Two-dimensional Stellar Evolution

Case for Support – STFC Rutherford Grant 2014

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The assumption of spherical symmetry is a good approximation when modelling stellar structure – if we ignore the fact that stars rotate. Especially in massive stars (Ramírez-Agudelo et al. A&A 560,A29 2013), rotation is a third key parameter of stellar evolution beside mass and metallicity (Maeder & Meynet ARA&A 38,143 2000). Stellar rotation is either intrinsic, i.e. it originates in the cloud from which the star formed, or it comes from interaction in a binary-star system (de Mink et al. ApJ 764,166 2013). Either way, stars that rapidly rotate are aspherical (Fig. 1) and *not* the idealised, one-dimensional objects of classical stellar evolution theory. Because they rotate, stars develop internal currents, such as the meridional (Eddington-Sweet) circulation, which mix material from their core to their surface. Such mixing may cause observable enhancements of nitrogen in massive B-type stars (Hunter et al. ApJ 676,L29 2008) and heavy elements in low-mass stars (Piersanti et al. ApJ 774,98 2013). Rotation and magnetic fields in stars (Wickramasinghe et al. MNRAS 437,675 2014) are linked by angular momentum transport and dynamo action throughout the star (Suijs et al. A&A 481,L87 2008), as seen in Kepler red giants (Mosser et al. A&A 548,A10 2012). The combined action of rotation and magnetic fields is a major contender as the key to the formation of gamma-ray bursts (MacFadyen & Woosley ApJ 524,262 1999) and magnetic white dwarfs (Tout et al. MNRAS 387,897 2008).

Rotational effects and magnetic fields in stars are multidimensional. Traditional 1D stellar evolution codes model them with an array of approximations and tuned free parameters.
It is time to step up to full 2D stellar evolution.

This project aligns perfectly with the STFC *Roadmap Science Challenges:*
A.6 *How are stars born and how do they evolve?* and B *How do stars and planetary systems develop...?*

State of the Art

Rotation has been included in one-dimensional (1D) stellar evolution codes by simplifying assumptions that reduce a three-dimensional (3D), rotating star to 1D. It is often argued that rotation is constant on pseudo-spherical shells (isobars) over which horizontal turbulence efficiently mixes the star. Examination of the solar surface coupled with helioseismology shows that the Sun does *not* rotate on such shells so this assumption is more for convenience than truth. Furthermore, interior motions, such as meridional circulation, caused by rotation are modelled as 1D advection-diffusion processes (Meynet & Maeder A&A 321,465 1997) but are really multidimensional fluid flows. Many tunable parameters are associated with such 1D simplifications. While 1D models are a useful first approximation, they are limited: they cannot model stars such as Be stars and accreting stars in binary systems spinning at close to break-up rotation. 1D models also fail to match observations of surface enhancements of nitrogen expected from rotational mixing (Brott et al. A&A 530,A116 2011), but that are not solely linked to rotation (Aerts et al. ApJ 781,88 2014). Stellar magnetic field models are usually equilibrium models, many based on the Tayler-Spruit dynamo (Spruit A&A 381,923 2002), which is approximated to work in 1D. These assumptions and associated disputes can be relaxed only with 2D or 3D models.

Multi-dimensional stellar models do exist but all 3D models of stars are hydrodynamical and so of limited use for computing *stellar evolution* on far longer thermal or nuclear timescales. The *Djehuty* code evolves a solar model *in real time* at the largest US supercomputers: the computing power required for actual 3D stellar evolution does not yet exist and will not for the foreseeable future. Such hydrodynamical models are however ideal to simulate rapid phenomena, such as convection (Dearborn et al. ApJ 639,405 2006), but cannot be used to evolve a star over its lifetime.

There have been a few attempts to model stars in 2D. The simplest 2D models are centrifugally distorted, non-evolving, uniformly-rotating 1D models mapped to 2D (Roxburgh A&A 428,171 2004). These are not evolutionary models. High-accuracy 2D solar models have been constructed (Li et al. ApJS 182,584 2009) but again

