# Rotation in 1-D simulations of massive stars: status and perspectives

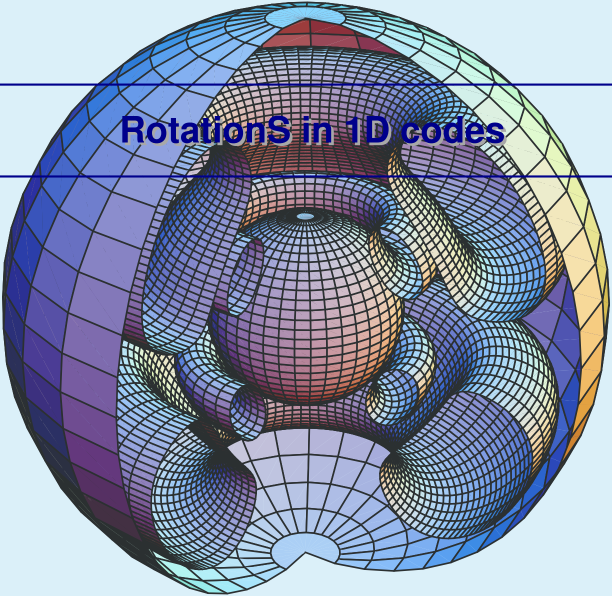
Cyril Georgy
Sylvia Ekström, Georges Meynet, André Maeder
Geneva Observatory

Raphael Hirschi
Keele University

Basel, September 29

UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES

# RotationS in 1D codes



# Why rotation is important in stars?

Rotation affects a star in two ways:

# Why rotation is important in stars?

Rotation affects a star in two ways:

## Surface properties

- How we see the star, particularly for fast rotators.
- Mass loss.

# Why rotation is important in stars?

Rotation affects a star in two ways:

## Surface properties

- How we see the star, particularly for fast rotators.
- Mass loss.

## Internal structure

- Additional support against the gravity (centrifugal force).
- Internal transport of chemical species and angular momentum.

# Basic implementation

Assuming Roche model and shellular rotation, and considering average over isobars, the structure equations keep the same form *(Meynet & Maeder 1997)*:

- $\frac{\partial r_P}{\partial M_P} = \frac{1}{4\pi r_P^2 \rho}$
- $\frac{\partial P}{\partial M_P} = -\frac{G M_P}{4\pi r_P^4} f_P$
- $\frac{\partial L_P}{\partial M_P} = \varepsilon_{\mathrm{nucl}} - \varepsilon_\nu + \varepsilon_{\mathrm{grav}}$
- $\frac{\partial \ln T}{\partial M_P} = -\frac{G M_P}{4\pi r_P^4} f_P \min\left(\nabla_{\mathrm{ad}}, \nabla_{\mathrm{rad}} \frac{f_T}{f_P}\right)$

1d treatment of a 2d process, and does not require major modifications of 1d codes.

# Transport processes

- Transport of angular momentum:

$$\rho \frac{\partial}{\partial t}\left(r^2\bar{\Omega}\right)_{M_r} = \underbrace{\frac{1}{5r^2}\frac{\partial}{\partial r}\left(\rho r^4 \bar{\Omega} U(r)\right)}_{\text{advection term}} + \underbrace{\frac{1}{r^2}\frac{\partial}{\partial r}\left(\rho D_{\text{v}} r^4 \frac{\partial \bar{\Omega}}{\partial r}\right)}_{\text{diffusion term}}$$

- Transport of chemical species:

$$\rho \frac{\partial X_i}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(\rho r^2 \left(D_{\text{v}} + D_{\text{eff}}\right)\frac{\partial X_i}{\partial r}\right)$$

$D_{\text{v}}$: diffusion coeff. due to various transport mechanisms (convection, shear)

$D_{\text{eff}}$: diffusion coeff. due to meridional circulation + horizontal turbulence

# A lot of options

## Different implementations

- Transport of angular momentum as a diffusion process only.
- Advective term accounted for in transport of angular momentum.

