TWO-DIMENSIONAL STELLAR EVOLUTION WITH **2DStars**

Introduction & Applications

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

Science goal

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

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.

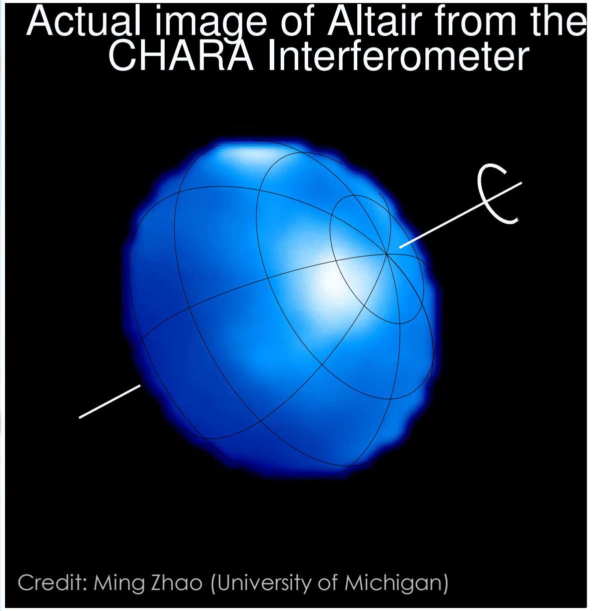
- **Rotating Stars**
- **Close Binaries**
- **Star Formation**
- **X-ray Binaries**

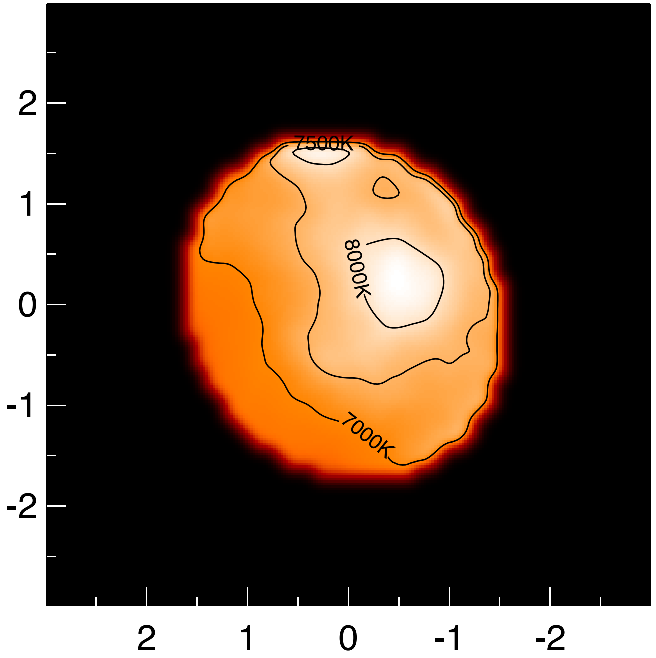
Rotating stars

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).





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).

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}.

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 α - Ω dynamo (Schmalz & Stix 1991, Potter, Chitre & Tout 2012).
- It may affect mass-loss or cause wind anisotropies: g_{eff} effect/ κ_{eff} effect (Maeder & Meynet 2000).

Stellar evolution is a function of **M, Z** and **Ω**.

Thus, stars can only be modelled properly in multi-dimensions.

State-of-the-art

1. 1D codes simplifications:

- First models assumed solid body rotation Ω = cnst.
- Differential rotation: $\Omega(r)$ = 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).

2DStars is aimed to fill this void

Setup & input physics

- 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.

