Stochastic Stellar Feedback in Low-Mass Galaxies

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What do we mean by stochastic feedback?

• Conditions for massive stars capable of producing potentially disruptive feedback - *UV photo-ionization, strong winds, supernovae, X-ray binaries* - *not deterministic.*

• Effects most likely to be pronounced in low-mass galaxies, reflecting;
  • Inefficient star formation & **triggering by perturbations**.
  • Low masses of star forming regions & **random sampling of initial mass function** regulates numbers of massive stars.
  • **Inefficient stellar feedback** – sites of star formation biased towards central regions, sensitive to local conditions (e.g. gas density, cooling, radiation field, etc..)
  • Formation paths of binaries into energetic (high) mass **X-ray binaries** subject to **complex evolution**
What is the impact of stochastic feedback?

1. Low masses of star forming regions & random sampling of initial mass function regulates numbers of massive stars.

2. Inefficient stellar feedback – sites of star formation biased towards central regions, sensitive to local conditions (e.g. gas density, cooling, radiation field, etc.)

3. Formation paths of binaries into energetic (high) mass X-ray binaries subject to complex evolution

How does this stochasticity impact the abundance and star formation histories in low-mass galaxies?
• **Occupancy** of low-mass dark matter sub-haloes with satellite galaxies apparently **stochastic** (e.g. Boylan-Kolchin et al. 2011)
• Power et al 2014 - result of stochastic star formation and feedback?
Stochastic Feedback in Low-Mass Halos I

Essential Idea

- Binding energy of gas comparable to a single supernova in halo with $10^8$-$10^9 \text{ M}_\odot$
- Star formation proceeds in random order in molecular clouds.
- Pre-MS timescale varies as $M^{-2.5}$ – high mass stars form more rapidly than lower mass counterparts.
- How does this influence stellar population that forms...?

Credit: ESA/NASA

Power et al. 2014
Stochastic Feedback in Low-Mass Halos II

Power et al. 2014

Model

- Monte Carlo Merger Trees for distribution of progenitors of present-day low-mass halos.

  - $M_{\text{vir}}=10^{7.7}-10^{10} \, M_\odot$ at $z=0$

- When were they first massive enough to support cooling, i.e. $T_{\text{vir}} \sim 10^3-10^4$ K?

- Estimate binding energy of gas in halo progenitor, and energy liberated by supernovae, assuming stochastic high mass star formation.
More massive subhalos at $z=0$ support cooling earlier – feedback can have greater effect, but more time to re-accrete gas and form stars – effects of stochasticity more pronounced for lower mass subhalos.
Locally Regulated Feedback Efficiency I

**Assumption:** Stellar-driven outflows (winds, supernovae) sufficiently energetic to expel ambient gas from the galaxy.

**Caveat:** How outflow couples to ambient gas is as important as energy and momentum carried by the outflow.

**Test:** Use hydrodynamical simulations to explore coupling of stellar wind driven outflow from a nuclear star cluster couples to gas.

*Feedback from multiple sources superposes, seeds dense clumps in the outflow, fraction of mass expelled lower than one might naively expect.*
Locally Regulated Feedback Efficiency II

From Bourne & Power 2016

Problem: Multiple sources less efficient at clearing out gas from nuclear regions – seeds dense clumps robust to feedback – available to grow stars, grow central black hole?
Locally Regulated Feedback Efficiency III

From Bourne & Power 2016

**Problem:** Cooling efficiency will influence rapidity with which gas clumpiness is seeded – and therefore efficiency with which gas is expelled from the potential.
High Mass X-Ray Binaries (XRBs)

- Binary fraction for massive stars close to unity; some uncertain fraction survives to form high mass X-ray binaries (e.g. Sana et al. 2012).
- Compact object accretes from main sequence companion via wind capture or Roche Lobe Overflow.
- Accretion liberates energetic radiation with luminosity $L_{\text{acc}} = \eta \dot{M} c^2$

XRBs potentially important stochastic source of feedback?
HMXB Photo-Ionizing Feedback I

- Explore ionizing output – UV and X-ray - from a coeval stellar population as a function of
  - IMF (e.g. Kroupa, Chabrier)
  - HMXB survival fraction
  - HMXB spectra (hard to soft)

- Can extend photo-ionizing lifetime of star cluster up to >80 Myrs....

- ... but photo-ionizing feedback is non-local in nature.
Ionizing power depends on hardness of spectrum (Power et al. 2009) – power-law spectra usually assumed, but more realistic empirical spectra have quite different shape (Power et al. 2013). Energy available for ionization indicates importance...!
HMXB Kinetic Feedback I

- **Cygnus X-1** - stellar mass black hole fed by wind accretion.

- Gallo et al. 2005 - amount of energy in form of kinetic feedback (i.e. jet) as high as photo-ionizing feedback (i.e. X-ray luminosity).

- Expect outbursts to occur over an extended period of time.

Jet inflates a lobe that is over-pressured relative to its surroundings, driving a thermalising shock

Gallo et al. 2005
Hydrodynamic simulations to explore impact of kinetic feedback from HMXBs in addition to supernovae, in isolated star-forming clouds.

**Run A**: SNe + HMXB feedback, ICs: $2 \times 10^6 \, M_\odot$, 100pc, $a_{\text{vir}} = 0.7$, 50K

**Run C**: Just SNe feedback, ICs: $2 \times 10^6 \, M_\odot$, 100pc, $a_{\text{vir}} = 0.7$, 50K

Gradual injection of energy acts to open up chimneys, releases thermal pressure, alters star formation rate.
HMXB Kinetic Feedback III

- Inherently stochastic
- Single ULX outburst powerful enough to unbind gas in a dwarf galaxy

- **Location, location, location....**
  - Can sweep galaxy free of gas...
  - ... or triggers star formation.

Power & Bourne, In Prep
Summary

• Sound physical reasons to expect that effects of stochastic feedback should be especially important in low-mass galaxies.

• Not captured in current galaxy formation models – a physics and numerical resolution problem. Necessary to reconcile theory and observation?

• How energy couples to ambient gas can dramatically impact efficiency of gas explosion and influence subsequent star formation – very sensitive to local conditions

• Photo-ionization? Gas fraction? Instabilities?

• High mass X-ray binaries – whose formation is effectively stochastic - can release significant amounts of energy, providing non-local feedback and powerful kinetic outflows.

• Drive turbulence in gas rich galaxies at high redshift? Suppress collapse of gas onto low-mass halos?