## Horizontal turbulence

3 possibilities:

- *Zahn (1992)*
- *Maeder (2003)*
- *Mathis et al. (2004)*

## Shear turbulence

2 possibilities:

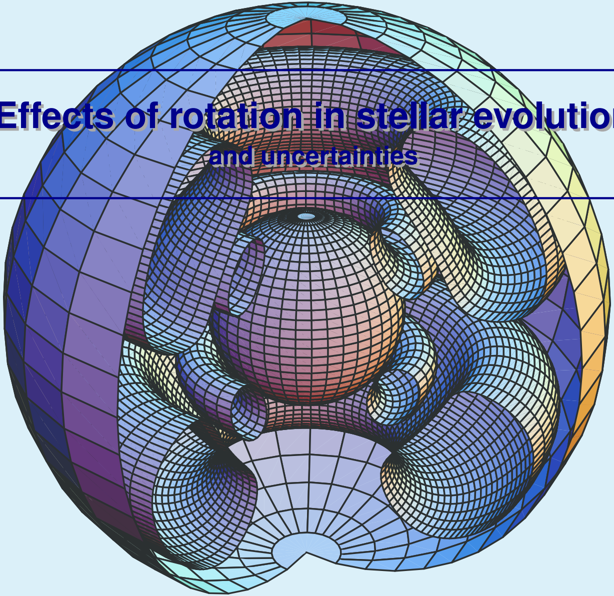
- *Maeder 1997*
- *Talon & Zahn (1997)*

## Other mixing processes:

Magnetic fields, GSF instability, Solberg-Høiland instability, ...

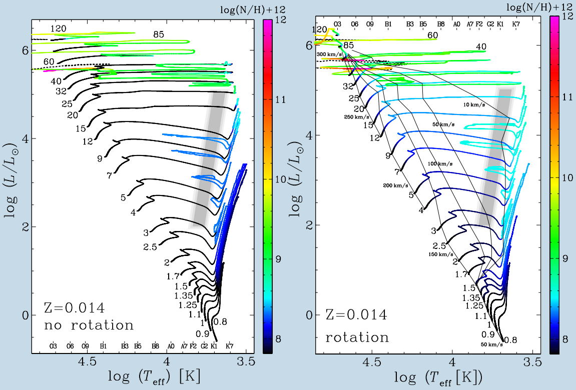
# Effects of rotation in stellar evolution

## and uncertainties



# Effects of rotation on stellar evolution

## HRD and mixing — *Ekström et al. (2012)*




On the ZAMS: rotation shifts the tracks at lower $L$ and lower $T_{\rm eff}$.

Enlarges the MS width.

Increases the MS lifetimes.

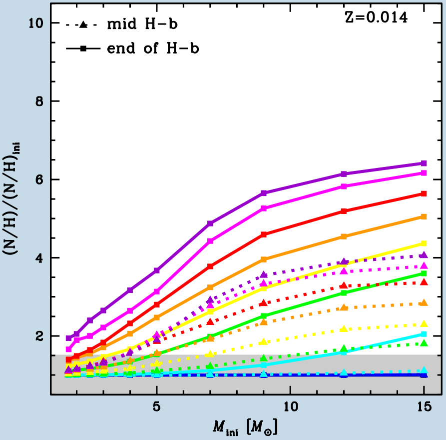
Considerably affects the advanced stages.

See `http://obswww.unige.ch/Recherche/evoldb/index/`

*(Ekström et al. 2012, Mowlavi et al. 2012, Georgy et al. 2013a,b)*

# Effects of rotation on stellar evolution

## Mixing and $\Omega_{ini}$ *Georgy et al. (2013a)*




Mixing is more efficient for:

- more massive stars,
- higher initial rotation.

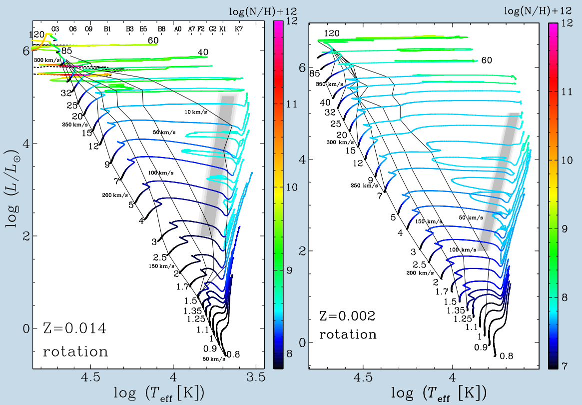
# Metallicity effects

At low $Z$, stars are more compact:

- shorter distance to diffuse through
- steeper $\Omega$-gradients

Thus, mixing is more efficient.