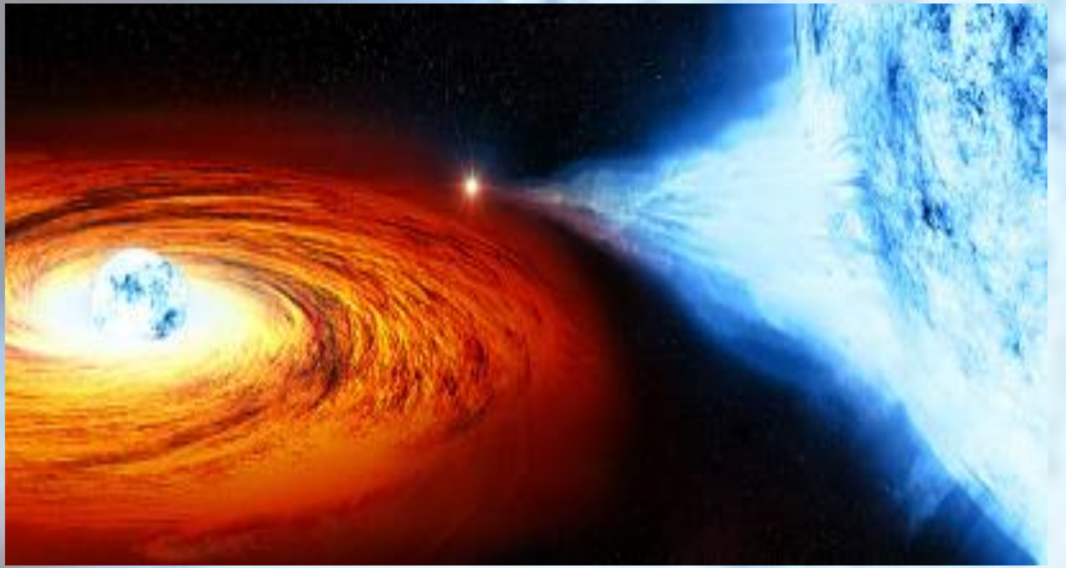
Application II:

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**.



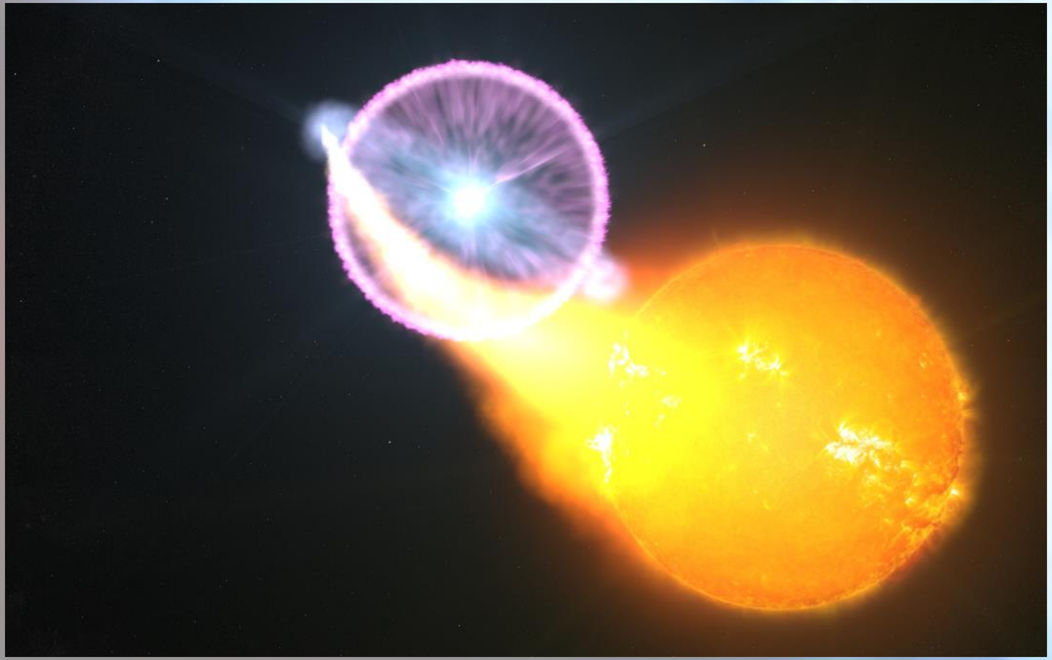
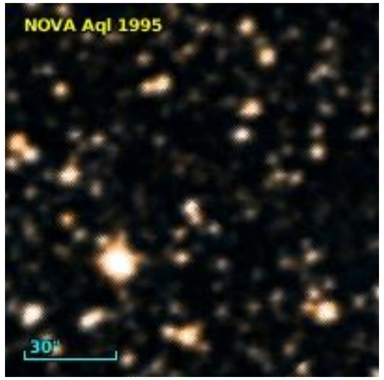
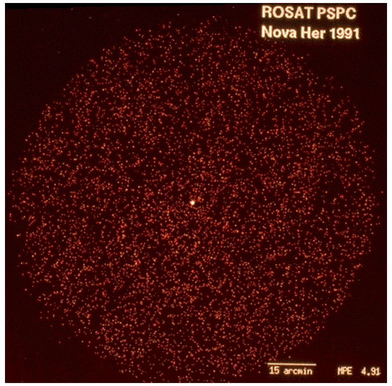