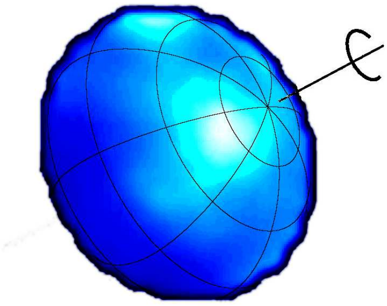

Figure 1: *Surface temperature variations (white is hotter, blue is cooler) and aspherical distortion caused by rapid rotation of the A-type star Altair measured with the CHARA interferometric array (Monnier et al. Science 317, 342 2007). It rotates at 90% of its breakup velocity with a period of 9 hours. Many other stars are known to rapidly rotate, both at the surface and in their interior. Such rotation drastically alters their chemistry, magnetic fields and future evolution and can only be modelled properly in multidimensions: stellar evolution in 2D is the major goal of this project.*

only on short timescales. The *ROTORC* code (Deupree ApJ 357,175 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 IAUS 272,93 2011) and to model pulsation for asteroseismological studies (Deupree et al. ApJ 753,20 2012) in main-sequence stars. Similarly, the spectral *ESTER* code (Espinosa Lara & Rieutord A&A 552,A35 2013) predicts pulsation frequencies but only in main-sequence stars. It has limiting assumptions such as small Ekman numbers.

Existing 2D stellar evolution codes do not evolve stars beyond the main sequence. No 2D code combines stellar evolution, magnetic fields, chemistry and binary interaction. This project will fill this void and lead the way in multi-dimensional stellar evolution modelling.

Science Goals and Physics Input

The goal is to develop a general-use 2D, adaptable to 3D, stellar evolution code including essential physics:

Rotation Stellar evolution including rotation, without assumptions required in 1D, is a major goal. Slow internal fluid flows, such as meridional circulation, driven by rotation will be modelled consistently.

Magnetic fields The Cambridge stellar physics group has developed a 1D model for magnetic field generation in stars (Potter et al. MNRAS 424,2358 2012). A more general poloidal-toroidal form will be implemented in the new 2D code. Magnetic fields enforce co-rotation and couple stellar cores to their envelopes. Only in at least 2D can this be done self-consistently with angular momentum transport.

Chemistry Slow internal mixing, such as meridional circulation, will be fully incorporated including resolved internal fluid flows. Fast mixing, e.g. convection, horizontal turbulence and other dynamical instabilities, will be parameterized (Lesaffre et al. MNRAS 431,2200 2013).

Binary stars Tides and mass transfer in binaries can spin stars to their critical breakup limit. While mass transfer is a 3D process, material usually accretes through an accretion disc and such situations should be modelled in 2D. Our new 2D code will be designed to be easily upgradeable to 3D. Hence we shall be ready for full binary evolution once sufficient computing power is available.

The combination of the above physics in one self-consistent package has not been attempted previously. One-dimensional codes contain a number of key tunable parameters which parameterize our ignorance. Our new 2D code outlined in this project will contain many fewer key parameters because we shall treat the relevant physical processes properly instead of approximating them.

Method and Milestones

This project demands expertise and experience in astrophysics and high-power computing. As such it is only suitable for a postdoc. Cambridge is rich in stellar physics expertise (PI **Izzard**, also **Tout**) and a consultant software engineer will be employed.

Year one. A detailed design review, led by the PI, will be drafted. This will include: the physics equations, discretization scheme, grid structure, numerics solver, data formats, storage strategy, code structure, application programming interface, testing framework and website. The postdoc will implement the physics package and discretization scheme. To ensure up to date physics, the equation of state, opacity and nuclear networks can be taken from the *MESA* code (Paxton et al. ApJS 192,3 2011). 2D energy transport and associated mixing (convection and turbulent viscosity) will be modelled based on 2D mixing length theory (Lesaffre et al. MNRAS2013) and other published methods (Zahn IAUS 59,185 1974, Prat & Lignières A&A 551,L3 2013). A 2D adaptive mesh scheme will be implemented based on an existing code such as *PARAMESH* (MacNeice et al. 2011 Ast. Src Code Lib). In this early phase, a 2D gravity field will be imposed on the star. The software engineer will advise on best practices for programming languages, testing and version control, and implement a 2D Henyey matrix solver. Also, with the PI, they will begin work on visualisation tools. The PI will develop the website for outreach purposes.

Year two. The postdoc will implement a full 2D Poisson gravity solver and further sub-grid mixing processes (thermohaline, shear, turbulence). The first 2D stellar models will be constructed, starting with a solar model. The PI will develop a test suite to enforce conservation laws, numerical accuracy and multi-core scaling, and to compare to existing 1D codes. The software engineer will develop visualisation and user interface software, as well as enhancing the technical aspects, the test suite and multi-core scaling.

