The sun, with all those planets revolving around it and dependent on it, can still ripen a bunch of grapes as if it had nothing else in the universe to do.
The sun, with all those planets revolving around it and dependent on it, can still ripen a bunch of grapes as if it had nothing else in the universe to do.

Francesca, with all the projects revolving around her and dependent on her, can still cultivate the joy of life as if she had nothing else in the universe to do.
Physics of spinstars and some consequences for the (early) chemical evolution of galaxies

Georges Meynet
Geneva Observatory, Geneva University

Cristina Chiappini (Potsdam, D)
Gabriele Cescutti (Potsdam, D)
Sylvia Ekstroem (Uni. Geneva)
Cyril Georgy (Keele, UK)
José Groh (Uni. Geneva)
Raphael Hirschi (Keele, UK)
Andre Maeder (Uni. Geneva)

Painting by Adolf Schaller, STScI-PRC02-02
SPINSTARS = STARS WHOSE EVOLUTION IS STRONGLY AFFECTED BY ROTATION

MIXING

SHEAR

D_{\text{shear}} \sim \nabla \Omega \quad t \sim R^2 / D_{\text{shear}}

MERIDIONAL CIRCULATION

U \sim 1/\rho \quad t \sim R / U

MASS LOSS

STELLAR WINDS

→ Anisotropie
→ Enhancement
→ Eddington limit changed
→ Indirect effects

MECHANICAL MASS LOSS

→ Equatorial mass loss

IMPORTANT IMPACT OF ROTATION IN METAL POOR REGIONS

WHY?

STARS ARE MORE COMPACT

→ Opacities smaller
→ CNO content smaller

CONSEQUENCES: SHEAR MIXING STRONGER

Ekstroem et al 2008
Gradients of $\Omega$ steeper at lower metallicity

20 $M_{\text{sol}}$, $X_c$ mass fraction of H at the centre, $V_{\text{ini}} = 300$ km/s

**Why?**

Stars more compact, mixing timescale scales with $R^2$
transport of angular momentum less efficient

**Consequences?**

More efficient mixing of the chemical elements
AN ILLUSTRATION OF STRONGER MIXING IN METAL POOR STARS
FROM THEORETICAL MODELS

$Z=0.014$  
$Z=0.002$

$9 \, M_{\odot}$  
$7 \, M_{\odot}$  
$5 \, M_{\odot}$  
$4 \, M_{\odot}$  
$3 \, M_{\odot}$

$\Delta \log(N/H)$  
$\log(T_{\text{eff}} \, [K])$

Georgy et al. 2013
Welcome to the interactive webpage for the Geneva stellar models

Through this portal, you'll access several tools designed for the Geneva stellar models. Don't hesitate to contact us if you have suggestions or comments (or to report a bug!).

We propose the following services:

- **Isochrone calculation**
  
  Compute a single isochrone of the desired age, or a sequence of isochrones giving the age range and the time steps.

- **Interpolation of a new model:**
  
  Create a new model by interpolating between existing tracks. Choose the mass, rotation rate and metallicity and obtain the corresponding model track.

Please select one of the following modes:

Compute an isochrone

Submit

Site created with DJ by C. Georgy & S. Ekström;
Site Map | admin | Last update: July 22, 2013 at 16:58
GePSy, Geneva Population Synthesis tool

Initial distribution of Velocities
Limb and gravity darkening accounted for
Where are the initially fast rotators?
Where are the actual fast rotators?
Where are stars seen equator.on/pole-on?
Where are the N-rich stars?
Where are the unresolved binaries?
The evolution of massive stars and their spectra

I. A non-rotating $60 M_\odot$ star from the ZAMS to the pre-SN stage

Jose H. Groh$^1$, Georges Meynet$^1$, Sylvia Ekström$^1$, and Cyril Georgy$^2$
The evolution of massive stars and their spectra

I. A non-rotating 60 $M_\odot$ star from the ZAMS to the pre-SN stage

Jose H. Groh\textsuperscript{1}, Georges Meynet\textsuperscript{1}, Sylvia Ekström\textsuperscript{1}, and Cyril Georgy\textsuperscript{2}