Image credits:
https://trkendall.wordpress.com
S. Wiessinger/Nasa Goddard Space Flight Center

IR novae observations: C-rich dust



Simbad



Credit: Max Planck Institute

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).

25 classical novae from IR measurements (Gehrz+1998)

Nova	Year	V_o (km s^{-1})	Types of Dust Formed[b]	t_3[c] (days)
FH Ser	1970	560	C	62
V1229 Aql	1970	575	C	37
V1301 Aql	1975	...	C	35
V1500 Cyg[a]	1975	1180	...	3.6
NQ Vul	1976	750	C	65
V4021 Sgr	1977	...	C	70
LW Ser	1978	1250	C	50
V1668 Cyg	1978	1300	C	23
V1370 Aql[d]	1982	2800	C; SiC; SiO_2	?
GQ Mus	1983	600	No dust	45
PW Vul	1984 #1	285	C	97
QU Vul[a]	1984 #2	1–5000	SiO_2	40
OS And[a,e]	1986	900	C?	22
V1819 Cyg[a]	1986	1000	No dust	87–104
V842 Cen	1986	1200	C; SiC; HC	48
V827 Her[a]	1987	1000	C	55
V4135 Sgr	1987	500	...	30
QV Vul	1987	700	C; SiO_2; HC; SiC	?
LMC 1988 #1	1988 #1	800	C?	43
LMC 1988 #2	1988 #2	1500	...	15
V2214 Oph	1988	500	...	73
V838 Her	1991	3500	C	5
V1974 Cyg[a]	1992	2250	No dust	47
V705 Cas	1993	840	C; HC; SiO_2	90
Aql 1995[a]	1995	1510	C	30

How is C-rich ejecta produced?

BUT ⚠

Most calculations obtain **O>C**

Determinant

C/O

Environment conditions

C > O
all O is locked up in the **very stable CO molecule**

O > C
all C is locked up in **CO**

Expected grains

SiC grains

graphite grains

oxides

silicates

Inconsistent with the observation of C-rich dust reported in some novae José+ (2004).

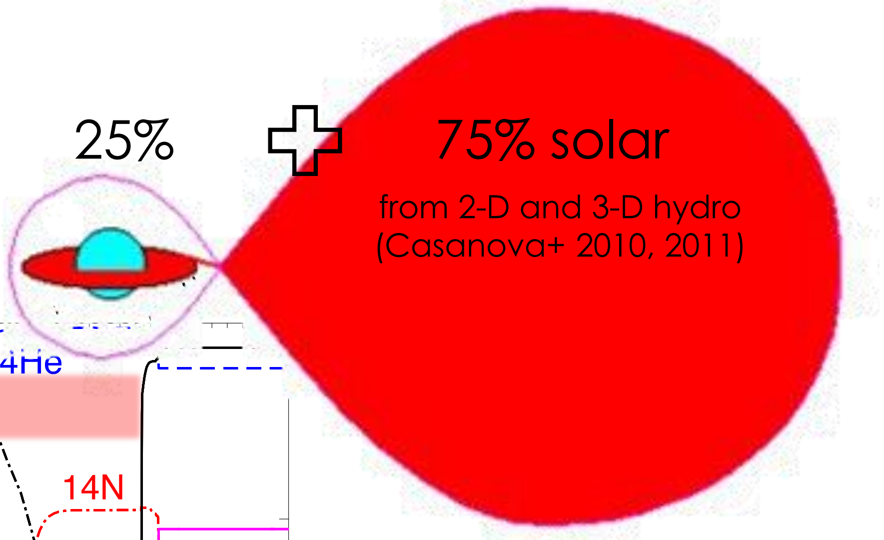
https://geosci.uchicago.edu/people/andrew-m.-davis

