The Importance of Winds and Radiative Feedback in Massive Star Formation

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Stellar feedback is one of the largest uncertainties in star and galaxy formation.
Massive stars affect their environments in a variety of ways

- **Direct Radiation pressure** ($P_{\text{dir}}$)  
  (Krumholz & Matzner 2009, Fall+2010, Murray+2010)

- **Dust reprocessed radiation pressure** ($P_{\text{IR}}$)  
  (Thompson+2005, Murray+2010)

- **Photoionization flows** ($P_{\text{HII}}$)  
  (Dale+2013)

- **Stellar Winds** ($P_X$)  

- **Supernovae**  
  (McKee & Ostriker 1977, Chevalier & Clegg 1985)
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- **Supernovae**
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Outline

• Motivation: The **damaging** effects stellar feedback has on star-forming environments

• The importance (or lack thereof) of **stellar winds** in star formation and HII region dynamics (aka “The Missing Wind Energy Problem”)

• The importance of **radiation pressure** in massive star formation and it’s application in star formation simulations (new **hybrid radiation scheme** in ORION)
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Feedback from massive stars ejects gas from clouds leading to low star formation efficiencies

Top: NIR, Bottom: Visible/Hα (red)

Bastian+2014
Super-bubbles are observed around young massive star clusters (MSC) which are devoid of gas.

T2005 in NGC 3256
Age < 5 Myr

Cluster 23 in ESO 338-IG04
Age ~ 6 Myr
Young ages and super-bubble sizes require efficient feedback

![Table]

Young ages imply most gas ejected before SNe go off.

$R_{\text{MSC}} \ll R_{\text{SB}}$
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High luminosities of massive stars produce fast line driven winds from the stellar surface

Wind-luminosity Relation
(Repolust 2004)

\[ \frac{L_{Bol}}{2c} = \dot{M}_W v_\infty \]
Total energy injected by massive stars is equivalent to resulting supernovae.

$$E_w = L_w t \approx 10^{51} \text{ erg} = E_{SN}$$
Injection of energy by stellar winds in a massive star cluster (MSC)

Stellar winds collide with each other and the ISM shock heating gas to $\sim 10^7$ K

Typical values for MSCs:

$$L_w = \sum_{i=1}^{N} \frac{1}{2} \dot{M}_{w,i} v_{w,i}^2$$

$$L_w \approx 10^{37} - 10^{39} \text{ erg s}^{-1}$$
Post-shock heated gas cools very inefficiently. “Cluster wind” adiabatically expands.

Shock heated gas fills HII region and primarily radiates in X-rays.
The importance of winds as a feedback mechanism in star formation and HII region dynamics relies on how the wind energy is transferred to the ISM.
X-ray observations of HII regions suggest that the shock-heated gas is not *dynamically important* (Dunne+03, Harper-Clark & Murray+09, Lopez+11)

\[
\frac{L_w t_{cl}}{V} \gg \frac{3}{2} n k_B T_x
\]
...so where’s the **missing energy**?

- Our model and HII region requirements
- Description of how we account for the missing energy
- Our results and how they affect our understanding for stellar winds as an important feedback mechanism in star formation
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(1) Require spectral typing of massive stars in HII region to estimate total $L_w$
(2) Require X-ray observations to characterize the properties of the hot gas

Our Model

Castor+1975, Weaver+1977
(3) Require radio observations to determine the HII region radius and shell expansion rate.
Our HII Region Sample

