Feedback-Regulated Star Formation
(Stellar & AGN Feedback: Now with Physics!)

Philip Hopkins

Norm Murray, Eliot Quataaert,
Lars Hernquist, Todd Thompson, Dusan Keres, Chris Hayward, Stijn Wuyts,
Kevin Bundy, Desika Narayanan, Ryan Hickox, Rachel Somerville, & more

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Q: WHY IS STAR FORMATION SO INEFFICIENT?

\[ \log(\text{Halo Mass}) \]

\[ \log(\text{Stellar/Halo Mass}) \]

10% of baryons

Moster 2009

Kennicutt 1998

\[ \dot{\Sigma}_* \approx 0.017 \Sigma / \tau_{\text{dyn}} \]
A: Stellar Feedback!
SO WHAT’S THE PROBLEM?

- Standard (in Galaxy Formation): 
  Couple SNe energy 
  as “heating”/thermal energy

- "Cheat":
  - Turn off cooling
  - Force wind by hand 
    (‘kick’ out of galaxy)

- FAILS:
  \[
  t_{\text{cool}} \sim 4000 \text{ yr} \left( \frac{n}{\text{cm}^{-3}} \right)^{-1}
  \]
  \[
  t_{\text{dyn}} \sim 10^8 \text{ yr} \left( \frac{n}{\text{cm}^{-3}} \right)^{-1/2}
  \]

Piontek & Steinmetz

make really \(\sim 1\) min

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Stellar Feedback: How Can We Do Better?
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- High-resolution (~1 pc), molecular cooling (<100 K), SF only at highest densities ($n_H > 1000 \text{ cm}^{-3}$)
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- Heating:
  - SNe (II & Ia)
  - Stellar Winds
  - Photoionization (HII Regions)
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- Heating:
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- **Explicit 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
    \[
    \dot{P}_W \sim \dot{M} v_{\text{wind}}
    \]
Hopkins, Quataert, & Murray, in prep
Stellar Feedback gives Self-Regulated Star Formation

Massive High-z Disk

Dwarf Starburst

HiZ

Sbc

no feedback

with feedback

MW

SMC

SFR [M_⊙yr⁻¹]

Time [Gyr]
Stellar Feedback gives Self-Regulated Star Formation

- Massive High-z Disk
- Dwarf Starburst

**no radiation pressure**
Stellar Feedback gives Self-Regulated Star Formation

Massive High-z Disk

Dwarf Starburst

no SNe or stellar winds
Stellar Feedback gives Self-Regulated Star Formation

Massive High-z Disk

Dwarf Starburst

No HII Photoheating
Stellar Feedback & Self-Regulation

WHICH MECHANISMS MATTER?

- SFR \(\sim 100+ M_{\text{sun}}/\text{yr} \) (\(L \sim L_{\text{EDD}}\))
- Optically thick
- \(<n> \sim 100 \text{ cm}^{-3}\)
- \(T_{\text{cool}} \sim 1000 \text{ yr}\)
Stellar Feedback & Self-Regulation
WHICH MECHANISMS MATTER?

- SFR $\sim 0.01 \, M_{\odot}/\text{yr}$
  \((L << L_{\text{edd}})\)
- Optically thin
- $<n> \sim 0.1 \, \text{cm}^{-3}$
  \(T_{\text{cool}} \sim \text{Myr}\)

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Kennicutt-Schmidt relation emerges naturally

no feedback

with feedback
Global Star Formation Rates are *INDEPENDENT* of High-Density SF Law

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

Index (SFR $\sim r^n$)

SF Density Threshold

Hopkins, Quataert, & Murray 2011
also Saitoh et al. 2008
Global Star Formation Rates are *INDEPENDENT* of High-Density SF Law

- Set by feedback (i.e. SFR) needed to maintain marginal stability

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Molecular Chemistry doesn’t change things above modest Metallicity

MOLECULES ARE A TRACER

No Chemistry (SF from all gas)
SF from molecules only
SF, cooling track molecules

SMC
Molecular Chemistry doesn’t change things above modest Metallicity
MOLECULES ARE A TRACER

Just need some cooling channel: changes at $M_{\text{gal}} < 10^6 M_{\odot}$, $Z < 0.01 Z_{\odot}$
How Does Star Formation Self-Regulate?

SELF-ADJUST THE MASS IN *DENSE* GAS

![Graph showing mass fraction vs. log(n) for different values of epsilon and n_0.](image)
How Does Star Formation Self-Regulate?