Year three will see the postdoc include the latest 2D magnetic field algorithm of the Cambridge group (Potter et al. MNRAS 424,2358 2012). The first 2D models including angular momentum and magnetic fields will be made. These will include main-sequence and giant branch stars, and so progress beyond any existing 2D stellar models. The PI will maintain the test suite, write detailed documentation and develop outreach material. The PI will also extend the code to include mass loss and gain, suitable for studies of binary-star systems, and run model sequences of spun-up stars in binaries. The software engineer will optimize the multi-core algorithms to allow the postdoc to extend their models over a wide parameter space. Our first 2D models of rotating, magnetic stars will be presented by the postdoc and PI at conferences and published in leading astronomy journals.

Personnel

PI: Robert Izzard This project will take about 20% of Izzard's time, mostly in years one and three. He has experience in project supervision, particularly of binary stellar codes (*binary_c*, *BINSTAR*, *BONNFIRES*), visualization software (*Window to the Stars*) and is an experienced programmer. Izzard will spend five years in Cambridge on a Rutherford fellowship to study planets in binary stars, a subject closely related to, but scientifically distinct from, this project. Planets form in (2D) accretion discs and Izzard will study how the planets affect (binary) stellar evolution.

Postdoc While this project is on stellar *evolution*, many of the skills required are more likely to be found in a *hydrodynamicist.* Fortunately, there are many good candidates available on the job market and one will be sought to start at the same time as Izzard.

Software engineer Textensor Ltd., based in Edinburgh, is uniquely qualified for this task. Their director Robert Cannon has a PhD in stellar astrophysics from Cambridge and a thorough understanding of the computational methods used in stellar evolution. He has worked on a number of projects in collaboration with the UK scientific research community involving numerical algorithms, software development and high performance computing. His combination of skills is a perfect fit to this project. The requested sum of £50k+VAT buys an average of one day per week over three years. Collaboration between software professionals and astronomers is increasingly important in modern astrophysics. Examples are the *MESA* stellar evolution code (Paxton et al. ApJS 192,3 2011), developed by software engineer Bill Paxton, and the *AMUSE* project (Portegies Zwart et al. NewA 14,369 2009) which employs two full-time programmers. In both cases it was vital to engage software engineers *from the start of the project* – a professional approach that will be followed here also.

Feasibility, Risks and Costs

The main practical constraints are CPU time and memory resources. 2D $N \times N$ matrix inversion uses $\mathcal{O}\left(N^3\right)$ FLOPs but runtime improves with dedicated sparse matrix solvers and multi-core CPUs. The postdoc and software engineer will develop a solution ideal for 2D stellar evolution on multi-core CPUs, e.g. a direct vs. iterative solver. Memory is a concern: a star of N^2 grid cells with m equations requires at least $N^3 m^2$ double precision numbers. With $N=100$, $m=10$, this is about 1GB, not excessive but hardware with the best memory bandwidth should be used. This will be purchased with the requested computing funds. Further CPU is available on the *CamGrid HTCondor* network and will be applied for at the STFC's *DIRAC* facility.

Because this project challenges the boundaries of our knowledge, there are risks. The numerical problem is stiff so care is needed in discretization and solution of the evolution equations. First steps toward 2D stellar evolution have been taken by others, so it is possible, and the inclusion of physics such as magnetic fields means this project has potentially very exciting outcomes. 2D models of rotating stars will relieve us of much of our present ignorance and no doubt reveal new phenomena of which we have yet to dream. We must step up to 2D before 3D which may soon be within reach on the STFC's multi-PFLOP *DIRAC-3* supercomputer.

Collaboration and Future Prospects

The postdoc and PI will collaborate closely with the new *BRIDGCE* UK network (www.astro.keele.ac.uk/bridgce) studying galactic chemical evolution. The 2D models we make will feed back directly to 1D simulations of rotating stars made in the UK (Cambridge, Keele, etc.). Collaboration with the *MESA* project is intended and should eventually offer users a choice between one and two dimensions when they model stars.

Once the 2D code is running, it will be the launchpad for many future projects for Masters and PhD students, and postdocs, such as to calculate models of binary-star interaction, pre-main-sequence stellar evolution in 2D, including spin up, stellar evolution with magnetic fields, gamma-ray burst progenitors, common-envelope evolution and perhaps even stellar mergers. The 2D code will also be used to model the evolution of core spin rates as stars ascend the giant branch (Beck et al. Ast. Nachr. 333,967 2012). This can be compared directly with Kepler data and with compact stellar remnant spin rates (Suijs et al. A&A 481,L87 2008).