Feedback Regulates Star Formation

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What Does Turbulence Do?

Stars & Pre-Stellar Gas Cores:

- Number (dN/dM) vs. Mass \( [M_{\odot}] \)

- Data from Bastian and Chabrier

- Regions: Orion, Perseus, Pleiades, Taurus, OMC, IC 348, CMa, Oph, Chamaeleon I, IC 5146, Orion, Cygnus X, IC 1499, Wolf 359, IC 4628, Auran, L1495

- Symbols: Associations, Dense clusters, Open clusters, Globular clusters

Giant Molecular Clouds:

- Mass vs. Number

- Data from Blitz, Rosolowski et al.

- MW, LMC, SMC, M33, M31, IC10

DM Halos?!
Turbulent Fragmentation: From GMCs to Stars

JUST COUNTING “CLOUDS IN CLOUDS”

Averaging Scale $R$ [pc]

Log $[\text{Density} / \text{Mean}]$ vs. $l_{kh}$

Thermal+ Magnetic

Angular Momentum

Turbulence

PFH 2011
Turbulent Fragmentation: From GMCs to Stars

JUST COUNTING “CLOUDS IN CLOUDS”

Z= 1.99

STRUCTURE FORMATION

STAR FORMATION

Matthew Bate
University of Exeter
The “First Crossing” Mass Function

VS GIANT MOLECULAR CLOUDS

\[
\frac{dn}{dM} \propto M^{-\alpha} e^{-(M/M_J)^\beta}
\]

\[\alpha \approx 2 - \epsilon(M)\]
The “Last Crossing” Mass Function

VS PROTOSTELLAR CORES

\[ v_{\text{turb}}(R) < c_s : \]
\[ \frac{\delta \rho}{\rho} \sim \frac{v_{\text{turb}}}{c_s} \ll 1 \]

(Hennebelle & Chabrier, Padoan & Nordlund, PFH 2012)
Clustering of Stars/Cores

CLUSTERING IS **INEVITABLE**

PFH 2012
From Cores to Stars

YOU CAN TAKE TURBULENT FRAGMENTATION TO THE IMF

“Fragmentation Tree”:

\[ \text{Time} \]

![Diagram of fragmentation tree](image)

\[ \text{arXiv tomorrow!} \]
What About Starbursts (Extreme Environments)?

BOTTOM-HEAVY: TURBULENCE WINS!

- ULIRG
- $M_{\text{Jeans}}$ is bigger but $M_{\text{Sonic}}$ is smaller (bigger clouds with more fragmentation)
- Van Dokkum & Conroy (nearby elliptical centers)
- MW
- Kroupa Chabrier

(see Giles’s talk, recent HC 2014 work)
Is Star Formation Self-Regulating?
Not Without Feedback!

TURBULENT FRAGMENTATION LEADS TO RUNAWAY COLLAPSE
(ALSO, WHAT DRIVES THE TURBULENCE?)

Federrath et al.

(see Paulo’s talk)
But Star Formation is Slow!

Q: WHY IS STAR FORMATION SO INEFFICIENT?

\[ \dot{M}_* \approx 0.017 \frac{M_{\text{gas}}}{\tau_{\text{dyn}}} \]
Galactic Scales: How Can We Do Better?

- High-resolution (~1-10 pc), molecular/metal cooling (~10 K), SF at $n_H > 100 \text{ cm}^{-3}$
- Energy/Mass/Metal Injection:
  - SNe (II & Ia)
  - Stellar Winds (O & AGB)
  - Photoionization (HII) & Photoelectric
- Momentum Flux:
  - Radiation Pressure
    \[ \dot{P}_{\text{rad}} \sim \frac{L}{c} (1 + \tau_{\text{IR}}) \]
  - SNe
    \[ \dot{P}_{\text{SNe}} \sim \dot{E}_{\text{SNe}} v_{\text{ejecta}}^{-1} \]
  - Stellar Winds
    \[ \dot{P}_{\text{W}} \sim \dot{M} v_{\text{wind}} \]
  - (also MHD, anisotropic conduction, diffusion)
Stars (Hubble image):
  Blue: Young star clusters
  Red: Dust extinction

Gas:
  Magenta: cold ($< 10^4 \, K$)
  Green: warm (ionized)
  Red: hot ($> 10^6 \, K$)
Is Star Formation Self-Regulating?
The Kennicutt Law Emerges

INDEPENDENT OF SMALL-SCALE SF LAW

PFH et al. (arXiv:1311.2073)
( Also Agertz+ 1404.2613)
Kennicutt-Schmidt relation emerges naturally

**ISOLATED GALAXIES**

\[
\dot{\Sigma}_* \sim \Sigma_{\text{gas}} / \tau_{\text{dyn}}
\]

**no feedback**

\[
\dot{\Sigma}_* \sim 0.02 \Sigma_{\text{gas}} / \tau_{\text{dyn}}
\]