SELF-ADJUST THE MASS IN DENSE GAS

- Need net momentum injection $dP/dt \sim L/c \sim SFR$
- to cancel dissipation $\sim M_{\text{gas}} s_{\text{disk}} W$ and maintain $Q \sim 1$
How Does Star Formation Self-Regulate?

SELF-ADJUST THE MASS IN *DENSE* GAS

- Need net momentum injection $\frac{dP}{dt} \sim \frac{L}{c} \sim \text{SFR}$
  to cancel dissipation $\sim M_{\text{gas}} s_{\text{disk}} W$ and maintain $Q \sim 1$

- Not just top-down collapse
Star Formation is Feedback-Regulated:  
MORE FEEDBACK = LESS STAR FORMATION
Star Formation is Feedback-Regulated:
MORE FEEDBACK = LESS STAR FORMATION

MW
“Normal” Feedback Strength

1/3 Feedback Strength

3x Feedback Strength

1/3 Strength
Normal Strength
3x Strength

SFR [$M_\odot$ yr$^{-1}$]

Time [Gyr]

Mass Fraction ($\Delta n$)

Log(n) [cm$^{-3}$]
Q ~ 1 Is a Boring Diagnostic
EVERYTHING GOES TO Q~1. SERIOUSLY.

Normal Feedback
Feedback Strength x30
No SNe or Stellar Winds
No Radiation Pressure
No HII Photoheating
No Feedback
Q $\sim$ 1 Is a Boring Diagnostic
EVERYTHING GOES TO Q$\sim$1. SERIOUSLY.
Properties of GMCs

STUFF TO EXAMINE IN THE FUTURE...

Sims
Observed

[Graph showing the relationship between linewidth and integrated star formation efficiency]

[Images of GMCs with scale bar 100 pc]
Galactic Super-Winds

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How Efficient Are Galactic Super-Winds?
AND WHAT MECHANISMS DRIVE THEM?

Massive High-z Disk

Dwarf Starburst

with feedback

no feedback
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How Efficient Are Galactic Super-Winds?
AND WHAT MECHANISMS DRIVE THEM?

Large mass-loading:

$$\dot{M}_{\text{wind}} \approx 10 \dot{M}_{\ast} \left( \frac{V_c}{100 \text{ km s}^{-1}} \right)^{-1.1} \left( \frac{\Sigma_{\text{gas}}}{10 M_{\odot} \text{ pc}^{-2}} \right)^{-0.5}$$
How Efficient Are Galactic Super-Winds?
AND WHAT MECHANISMS DRIVE THEM?

Large mass-loading:

\[ \dot{M}_{\text{wind}} \approx 10 \dot{M}_* \left( \frac{V_c}{100 \text{ km s}^{-1}} \right)^{-1.1} \left( \frac{\Sigma_{\text{gas}}}{10 M_\odot \text{ pc}^{-2}} \right)^{-0.5} \]
Future Directions
WHAT CAN WE EXPLORE WITH MORE REALISTIC ISM/FEEDBACK MODELS?

- **Mergers:**
  - Star cluster formation? Starburst environments?

- **AGN Feedback:**
  - How does it couple to a multi-phase ISM?

- **Cosmological simulations:**
  - “Zoom-in” disk formation simulations (D. Keres)
  - Cosmological volume AMR: dwarf populations and mass function evolution (M. Kuhlen)

- **GMCs & ISM Structure:**
  - Formation & destruction of GMCs, lifetimes, star formation efficiencies

~30 sec

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What About The Quasars?

- BALs: Preferentially in high-L quasars
- Covering factor ~20%

- of ~16 measured, 14 have:
  \[
  \dot{M}_{\text{wind}} v \gtrsim \frac{L_{\text{AGN}}}{c} \\
  L_{\text{wind}} \gtrsim 0.01 L_{\text{AGN}}
  \]

\[
\begin{align*}
R_{\text{wind}} &\sim 1 - 20 \text{ kpc} \\
\nu &\gtrsim 1000 \text{ km s}^{-1} \\
\dot{M}_{\text{wind}} &\sim 100 - 600 M_\odot \text{ yr}^{-1}
\end{align*}
\]

Arav et al.
Wampler et al. 1995
Hamann et al. 2001
de Kool et al. 2001&2
Korista et al. 2008
Moe et al. 2009
Dunn et al. 2010
Aoki et al. 2011
Kaastra et al. 2011
Molecular Ionized Outflows:

\[ \dot{M}_{\text{wind}} \geq 1000 M_\odot \text{yr}^{-1} \]

\[ v > 500 \text{ km s}^{-1} \]

\[ R_{\text{wind}} \sim 1 - 4 \text{kpc} \]

\[ M_{\text{wind}} \geq 1000 M_\odot \text{yr}^{-1} \]

