2023, 11, 75.
5. Böhm-Vitense, E. Über die Wasserstoffkonvektionszone in Sternen verschiedener Effektivtemperaturen und Leuchtkräfte. Mit 5 Textabbildungen. Z. Astrophys. 1958, 46, 108.
6. Arnett, W.D.; Meakin, C.; Viallet, M.; Campbell, S.W.; Lattanzio, J.C.; Mocák, M. Beyond Mixing-length Theory: A Step toward 321D. Astrophys. J. 2015, 809, 30.
7. Christensen-Dalsgaard, J. Helioseismology. Rev. Mod. Phys. 2002, 74, 1073–1129.
8. Aerts, C.; Christensen-Dalsgaard, J.; Kurtz, D.W. Asteroseismology; Springer: Berlin/Heidelberg, Germany, 2010.
9. Basu, S. Global seismology of the Sun. Living Rev. Sol. Phys. 2016, 13, 2.
10. Kurtz, D.W. Asteroseismology Across the Hertzsprung-Russell Diagram. Annu. Rev. Astron. Astrophys. 2022, 60, 31–71.

11. Borucki, W.J.; Koch, D.; Basri, G.; Batalha, N.; Brown, T.; Caldwell, D.; Caldwell, J.; Christensen-Dalsgaard, J.; Cochran, W.D.; DeVore, E.; et al. Kepler Planet-Detection Mission: Introduction and First Results. Science 2010, 327, 977–980.
12. Koch, D.G.; Borucki, W.J.; Basri, G.; Batalha, N.M.; Brown, T.M.; Caldwell, D.; Christensen-Dalsgaard, J.; Cochran, W.D.; DeVore, E.; Dunham, E.W.; et al. Kepler Mission Design, Realized Photometric Performance, and Early Science. Astrophys. J. Lett. 2010, 713, L79–L86.
13. Chaplin, W.J.; Miglio, A. Asteroseismology of Solar-Type and Red-Giant Stars. Annu. Rev. Astron. Astrophys. 2013, 51, 353–392.
14. Hekker, S.; Christensen-Dalsgaard, J. Giant star seismology. Astron. Astrophys. Rev. 2017, 25, 1.
15. Silva Aguirre, V.; Lund, M.N.; Antia, H.M.; Ball, W.H.; Basu, S.; Christensen-Dalsgaard, J.; Lebreton, Y.; Reese, D.R.; Verma, K.; Casagrande, L.; et al. Standing on the Shoulders of Dwarfs: The Kepler Asteroseismic LEGACY Sample. II.Radii, Masses, and Ages. Astrophys. J. 2017, 835, 173.
16. García, R.A.; Ballot, J. Asteroseismology of solar-type stars. Living Rev. Sol. Phys. 2019, 16, 4.
17. Bowman, D.M. Asteroseismology of high-mass stars: New insights of stellar interiors with space telescopes. Front. Astron. Space Sci. 2020, 7, 70.
18. Tayar, J.; Somers, G.; Pinsonneault, M.H.; Stello, D.; Mints, A.; Johnson, J.A.; Zamora, O.; García-Hernández, D.A.; Maraston, C.; Serenelli, A.; et al. The Correlation between Mixing Length and Metallicity on the Giant Branch: Implications for Ages in the Gaia Era. Astrophys. J. 2017, 840, 17.
19. Joyce, M.; Chaboyer, B. Not All Stars Are the Sun: Empirical Calibration of the Mixing Length for Metal-poor Stars Using One-dimensional Stellar Evolution Models. Astrophys. J. 2018, 856, 10.
20. Joyce, M.; Chaboyer, B. Classically and Asteroseismically Constrained 1D Stellar Evolution Models of α Centauri A and B Using Empirical Mixing Length Calibrations. Astrophys. J. 2018, 864, 99.
21. Dotter, A.; Conroy, C.; Cargile, P.; Asplund, M. The Influence of Atomic Diffusion on Stellar Ages and Chemical Tagging. Astrophys. J. 2017, 840, 99.