*Ekström et al. (2012)* *Georgy et al. (2013b)*



# What is improved by the inclusion of rotation?

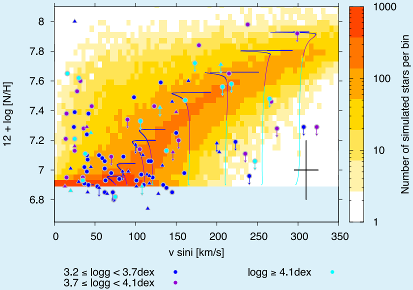
- Better agreement with the observed surface enrichment *(Meynet & Maeder 2000, Maeder et al. 2009, Brott et al. 2011, Ekström et al. 2012, Chieffi & Limongi 2013)*.
- Helps to reproduce the observed positions of RSGs (maximal $L$) *(Ekström et al. 2012, Georgy et al. 2012)*.
- Improves the agreement with observed populations of WR stars (accounting for $\sim 50\%$ of binaries) *(Meynet & Maeder 2003,2005, Eldridge et al. 2008, Georgy et al. 2012, Neugent et al. 2012).*

# What is improved by the inclusion of rotation?

- Better agreement with the observed surface enrichment *(Meynet & Maeder 2000, Maeder et al. 2009, Brott et al. 2011, Ekström et al. 2012, Chieffi & Limongi 2013)*.
- Helps to reproduce the observed positions of RSGs (maximal $L$) *(Ekström et al. 2012, Georgy et al. 2012)*.
- Improves the agreement with observed populations of WR stars (accounting for $\sim 50\%$ of binaries) *(Meynet & Maeder 2003,2005, Eldridge et al. 2008, Georgy et al. 2012, Neugent et al. 2012).*

HOWEVER

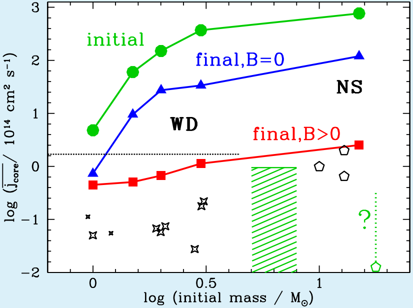
# Some of the actual problems




*Brott et al. (2011)*, see also *Grin et al. 2016*

Some groups of stars are difficult to understand in the current framework.

The predicted rotation periods of white dwarfs and neutron stars are too low.

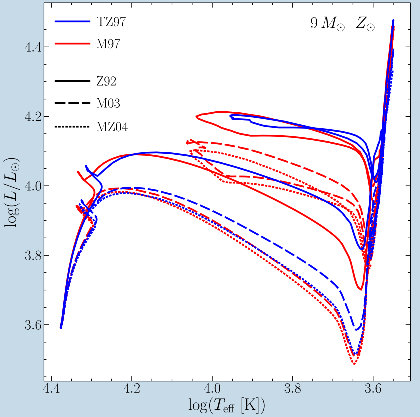



*Suijs et al. (2008)*

# and some of the uncertainties

Effect of changing the prescriptions for rotation:

*Meynet et al. (2013)*

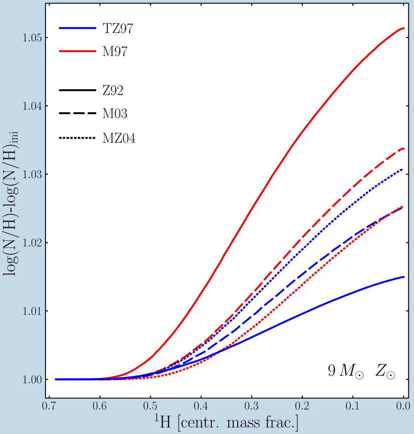



The behaviour in the HRD (even during the MS!) is seriously affected by the choice of the various parameters.