Submitted
The evolution of massive stars and their spectra

I. A non-rotating 60 $M_\odot$ star from the ZAMS to the pre-SN stage

Jose H. Groh$^1$, Georges Meynet$^1$, Sylvia Ekström$^1$, and Cyril Georgy$^2$

---

$O3 \ I$ (ZAMS) $\rightarrow$ $O4 \ I$ (mid H-core burning) $\rightarrow$ hot LBV (end H-core burning) $\rightarrow$ cool LBV (start He-core burning) $\rightarrow$ WNL $\rightarrow$ WNE $\rightarrow$ WC (mid He-core burning) $\rightarrow$ WO (end He-core burning until core collapse).
SPECTROSCOPIC AND PHOTOMETRIC PROPERTIES OF CORE-COLLAPSE PROGENITORS
Why so few detections of type Ibc progenitors? ~13 archives images, only one detection

Pre SN are WO stars not WN or WC stars
Too low L for being detected

THE ONLY PROGENITOR DETECTED SO FAR FOR A TYPE Ibc: iPTF13bvn Cao et al. 2013

Models

Obs of iPTF13bvn

Groh et al. 2013

...QUITE WELL EXPLAINED BY THEORY OF SINGLE STARS
THE ONLY PROGENITOR DETECTED SO FAR FOR A TYPE Ibc: iPTF13bvn Cao et al. 2013

Models of iPTF13bvn Groh et al. 2013...QUITE WELL EXPLAINED BY THEORY OF SINGLE STARS
EXPECTED FREQUENCIES OF CC-SNe

Rotating models

THEORY

OBSERVATIONS

IIP progenitors
- RSG 100%
  (8.0-16.8 M☉)
- IIP 65%
  (8.0-16.8 M☉)

II/L/b progenitors
- LBV
  (19-25.0 M☉)
- YHG
  (16.8-19 M☉)
  44%

Ib progenitors
- WN10-11
  96%
  (25.0-30.1 M☉)
- WO 1-3
  4%
  (82.0-88.7 M☉)

Ic progenitors
- WO 1-3
  100%
  (30.1-82.0 M☉)
  (88.7-120.0 M☉)

EXPECTED FREQUENCIES

NATURE OF PROGENITORS

Observed rates
Eldridge et al 2013
Smith et al 2012
$V/V_{\text{crit}} = 0.70$  
$60 \, M_{\odot}, \, Z=10^{-5}$  
$V/V_{\text{crit}} = 0$

→ SIMILAR MIXING IN INTERMEDIATE MASS STARS  
→ LOW METALLICITY REQUIRED

Rotating star has lost Material through winds

Meynet et al. 2010
WHAT IS NEEDED FOR PRIMARY NITROGEN IN ROTATING STARS?

STRONG OMEGA GRADIENT AT THE BORDER OF THE CORE He-BURNING CORE AT A TIME WHEN mu-GRADIENTS ARE STILL NOT TOO STRONG → EARLY PHASES OF CORE He-BURNING

AT LOW- Z → stars more compact → shorter timescales

AT LOW- Z → more angular momentum is retained in the core

AT Z=0 → less efficient N production because less contraction at the end MS phase

AT high Z → less efficient N production because...
→ shallower gradients and longer timescales
Z = 0.0004, typical Z of I Zw18

60 $M_{\text{sun}}$, Main-Sequence

40 $M_{\text{sun}}$, pre-SN, $<v> \sim 350$ km s$^{-1}$

Groh et al. 2013
**Z=0.0004, typical Z of I Zw18**

*SOME PRIMARY NITROGEN MAY BE PRODUCED AT THE METALLICITY OF I Zw18*

60 $M_{\text{sun}}$, Main-Sequence

40 $M_{\text{sun}}$, pre-SN, $<v>\sim 350$ km s$^{-1}$

**Groh et al. 2013**
IMPACT OF VARIOUS PRESCRIPTIONS

$D_{\text{shear}}$ from Maeder (1997, M97)

$D_{\text{shear}} = f_{\text{energ}} \frac{H_P}{8 \delta} \frac{K}{(1 + K/D_h)} \left( \frac{\mathcal{Q}}{\Omega} \frac{\Omega}{\text{dln} \Omega} \right)^2$

where $K = \frac{4 \pi T^4}{3 \kappa}$, and with $f_{\text{energ}} = 1$, and $\varphi = \left( \frac{\text{dln} \rho}{\text{dln} \mu} \right)_{P,T} = 1$.