<table>
<thead>
<tr>
<th>Name</th>
<th>$D$ (kpc)</th>
<th>$R_{sh}$ (pc)</th>
<th>$v_{sh}$ (km s$^{-1}$)</th>
<th>$t_{cl}$ (Myr)</th>
<th>log $L_{bol}$ (L$_{\odot}$)</th>
<th>$L_w$ ($10^{37}$ erg s$^{-1}$)</th>
<th>$L_X$ ($10^{35}$ erg s$^{-1}$)</th>
<th>$T_X$ ($10^6$ K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 Doradus</td>
<td>50</td>
<td>100</td>
<td>25</td>
<td>2</td>
<td>8.4</td>
<td>224</td>
<td>45.0</td>
<td>7.4</td>
</tr>
<tr>
<td>Carina</td>
<td>2.3</td>
<td>20</td>
<td>20</td>
<td>3</td>
<td>7.23</td>
<td>35.0</td>
<td>1.71</td>
<td>4.5$^a$</td>
</tr>
<tr>
<td>NGC 3603</td>
<td>7.0</td>
<td>21</td>
<td>20</td>
<td>1</td>
<td>–</td>
<td>62.0</td>
<td>2.6</td>
<td>6.2$^a$</td>
</tr>
<tr>
<td>M17</td>
<td>2.1</td>
<td>5.8</td>
<td>25</td>
<td>1</td>
<td>6.58</td>
<td>1</td>
<td>0.2</td>
<td>5.3$^a$</td>
</tr>
</tbody>
</table>

$^a$Temperatures shown are surface-brightness-weighted values from Townsley et al. (2011c).

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Avenues that the **hot gas** can transfer energy

**$L_{\text{cool}}$: Radiative cooling of the hot gas**

(from Castor+1975, Weaver+1977, Dere+1997, Draine 2011)

$\mathcal{L}_{\text{cool}} \propto (\Lambda(T))^{-1/2}$

![Graph showing $n_{X}$ vs. $T$]
Avenues that the hot gas can transfer energy

$L_{\text{mech}}$: Mechanical work on the dense shell

(Castor+1975, Weaver+1977)
Avenues that the **hot gas** can transfer energy

$L_{\text{cond}}^*$: Laminar Thermal Conduction of the Hot Electrons

(Spitzer 1962, Cowie & McKee 1977)

(* conservative estimate)

(* conservative estimate)
Avenues that the **hot gas** can transfer energy

$L_{\text{dust}}^*$: Collisional **Heating** of Dust Grains


(* conservative estimate)
...so where’s the **missing energy**?

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$L_{X, \text{obs}}$ constrains hot gas density and temperature

\[ L_{X, \text{obs}} = 0.9n_X^2 V \int_{\nu_0}^{\nu_1} j_\nu(T, Z) d\nu \]
Allowed $T-n_X$ curves for our HII region sample
Accounting for the missing energy

\[ \frac{L}{L_w} \]

- \(30 \text{ Dor}\)
- \(\text{Carina}\)
- \(\text{NGC 3603}\)
- \(\text{M17}\)

\[ T \text{ [K]} \]

- \(L_{\text{total}}\)
- \(L_{\text{mech}}\)
- \(L_{\text{cool}}\)
- \(L_{\text{cond}}\)
- \(L_{\text{dust}}\)

Rosen+ 2014
Accounting for the **missing** energy

Hot gas **not strongly coupled** with the ISM.
Accounting for the **missing** energy

Could winds be **important** for young, compact HII regions?
Ways Out: Where’s the Missing Energy?

Thermal conduction? Probably not.

Dust heating via collisions? It might help.

Krumholz+2007

Rosen+ 2014

\[ a = 0.1 \, \mu m \]
Ways Out: Where’s the Missing Energy?

Physical leakage of the hot gas
(Harper-Clark & Murray 2009, Rogers & Pittard 2013, Dale+2014)

<table>
<thead>
<tr>
<th>Name</th>
<th>$n_X$ (cm$^{-3}$)</th>
<th>$C_f^a$</th>
<th>$C_f,all^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 Doradus</td>
<td>0.058</td>
<td>&gt;0.84</td>
<td>–</td>
</tr>
<tr>
<td>Carina</td>
<td>0.14</td>
<td>&gt;0.36</td>
<td>&lt;0.58</td>
</tr>
<tr>
<td>NGC 3603</td>
<td>0.13</td>
<td>&gt;0.36</td>
<td>&lt;0.70</td>
</tr>
<tr>
<td>M17</td>
<td>0.27</td>
<td>&gt;0.95</td>
<td>–</td>
</tr>
</tbody>
</table>

(a) $L_{rad} + L_{mech}$

(b) $L_{rad} + L_{mech} + L_{dust} + L_{cond}$

Rogers & Pittard 2013

Harper-Clark & Murray 2009

Rosen+ 2014
Ways Out: Where’s the **Missing Energy**?

