FEEDBACK AND GALAXY FORMATION

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OUTLINE

- Galaxy Phenomenology
- Small scale feedback & winds
- GMC simulations
- Galaxy scale simulations of stellar driven outflows

Friday, June 15, 12
HALOS OUTNUMBER GALAXIES

Credit: Simon White
Dai et al. (2010)  

MCGAUGH ET AL. (2010) APJL, 708, 1
OUTFLOW PHENOMENOLOGY

• Star forming galactic disks have $Q \approx 1$, and GMCs/clumps; disruption of GMCs requires (nuclear powered) feedback throughout the galaxy

• We see outflows of $\sim 100s$ of km/s from individual star clusters and GMCs

• We see winds in all high $z$ star forming galaxies, but few of these galaxies have AGN; so most of these winds are not accretion powered (by AGN)

• AGN have a low duty cycle (compared to star formation) so they do not drive out the bulk of the disk baryons (though they may prevent the bulk from entering!)

• Broad absorption lines show that quasars drive outflows from $r << 1$ pc

• See $>1000$ km/s molecular outflows in nearby AGN powered ULIRGS

• See fast outflows from radio galaxies
GMCS AND CLUMPS

Spiral galaxies with GMCs on the left, clump galaxies on the right (Elmegreen et al ApJ 701 306 2009)
NGC 3310

WINDS IN STACKED SPECTRA OF Z=1 GALAXIES

DRIVING OUTFLOWS FROM A PHYSICIST’S POINT OF VIEW

• Energy: deposit energy into the ISM, heating it.
  • the resulting overpressure can push the surrounding ISM around, resulting in turbulence, or ejection of hot gas
  • sources: HII regions, stellar winds, SN, cosmic rays, AGN winds (BALs, Narrow line outflows), AGN radiative heating (X-rays), and AGN jets
  • Usually subject to radiative losses---not relevant in low mass galaxies, but in ULIRGs and SMGs this is a major problem. BALs, when shocked, may not be radiative

• Momentum: deposit momentum into the ISM, pushing it around
  • sources: HII regions, radiation pressure, BAL winds, cosmic rays, jets
  • not subject to radiative cooling
WHY IS ENERGY DRIVING ATTRACTIVE?

- Accelerating gas: \( \frac{dP}{dt} = d/dt (M(r) v) = 4\pi r^2 P \)
- \( P = E/V = E/r^3 \) if \( E \) = constant, momentum increases with time
- \( P = (2M_{sh} E)^{1/2}; \ P_f = (M_f/M_{in})^{1/2} P_{in} \) \( f \) = end of \( E \) cons. phase
- For SN, \( P/M_\ast = 3000\text{km/s} \)
- For a single SN, \( P_{max} = 5 \times 10^{43} \text{n}^{1/5} \text{g cm/s} \)
WHY IS MOMENTUM DRIVING ATTRACTIVE?

\[ \rho \frac{dv}{dt} = -\frac{dP}{dr} - \rho \left( v_{\text{dyn}}^2 / r \right) + (1 + \tau) L/c + F_{\text{cr}} + \ldots \]

- SN: P jumps instantly \( \Rightarrow v \gg v_c \)
- L, F_{cr}, change on times longer than the dynamical time, until \( L/c \) (or other force) exceeds the local gravity, when things start to move. As a result, \( v \sim v_{\text{dyn}} \)
- if local gravity is \( v_c \), then a galactic wind with \( v \sim v_c \) will result
\[ F_{\text{obs}} = \sigma T_{\text{eff}}^4 \]

