High-resolution Galaxy Formation with Radiating Molecular Cloud Particles

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Towards An Unabridged Understanding of Galaxy Formation

- Modeling the Physics of Galaxy Formation in ∼pc Resolution Era
  - Radiating Molecular Cloud Formation and Feedback (Radiation & Supernova)

- Applications and Results
  - Dwarf Galaxies with Radiating Molecular Cloud Particles
  - Simulated Observations & UV Escape Fraction
Contemporary High-resolution Galaxy Simulations

$R_{\text{MC}} \sim 3\, \text{pc}$  

Star Formation  
Feedback

Gas

$R_{\text{galaxy}} \sim 100\, \text{kpc}$
It is crucial to include proper molecular cloud physics for $\Delta x \sim \text{pc}$ resolution simulations (corresponding $\Delta t \sim 10^4$ yrs)

→ Need transition from phenomenology (i.e. Schmidt model) to realistic physics
Molecular Cloud Particle - Formation

- Max resolution of $3.8 \text{ pc}$
  $= L_{\text{Jeans}}$ of molecular clouds of 1000 protons/cm$^3$ at $\sim 100 \text{ K}$

$$M_{\text{MC}} = \epsilon_\text{*} \rho_{\text{gas}} \Delta x^3$$

- Self-consistently deposit a particle when a cell of a typical molecular cloud size actually gets *Jeans unstable*, i.e. $M_{\text{cell}} > M_{\text{Jeans}}$

  $\rightarrow$ each particle describes a MC of $1000 M_\odot$
MC Particle - Supernova Feedback

- Both mass and energy are added back to gas
  - 20% remains as “stars” after 6 Myrs + 80% returns to gas phase
  - returning mass carries the thermal energy of $10^{51}$ ergs per $M_{\text{star}} = 750 \ M_{\odot}$ peaking at 5 Myrs
MC Particle - Radiation Feedback

- UV photons from MCs traced so its energy is added to ISM
  - 16.0 eV photon interact with H by photo-ionization and heating

- Photoionization + Photoheating + Radiation pressure (no $\tau_{IR}$)
- $E_{ph} = 16.0 \text{ eV}$ (Whalen et al. 2004, 2006)
- $L_{MC} = 6.3 \times 10^{46} M_{MC} E_{ph} \text{ eV/s}$ (Murray & Rahman 2010)
- Early stellar fbck important (Hopkins et al., Stinson et al.)
Test on An Isolated Dwarf Galaxy

- $2.3 \times 10^{11}$ M$_\odot$ halo hosts $<10^4$ radiating MCs (excluding galactic center)

  - 3.8 pc resolution with Enzo on a well-defined dwarf galaxy
  - SF suppressed by 22.4% in 20 Myrs when compared to SN fbck only case

- Simulated observation possible because of
  - radiation physics
  - spatial+temporal resolution
  - post-processing with yt

Analysis tool yt by Matthew Turk; his talk tomorrow!
I. Escape of Ionizing Photons
Beyond Integrated Radiation Fields

- Integrated fields are interesting, but let’s move to the next stage.
Escaped Photons From An Individual MC

- Projected HI Number Density (#/cm²)
- Projected HI Fraction (Density-weighted)
- Directional Escape Fraction (at 100 kpc)

- From each MC, directional escape fraction can be easily calculated.
Total Escaped Photons at R=100 kpc

- From $f_{\text{esc}}(i)$ of an individual MC to $f_{\text{esc}}$ of the entire galaxy

(1) Individual MC:

(2) For Entire Galaxy:

High $f_{\text{esc}}(i)$ clumps: size by $f_{\text{esc}}(i)$, color by age
Only A Few Clumps Have High $f_{\text{esc}}(i)$

- Overall galactic $f_{\text{esc}}$ stays at around 1% during 20 Myrs
A small number of MCs with high escape fraction dominates the overall galactic escaped ionizing photons

- e.g. galactic $f_{\text{esc}} = 0.01 \rightarrow 1\%$ of particles with $f_{\text{esc}}(i) = 1.00$
  rather than
  $100\%$ of particles with $f_{\text{esc}}(i) = 0.01$
High $f_{\text{esc}}(i)$ Clumps Tend To Be Old

- Young MCs still buried in cold gas
- **Old MCs** tend to have higher $f_{\text{esc}}(i)$ and contribute equally to the total escaped photons
  - MC drifts from dense clump + aided by SN peaking at 5 Myr
  - $f_{\text{esc}}(i) = 0.0031 \times (\text{age})_{\text{MC}} + 0.0033$

### Diagram

- $f_{\text{esc}}(i) = 0.0033$ at $t=0$ Myr
- $f_{\text{esc}}(i) = 0.0219$ at $t=6$ Myr

**Graph:**
- **x-axis:** Molecular cloud particle age
- **y-axis:** Escape fraction
- **Legend:**
  - $f_{\text{esc}}$ Binned by Age
  - Best fit: $0.0031 \times (\text{age})_{\text{MC}} + 0.0033$
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![Graph showing escape fraction vs. cumulative number of escaped photons]

- age = 4-6 Myrs
- age = 0-2 Myrs
II. Star Formation Relation via Simulated Observation
Mock Observation in Simulations

- Simulated observations
  - Estimate SFR by $\text{H}\alpha$: Dong & Draine (2011) + Schruba et al. (2010)
  - Estimate $\text{H}_2$ by $f_{\text{H}_2}$: Krumholz et al. (2009) + Kuhlen et al. (2011)
Star Formation Laws via Simulated Obs.

- **Kennicutt-Schmidt** plane with estimated SFR and H$_2$ densities
Using Different Aperture Sizes

- 0.150 kpc aperture
- 0.050 kpc aperture
- 1.200 kpc aperture
Observation with Different Apertures

- Smaller aperture $\rightarrow$ more scatter

M51, Liu et al. (2011)
Kennicutt-Schmidt Plane

**Ideal World**

SFR Surface Density

Molecular Hydrogen Surface Density

**Real World**

SFR Surface Density Proxy (e.g. Hα)

Molecular Hydrogen Surface Density Proxy (e.g. CO)

Hot gas slightly far from the ongoing SF site

Cold gas right at the ongoing SF site
Which Peaks to Choose: $\text{H}_2$ or $\text{H} \alpha$?

**Ideal World**

- SFR Surface Density
- Molecular Hydrogen Surface Density

**Real World**

- SFR Surface Density Proxy (e.g. $\text{H} \alpha$)
- Molecular Hydrogen Surface Density Proxy (e.g. $\text{CO}$)
  - Hot gas slightly far from the ongoing SF site
  - Cold gas right at the ongoing SF site
Averages for H$_2$ or H$\alpha$ Peaks

- Average depletion time depends on which peaks you choose.
Averages for $H_2$ or $H\alpha$ Peaks

- Average for $H_2 \rightarrow$ relatively recent SF
- Average for $H\alpha \rightarrow$ relatively old SF sites

M33, Schruba et al. (2010)
Scale Dependence of SF Relation

- Kennicutt-Schmidt law holds well with large aperture size

→ may break down at <0.300 kpc where each datapoint no longer averages over many different evolutionary states
Conclusions
Towards An “Unabridged” Understanding of Galaxy Formation

- We are at a critical junction in numerical study of galaxies
- Realistic treatments of stellar feedback from molecular cloud particles is a key in \( \sim \)pc resolution galactic simulations
- Radiation feedback of molecular cloud particles combined with a versatile post-processing tool enables us to make intriguing mock observations