Open Questions in Massive Stars Evolution

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Massive Stars: The most uncertain physics

- Stability and energy transport
- Mass loss
- Rotation
- Magnetic Fields
- Binary interactions

Important for central engines (SLSNe, LGRBs...)

See Selma’s Talk
Massive Stars: Rotation & Magnetic Fields

- The final rotation rate and magnetization of stellar cores are important for the physics of central engines (SLSNe, LGRBs...)

- Current models for angular momentum transport relies on 1D diffusion approximation of some (local) physical mechanisms.

- Large scale magnetic fields are usually not included

See e.g. Paxton+ 2013
Q: What is the Final $j$-distribution?

GRB (?): enough angular momentum in the core to make an accretion disk during collapse / create a rapidly rotating NS

SN: no accretion disk during collapse / no rapidly rotating NS

Q: What is the Final core magnetization?

1D MESA
Stellar evolution calculations
Asteroseismology now allows to probe the deep interiors of (low-mass) stars and measure properties like radial differential rotation and internal magnetic fields! Important results:

1. Internal J-transport not fully understood [Cantiello et al. (2014)]
   Large coupling core-envelope seems required

2. Strong core B-fields potentially ubiquitous in massive stars [Fuller, MC et al. (2015), Stello, MC et al. (2016)]
Massive Stars: The most uncertain physics

- Stability and energy transport
- Mass loss
- Rotation
- Magnetic Fields
- Binarity
Stability and energy transport

Q: How is the energy transported in massive stars envelopes? (Radii, stability...)

MLT is not supposed to work!

Jiang, MC et al. 2015, 2017

Radii Important: See e.g. Tony Piro’s and Ryan Chornock’s Talks
Different regimes in Radiation Dominated Convection

Diff. Rad Flux
Advection Flux ("convection"...)

$$F_{\text{dif}} \sim \frac{a_r T^4 c}{\tau}$$

$$F_{\text{adv}} \sim c_s a_r T^4$$

Critical optical depth

$$\tau_c = \frac{c}{c_s}$$

Optical depth where radiation diffusion timescale = dynamical timescale

MLT is not supposed to work!
Stability and energy transport

1D Stellar Evolution (MESA)

3D Local Radiation MHD (ATHENA)

3D Global Radiation MHD (ATHENA++)

Jiang, MC et al. 2015, 2017
Initial Conditions
Guided from MESA 1D models

Jiang, MC et al. 2015
The Opacity: Iron Peak

At fixed density around Iron Opacity peak. Neighboring lines: x10 in rho

Cantiello et al. 2009, Paxton, MC et al. 2013, Jiang, MC et al. 2015

\[ \kappa_{\text{Fe}} / \text{cm}^2/\text{g} \]

\[ 3.6 \times 10^{-8} \text{ g/cm}^3 \]

\[ 3.6 \times 10^{-12} \text{ g/cm}^3 \]
The case with inefficient convection

ATHENA + VET

<table>
<thead>
<tr>
<th>Variables/Units</th>
<th>StarTop</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r_0/r_\odot$</td>
<td>13.6</td>
</tr>
<tr>
<td>$T_0/K$</td>
<td>$1.57 \times 10^5$</td>
</tr>
<tr>
<td>$\rho_0/(g \text{ cm}^{-3})$</td>
<td>$5.52 \times 10^{-9}$</td>
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<tr>
<td>$g/(\text{cm s}^{-2})$</td>
<td>$1.17 \times 10^4$</td>
</tr>
<tr>
<td>$F_{r,i}/(\text{erg cm}^{-2} \text{ s}^{-1})$</td>
<td>$3.06 \times 10^{14}$</td>
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<tr>
<td>$H_0/cm$</td>
<td>$2.37 \times 10^{10}$</td>
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<tr>
<td>$t_0/s$</td>
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<tr>
<td>$\tau_c \equiv c/c_{g,0}$</td>
<td>$6.54 \times 10^3$</td>
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<tr>
<td>$\tau_0$</td>
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<tr>
<td>$P_{r,0}/P_0$</td>
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<tr>
<td>$L_{x,y}/H_0$</td>
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<td>$L_z/H_0$</td>
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<tr>
<td>$N_{x,y}$</td>
<td>128</td>
</tr>
<tr>
<td>$N_z$</td>
<td>512</td>
</tr>
</tbody>
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Jiang, MC et al. 2015
Initial Conditions
Guided from MESA 1D models

\[ \log \left( \frac{L}{L_\odot} \right) \]

\[ \log \left( \frac{T_{\text{eff}}}{K} \right) \]

\( \tau_0 \ll \tau_c \)

\( 80 \, M_\odot \)

\( 40 \, M_\odot \)

\( \tau_0 \approx \tau_c \)

\( \tau_0 \gg \tau_c \)

StarTop

StarMid

StarDeep

Jiang, MC et al. 2015
Preliminary Results!

