A physical model of supernova feedback and outflows from the ISM

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Outline

• Motivation
  – More physical treatment of SN feedback in semi-analytical models of galaxy formation

• New feedback model
  – Expanding superbubbles in ISM

• Effect in semi-analytical models

• Comparison with simulations & observations
The feedback problem

Baugh et al. (2006)

• galaxy stellar mass function and luminosity function have different shape from dark halo mass function
• cannot be explained by baryon cooling alone
Standard treatment of SN feedback in semi-analytical models

- assume mass ejection rate $\alpha$ SFR ($\psi$), so mass loading factor
  \[ \beta = \frac{\dot{M}_{\text{eject}}}{\psi} \]
- typically assume power law dependence of $\beta$ on circular velocity, which is proxy for depth of grav potential well
  \[ \beta \propto V_{\text{circ}}^{-\alpha} \]
- slope and normalization adjusted to make model predictions fit observations, e.g. faint end of galaxy LF
- this form has physical motivation for:
  - “energy driven” outflows: $\beta \propto V_{\text{circ}}^{-2}$ (const frac SN energy)
  - “momentum driven” outflows: $\beta \propto V_{\text{circ}}^{-1}$ (const frac SN radial mtm)
- while making model fit obs seems to favour even steeper relation:
  \[ \beta \sim V_{\text{circ}}^{-3} \]
- but do any of these phenomenological forms provide accurate description of SN feedback?
New coupled model of SF & SN feedback in 2-phase ISM in galaxy disk

• 2 phase ISM:
  – Giant molecular clouds ($H_2$) + warm atomic (HI) intercloud medium
  – $H_2$/HI ratio set by ISM pressure

• SFR $\alpha$ molecular gas mass

• Superbubbles produced by SN explosions from OB star clusters in GMCs
  – Drive expansion of superbubble into HI intercloud medium until breaks out of disk ISM
  – Superbubbles produce hot ($3^{rd}$) phase in ISM

(related earlier work on feedback due to SN bubbles/superbubbles: Efstathiou 2000, Monaco 2004 – different assumptions, not incorporated into full SAM)
2 phase ISM model

- diffuse atomic (HI) gas + molecular (H$_2$) clouds (GMCs)
- ratio of surface densities set by empirical pressure law (Blitz & Rosolowsky 2006)
  - $\Sigma(H_2)/\Sigma(HI) = (P_{gas}/P_0)^\alpha$
  - $P_0$ & $\alpha_p$ from observations
- vertical scaleheight of gas $h_g$ set by local hydrostatic equilibrium
  \[
  h_g(r_i) = \frac{\sigma_d^2}{\pi G \left[ \Sigma_g(r_i) + \frac{\sigma_d(r_i)}{\sigma_*(r_i)} \Sigma_*(r_i) \right]}
  \]
- gas velocity dispersion also from obs: $\sigma_d = 10$ km/s
\( \frac{\Sigma(H_2)}{\Sigma(HI)} = \left( \frac{P_{\text{ext}}}{P_0} \right)^\alpha \)

- Empirical relation between \( H_2/HI \) ratio and inferred midplane gas pressure in local disk galaxies (Blitz & Rosolowsky 2006, Bigiel+2008)

- Pressure inferred assuming local hydrostatic equilibrium

\[ P_{\text{ext}} \approx \frac{\pi}{2} G \Sigma_{\text{gas}} \left[ \Sigma_{\text{gas}} + \left( \frac{\sigma_g}{\sigma_*} \right) \Sigma_* \right] \]
Star formation & SN

- empirically based SFR law:
  \[ \Sigma_{\text{SFR}} = \nu_{\text{SF}} \Sigma_{\text{mol}} = \nu_{\text{SF}} f_{\text{mol}} \Sigma_{\text{gas}} \]
  \[ \nu_{\text{SF}} \text{ from obs} \]
- assume applies at level of individual GMCs: \( \psi_{\text{GMC}} = \nu_{\text{SF}} M_{\text{GMC}} \)
- all SF & SN occur in GMCs & associated OB star cluster
- all GMCs have same mass \( (M_{\text{GMC}} \sim 10^6 M_\odot) \) & lifetime \( (\tau_{\text{GMC}} \sim 10 \text{ Myr}) \) from obs
- const SFR in each cloud => const SNII rate for lifetime of cloud (neglect delay due to stellar lifetimes)
SF law in local disk galaxies

Bigiel et al. (2008), Wyder et al. (2009), Schruba et al. (2010, 2011), Bigiel et al. (2011)

