Stars form inside molecular clouds

Massive stars produce energy in a number of ways
Radiation, winds, jets, supernovae

These energetic processes heat and disperse cloud material

Competition between gravity and “feedback”

The problem is complex – turbulence, MHD, interaction between feedback processes, scales, etc

There’s a reason that this is an open question spanning whole careers

Focus on two questions:
- Can we explain how photoionisation shapes the cloud?
- How does this affect supernova efficiency?
1) UV photons stream out of the star, ionising hydrogen until all the photons are used to keep the gas ionised (called the “Strömgren radius”)

2) The photoionised gas is at ~ 10,000 K so a shock begins to expand at ~ 10 km/s (still in photoionisation equilibrium)

3) The expansion can be stopped or even reversed by turbulence or accretion

We can solve the expansion algebraically (see Raga+ 2012)

\[ n_0 (r_i \dot{r} + v_0^2) = n_i c_i^2 \]

Ram pressure in neutral gas
(ionisation front expansion \( r_i \),
external velocity \( v_0 \),
external density \( n_0 \))

Thermal pressure
in ionised gas
(\( c_i \sim 10 \text{ km/s} \),
ionised gas density \( n_i \))

(See paper or ask me for derivations)

We can solve with this (assuming also photoionisation equilibrium, a turbulent, virialised cloud)

This gives us:

\[ \frac{\dot{R}}{R} = 0.86 \frac{\alpha_{vir} t_{ff}}{t_{ff}} \left( R^{-3/4} - 1 \right) \]

\( \dot{R} \) is a scale-free radius, \( r_i \) divided by the "stall" radius, where \( dr_i/dt \to 0 \), so \( R \to 1 \)

Ionisation fronts expand on a timescale of the freefall time in the cloud and its virial parameter

Take an *isothermal gas sphere* of a given mass
Include Kolmogorov *turbulence, self-gravity, B-field*

Put it in a box, refine in the central volume and on Jeans unstable cells up to some maximum resolution

**EITHER** put in a *fixed source* of energy (winds, radiation, supernovae) → focus of this talk
**OR** form “*sink particles*” - particles that accrete dense material around them (see paper on arXiv)
Sink particles emit photons – treat cluster as a population and distribute photons across sinks
Trace ionising photons with M1 method → photons are a fluid on the AMR grid

See **Geen, Hennebelle, Tremblin & Rosdahl, 2015 or 2016**
Assume a constant density field
Turbulent ram pressure term up to 3.6 pc
Free expansion after that (photons escape the cloud)

\[ S_\ast = 10^{51} \text{ s}^{-1} \quad \text{No SN} \]
\[ S_\ast = 10^{50} \text{ s}^{-1} \quad \text{No SN} \]
\[ S_\ast = 10^{49} \text{ s}^{-1} \quad \text{No SN} \]
Lots of work has been done on supernovae. Early adiabatic phase follows Sedov / Taylor solution from the 1950s. Cooling is important for supernovae – see, e.g., Chevalier 1974, Cioffi 1988, Thornton 1998, Haid 2016).

Recent simulations in complex environments by Iffrig & Hennebelle (2015); Kim & Ostriker (2015); Martizzi et al. (2015); Walch & Naab (2015); Körtgen et al. (2016).

Very simple picture:
1) Injection of energy
2) Momentum goes up:
   \( E = \frac{1}{2}mv^2 \)
   > As we gather mass, \( E = \) const but \( m \) goes up
   \( mv = \sqrt{2E}\ m \)
   So momentum goes up
3) Gas cools after 1 cooling time (Cox 1972)
   After cooling time, shell becomes momentum conserving
4) Momentum freezes out

![Graph](image-url)
How does the environment affect the efficiency of supernovae?

In Geen+ (2016) we find less than half the momentum in other papers... (cough)

It’s a very dense, turbulent cloud – could be ram pressure? Evaporation of dense clumps? Resolution problems (I hope not)? Gravity? Noise from other flows in the cloud? (The whole cloud has 10x more momentum in turbulence than the supernova produces)

Other thoughts:
Supernovae happen too late to stop star formation in clouds (4-20 Myr typically) Probably most important for the ISM pressure / galactic winds / metal enrichment
Some Thoughts

Stars form in dense gas in molecular clouds.

They regulate their environment through different energetic processes

Photoionisation provides a lot of energy (at a low-ish temperature)
In clouds with a lot of turbulence, ionisation front can be trapped
Cloud less likely to be dispersed – higher SFE?

Supernovae are very inefficient in dense clouds
Pre-supernova feedback allows supernova to escape
Roughly constant momentum injection? Role of turbulence / cloud structure?

Analytic models can still explain the broad behaviour of more complex systems
Feedback loops complicate this → systems become very nonlinear
How will theorists tackle this problem in the decades to come?
T H A N K  Y O U

ANY QUESTIONS?

Relevant papers:
Geen et al (2015a,b, 2016)
If the source of photons is too weak, the HII region is crushed by gravitational collapse (Larson 1981). We allow the cloud to collapse over a freefall time.
Emission from clusters
This also gets complicated!

Photoionisation pressure: density × temperature (= $10,000 \text{ K} = \text{constant}$)

Wind pressure: Wind luminosity × time (builds up constantly)

There's a limit where one overpowers the other

When winds dominate, photoionisation does nothing (gas is collisionally ionised)

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**15 solar mass star**
Winds are very weak, photoionisation dominates
Winds add almost nothing to the final momentum

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**$10^4$ solar mass cluster (preliminary results)**
Winds dominate
Gas free-streams then shocks to up to $10^8 \text{ K}$
NO MORE SLIDES
WE ARE DONE