**with feedback**

PFH, Quataert, & Murray, 2011a
Kennicutt-Schmidt relation emerges naturally

- Efficient cooling $\rightarrow$ the gas disk dissipates its support:

\[
\dot{P}_{\text{diss}} \sim \frac{M_{\text{gas}} \nu_{\text{turb}}}{t_{\text{crossing}}} \sim M_{\text{gas}} \sigma_{\text{disk}} \Omega
\]

- Collapse stops when momentum input from feedback:

\[
\dot{P}_\ast \sim \dot{P}_{\text{diss}}
\]

\[
\dot{P}_\ast \sim \text{few} \times \frac{L}{c} \sim \epsilon_\ast \dot{M}_\ast c
\]

\[
\dot{\Sigma}_\ast \sim \left(\frac{\sigma}{\epsilon_\ast c}\right) \Sigma_{\text{gas}} \Omega \sim 0.02 \Sigma_{\text{gas}} \Omega
\]

Shetty & Ostriker ’12
CAFG et al. ’13
(Galactic) Star Formation Rates are *INDEPENDENT* of how stars form!

> Set by feedback (SFR) needed to maintain marginal stability

Hopkins, Quataert, & Murray 2011

also Saitoh et al. 2008
How Does Star Formation Self-Regulate?

SELF-ADJUST THE MASS IN DENSE GAS

Efficiency (SF per $t_{\text{dyn}}$)

SF Density Threshold

- Pile up more dense gas until the SFR “needed” is obtained!

Hopkins, Quataert, & Murray 2011
Are We Done?
No! Star Formation is Inefficient In the Integral

Q: WHAT KEEPS GAS OUT OF GALAXIES?

[Graph showing number density vs. star mass with labels: No Feedback, Observed]
How Efficient Are Galactic Super-Winds?
WHAT MECHANISMS DRIVE THEM?

S. Muratov et al., in prep

\[ \frac{\dot{M}_{\text{wind}}}{SFR} \sim 100 \dot{M}_{\text{stars}} \]

\[ \propto V_{\text{esc}}^{-2} \]

\[ \dot{M}_{\text{wind}} \sim \dot{M}_{\text{stars}} \]

\[ \propto V_{\text{esc}}^{-1} \]

No Feedback

With Feedback
Does Stellar Feedback Explain the Mass Function?

HOW EFFICIENT ARE GALACTIC WINDS?

\[ \log \left( \frac{M_*}{M_\odot} \right) = f_{\text{baryon}} M_{\text{halo}} \]

PFH et al. (arXiv:1311.2073)
Sub-Grid Is Not Enough
PHASE STRUCTURE AND RECYCLING OF OUTFLOWS MUST BE CAPTURED!

Proto-MW: Gas Temperature:

Insert Winds “By Hand” (Sub-Grid) Following Full Feedback

S. Muratov
(stay tuned)
Feedback Determines the Halo Gas Properties

ABSORBERS FALL OUT NATURALLY (EXCEPT QUASARS)

Governato F., Brook C., Mayer L., Brooks A., Rhee G.,
Genel S., Vogelsberger M., Springel V., Sijacki D., Nelson
Fumagalli M., Hennawi J. F., Prochaska J. X., Kasen D.,
Ford A. B., Oppenheimer B. D., Davé R., Katz N.,
Wadsley J., Jonsson P., Willman B., Stinson G., Quinn

No feedback

Top:
HI maps for our simulation with full stellar feedback at $z=2$, LLSs and DLAs in this example are exclusively restricted to galaxies and their immediate vicinity but with a sub-resolution ISM model and no galactic winds. Lyman limit systems (LLSs) and DLAs are greatly enhanced owing to galactic winds.

Bottom:
HI covering fractions in galaxy halos both by directly ejecting cool gas from galaxies and through the interaction of galactic winds initially but with no feedback areas covered by LLSs and DLAs are greatly enhanced owing to galactic winds.

Feedback increases with stellar feedback areas covered by LLSs and DLAs are greatly enhanced owing to galactic winds.

With feedback

No feedback

$N_{HI}$ (cm$^{-2}$)
Dwarf Metallicities: Revealing Feedback

DEPENDS ON DETAILS OF INFLOW-OUTFLOW INTERACTIONS

- Outflows suppress “new” infall of pristine material
- Metal-rich gas preferentially re-accretes in fountains

observed

sims

“sub-grid” sims
SAMs
“Bathtub Models”
“Turbulent Fragmentation” at all scales:
- **GMCs**: universal mass function (power-law $1.x +$ cutoff at Toomre)
- **Larson’s Laws**: trace the turbulence
- **Cores**: universal slope $2.x$, turnover at sonic scale
- **IMF**: fragmentation from cores: Salpeter slope & weak dependence of $M_{\text{peak}}$
- **Stellar Clustering**: $\sim 0.1 \text{pc} - \text{kpc}$, follows directly from turbulent fluctuations

**Star formation is Feedback-Regulated:**
- **KS law is independent** of small-scale SF physics!
- SF is not “slow because of turbulence”: is slow because feedback unbinds gas!

**Cosmologically:**
- **Winds** determine IGM enrichment, temperature, & subsequent inflow
- **Resolved feedback** $\neq$ sub-grid feedback!
- Mass-metallicity, SFHs, morphology *not the same*