TWO-DIMENSIONAL STELLAR EVOLUTION WITH 2DStars

Introduction & Applications

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Two-dimensional Stellar Evolution: **2DStars**

- **Science goal**
  - Rotating stars
    - effects of rotation
  - Classical novae
    - C-rich ejecta
    - current problem
    - recent result & its importance
    - current state-of-the-art
Science goal

The goal is to develop a general-use 2D, adaptable to 3D, stellar evolution code (Izzard 2015) to model a variety of multi-dimensional phenomena in the evolution of single and binary stars.

- Rotating Stars
- Close Binaries
- Star Formation
- X-ray Binaries
Rotating stars

A large fraction of stars rotate rapidly, are not spherical and exhibit surface temperature variations.

- The **centrifugal force** caused by rotation changes the hydrostatic balance, which alters the structure. This affects intrinsic stellar properties like luminosity (Potter + 2012), oscillation frequencies (Reese 2015) …

- Rotation introduces a **brightness asymmetry** due to the variation in the flux flowing through the surface as a function of latitude (**von Zeipel's theorem**: higher radiative flux at higher latitudes).

Altair rotates at 90% of its breakup velocity with a period of 9 hours (2.8 rev/day). This causes the **equator to bulge and darken** (cooler). $I_{eq} = 60\% I_{pole}$. 

Left: Surface temperature variations and aspherical distortion in the rapidly rotating A-type star Altair. Right: Reconstructed image with intensities converted into the corresponding blackbody temperatures shown as contours (Monnier+2007).
Rotating stars cont’d

- Rotation alters the stellar chemistry by developing internal currents (such as the meridional Eddington-Sweet circulation).

- It couples to magnetic fields, commonly referred to as an $\alpha - \Omega$ dynamo (Schmalz & Stix 1991, Potter, Chitre & Tout 2012).

- It may affect mass-loss or cause wind anisotropies: $g_{\text{eff}}$ effect/ $\kappa_{\text{eff}}$ effect (Maeder & Meynet 2000).

Stellar evolution is a function of $M$, $Z$ and $\Omega$.

Thus, stars can only be modelled properly in multi-dimensions.
State-of-the-art

1. 1D codes simplifications:
   - First models assumed solid body rotation $\Omega = \text{cnst}$.
   - Differential rotation: $\Omega(r) = \text{cnst}$ on isobars (shellular rotation).
   - Modelling meridional circulation: free parameters.

2. 2D codes:
   - Roxburgh (2004): non-evolving uniformly-rotating models
   - Li+ (2009): solar models but on short timescales
   - ROTORC (Dupree 1990): only models main-sequence stars on short timescales
   - ESTER (Espinosa Lara & Rieutord 2013): predicts pulsation frequencies of main-sequence stars

3. 3D codes:
   - Djehuty (Dearborn+ 2006): hydrodynamical code (ideal for rapid phenomena but not to evolve a star).
We are interested in the long term evolution (nuclear/thermal time scale) i.e. that of the order of the stellar lifetime.

Initial setup: A single axisymmetric rotating star that evolves in time, for a given set of initial conditions.

Rotation and slow internal fluid rotation-driven flows including meridional circulation will be modelled consistently.

Magnetic fields: Initially ignored but to be included later as they enforce co-rotation and couple stellar cores to their envelopes.

Chemistry: Fast mixing (convection, horizontal turbulence…) will be parameterized. Work on 2D MLT is currently underway (Jermyn, Tout, Chitre & LeSaffre).

Mass transfer: Material accretes through an accretion disc which should be modelled in 2D.
Application II:

**Mass Transfer in Close Binaries**

Formation of an *accretion disc* by Roche-lobe overflow from the giant companion star.

It is suggested that oblate distortion of rotating WDs drive *latitude-dependent* abundance gradients that may affect dust formation following a nova ejection (Scott 2000) (*prolate ejecta?).*

2D models may provide important feedback on the accretion process preceding the synthesis of C-rich dust in *CO nova ourbursts.*

Image credits: 
https://trikendall.wordpress.com
S. Wiessinger/Nasa Goddard Space Flight Center
The presence of **C-rich dust in nova ejecta** (SiC, C) has been observed (Gehrz+ 1993, 1998, 1999, Starrfield+ 1997) and is established from spectroscopic measurements (José+ 2014).