22. Semenova, E.; Bergemann, M.; Deal, M.; Serenelli, A.; Hansen, C.J.; Gallagher, A.J.; Bayo, A.; Bensby, T.; Bragaglia, A.; Carraro, G.; et al. The Gaia-ESO survey: 3D NLTE abundances in the open cluster NGC 2420 suggest atomic diffusion and turbulent mixing are at the origin of chemical abundance variations. Astron. Astrophys. 2020, 643, A164.
23. Asplund, M.; Grevesse, N.; Sauval, A.J.; Scott, P. The Chemical Composition of the Sun. Annu. Rev. Astron. Astrophys. 2009, 47, 481–522.

24. Iglesias, C.A.; Rogers, F.J. Radiative Opacities for Carbon- and Oxygen-rich Mixtures. Astrophys. J. 1993, 412, 752.
25. Iglesias, C.A.; Rogers, F.J. Updated Opal Opacities. Astrophys. J. 1996, 464, 943.
26. Seaton, M.J.; Yan, Y.; Mihalas, D.; Pradhan, A.K. Opacities for Stellar Envelopes. Mon. Not. R. Astron. Soc. 1994, 266, 805.
27. Seaton, M.J. Opacity Project data on CD for mean opacities and radiative accelerations. Mon. Not. R. Astron. Soc. 2005, 362, L1–L3.
28. Alecian, G.; Deal, M. Opacities and Atomic Diffusion. Galaxies 2023, 11, 62.
29. Borra, E.F.; Landstreet, J.D.; Mestel, L. Magnetic stars. Annu. Rev. Astron. Astrophys. 1982, 20, 191–220.
30. Donati, J.F.; Landstreet, J.D. Magnetic Fields of Nondegenerate Stars. Annu. Rev. Astron. Astrophys. 2009, 47, 333–370.
31. Kochukhov, O. Magnetic fields of M dwarfs. Astron. Astrophys. Rev. 2021, 29, 1.
32. Wade, G.A.; Neiner, C.; Alecian, E.; Grunhut, J.H.; Petit, V.; de Batz, B.; Bohlender, D.A.; Cohen, D.H.; Henrichs, H.F.; Kochukhov, O.; et al. The MiMeS survey of magnetism in massive stars: Introduction and overview. Mon. Not. R. Astron. Soc. 2016, 456, 2–22.
33. Alecian, E.; Neiner, C.; Wade, G.A.; Mathis, S.; Bohlender, D.; Cébron, D.; Folsom, C.; Grunhut, J.; Le Bouquin, J.B.; Petit, V.; et al. The BinaMIcS project: Understanding the origin of magnetic fields in massive stars through close binary systems. In New Windows on Massive Stars, Proceedings of the IAU Symposium, Geneva, Switzerland, 23–27 June 2014; Meynet, G., Georgy, C., Groh, J., Stee, P., Eds.; Cambridge University Press: Cambridge, UK, 2015; Volume 307, pp. 330–335.
34. Schneider, F.R.N.; Ohlmann, S.T.; Podsiadlowski, P.; Röpke, F.K.; Balbus, S.A.; Pakmor, R.; Springel, V. Stellar mergers as the origin of magnetic massive stars. Nature 2019, 574, 211–214.
35. Keszthelyi, Z.; Meynet, G.; Georgy, C.; Wade, G.A.; Petit, V.; David-Uraz, A. The effects of surface fossil magnetic fields on massive star evolution: I. Magnetic field evolution, mass-loss quenching, and magnetic braking. Mon. Not. R. Astron. Soc. 2019, 485, 5843–5860.
36. Keszthelyi, Z.; Meynet, G.; Shultz, M.E.; David-Uraz, A.; ud-Doula, A.; Townsend, R.H.D.; Wade, G.A.; Georgy, C.; Petit, V.; Owocki, S.P. The effects of surface fossil magnetic fields on massive star evolution—II. Implementation of magnetic braking in MESA and implications for the evolution of surface rotation in OB stars. Mon. Not. R. Astron. Soc. 2020, 493, 518–535.
37. Keszthelyi, Z.; Meynet, G.; Martins, F.; de Koter, A.; David-Uraz, A. The effects of surface fossil magnetic fields on massive star evolution—III. The case of τ Sco. Mon. Not. R. Astron. Soc. 2021, 504, 2474–2492.

