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2DStars: a two-dimensional stellar evolution code

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Abstract. We introduce the 2DStars code, a new two-dimensional stellar evolution code under construction to model rotating stars. Most of our current understanding of stellar interiors and evolution is based largely on one-dimensional models. In these models, complex physical processes such as convection, rotation and magnetic fields are typically described by simplified approaches which rely on free parameters. Such parametrized descriptions have little predictive power and often fail to capture the physical nature of the underlying processes responsible for discrepancies between models and observations. Given the increasing computational power and algorithmic efficiency, multi-dimensional models are now timely and crucial in order to make progress in the field of stellar astrophysics and take full advantage of the unprecedented developments in observational astronomy, notably high-resolution spectroscopy, as well as present and future spectroscopic surveys.

Key words. Stars: evolution – Stars: interiors – Stars: rotation

1. Introduction

The assumption of spherical symmetry in stellar modelling has been encouraged by the successes of the one-dimensional (1D) theory of stellar evolution. As a result, rotation has been often reduced to a tractable 1D problem.

However, recent observations of surface abundances show a number of discrepancies with 1D models. These include surface enhancements of helium and nitrogen abundances in massive O- and B-type stars (Brott et al. 2011), as well as the distribution of stars in the Hertzsprung-Russell diagram (Maeder & Meynet 2000). These discrepancies challenge 1D models and question the fidelity of their imposed spherical geometry.

It is well-established that rotation is a third key parameter in stellar evolution, alongside the mass and metallicity. Data from interferometry (Meilland et al. 2007; Monnier et al. 2007; Che et al. 2011) revealed rapidly rotating stars with angular velocities larger than 50% of critical. The centrifugal and the Coriolis forces owing to axial rotation have substantial structural and chemical consequences. The centrifugal force disturbs the hydrostatic balance and flattens the star, so it is not spherically symmetric. The Coriolis force affects oscillatory motions and pulsational properties (Reese et al. 2014), and couples meridional and axial convective motions (Lesaffre et al. 2013). Baroclinic torque resulting from the centrifugal force drives meridional (Eddington-Sweet) circulation (Sweet 1950) in the radiative regions and leads

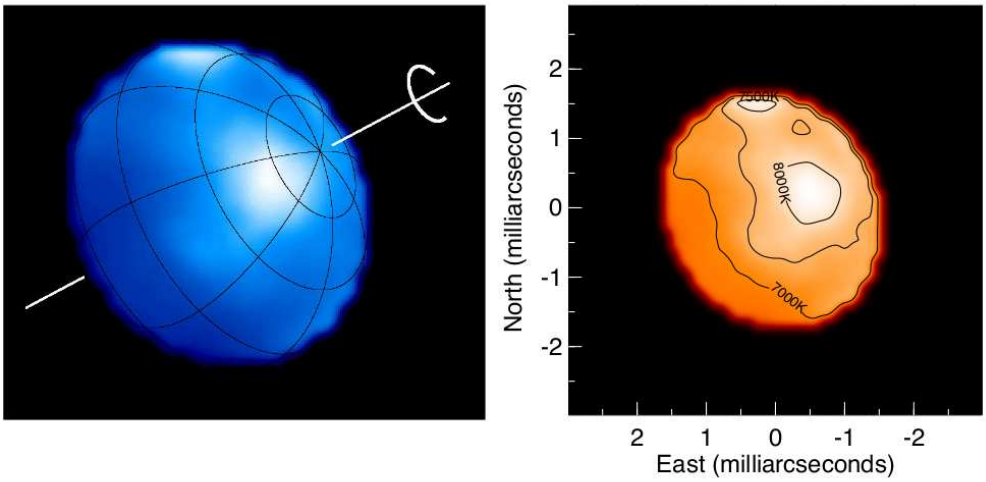

Fig. 1. CHARA interferometric array image of the A-type star Altair (image credit: Ming Zhao, University of Michigan). Aspherical distortion because of rapid rotation causes the equator to bulge and darken (become cooler) thus exhibiting surface temperature variations. On the right is the synthesized intensity image of the surface of Altair created with the MACIM/MEM imaging method. Brighter shades correspond to larger intensities and the specific intensities are converted into the corresponding blackbody temperatures and shown as contours, from Monnier et al. (2007). Reprinted with permission from AAAS and the author.

to shear instabilities (Spiegel & Zahn 1970). These currents and instabilities mix angular momentum and chemical elements within the star, changing observable surface properties such as surface gravity, temperature, chemical composition and luminosity.

Besides aspherical distortion, rotation also causes surface temperature variations which introduce a brightness asymmetry owing to the variation in the flux flowing through the surface as a function of latitude. This was first described by Von Zeipel (1924) and is also known as gravity darkening. Fig. 1 shows the CHARA interferometric array image of the A-type star *Altair* which rotates at 90% of its breakup velocity with a period of 9 hours (2.8 rev/day). The observed intensity at the equator is about 60–70% that of the pole (Monnier et al. 2007).

This spectacular departure from spherical geometry prompts the need for multi-dimensional models so we can interpret high precision observational data whether from astrometry, spectroscopy, interferometry or astroseismology. Upgrading full stellar evolution to 2D axisymmetry is a major step-up that is currently computationally tractable.

Rotation has been included in 1D stellar evolution codes by introducing assumptions such as shellular rotation which can be incorporated into 1D stellar structure equations (Zahn 1992; Meynet & Maeder 1997; Frischknecht et al. 2010). However, helioseismology shows that the Sun does not rotate on such shells, so this assumption is mostly for convenience. Multi-dimensional stellar models do exist but all current 3D models of stars are hydrodynamical and thus not suitable for stellar evolution which occurs on much longer thermal or nuclear timescales. The *Djehuty* code for example evolves a 3D solar model in real time which is ideal to simulate rapid phenomena, such as convection, but the computing power required for actual 3D stellar evolution does not yet exist. The simplest 2D models are centrifugally distorted, non-evolving, uniformly-rotating 1D models mapped to 2D (Roxburgh 2004). High-accuracy 2D solar models have been constructed (Li et al. 2009) but again only on short timescales. The ROTORC code (Deupree 1990) is a hydrodynamic-hydrostatic hybrid that has been used most recently to investigate mass loss from a 2D main-sequence star on short timescales (Lovekin & Deupree 2011) and to model pulsation for asteroseismological studies (Deupree et al. 2012) in main-sequence stars. An ongoing project is the spectral ESTER code (Espinosa Lara & Rieutord 2013) that predicts pulsation frequencies but is limited to evolving main-sequence stars.

The 2DStars code we are constructing is designed to solve the stellar structure equations in 2D assuming axisymmetric geometry. We are developing it with two independent discretization schemes in parallel, the finite difference and the finite element methods. In addition to modelling rotating stars, the code's applications encompass a variety of multi-dimensional phenomena in stellar evolution such as accretion and mass transfer in close binary systems, star formation, X-ray binaries and excretion disks around Be stars.

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