Molecular Outflows in AGN ULIRGs

Rupke & Veilleux 2005, 2011
Fischer et al. 2010 (Mrk 231)
Feruglio et al. 2010 (Mrk 231)
Alatalo et al. 2011 (NGC 1266)
Sturm et al. 2011 (6 Herschel gal)
Step 1: Inflow

- Beginning to directly follow inflow to sub-pc scales

PFH & Quataert 2009,10,11
Levine, Gnedin, Kravtsov 09,10
Mayer, Callegari, 09,10
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Bars w/in Bars
(Shlosman et al. 1989)

“It’s Bars all the Way Down ...”
Bars w/in Bars
(Shlosman et al. 1989)

“It’s Bars all the Way Down ...”

\[ \dot{M} \approx 10 M_\odot \text{ yr}^{-1} \left( \frac{\text{Disk}}{\text{Total}} \right)^{5/2} M_{\text{BH}}^{-1/6} M_{\text{gas}}^{-1} R_0^{-3/2} \]
Derive 'Instability' Rate:

\[
\dot{M} \approx 10 \, M_\odot \, \text{yr}^{-1} \left( \frac{\text{Disk}}{\text{Total}} \right)^{5/2} \left[ M_{\text{BH}}^{-1/6} M_{\text{gas}}^{-1/6} R_{0,100}^{-3/2} \right]
\]

Bars w/in Bars
(Shlosman et al. 1989)

“It’s Bars all the Way Down ...”

More accurately ...

“It’s Non-axisymmetric Features all the Way Down ...”

(PFH & Quataert 2010)
Step 2: Feedback

- $L/L_{Edd} \gtrsim 0.1$
- Covering factor $\sim 10\text{-}30\%$
- Launched at $< pc$

\[ \dot{M}_{\text{launch}} \sim \dot{M}_{\text{BH}} \]

\[ v_{\text{launch}} \sim 30,000 \text{ km/s} \]
BAL Winds on ~1pc - 1kpc scales:

\[
\dot{M}_{\text{launch}}(0.1\,\text{pc}) = 0.5\,\dot{M}_{\text{BH}}
\]

\[
v_{\text{launch}}(0.1\,\text{pc}) = 10,000\,\text{km/s}
\]
Do we still need ‘Quasar Mode’ Feedback?

Springel et al. 2005

![Graph showing SFR (M_☉/yr) vs. time (Gyr) with and without Quasar Feedback.](image)
Do we still need ‘Quasar Mode’ Feedback?

Springel et al. 2005

Stellar Feedback, No Quasar

With Quasar Feedback
Step 3: Profit
CAN IT REALLY AFFECT STAR FORMATION?

- Recover $M_s$
- Normalization $\sim$ (efficiency)$^{-1}$
- Launch $\sim$1000 km/s “tail” in winds
- Suppress SFR

Novak et al. 2010,11
Debuhr, Ma, Quataert 2010,11

with BAL winds
Summary:

- Global **Star formation is Feedback-Regulated**: independent of small-scale SF ‘law’
  - Need ‘enough’ stars to offset dissipation (set by gravity)

- Feedback leads to Kennicutt relation & super-winds:
  \[
  \dot{M}_{\text{wind}} \approx 10 \dot{M}_* \left( \frac{V_c}{100 \text{ km s}^{-1}} \right)^{-1.1} \left( \frac{\Sigma_{\text{gas}}}{10 \text{ M}_\odot \text{ pc}^{-2}} \right)^{-0.5}
  \]

- Different mechanisms dominate different regimes:
  - High densities: radiation pressure
  - Intermediate: HII heating, stellar wind momentum
  - Low densities: SNe & stellar wind shock-heating
  - **No one mechanism works**

- Quasar feedback is here to stay:
  - **BAL Winds**:
    - **CAN** explain $M_{\text{BH}}$-s
    - **WILL** suppress SFRs
    - **SHOULD** heat & help clear IGM & Proto-Group Environments

- Inflows: “Stuff within Stuff”: Cascade of instabilities with diverse morphology
  \[
  \dot{M}_{\text{BH}} \propto f(B/T) \ M_{\text{gas}}(R)/t_{\text{dyn}}
  \]