Star formation up close

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1. Bubbles: the end and the beginning
IRAS 100\(\mu\text{m}\) dust emission
locally, stellar energy input stops, starts star formation

(Elmegreen & Lada)
more star-forming bubbles

Cep OB2

100 pc diameter “star forming cloud”

extragal vs. galactic: semantics ⇔ scale

~ 10 Myr-old cluster: supernova/winds

~ 4 Myr-old cluster, H II region

100 µm IRAS dust emission

1 Myr-old stars
Spiral arms collect gas, shock; but each H II region is the site of molecular gas destruction, halting star formation locally and triggering it nearby.

This “churning” is part of the reason it is so difficult to estimate star formation efficiencies.
2. Density “thresholds” for star formation and linear gas-SFR relations
Surface density threshold for star formation?

Heiderman et al. 2010; Lada et al. 2010

$\Sigma (\text{th}) \sim 120 \text{ Msun/pc}^2 \sim A_V \sim 7; n > 10^4 \text{ cm}^{-2}; \text{linear SFR above?}$
Lada et al. 2010:
stars / dense gas ~ constant (same t)
stars/(same t_{cloud}) / dense gas
= SFR/ dense gas ~ constant

First conclusion: because stars continue to form, dense gas mass must increase with time!

Continued input from lower-density cloud regions
(Burkert & Hartmann 2012)
Second conclusion: constant ratio of stars to gas means *dense gas mass increases NON-LINEARLY with time!*

For example:

\[ M_g(t) = qM_*(t) = q\epsilon M_g(t - \tau_{ff}), \quad q = \text{constant} \]

\[ \epsilon = \text{efficiency} / \tau_{ff} \sim \text{const.} \]

\[ M_g(t) = M_g(0) \exp(t/t_0), \quad t_0 = \frac{\tau_{ff}}{\ln(q\epsilon)} \]

This non-linear increase with \( t \) is seen in many simulations with “global” gravitational collapse.

(Burkert & Hartmann 2012)
Toy model of finite sheet evolution with gravity

Burkert & Hartmann 04; piece of bubble wall $\approx$ sheet

start here

eventual gravitational collapse!
Finite sheet evolution with gravity

uniform surface density $\Sigma$, isothermal, circular sheet:

$\Rightarrow$ pileup of material at edge!

(simple way to make a filament without making “clusters” at filament ends; see later)

(Burkert & Hartmann 2012)
Global collapse of circular sheet:

exponential growth at high densities fits the simulation remarkably well

\[ n > 10^3 \text{ cm}^{-3} \]

\[ n > 10^4 \text{ cm}^{-3} \]
Global collapse of circular sheet:

dense gas mass naturally increases non-linearly with time

approx threshold density

Burkert & Hartmann 2012
Global collapse under gravity:

There is NOT a specific magic density or $\Sigma$ above which stars form;

the observational “threshold” $\sim$ where evolution becomes $\approx 10x$ faster than the global cloud evolutionary time of a few Myr.

approx “threshold” density

Burkert & Hartmann 2012
Global collapse under gravity:

But why $\sim 10^4$ cm$^{-3}$? or $\Sigma \sim 100$ Msun/pc$^2$?

At this surface density, the pressure $P(\text{grav}) = \pi G \Sigma^2 / 2 > 300x$ typical $P(\text{ISM})$ ⇒ gravity dominates

⇒ most of the cloud is at lower $\Sigma$ because it was formed by lower-pressure ISM flows

Need low $\Sigma$ cloud to form the impression of a “threshold”

Burkert & Hartmann 2012
3. This is too simple! No turbulence!...
Sheet made by uniform inflows with cooling; instability $\Rightarrow$ turbulence + cooling $\Rightarrow$ density fluctuations; then gravity wins!

Heitsch+ 2007, 2008

also Hennebelle; Vazquez-Semadeni+ 2007, 2010; Clark & Glover
Simulations of cloud flow with gravity show accelerating collapse.

Heitsch

Vazquez-S.

*Figure 4.* Histograms of the newborn sink particles as a function of time for run 20 in Vázquez-Semadeni et al. (2007). The number of newborn sink particles is shown as a function of time. (Myr: million years)

*Figure 2.* History of massive core formation in the simulation Gs of Heitsch et al. (2008), plotted as a function of time prior to the end of the simulation (see text).
Orion Nebula region

Megeath et al. 2012

T Tauri stars

Protostars:
collapse down to extremely dense filament

$P_{\text{grav}} \gg P(\text{ISM})$
4. Are molecular clouds gravitationally bound?
Orion A (Hartmann & Burkert 2007): rotating oval sheet with a surface density gradient ~ 2 Myr
Upper mass IMF: “competitive accretion” (Bonnell, Bate); essentially Bondi-Hoyle accretion (Zinnecker 1982)

Hsu+ 2010 simulation “turbulence” is only density, not velocity fluctuations; result is evolution toward Salpeter purely due to gravity

implies non-universal IMF; consistent with fewer high-M stars in lower-\(\rho\) environments (less gas to accrete) (Hsu talk)

Upper IMF similar to star cluster IMF (Lada\(^2\), Fall, Chandar); gravitational focusing to make clusters?
Evidence for large-scale gravity; focusing in elongated clouds causes clusters to form preferentially at ends (Bonnell; Burkert & LH, “focal points”)

Pipe (Lombardi)

Orion A/B

Perseus (Rebull)

NGC 2264 (Sung+)
Summary

1. Star formation is dynamic: locally, strongly driven by stellar energy input; dispersal and formation on 10s of pc scales

2. Star-forming molecular clouds are dynamically evolving with long-range gravitational collapse continually producing dense gas at an increasing rate

3. Long-range gravity ⇒ Upper-mass stellar IMF, clusters