38. Briquet, M.; Neiner, C.; Aerts, C.; Morel, T.; Mathis, S.; Reese, D.R.; Lehmann, H.; Costero, R.; Echevarria, J.; Handler, G.; et al. Multisite spectroscopic seismic study of the β Cep star V2052 Ophiuchi: Inhibition of mixing by its magnetic field. Mon. Not. R. Astron. Soc. 2012, 427, 483–493.
39. Buysschaert, B.; Aerts, C.; Bowman, D.M.; Johnston, C.; Van Reeth, T.; Pedersen, M.G.; Mathis, S.; Neiner, C. Forward seismic modeling of the pulsating magnetic B-type star HD 43317. Astron. Astrophys. 2018, 616, A148.
40. Freytag, B.; Ludwig, H.G.; Steffen, M. Hydrodynamical models of stellar convection. The role of overshoot in DA white dwarfs, A-type stars, and the Sun. Astron. Astrophys. 1996, 313, 497–516.
41. Herwig, F. The evolution of AGB stars with convective overshoot. Astron. Astrophys. 2000, 360, 952–968.
42. Scott, L.J.A.; Hirschi, R.; Georgy, C.; Arnett, W.D.; Meakin, C.; Kaiser, E.A.; Ekström, S.; Yusof, N. Convective core entrainment in 1D main-sequence stellar models. Mon. Not. R. Astron. Soc. 2021, 503, 4208–4220.
43. Herwig, F.; Woodward, P.R.; Mao, H.; Thompson, W.R.; Denissenkov, P.; Lau, J.; Blouin, S.; Andrassy, R.; Paul, A. 3D hydrodynamic simulations of massive main-sequence stars. I. Dynamics and mixing of convection and internal gravity waves. Mon. Not. R. Astron. Soc. 2023, 525, 1601–1629.
44. Lecoanet, D.; Edelmann, P.V.F. Multidimensional Simulations of Core Convection. Galaxies 2023, 11, 89.
45. Kaiser, E.A.; Hirschi, R.; Arnett, W.D.; Georgy, C.; Scott, L.J.A.; Cristini, A. Relative importance of convective uncertainties in massive stars. Mon. Not. R. Astron. Soc. 2020, 496, 1967–1989.
46. Zahn, J.P. Convective penetration in stellar interiors. Astron. Astrophys. 1991, 252, 179–188.
47. Augustson, K.C.; Mathis, S. A Model of Rotating Convection in Stellar and Planetary Interiors. I. Convective Penetration. Astrophys. J. 2019, 874, 83.
48. Anders, E.H.; Jermyn, A.S.; Lecoanet, D.; Brown, B.P. Stellar Convective Penetration: Parameterized Theory and Dynamical Simulations. Astrophys. J. 2022, 926, 169.
49. Jermyn, A.S.; Anders, E.H.; Lecoanet, D.; Cantiello, M. Convective Penetration in Early-type Stars. Astrophys. J. 2022, 929, 182.
50. Claret, A.; Torres, G. The dependence of convective core overshooting on stellar mass. Astron. Astrophys. 2016, 592, A15.
51. Martinet, S.; Meynet, G.; Ekström, S.; Simón-Díaz, S.; Holgado, G.; Castro, N.; Georgy, C.; Eggenberger, P.; Buldgen, G.; Salmon, S.; et al. Convective core sizes in rotating massive stars. I. Constraints from solar metallicity OB field stars. Astron. Astrophys. 2021, 648, A126.

52. Johnston, C. One size does not fit all: Evidence for a range of mixing efficiencies in stellar evolution calculations. Astron. Astrophys. 2021, 655, A29.
53. Jiang, Y.F. Multi-D simulations of core convection. Galaxies, 2023; under review.
54. Petrovic, J.; Pols, O.; Langer, N. Are luminous and metal-rich Wolf-Rayet stars inflated? Astron. Astrophys. 2006, 450, 219–225.
55. Grassitelli, L.; Langer, N.; Mackey, J.; Gräfener, G.; Grin, N.J.; Sander, A.A.C.; Vink, J.S. Wind-envelope interaction as the origin of the slow cyclic brightness variations of luminous blue variables. Astron. Astrophys. 2021, 647, A99.