<table>
<thead>
<tr>
<th>Nova</th>
<th>Year</th>
<th>$V_0$ (km s$^{-1}$)</th>
<th>Types of Dust Formed</th>
<th>$t_0^*$ (days)</th>
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<tr>
<td>FH Ser</td>
<td>1970</td>
<td>560</td>
<td>C</td>
<td>62</td>
</tr>
<tr>
<td>V1229 Aql</td>
<td>1970</td>
<td>575</td>
<td>C</td>
<td>37</td>
</tr>
<tr>
<td>V1301 Aql</td>
<td>1975</td>
<td>...</td>
<td>C</td>
<td>35</td>
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<tr>
<td>V1500 Cyg</td>
<td>1975</td>
<td>1180</td>
<td>...</td>
<td>3.6</td>
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<tr>
<td>NQ Vul</td>
<td>1976</td>
<td>750</td>
<td>C</td>
<td>65</td>
</tr>
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<td>V4021 Sgr</td>
<td>1977</td>
<td>...</td>
<td>C</td>
<td>70</td>
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<tr>
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<td>1978</td>
<td>1250</td>
<td>C</td>
<td>50</td>
</tr>
<tr>
<td>V1668 Cyg</td>
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<tr>
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<td>1982</td>
<td>2800</td>
<td>C; SiC; SiO$_2$</td>
<td>?</td>
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<tr>
<td>GQ Mus</td>
<td>1983</td>
<td>600</td>
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<td>45</td>
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<tr>
<td>PW Vul</td>
<td>1984 #1</td>
<td>285</td>
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<td>97</td>
</tr>
<tr>
<td>QU Vul</td>
<td>1984 #2</td>
<td>1–5000</td>
<td>SiO$_2$</td>
<td>40</td>
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<tr>
<td>OS And*</td>
<td>1986</td>
<td>900</td>
<td>C?</td>
<td>22</td>
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<tr>
<td>V1819 Cyg</td>
<td>1986</td>
<td>1000</td>
<td>No dust</td>
<td>87–104</td>
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<tr>
<td>V842 Cen</td>
<td>1986</td>
<td>1200</td>
<td>C; SiC; HC</td>
<td>48</td>
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<tr>
<td>V827 Her</td>
<td>1987</td>
<td>1000</td>
<td>C</td>
<td>55</td>
</tr>
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<td>V4135 Sgr</td>
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<td>C</td>
<td>30</td>
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<tr>
<td>QV Vul</td>
<td>1987</td>
<td>700</td>
<td>C; SiO$_2$; HC; SiC</td>
<td>?</td>
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<tr>
<td>LMC 1988 #1</td>
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<td>C?</td>
<td>43</td>
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<td>15</td>
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<tr>
<td>V2214 Oph</td>
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<td>C</td>
<td>5</td>
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<td>1992</td>
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<tr>
<td>V705 Cas</td>
<td>1993</td>
<td>840</td>
<td>C; HC; SiO$_2$</td>
<td>90</td>
</tr>
<tr>
<td>Aql 1995*</td>
<td>1995</td>
<td>1510</td>
<td>C</td>
<td>30</td>
</tr>
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How is C-rich ejecta produced?

Most calculations obtain O>C.

Inconsistent with the observation of C-rich dust reported in some novae José+ (2004).
Why is it so?

Traditionally, nova models assumed that the CO WD hosting the outburst has

\[ X(^{12}C) = X(^{16}O) \sim 0.5 \]

(Salaris+ 1996)
New models: Updated CO WDs (project led by Jordi Jose)

Mean composition of the ejecta (CNO-group).

<table>
<thead>
<tr>
<th>Model</th>
<th>$^{12}$C</th>
<th>$^{13}$C</th>
<th>$^{14}$N</th>
<th>$^{15}$N</th>
<th>$^{16}$O</th>
<th>$^{17}$O</th>
<th>$^{18}$O</th>
<th>Ejecta</th>
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<td>1</td>
<td>2.90-2</td>
<td>7.56-2</td>
<td>1.06-1</td>
<td>8.42-3</td>
<td>3.85-2</td>
<td>8.36-4</td>
<td>5.27-7</td>
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<tr>
<td>2</td>
<td>8.89-3</td>
<td>1.43-2</td>
<td>3.56-2</td>
<td>2.73-3</td>
<td>5.62-3</td>
<td>1.46-4</td>
<td>9.23-8</td>
<td>C-rich</td>
</tr>
<tr>
<td>3</td>
<td>2.04-3</td>
<td>3.02-3</td>
<td>7.21-3</td>
<td>5.26-4</td>
<td>3.07-4</td>
<td>9.46-6</td>
<td>6.52-9</td>
<td>C-rich</td>
</tr>
<tr>
<td>4</td>
<td>1.79-3</td>
<td>2.66-3</td>
<td>7.73-3</td>
<td>4.04-4</td>
<td>3.92-4</td>
<td>1.01-5</td>
<td>7.19-9</td>
<td>C-rich</td>
</tr>
<tr>
<td>5</td>
<td>1.63-3</td>
<td>2.47-3</td>
<td>8.08-3</td>
<td>3.44-4</td>
<td>5.09-4</td>
<td>1.14-5</td>
<td>8.24-9</td>
<td>C-rich</td>
</tr>
<tr>
<td>6</td>
<td>2.05-2</td>
<td>4.17-2</td>
<td>8.20-2</td>
<td>7.26-3</td>
<td>1.17-1</td>
<td>2.75-3</td>
<td>1.72-6</td>
<td>O-rich</td>
</tr>
</tbody>
</table>

Chemical profiles of an $8M_\odot$ star, after a series of thermal pulses, computed with the HYADES code (Halabi & El Eid 2015).
Why is this finding important?