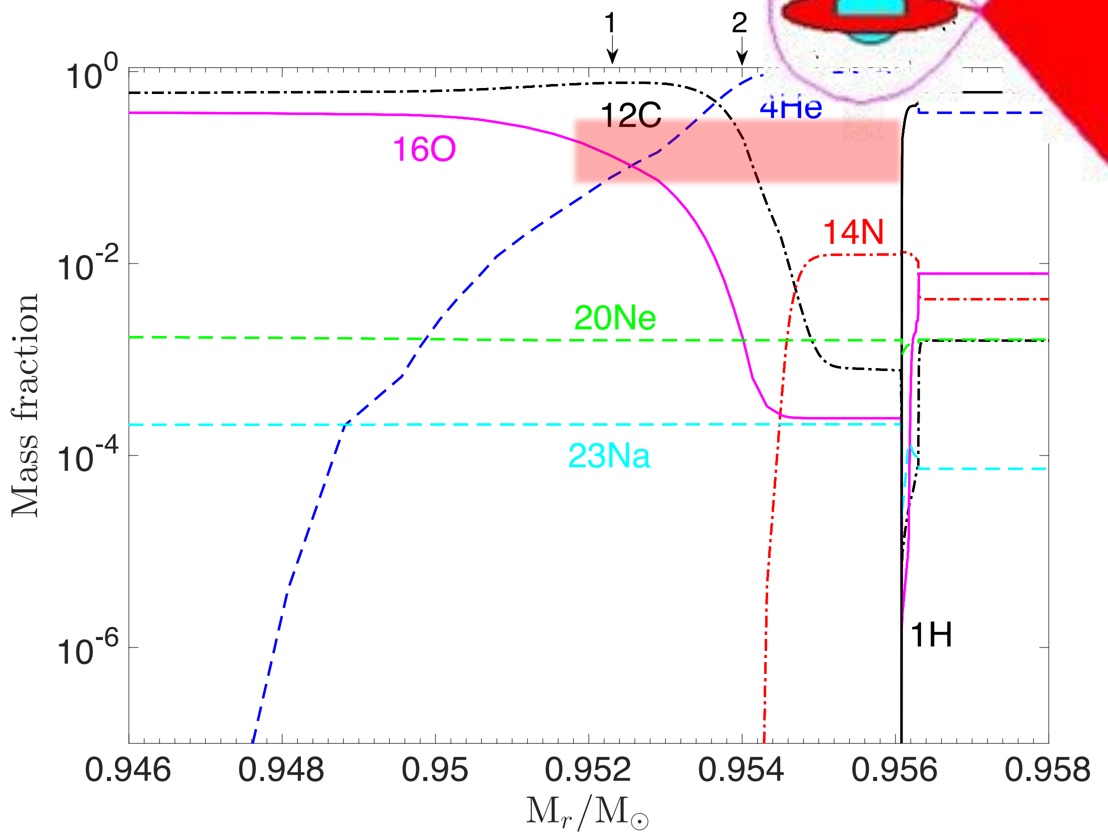
Why is it so?

Traditionally, nova models assumed that the CO WD hosting the outburst has
$\boldsymbol{X(^{12}C) = X(^{16}O) \sim 0.5}$

(Salaris+ 1996)

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





Chemical profiles of an **8M$_\odot$** star, after a series of thermal pulses, computed with the HYADES code (Halabi & El Eid 2015).

+ Model 6:
WD material: **C/O=1**

Mean composition of the ejecta (CNO-group).

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

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**.