# and some of the uncertainties

Effect of changing the prescriptions for rotation:

*Meynet et al. (2013)*

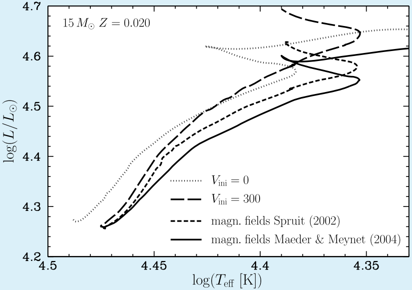



The mixing depends also strongly on the prescription.

# Need for additional coupling?

Standard rotating models predict too fast cores at the pre-SN stage *(Suijs et al. 2008)*.

- Internal magnetic field could couple the core and the surface efficiently *(Spruit 2002, Maeder & Meynet 2002)*.

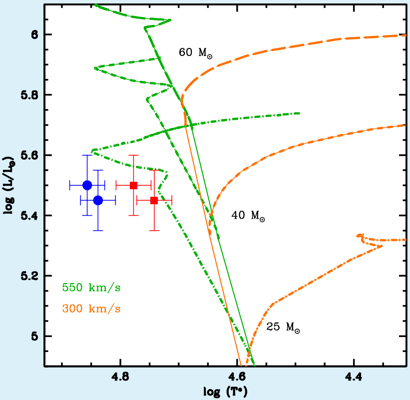



*Suijs et al. (2008)*

# Need for additional coupling?

Standard rotating models predict too fast cores at the pre-SN stage *(Suijs et al. 2008)*.

- Internal magnetic field could couple the core and the surface efficiently *(Spruit 2002, Maeder & Meynet 2002)*.
- Naturally leads to homogeneous chemical evolution *(Yoon & Langer 2005, Meynet & Maeder 2007, Brott et al. 2011)*.

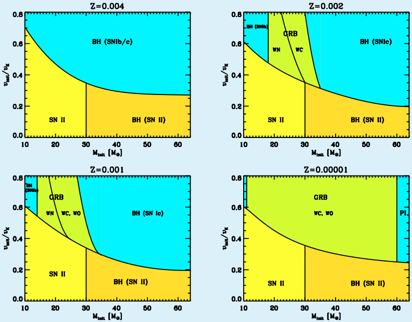



*Martins et al. (2013)*

# Need for additional coupling?

Standard rotating models predict too fast cores at the pre-SN stage *(Suijs et al. 2008)*.

- Internal magnetic field could couple the core and the surface efficiently *(Spruit 2002, Maeder & Meynet 2002)*.
- Naturally leads to homogeneous chemical evolution *(Yoon & Langer 2005, Meynet & Maeder 2007, Brott et al. 2011)*.
- Origin of LGRB? *(Yoon et al. 2006)*




*Yoon et al. (2006)*

# Need for additional coupling?

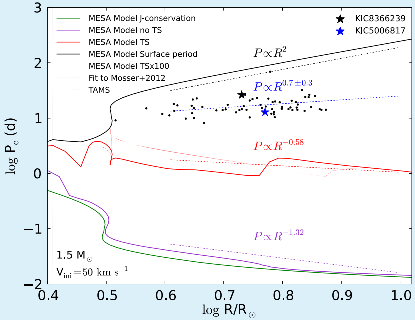
However:

- Differential rotation between core and envelope observed in (at least) some massive MS stars *(Aerts et al. 2008)*.

# Need for additional coupling?

However:

- Differential rotation between core and envelope observed in (at least) some massive MS stars *(Aerts et al. 2008)*.
- Classical magnetic coupling unable to reproduce the core-envelope differential rotation during the RG phase of lower mass stars *(Beck et al. 2012, Eggenberger et al. 2012, Cantiello et al. 2014, Eggenberger et al. sub.)*.




*Cantiello et al. (2014)*

# Various codes, various physics, various outputs

## A comparison between 3 different codes:

*Chieffi & Limongi (2013)*