Linear correlation of SFR with $M(H_2)$

$$\Sigma_{SFR} = \nu_{SF} f_{mol} \Sigma_{gas}$$

- $f_{mol}$ depends on gas pressure

$$\frac{\Sigma(H_2)}{\Sigma(HI)} = \left( \frac{P_{ext}}{P_0} \right)^\alpha$$

Expanding superbubble driven by SN from star cluster in GMC

- SN inject mass & energy at const rate over GMC lifetime $\tau_{\text{GMC}}$
- drive spherical superbubble in HI intercloud medium
- calc evoln of bubble radius $R$ by numerically integrating bubble eqns including SN source terms, radiative cooling & external pressure (Weaver+1977, Ostriker & McKee 1988)
- 3 stages in bubble expansion:
  - adiabatic (ad): energy conserved, pressure-driven
  - pressure-driven snowplow (pds): shell radiatively cooled, pressure from adiabatic hot interior
  - momentum-driven snowplow (mds): shell+interior radiatively cooled, radial momentum flux from continuing SN
Evolution of superbubble

Quasi 2-D simulation in idealized disks (edge-on view):

Lagos, Lacey, Baugh (2013)

Gas escapes through minor axis → Bipolar Outflows
Bubble breakout or confinement

- bubble confinement if: $v_s = \frac{dR}{dt} = \sigma_d$
- otherwise breakout when: $R = f_r^* h_g (f_r \sim 1.5$ from detailed 2D/3D hydro sims) 
  \[ h_g(r_i) = \frac{\sigma_d^2}{\pi G \left[ \Sigma_g(r_i) + \frac{\sigma_{\star}(r_i)}{\sigma^*} \Sigma^*(r_i) \right]} \]
- fraction of gas in shell and all of gas in interior escape into halo: $f_{bo} = (1-h_g/R)$
- sum all superbubbles breaking out $\rightarrow$ total gas outflow rate from disk ISM into halo
Embedding of new SN feedback model in SAM

• to investigate effects of this new feedback model across galaxy population and redshift, embed it in semi-analytic galaxy formation model GALFORM
• physical model for galaxy formation based on ΛCDM, previously tuned to reproduce galaxy LF and its evolution
• GALFORM predicts stellar & gas masses, SF histories, galaxy radii and metallicities
• use to investigate how outflow rates depend on global galaxy properties for realistic galaxy population
• also see whether there is simple parametrization of mass loading in new feedback model
GALFORM semi-analytical model: inputs and outputs

- Dark matter and gas distributions
- Gas cooling rates
- Star formation, feedback
- Galaxy merger rates
- Positions and velocities
- Star formation, rate, ages, composition
- Luminosities, colours
- Morphology
- Structure and dynamics
- Gravitational collapse
- Positions and velocities
- Star formation, rate, ages, composition
Assembly of dark matter halos

- N-body simulation
  -> spatial + mass distribution of DM halos
  + halo merger histories
Baryons in galaxy formation

Hot halo gas

Gaseous disk

Molecular gas

Atomic gas

Stars

Ejected mass from the disk

Bubbles ISM

Halo

ISM

\[ \frac{M_{\text{ reheate}, 0}}{\tau_{\text{ rei}n}} \]

\[ \frac{M_{\text{ reheate}, 0}^Z}{\tau_{\text{ rei}n}} \]

\[ \dot{M}_{\text{conf}, \text{ISM}} \]

\[ (1 - f_{\text{bo}}) \dot{M}_{\text{bo, ISM}} \]

\[ (1 - f_{\text{bo}}) \dot{M}_{\text{bo, ISM}}^Z \]

\[ R_{\text{ES}} \psi \]

\[ (p_{\text{ES}} + R_{\text{ES}} Z_{\text{g}}) \psi \]

\[ R_{\text{SN}} \psi \]

\[ (p_{\text{SN}} + R_{\text{SN}} Z_{\text{g}}) \psi \]

\[ \dot{M}_{\text{sw, ISM}} \]

\[ \dot{M}_{\text{sw, ISM}}^Z \]

\[ \frac{\Sigma(\text{H}_2)}{\Sigma(\text{HI})} = \left( \frac{P_{\text{ext}}}{P_0} \right)^{\alpha_{\text{p}}} \]

\[ \psi \]

\[ Z_g \psi \]

Mass and chemical exchange

Gas mass partition into HI and H$_2$
Mass loading of the outflow from disk

\[ \beta = \frac{\dot{M}_{\text{eject}}}{\psi} \]

\[ \beta = \left( \frac{v_{\text{circ}}}{300 \text{ km s}^{-1}} \right)^{-2} \]
\[ \beta = \left( \frac{v_{\text{circ}}}{300 \text{ km s}^{-1}} \right)^{-1} \]
\[ \beta = \left( \frac{v_{\text{circ}}}{485 \text{ km s}^{-1}} \right)^{-3.2} \]
\[ \beta = 6.5 \left[ 0.5 + \left( \frac{v_{\text{circ}}}{70 \text{ km s}^{-1}} \right) \right]^{-3.5} \]