José, J., Halabi G. M. & El Eid, M. (2016) Accepted to A&A
(arXiv:1606.05438)

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, θ)*
- Uniform mesh (in *r* and *θ*)

Next:

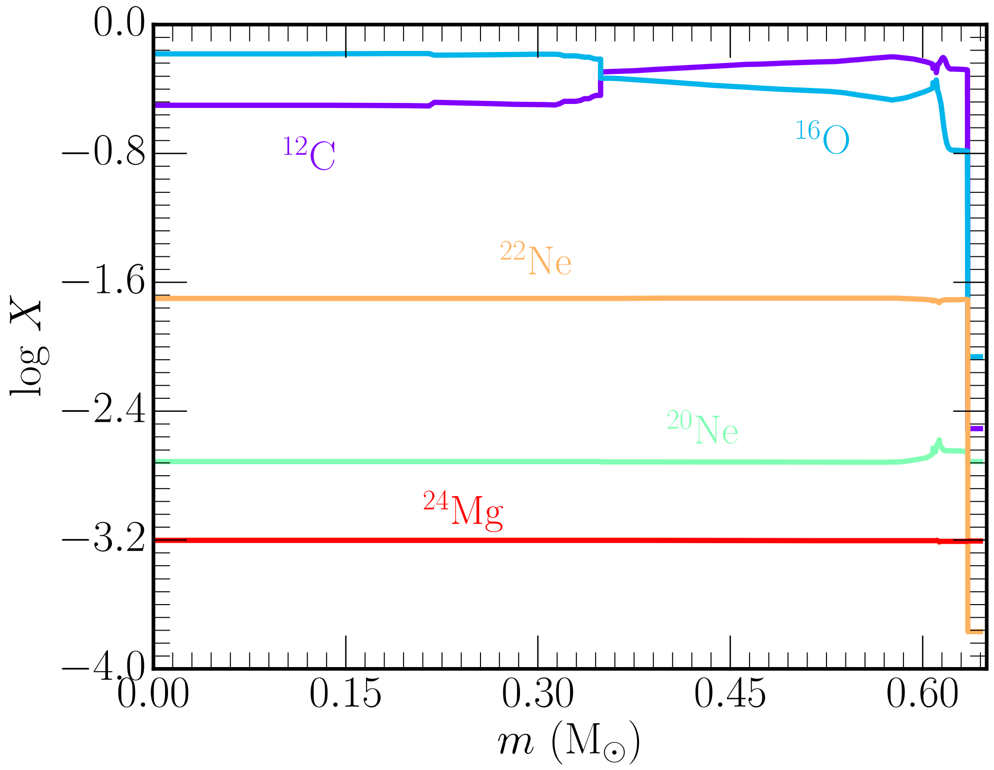
- Consider a non-uniform mesh
- Adding energy transport equation with convective transport coefficients in 2D (Jermyn, Tout, Chitre & Lesaffre)

Conclusions

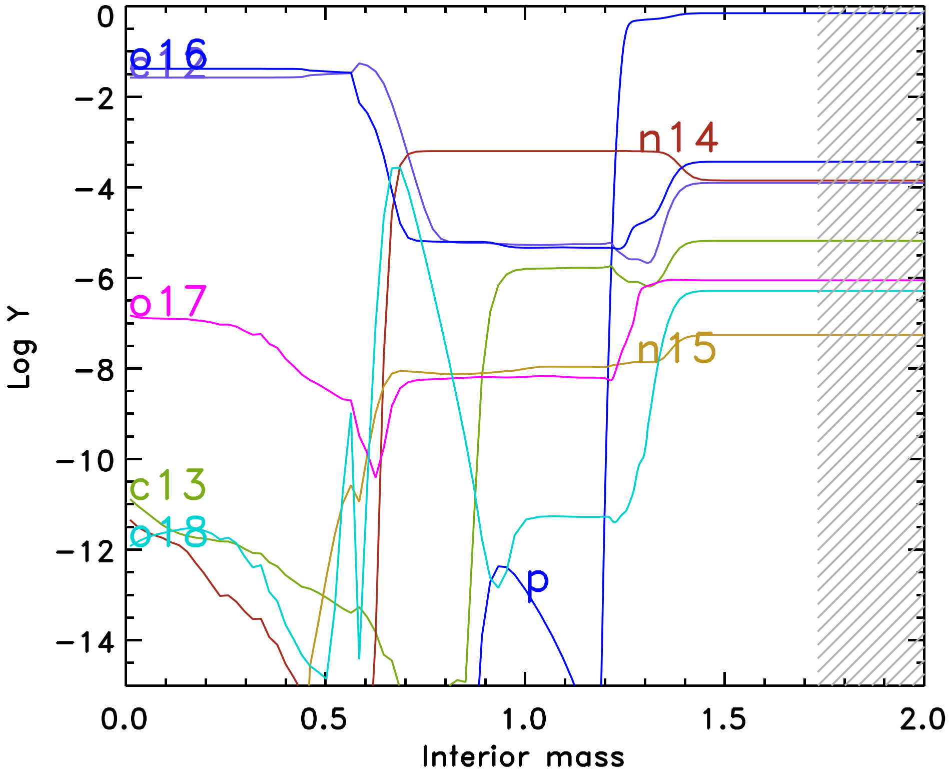
- Many astrophysical phenomena require **multi-D** approaches. **2DStars** aims to provide such a framework.
- Most model output is affected by **rotation** by various degrees depending on rotational velocity (tracks in the HR diagram, lifetimes, masses, chemical composition…). Stellar evolution is thus a function of **M**, **Z** and **Ω**.
- 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 form 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 $^{12}C(\alpha,\gamma)^{16}O$ 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 (ξ, θ, ϕ) where ξ is specified by the relation: $r = f(\xi, \theta), \xi = 1$ corresponding the star's surface.