By induction

\[ F(\tau) = \tau F_{\text{obs}} \]

\[ F_{\text{obs}} = \sigma T_{\text{eff}}^4 \]

\[ T(\tau) = \tau^{1/4} T_{\text{eff}} \]

\[ P_{\text{rad}} = aT^4 = a\tau T_{\text{eff}}^4 \]

\[ F_{\text{rad}} = A\Delta P_{\text{rad}} = AT aT_{\text{eff}}^4 \]

\[ = AT\sigma T^4/c = \tau L/c \]
Need Radiative Feedback in the Milky Way
Carina: \( M = 5 \times 10^5 M_{\text{sun}} \), \( v = 10 \text{ km/s} \), \( P = 10^{45} \), or 10 SN worth
\( P = \frac{L}{c} \ast \text{age} = 4 \times 10^{44} \)
BLOWING UP GMCS IN COLOR 3D

Harper-Clark; ENZO2 raytracing
BLOWING UP GMCS IN COLOR 3D

Boxes are 179.20 pc wide, Time = 0.0000 Myr

Harper-Clark; ENZO2 raytracing
Note

SN have little effect

$\varepsilon_{\text{GMC}} \approx 0.1$

STELLAR MASS VS TIME FOR DIFFERENT FEEDBACK
NOTE SNE MAKE NO DIFFERENCE (CYAN)!
Star formation, and feedback, is stochastic and intermittent!

WMAP FREE-FREE EMISSION
HALF THE GALAXY’S STAR FORMATION OCCURS IN 5% OF THE GMCS

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Star formation, and feedback, is stochastic and intermittent!

WMAP FREE-FREE EMISSION
HALF THE GALAXY’S STAR FORMATION OCCURS IN 5% OF THE GMCS
A MASSIVE STAR CLUSTER (~$10^5 M_{\text{Sun}}$)

RAPID STAR FORMATION IN THE MILKY WAY
LAUNCHING WINDS FROM MASSIVE STAR CLUSTERS

• Cluster mass scales with star formation rate

• Massive clusters have high escape velocities---they can radiatively launch winds that escape the galactic disk

• This happens before SN explode, protecting the ‘cool’ (10^4) gas

• ε_GMC as in bubble models; more gas leaves the galaxy than is retained in stars

• Cool gas survives to large distances (5-10kpc) where hot gas ram pressure takes over
NGC 3310

PUSHING WITH HOT GAS DESTROYS COLD CLOUDS


Figure 4. Logarithm of the density through the $y = 0$ plane in model rf384 showing evolution of a radiative fractal cloud.
ID NUMERICAL MODELS

Diamond-Stanic et al.

- HST-WISE sample (this paper, $z \sim 0.6$)
- Gas-rich mergers ($z < 0.3$)
- Star-forming galaxies ($z \sim 1$)

- Eddington limit
- Meurer+97 limit
- Threshold for winds
Diamond-Stanic 1205.2368
GALACTIC SCALE SIMULATIONS
FEEDBACK SLOWS STAR FORMATION AND DRIVES WINDS
HOPKINS, QUATAERT  Gadget (sph)
MODIFIED GADGET SIMULATIONS

- Particle mass from 100 solar masses
- force resolution ~ 0.3-3 parsecs
- several different types of galaxy
- no radiative transfer---instead deposit momentum from stars directly in gas
  - treat stars as being located in a single cluster near the center of their host GMCs
- track L(t) for each star
- calculate optical depth from location of cluster
MOMENTUM FEEDBACK REGULATES STAR FORMATION
DIFFERENT FORMS OF FEEDBACK
3D Hydrodynamic Winds

DIFFERENT FORMS OF FEEDBACK

Standard  No Heating (SNe/Wind/HII)  No Radiation Pressure
3-D WIND MODELS
CONCLUSIONS

• Radiative feedback is seen to act in the Milky Way (bubbles)

• Simple 1-D models, 3-D radiative MHD, and high resolution 3-D hydro calculations suggest radiation pressure is important in limiting the rate of star formation in all disk galaxies

• Contribution of SN in Milky Way uncertain

• SN dominate in the Small Magellenic Cloud

• A combination of radiation pressure and SNe ram pressure driving looks promising as a way launching galactic winds and removing baryons from L* galaxy halos