Rapid *mixing* of cold and hot gas via turbulent conduction

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Radiation pressure extremely important in massive star and massive star cluster formation.

Accretion is Eddington limited

\[
\frac{L_\star}{M_\star} > \frac{4\pi G c}{\kappa_R}
\]

\[
\frac{L_\star}{M_\star} = 1300 \left( \frac{L_\odot}{M_\odot} \right) \left( \frac{\kappa_R}{10 \text{ cm}^2 \text{ g}^{-1}} \right)^{-1}
\]

Fails for stars with \(M_\star \gtrsim 20 M_\odot\).

Instead material funneled through disk via gravitational torques and envelope via radiative Rayleigh Taylor instabilities.
Radiation pressure extremely important in massive star and massive star cluster formation.

Observed dense, massive star clusters are radiation pressure dominant.
Massive star formation simulations require radiation. However, most treatments to date are approximate.
Treatment of radiation in the astrophysical AMR code ORION

**Old**: Flux Limited Diffusion (FLD)

\[
\vec{F}_r \propto -\nabla E_r
\]

\[
\frac{\partial E_{r,*}}{\partial t} = \sum_i L_{*,i} W(\vec{x} - \vec{x}_i)
\]

**New**: Hybrid Radiation Scheme

Adaptive multi-ray tracing

\[
\vec{F}_r = \vec{F}_{*,RT} + \vec{F}_{th,FLD}
\]

Lopez+2011
Treatment of Direct Radiation Pressure with Adaptive Ray Trace

Number of rays spread equally on initial healpix level $l_0$:

$$N_{\text{pix}}(l_0) = 12 \times 4^{l_0}$$

Parent ray splits into 4 child rays when

$$\frac{(\Delta x)^2}{\Omega_{\text{ray}} R_0^2} < \Phi_c$$

where

$$\Omega_{\text{ray}} = \frac{4\pi}{N_{\text{pix}}}$$

Energy and solid angle conserving!

Gorski, Hivon, & Wandelt 1998; Abel & Wandelt 2002
Treatment of Direct Radiation Pressure with Adaptive Ray Trace

“Photon packet” radiative transfer equation

\[
\frac{1}{c} \frac{\partial N_p}{\partial t} = \frac{\partial N_p}{\partial r} = -\kappa N_p
\]

Photons absorbed across cell

\[
dN_p = N_p \left( 1 - e^{\kappa \rho dl} \right)
\]

Energy and momentum added to cell

\[
dE = \sum_{j=1}^{N_\nu} L_{ray,j} e^{-\kappa \nu_j \rho dl} dt
\]

\[
dp_i = \sum_{j=1}^{N_\nu} \frac{L_{ray,j}}{c} e^{-\kappa \nu_j \rho dl} \hat{n}_{ray,i} dt \quad \text{for} \ i = x, y, z
\]
Current Hybrid Radiation Application: Massive Star Formation

FLD only simulation
$t_{\text{ff}}=42,710$ yrs
$R_c=0.1$ pc
$M_c=150$ M$_\odot$
$\Sigma=1$ g cm$^{-2}$
$\Delta x_{\text{min}} = 20$ AU
$E_{\text{rot}}/E_{\text{grav}}=0.02$

Simulations with ray tracing are being run!
(Very) Preliminary Results: Massive Star Formation

t_{ff}=42,710 \text{ yrs}
R_{c}=0.1 \text{ pc}
M_{c}=150 \, M_{\odot}
\Sigma=1 \, \text{g cm}^{-2}
E_{\text{rot}}/E_{\text{grav}}=0.02
\Delta x_{\text{min}} = 20 \, \text{AU}
Ray \text{ slit} \text{ting criterion } \Omega_{c}=4
Summary

Bulk of the stellar wind energy does not go into mechanical work for young HII regions surrounding MSCs.

We have implemented a hybrid radiation scheme in ORION to accurately treat the radiation field in star formation simulations.

Hybrid scheme splits radiative transport step into:

1. Adaptive raytracing step for stellar radiation ($P_{\text{dir}}$)
2. Diffusion step for thermal radiation ($P_{\text{ir}}$).