1) single power law fit in \( v_{\text{circ}} \) does not describe dependence of \( \beta \)
2) turnover at low \( v_{\text{circ}} \)
3) also strong redshift evolution

much tighter relation of \( \beta \) with total surface density \( \Sigma_{\text{gas}} + \Sigma_{\text{star}} \)

\[ \beta_{\text{old}} = \left( \frac{V_{\text{circ}}}{485 \text{ km/s}} \right)^{-3.2} \]
parametrizations of mass loading: total surface density vs gas scaleheight

- equally tight dependence of $\beta$ on gas scaleheight $h_g$ as on total surface density (these are closely related)
- furthermore, redshift trends can be mostly removed by adding dependence on gas fraction

$$\beta = \left[ \frac{h_g (r_{50})}{15 \text{ pc}} \right]^{1.1} \left[ \frac{f_{\text{gas}}}{0.02} \right]^{0.4}$$
Effect of varying ISM $\text{H}_2$/HI ratio on mass loading

- our standard model with $\text{H}_2$/HI ratio increasing with $P$ leads to much lower $\beta$ for low $h_g$ (high $\Sigma$) than assuming a fixed $\text{H}_2$/HI ratio

- correlation of $\beta$ with $h_g$ (or $\Sigma$) is because bubble mass at breakout depends on $h_g$, $\Sigma_g$ & $f_{\text{mol}}$, which all closely related

\[
\beta = \frac{\dot{M}_{\text{eject}}}{\psi}
\]
Dependence of mass loading & outflow speed on feedback model parameters

- Factor 2-3 changes of ISM/SN feedback model parameters around standard values change normalization but not shape of dependence of $\beta$ on $h_g$
- Modest changes in mean outflow speed
- Outflow speed decreases with increasing $h_g$ & decreasing $\Sigma$
Breakout & confinement fractions

- mass outflow rates dominated by bubbles breaking out in radiative rather than adiabatic phase
- pressure-driven snowplow phase for low $z$ / small $h_g$
- momentum-driven snowplow for high $z$ / large $h_g$
- only small fraction of bubbles (by mass flux) confined

$0 < z < 1$

$2 < z < 4$

$5 < z < 7$
Comparison with high resolution hydro simulations

- measure $\beta$ in disk annuli, quite well fit by
  \[
  \beta_{\text{annulus}} = \left[ \frac{\Sigma_{\text{gas}} + \Sigma_\star}{69 \, M_\odot \, \text{pc}^{-2}} \right]^{-1.3}
  \]

- Comparison with high resolution hydro sims by Creasey+2013 of ISM in cylinder through disk
- quite similar for mass loading and outflow speed, even though hydro simulation makes some different assumptions (e.g. SN not clustered)
Comparison with observed outflow properties

\[ \beta = \frac{\dot{M}_{\text{eject}}}{\psi} \]

- model predicts similar mass loading & outflow velocities to those inferred from observations (absorption line studies)
Effect on the faint end of luminosity function

new feedback model typically flattens faint end of LF at $z<3$ - although also increases its amplitude

- variants with different ISM parameters:
  - ----- Lagos12.OldBeta
  - ------ Lagos12.WeakSN
  - -------- Lagos12.StrongSN
  - ---------- Lagos12.InterSNa

- however, proper study requires calculating escape/confined outflows in halo (work in progress)
Limitations/extensions

• No treatment of bubble overlap – bubbles from different GMCs do not interact
• No treatment of vertical density gradient in ISM, GMCs all at midplane
• No treatment of gas flows in halo following bubble break-out from disk ISM, & fate of ejected gas (confinement or ejection from halo) (in progress)
• relies on empirical relations for molecular/atomic ratio and SFR
Summary

• physical model for SN-driven outflows based on superbubbles expanding from GMCs into diffuse HI and followed through adiabatic & radiative phases
• predicted mass loading $\beta$ not well described by scalings with circular velocity typically assumed in semi-analytical models
  – large $\beta$ for small $\Sigma$ or large $h_g$
• also sensitive to fraction of gas in diffuse HI phase
• outflow rates & velocities seem in reasonable agreement with both observational inferences and some high-resolution hydro sims
• including new feedback model in semi-analytical models leads to shallower faint-end slope for K-band luminosity function