Feedback: Now With Physics!

0.0 Gyr

Stars 0.1 Gyr

Stars

10 kpc

10 kpc

Philip Hopkins

Eliot Quataert, Norm Murray,

Lars Hernquist, Dusan Keres, Todd Thompson, Desika Narayanan, Dan Kasen, T. J. Cox, Chris Hayward, Kevin Bundy, & more

Q: WHY IS STAR FORMATION SO INEFFICIENT?



Stellar Feedback is (a/the) Key to Galaxy Formation! SO WHAT'S THE PROBLEM?

 Standard (in Galaxy Formation):
 Couple SNe energy as "heating"/thermal energy **FAILS**:

$$t_{\rm cool} \sim 4000 \,\mathrm{yr} \left(\frac{n}{\rm cm^{-3}}\right)^{-1}$$
$$t_{\rm dyn} \sim 10^8 \,\mathrm{yr} \left(\frac{n}{\rm cm^{-3}}\right)^{-1/2}$$





 High-resolution (~1pc), molecular cooling (<100 K), SF only at highest densities (n_H>1000 cm⁻³)



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> SNe

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Stellar Winds

$$\dot{P}_{\rm W} \sim \dot{M} v_{\rm wind}$$

















Hopkins, Quataert, & Murray, 2011

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Stellar Feedback gives Self-Regulated Star Formation





PFH, Quataert, & Murray, 2011a



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$$\longrightarrow \dot{\Sigma}_* \sim \left(\frac{\sigma}{\epsilon_* c}\right) \, \Sigma_{\rm gas} \Omega \sim 0.02 \, \Sigma_{\rm gas} \Omega$$

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



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

Hopkins, Quataert, & Murray 2011 also Saitoh et al. 2008

Molecules Don't Matter! THEY ARE A *TRACER*



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> Just need *some* cooling channel: changes at $M_{gal} < 10^6 M_{sun}$, Z<0.01 Z_{sun}

Star Formation is Feedback-Regulated: MORE FEEDBACK = LESS STAR FORMATION



Star Formation is Feedback-Regulated: MORE FEEDBACK = LESS STAR FORMATION



Starburst Galaxy (Gas-Rich) Merger



Galaxy Mergers LABORATORY FOR STUDYING EXTREME CONDITIONS



Galaxy Mergers LABORATORY FOR STUDYING EXTREME CONDITIONS



Properties of GMCs & Gas "Clumps"



SMC

Feedback is Reflected in Dense Gas TRACERS OF STAR FORMATION EFFICIENCY





Gas









How Efficient Are Galactic Super-Winds?



How Efficient Are Galactic Super-Winds?



Cosmological Simulations "ZOOM-IN" ON THE FORMATION OF A MASSIVE GALAXY



Cosmological Simulations "ZOOM-IN" RUNS

Proto-MW: Gas Temperature:

Phenomenological Winds	Full Feedback

Starburst-Driven Winds SUB-GRID vs. PHYSICAL MATTERS!



"Clumpy" Disks FEEDBACK SUPPRESSES CLUMP INSPIRAL





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Tuesday, December 25, 12

What About the AGN?

What can AGN Feedback Do For You?



Removing/heating gas in groups

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- Lowering mass of >M* galaxies
- Removing/heating gas in groups

Step 1: Inflow



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100 pc

Step 2: Stellar Feedback & the ISM

- Heating:
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Step 3: Observed Sources of AGN Feedback

• Jets

• heat IGM/ICM (low-density), but not dense ISM



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- Radiation Pressure
 - $L_{AGN} >> L_{stars}$
- Accretion Disk Winds
 - Broad Absorption Line Winds 3







BAL Winds on ~1pc - 1kpc scales:

PFH in prep Wada et al.



 $v_{\rm launch}(0.1\,{\rm pc}) = 10,000\,{\rm km/s}$

Do we need 'Quasar Mode' Feedback?



BH Growth in Isolated Disks?



Summary:

- Star formation is Feedback-Regulated:
 - Independent of small-scale SF 'law' & chemistry
 - Leads to Kennicutt relation & super-winds
- Different mechanisms dominate different regimes:
 - High-r: radiation pressure
 - Intermediate: HII heating, stellar wind momentum
 - Low-r: SNe & stellar wind shock-heating
 - No one mechanism works
- Mergers: Extreme laboratory (>100x GMC densities!)
 - No "unique" physics
 - Super-winds: ~10-500 M_{sun}/yr
- Most Massive Galaxies: Need "AGN" Feedback!
 - Disk Winds+Radiation Pressure+Jets: Explain M_{BH}-s & suppress SF
 - BH Requires Bulge Growth