$D_{\text{shear}}$ from Talon & Zahn (1997, TZ97)

$D_{\text{shear}} = f_{\text{energ}} \frac{H_P}{8 \delta} \left[ \frac{8}{5} \nabla \mu \left( \nabla_{\text{ad}} - \nabla_{\text{rad}} \right) \right] \left( \frac{9 \pi}{32} \frac{\Omega}{\text{dln} \Omega} \right)^2$

with $K$, $f_{\text{energ}}$, and $\varphi$ as in (1).

$D_h$ from Zahn (1992, Z92)

$D_h = \frac{1}{c_h} r \left| 2 V(r) - \alpha U(r) \right|$

where $\alpha = \frac{1}{2} \frac{\text{dln}(r^2 \Omega)}{\text{dln} r}$ and $c_h = 1$.

$D_h$ from Maeder (2003, M03)

$D_h = A r \left( r \Omega(r) V \left| 2V - \alpha U \right| \right)^{1/3}$

with $\alpha$ as in Eq. (5) and $A = 0.002$.

$D_h$ from Mathis et al. (2004, MZ04)

$D_h = \left( \frac{\beta}{10} \right)^{1/2} \left( r^2 \Omega \right)^{1/2} \left( r \left| 2V - \alpha U \right| \right)^{1/2}$

with $\alpha$ as in Eq. (5) and $\beta = 1.5 \cdot 10^{-6}$.

All models produce primary nitrogen

In most of cases (4/6), the quantities of primary nitrogen produced is about 10 times the initial content of CNO in the ejected mass.
Some Possible Consequences

Mass loss triggered by rotation even in Pop III stars
Ekström et al. 2008

Origin of primary nitrogen, $^{13}\text{C}$, $^{22}\text{Ne}$ in the early phases of the chemical evolution of galaxies
Meynet et al. 2006; Chiappini et al. 2005, 2006, 2008; Cescutti and Chiappini 2010

Origin of the CEMP stars (at least the CEMP-no :no s-elements)
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Decressin et al. 2007ab

Origin of the high He-abundance in some stars in globular clusters
Maeder and Meynet 2006; Charbonnel et al. 2013

New s-process in massive metal poor rotating stars
Pignatari et al. 2008; Chiappini et al. 2011; Frischknecht et al. 2012; Cescutti et al. 2013

Primary-like evolution of Be and B
Prantzos 2012
\[ \frac{V}{V_{\text{crit}}} = 0.70 \]

\[ 60 \, M_{\odot}, \, Z = 10^{-5} \]

\[ \frac{V}{V_{\text{crit}}} = 0 \]

Rotating star has lost material through winds.
-Integration in the Geneva stellar models of nuclear networks with 613 isotopes up to end He-burning with 737 isotopes from He-burning on.

Reaction library (REACLIB) from Rauscher & Thielemann (2000)

### Table 3.1: Important reaction rates for the s process

<table>
<thead>
<tr>
<th>Nuclear reaction</th>
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NON-STANDARD S-PROCESS IN ROTATING MASSIVE STARS

- Integration in the Geneva stellar models of nuclear networks with 613 isotopes up to end He-burning with 737 isotopes from He-burning on.

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<td>Takahashi &amp; Yokoi (1987)</td>
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<td>Goriely (1999)</td>
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Karakas et al. 2006 lower
Descouvemont 1993 lower

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RESULTS LIKELY ARE UNDERESTIMATED

Karakas et al. 2006 lower
Descouvemont 1993 lower

NON-STANDARD S-PROCESS IN ROTATING MASSIVE STARS

Horizontal shear diffusion coefficient Zahn (1992)
Vertical shear diffusion coefficient Talon & Zahn (1997)

$25 \, M_{\text{Sol}}, \, Z=10^{-5}$

Z=10^{-5}, \frac{V_{ini}}{V_{crit}} = 0.4

Frischknecht et al. 2012
The details are making the perfection and the perfection is not a detail.

Léonard de Vinci

Extrait des carnets
Some Possible Consequences

Mass loss triggered by rotation even in Pop III stars

Origin of primary nitrogen, $^{13}\text{C}$, $^{22}\text{Ne}$ in the early phases of the chemical evolution of galaxies

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Meynet et al. 2006, 2010

Decressin et al. 2007ab

Maeder and Meynet 2006

Pignatari et al. 2008; Chiappini et al. 2011; Frischknecht et al. 2012; Cescutti et al. 2013

Prantzos 2012

Observations by Spite et al. 2005
Israelian et al. 2004
Similar angular momentum content

Smaller angular momentum content

Observations by Spite et al. 2005
Israelian et al. 2004

(Hirschi 2007)

