How do massive stars get their mass?

Massive star formation is a competition between gravity and (direct+indirect) radiation pressure

Gravitational Force:
\[
f_{\text{grav}}(r) = \frac{GM_\star \Sigma}{r^2} \]
\[
\Sigma(r) = \int_0^r \rho(r')dr'
\]

Radiative Force:
\[
f_{\text{rad}} = \frac{L_\star}{4\pi r^2 c} (1 + f_{\text{trap}})
\]
\[
L_\star \propto M_\star^3
\]
\[
f_{\text{edd}} = 7.7 \times 10^{-5} (1 + f_{\text{trap}}) \left( \frac{L_\star}{M_\star} \right)_\odot \left( \frac{\Sigma}{1 \text{ g cm}^{-2}} \right)^{-1}
\]

Radiation halts isotropic accretion when \( f_{\text{edd}} \gtrsim 1 \) for \( M_\star \gtrsim 20 M_\odot \)

Larson & Starrfield 1971, Kahn 1974, Yorke 1979, Yorke+1995, Wolfire & Cassinelli 1986, 1987; Yorke & Bodenheimer 1999, Krumholz+2009
Modeling massive star formation requires multi-dimensional radiation-hydrodynamic simulations.
How do massive stars get their mass?

- Star grows via disk accretion and radiative Rayleigh Taylor (RT) instabilities
- Only includes indirect $P_{\text{rad}}$

- Star grows via disk accretion only.
- RT instabilities do not develop
- Includes both direct and indirect $P_{\text{rad}}$
Questions:

1. Is mass supplied to massive stars via radiative RT instabilities?
2. How do massive stars *overcome* the radiation pressure barrier under more realistic conditions? (i.e., turbulence)
Hybrid Adaptive Ray-Moment Method (HARM$^2$): New Hybrid Radiative Transfer Method for AMR RHD simulations

Adaptivity reduces cost!

Abel & Wandelt 2002, Wise & Abel 2011

Adaptive ray-tracing for point sources

Moment method for “dusty” fluid

HARM$^2$ models radiative heating and pressure from the direct (stellar) and indirect (dust-reprocessed) radiation fields
Revisiting radiative RT instabilities

Initial Conditions:

- $M_{\text{core}} = 150 M_{\odot}$
- $R_{\text{core}} = 0.1 \text{ pc}$
- $\rho(r) \propto r^{-3/2}$
- $E_{\text{rot}} / E_{\text{grav}} = 0.04$
- $\Delta x_{\text{min}} = 20 \text{ AU}$
- $t_{\text{ff}} = 42,710 \text{ yrs}$

Top panel: (40,000 AU x 40,000 AU)
Bottom panel: (8,000 AU x 8,000 AU)

(★ = stars with masses > 0.1$M_{\odot}$)
$t = 0.69 \, t_{ff}$

$M_{\star} = 40.07 \, M_{\odot}$

Rosen+2016
RT instability growth is sensitive to resolution

Classical RT instabilities grow exponentially.

$$\eta(t) \propto \exp(\omega t) \text{ where } \omega \propto \sqrt{\lambda}$$

Growth rate faster for smaller modes.

$$\tau_{RT} \propto \sqrt{\lambda}$$

Diffuse \hspace{1cm} Direct

$P_{dir}$ may suppress initial non-linear growth of RT instabilities but...

Asymmetry drives instability!

$\Delta x_{sh} \approx 160 \text{ AU}$

Klassen+2016

Rosen+2016

$\Delta x_{sh} = 20-40 \text{ AU}$

Wikipedia
Testing our hypothesis: Low-Res Run

RT instabilities take longer to grow in lower-resolution shells.

RT instabilities still develop (later*) due to shielding/shadowing of direct radiation field.

*For comparison: Shells start to become unstable when $M_\star \approx 25-30 \, M_\odot$ in higher resolution simulation.

No refinement on $\nabla E_R$!
…but star forming cores are turbulent

Turbulence should be initial seeds for RT instabilities.
Collapse of turbulent core with $HARM^2$

**Initial Conditions:**

- $M_{\text{core}} = 150 \, M_\odot$
- $R_{\text{core}} = 0.1 \, \text{pc}$
- $\rho(r) \propto r^{-3/2}$
- $\sigma_{1D} = 0.4 \, \text{km s}^{-1}$
- $\Delta x_{\text{min}} = 20 \, \text{AU}$
- $t_{\text{ff}} = 42,710 \, \text{yrs}$

*Top panel: (40,000 AU x 40,000 AU)*

*Bottom panel: (8,000 AU x 8,000 AU)*

Rosen+2016
Mass delivered to star via infalling dense filaments, RT instabilities, and disk accretion.

$(20,000 \text{ AU})^2$

$(3,000 \text{ AU})^2$

Rosen+2016
High accretion rates and infalling filaments provide sufficient ram pressure to overcome radiation pressure.

(10,000 AU)$^2$

Agrees with turbulent core model for massive star formation
(McKee & Tan, 2003)
Did I solve all of massive star formation?

NOPE.
Many important elements are missing

Outflows

Stellar Winds

Does feedback set the upper mass limit of the IMF?
Summary

New hybrid radiative transfer method, HARM², models direct and dust-reprocessed radiation pressure for AMR RHD simulations.

![Image of simulation result](image1)

Performed 3D RHD simulations of the formation of massive stellar systems from the collapse of (laminar and turbulent) massive pre-stellar cores.

![Image of pressure versus mass](image2)

The “Radiation Pressure Barrier” is no longer a barrier. RT instabilities, dense filaments, and gravitational instabilities deliver mass to massive stars’ during their formation.

Simulation movies can be found at [www.anna-rosen.com/movies](http://www.anna-rosen.com/movies)
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