- It explains the presence of observed C-rich nova ejecta

- It extends the possible contribution of novae to the inventory of carbonous presolar grains (diamonds, silicon carbides and graphites)

- C-rich ejecta in nova outbursts may also account for the origin of C-rich J-type stars (10-15% of the observed C stars in our Galaxy and in the LMC) (Sengupta, Izzard, & Lau 2013)

- More realistic models yield more realistic results.

2DSTARS: What we have so far

A well-structured 1D Java code that:

1. Solves the equations of stellar structure using finite difference discretization (hydrostatic equilibrium & Poisson equation) + polytropic equation of state, without considering energy generation and opacity. This is helpful since an analytical solution exists to test the code.

2. Is highly modular:
   - Integrator (Euler integrator, relaxation integrator)
   - Building models
   - Writing files
   - Constants
   - Visualizations

3. Can be easily modified to accommodate more complicated physics/solvers etc..
Currently underway...

- Upgrading the 1D code to 2D \((r, \theta)\)
- Uniform mesh (in \(r\) and \(\theta\))

Next:

- Consider a non-uniform mesh
- Adding energy transport equation with convective transport coefficients in 2D (Jermyn, Tout, Chitre & Lesaffre)
Conclusions

- Many astrophysical phenomena require multi-D approaches. 2DStars aims to provide such a framework.

- Most model output is affected by rotation by various degrees depending on rotational velocity (tracks in the HR diagram, lifetimes, masses, chemical composition…). Stellar evolution is thus a function of $M$, $Z$ and $\Omega$.

- A number of serious discrepancies between current models and observations have been noticed over the past few years (the distribution of stars in the HR diagram at various metallicities, He and N abundances in massive O- and B-type stars and in giants and supergiants..).

- Data is available to constrain the models: The VLT–FLAMES survey of massive stars (Evans+ 2005, 2006), VLT–FLAMES Tarantula Survey (Evans 2011) and the ongoing Gaia-ESO Survey make such comparisons possible.

- 2D models may provide important feedback on the accretion process during mass transfer in close binary systems.
Supplementary material
Results from other works: also show C-rich outer cores

Abundance profiles in the 0.64 M⊙ CO WD remnant produced by the 3M⊙ model using MESA (Fields+ 2016)

6M⊙ model at the end of He-burning using Fynbo+ (2005) rate for the 3-α and Xu+ (2013) rate for the $^{12}$C($\alpha$,γ)$^{16}$O reaction (Karakas & Lugaro 2016)
Coordinate System

- The issue arises because of centrifugal deformation: Spheroidal geometry.
- The stellar surface no longer coincides with a constant-coordinate surface.
- To avoid approximate treatment of surface boundary conditions, one can use a surface-fitting coordinate system $(\xi, \theta, \phi)$ where $\xi$ is specified by the relation: $r = f(\xi, \theta)$, $\xi = 1$ corresponding the star’s surface.

The following definition for the radial coordinate $\zeta$, which ensures a good convergence of the numerical method:

$$r(\zeta, \theta) = (1 - \varepsilon)\zeta + \frac{5\zeta^3 - 3\zeta^5}{2} (R_s(\theta) - 1 + \varepsilon),$$

(29)

where $\varepsilon$ is the flatness given by Eq. (4), $(r(\zeta, \theta), \theta, \phi)$ are the spherical coordinates corresponding to the point $(\zeta, \theta, \phi)$, and $R_s(\theta)$ is the surface of the star. By setting $\zeta = 1$, one obtains $r(1, \theta) = R_s(\theta)$, and the centre $r = 0$ is given by $\zeta = 0$.

Lignières, Rieutord, & Reese 2006, A&A 455, 607
Some results

\[ n=3 \]

\[ \frac{1}{\xi^2} \frac{d}{d\xi} \left( \xi^2 \frac{d\theta}{d\xi} \right) = -\theta^n \quad \text{where } r = \alpha \xi \]

\[ \rho = \rho_0 \theta^n \]
Density profile

Temperature profile

Mass profile