- $M_{\text{ini}} = 20 M_{\odot}$
- $V_{\text{ini}}$
- $Z_{\text{ini}}$ solar
- $J_{\text{ini}} [10^{53} \text{ erg s}]$
  - 300
  - $10^{-8}$
  - 0.36
  - 300
  - $10^{-8}$
  - 0.18
  - 600
  - $10^{-8}$
  - 0.33
Observations from
Spite et al. 2005
Akerman et al. 2004
Nissen 2004; see also Fabbian et al. 2009
Dotted red
$7 \, M_\text{sun}$
0 km/s
Envelope
D=100

Dotted blue
$60 \, M_\text{sun}$
0 km/s
$M_{\text{cut}}=18.2$
D=100

Massive stars
Dilution → small He-rich
$M_{\text{cut}}$ → small N/C, N/O
large $^{12}\text{C}/^{13}\text{C}$

Meynet et al. 2010
Chiappini, private communication
Models from Cescutti & Chiappini 2010; Cescutti et al. 2009
<table>
<thead>
<tr>
<th>Element</th>
<th>B-8 (1)</th>
<th>B-107 (2)</th>
<th>B-108 (3)</th>
<th>B-118 (4)</th>
<th>B-122 (5)</th>
<th>B-128 (6)</th>
<th>B-130 (7)</th>
<th>F-121 (8)</th>
</tr>
</thead>
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<tr>
<td>[O/Fe]$^1$</td>
<td>+0.25:</td>
<td>+0.5:</td>
<td>+0.7:</td>
<td>+0.3:</td>
<td>+0.7:</td>
<td>--</td>
<td>+0.50:</td>
<td>+0.5:</td>
</tr>
<tr>
<td>[Mg/Fe] $^1$</td>
<td>+0.10</td>
<td>+0.27</td>
<td>+0.33</td>
<td>+0.20</td>
<td>+0.20</td>
<td>+0.25</td>
<td>+0.40</td>
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</tr>
<tr>
<td>[Si/Fe] $^1$</td>
<td>+0.34</td>
<td>+0.20</td>
<td>+0.20</td>
<td>+0.29</td>
<td>+0.13</td>
<td>+0.24</td>
<td>+0.35</td>
<td>+0.27</td>
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<tr>
<td>[Ca/Fe] $^1$</td>
<td>+0.15</td>
<td>+0.04</td>
<td>+0.18</td>
<td>+0.21</td>
<td>+0.21</td>
<td>+0.16</td>
<td>+0.23</td>
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<tr>
<td>[Ti/Fe] $^1$</td>
<td>+0.12</td>
<td>+0.14</td>
<td>+0.21</td>
<td>+0.11</td>
<td>+0.19</td>
<td>+0.17</td>
<td>+0.21</td>
<td>+0.16</td>
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<tr>
<td>[Ba/Fe] $^1$</td>
<td>+0.95</td>
<td>+0.50</td>
<td>0.0</td>
<td>+1.00</td>
<td>+0.60</td>
<td>+0.90</td>
<td>+0.25</td>
<td>-0.25</td>
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<tr>
<td>[La/Fe] $^1$</td>
<td>+0.50</td>
<td>+0.50</td>
<td>+0.30</td>
<td>+0.50</td>
<td>+0.30</td>
<td>--</td>
<td>--</td>
<td>0.00</td>
</tr>
<tr>
<td>[Y/Fe]$^a$</td>
<td>+1.20</td>
<td>+1.30</td>
<td>+1.00</td>
<td>+0.50</td>
<td>+1.20</td>
<td>+1.5</td>
<td>+1.20</td>
<td>+1.20</td>
</tr>
<tr>
<td>[Sr/Fe]$^a$</td>
<td>+1.20</td>
<td>+1.00</td>
<td>+1.55</td>
<td>+1.50</td>
<td>+0.50</td>
<td>+1.5</td>
<td>--</td>
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<tr>
<td>[Eu/Fe] $^1$</td>
<td>+0.50</td>
<td>0.00</td>
<td>+0.50</td>
<td>+0.50</td>
<td>+0.30</td>
<td>0.00</td>
<td>+0.80</td>
<td>+0.50</td>
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<tr>
<td>[Na/Fe] $^1$</td>
<td>+0.35</td>
<td>-0.30</td>
<td>-0.15</td>
<td>+0.10</td>
<td>+0.15</td>
<td>+0.10</td>
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Chiappini et al., Nature 2011