Jiang, MC et al. In Prep
Jiang, MC et al. In Prep  

Preliminary Results!
Massive Stars: Mass Loss

Q: How massive stars loose their mass?

- Line Driven Winds
- "Cool" Winds
- LBV eruptions
- Pulsationally enhanced winds
- Binary RLOF
- Pre SN massloss

Smith 2014
Pre SN Mass Loss and Outbursts

**Type IIn**: e.g. Smith 2016, heterogenous class. But large mass loss rates required in last phases of stellar life

**Pre SN Outbursts**: 2009ip (e.g. Margutti et al. 2014), 2010mc (Ofek et al. 2013), LSQ13zm (Tartaglia et al. 2016), 2015bh (e.g. Ofek et al. 2016)

**Type Ibn**: e.g. SN 2014C transitioned into a IIn, due to H-rich CSM ejected by its progenitor in its final ~decades of life (Milisavljevic et al. 2015, Margutti et al. 2017)

**Type IIP**: SN 2013fs Early time flash spectroscopy reveals modest mass ejection ($10^{-3} \, M_{\text{Sun}}/\text{yr}$) in final year of progenitor’s life (Yaron et al. 2017)

See e.g. Maria Drout and Ori Fox talks
Wave Driven Heating & Mass Loss

Late Nuclear Burning Phases

<table>
<thead>
<tr>
<th>Stage</th>
<th>Duration ($t_{nuc}$)</th>
<th>$L_{fusion}$ ($L_{\odot}$)</th>
<th>Mach ($M_{conv}$)</th>
<th>$\tau_c$ (s)</th>
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<tbody>
<tr>
<td>Carbon</td>
<td>$\sim 10^3$ yr</td>
<td>$\sim 10^6$</td>
<td>$\sim 0.003$</td>
<td>$\sim 10^{4.5}$</td>
</tr>
<tr>
<td>Neon</td>
<td>$\sim 1$ yr</td>
<td>$\sim 10^9$</td>
<td>$\sim 0.01$</td>
<td>$\sim 10^3$</td>
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<td>Oxygen</td>
<td>$\sim 1$ yr</td>
<td>$\sim 10^{10}$</td>
<td>$\sim 0.02$</td>
<td>$\sim 10^3$</td>
</tr>
<tr>
<td>Silicon</td>
<td>$\sim 1$ day</td>
<td>$\sim 10^{12}$</td>
<td>$\sim 0.05$</td>
<td>$\sim 10^2$</td>
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$L_{wave} \sim M_{conv} L_{conv}$

Fuller 2017, Quataert & Shiode 2012
Wave Driven Heating & Mass Loss

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$L_{\text{wave}} \sim M_{\text{con}} L_{\text{con}}$

Waves can deposit $\sim 10^{48}$ ergs in the envelope in the last months to years before SN explosion.

Shiode & Quataert 2014, Fuller 2017
Quataert et al. 2016 (SuperEddington outflows)
Time Until Collapse
108.710 years
Wave Driven Heating & Mass Loss
For a typical Type IIP progenitor

- Modest luminosity excursions (less than 2 mags during last few years)
- Impact on radius and envelope structure (Important for light curve, in particular early peak luminosity).
  See Tony Piro’s Talk
- Can explain mild Pre SN outbursts in RSGs, leading to observed flash spectroscopy
- Ejecta masses small (< 1M$_{\text{Sun}}$, and with velocity < 50 km/s)

Fuller 2017
Other Pre SN Mass Loss Mechanisms

- Pulsationally enhanced winds in RSG (Heger+ 1997, Yoon & Cantiello 2010, Moryia & Langer 2017)

- Pulsation Pair Instability (Woosley 2017)

- Burning Shell Instabilities (e.g. Meakin & Arnett 2006, 2007)

- Si-Burning Flashles (Woosley & Heger 2015)
Q: How massive stars lose their mass?

**LSST**: Pre SN outbursts. Early(?) and Late time light curves, to probe CSM interaction

Q: Are the cores of (some) massive stars magnetized and/or rapidly rotating?

**LSST**: Early(?) and Late time light curves, to probe energetics of central engines (vs other energy sources)