following definition for the radial coordinate ζ, which ensures a good convergence of the numerical method:

$$r(\zeta, \theta) = (1 - \varepsilon)\zeta + \frac{5\zeta^3 - 3\zeta^5}{2}(R_s(\theta) - 1 + \varepsilon), \quad (29)$$

where ε is the flatness given by Eq. (4), $(r(\zeta, \theta), \theta, \varphi)$ are the spherical coordinates corresponding to the point (ζ, θ, φ), 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 $\zeta = 0$.

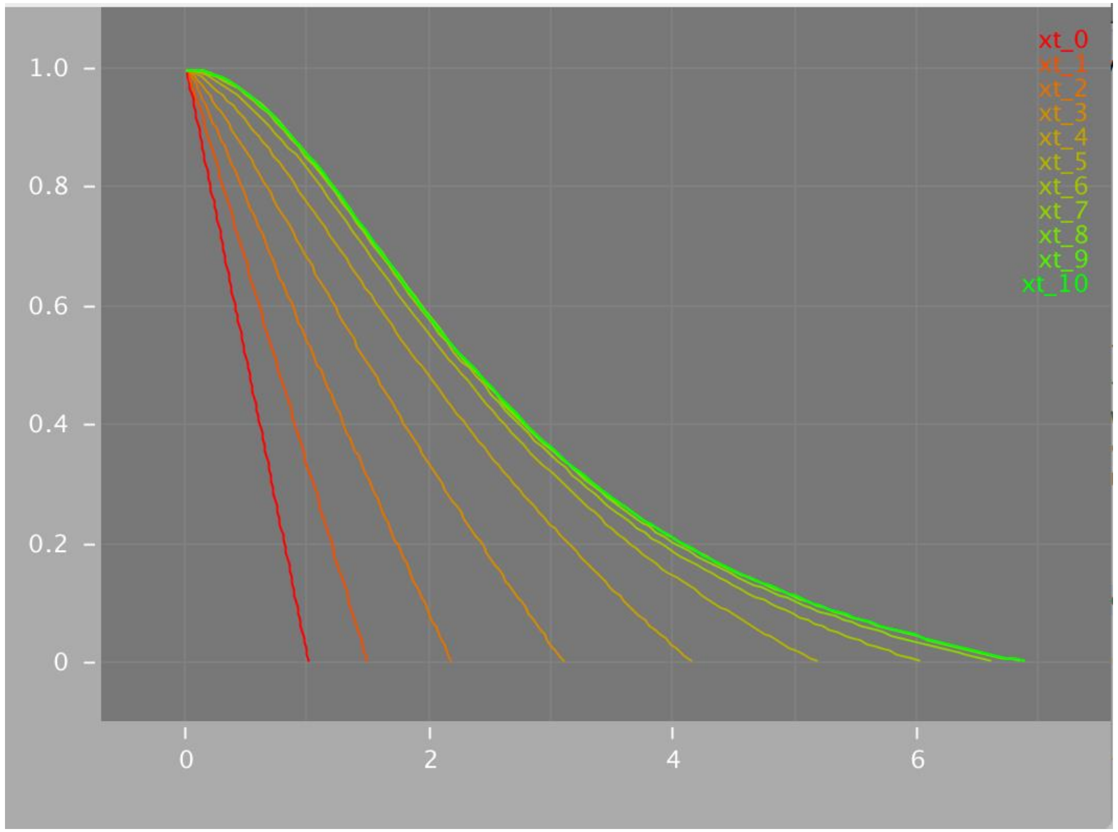
Lignières, Rieutord, & Reese **2006**, A&A 455, 607

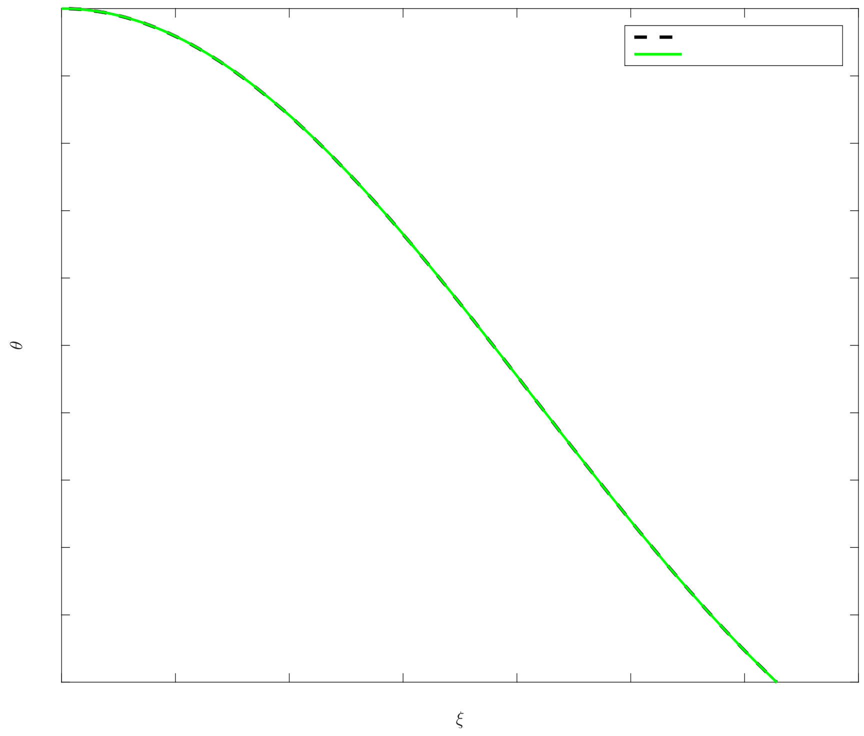
Some results

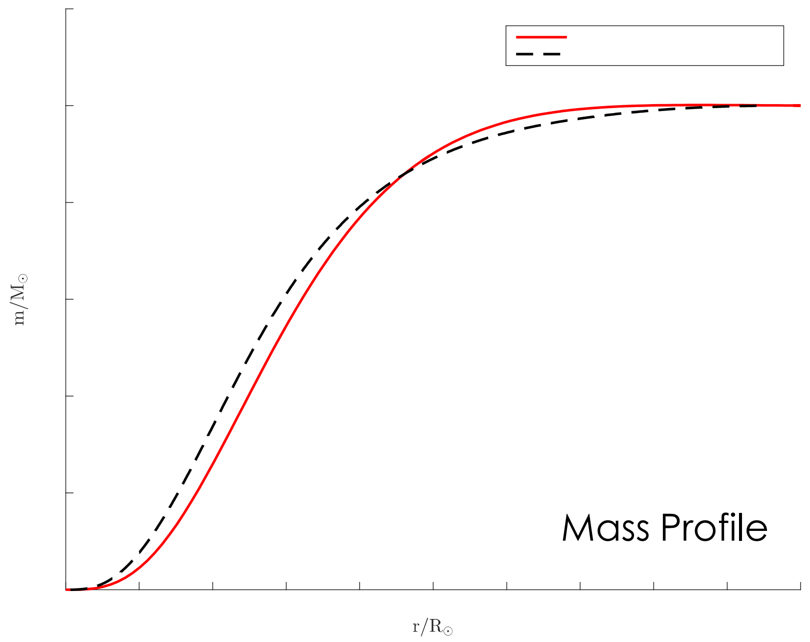
- **n=3**

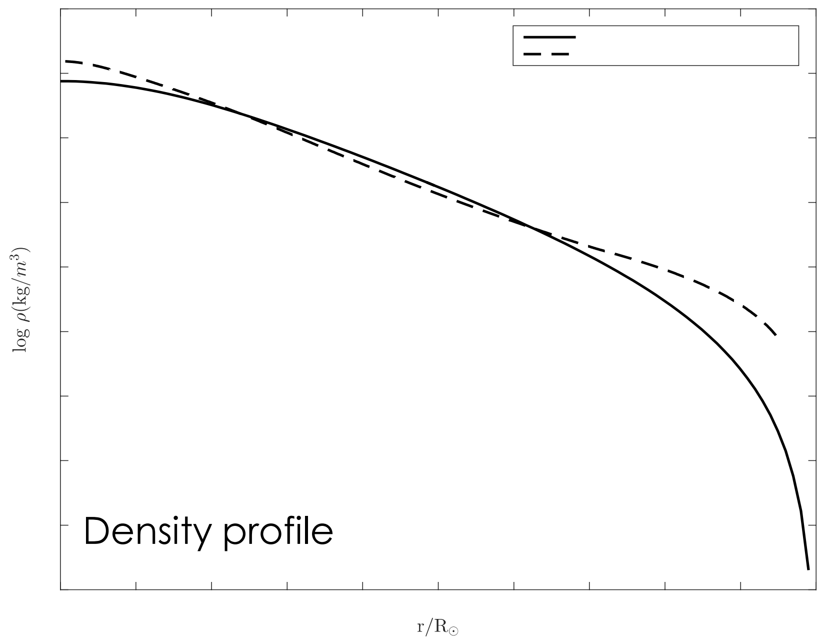
$$\frac{1}{\xi^2}\frac{d}{d\xi}\left(\xi^2\frac{d\theta}{d\xi}\right) = -\theta^n \qquad \text{where } r = \alpha\xi$$

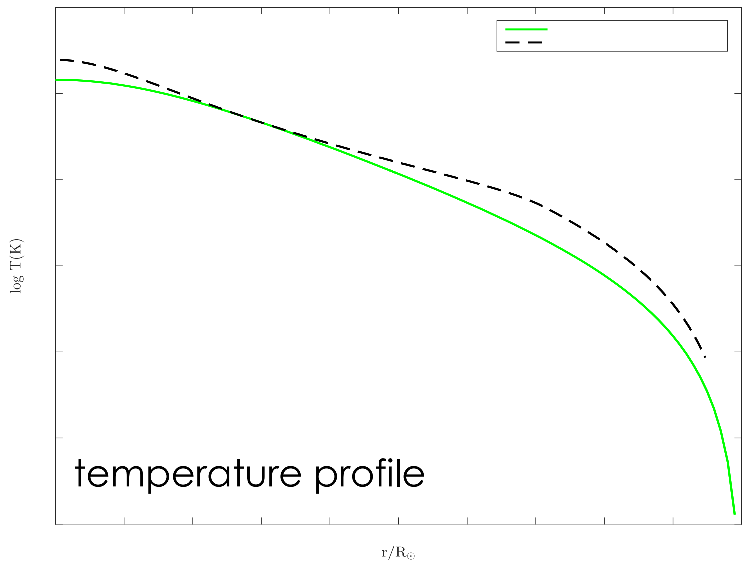
$$\rho = \rho_c\theta^n$$






Mass Profile
m/M$_\odot$
r/R$_\odot$


Density profile
log ρ(kg/m^3)
r/R$_\odot$


temperature profile
log T(K)
r/R$_\odot$