Star Formation & DLAs in Cosmological Simulations

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Outline

• Recipes for star formation (SF) & feedback in cosmological simulations -- past efforts

• Some highlighted results on galaxies and DLAs from Eulerian & SPH simulations

• Alternative SF recipe: Blitz’s pressure criteria

• Problems in current simulations

• Future efforts
SF recipes

Two basic models:

• Cen & Ostriker (1992)
  Eulerian hydro simulation

• Springel & Hernquist (2003):
  SPH (smoothed particle hydrodynamics),
  subparticle multiphase ISM model -- extention of
  Yepes et al. (1997)
4 criteria for a cell to be star-forming:

1. \( \delta > \delta_{\text{th}} \) (overdense)
2. \( \nabla \cdot \vec{v} < 0 \) (contracting)
3. \( t_{\text{cool}} < t_{\text{dyn}} \) (cooling fast)
4. \( m_{\text{gas}} > m_{\text{Jeans}} \) (Jeans unstable)

then,

\[
\dot{\rho}_* = c_* \frac{\rho_g}{t_*}
\]

\((c_* \sim 0.1)\)

if \( t_* = t_{\text{dyn}} \propto \frac{1}{\sqrt{G\rho}} \)

\[\dot{\rho}_* \propto \rho_g^{1.5}\]
\[
\dot{\rho}_* = (1 - \beta) \frac{\rho_c}{t_*} \\

\dot{t}_* = t_0^0 \left( \frac{\rho_g}{\rho_{th}} \right)^{-0.5} \\
t_*^0 = 2.1 \text{ Gyr}
\]

subparticle multiphase ISM model

\[
\rho_h \frac{du_h}{dt} = \beta \frac{\rho_c}{t_*} (u_{sn} + u_c - u_h) - A \beta \frac{\rho_c}{t_*} (u_h - u_c) - f \Lambda_{\text{net}}
\]

\[u_c = \text{const.}\]
Feedback

- **Cen, KN & Ostriker ’05**

\[
\Delta E_{SN} = \epsilon_{sn} m_* c^2 \\
(\epsilon_{sn} = 10^{-6} - 10^{-5})
\]

\[
\Delta E_{UV} = f_{esc,Z} \epsilon_{uv,Z} m_* c^2 \\
(\epsilon_{uv,Z} = 10^{-6} - 10^{-4}) \ (f_{esc} = 2 - 4\%)
\]

\[
\Delta E_{AGN} = f_\nu \epsilon_{AGN} m_* c^2 \\
(\epsilon_{AGN} \sim 10^{-5})
\]

- **Springel & Hernquist ’03**

\[
\left. \frac{d\rho_c}{dt} \right|_{EV} = A \beta \rho_c. 
\]

(evaporation of cold gas by SN feedback)

\[
A(\rho) = A_0 \left( \frac{\rho}{\rho_{th}} \right)^{-4/5},
\]

(McKee & Ostriker ’77)

\[
\rho_{th} = \frac{x_{th}}{(1 - x_{th})^2} \frac{\beta u_{SN} - (1 - \beta)u_c}{t_0 \Lambda(u_{SN}/A_0)},
\]

Self-regulated star formation
Galactic wind in SPH simulation

mass loss rate:

\[ \dot{M}_w = \eta \dot{M}_*, \quad (\eta = 2) \]

wind energy:

\[ \frac{1}{2} \dot{M}_w v_w^2 = \chi \epsilon_{\text{SN}} \dot{M}_*, \quad (\chi = 0.25) \]
Some highlighted results on galaxies and DLAs
Cosmic Star Formation History

(b)

KN + (2001)

KN + (2006)

Springel & Hernquist (2003)
Metal mass density

(a)

\[ \rho_z [M_\odot \, \text{Mpc}^{-3}] \]

\[ \Omega_\ast [10^{-5}] \]

Redshift

Fig. 7.— Metal mass density as a function of redshift. The curves represent the model predictions specified in...al. (2006, black lower limit at \( z = 2 \), shifted for clarity. Only for damped Lyα systems and super Lyman Limit systems).

Fig. 9.— EBL as a function of redshift for the models shown in the legend. The observationally allowed range at \( z = 0 \), equation (9), is indicated by the error bar.

Fig. 10.— Stellar mass density and EBL as a function of redshift for the models shown in the legend. The observationally allowed range at \( z = 0 \), equation (9), is indicated by the error bar.
Lyman-break Galaxies at z=3-6

Figure 8. Star formation rates (SFRs) of high-redshift galaxies as a function of age of the Universe. The plots show the evolution of SFRs for different redshifts (z=3 and z=5). The redshift distribution is indicated on the right side of each plot. The number of galaxies (N) for each redshift is also provided.

KN+ 2004

Night, KN+ 2006
HI & DLA statistics

HI mass density

DLA rate-of-incidence

KN+ (2004a,b; 2006)
$M_{\text{tot}} = 1.7 \times 10^{12} h^{-1} M_{\odot}$

$4.7 \times 10^{11} h^{-1} M_{\odot}$

Q5 $z=3$
DLA statistics

\[ \text{Column density distribution function} \quad \text{DLA cross section vs. Halo mass} \]

\( \text{KN+ (2004a,b; 2006)} \)
Kennicutt Law
Kennicutt Law in Cosmological SPH Simulations

- Too much SF at low $N_{\text{HI}}$ in the original sim?
- Raising $\rho_{\text{th}}$ seems to work better (cf. Kravtsov ‘03: $n=50$ cm$^{-3}$)
- Making SF time-scale longer just lowers normalization
Column density distribution

- Longer SF time-scale: $t^0_x = 12.6$ Gyr
- Higher $\rho_{\text{th}}$ (x10)
- Stronger feedback (x10)

Original formulation

Log-log plot of $f(N, X)$ vs $N_{\text{HI}}$ [cm$^{-2}$]
Alternative SF recipe: Blitz’s Pressure Criteria
Blitz’s Pressure SF Criteria

\[ \Sigma_{SFR} = \epsilon \Sigma_g f_{mol} \left[ \frac{\Sigma_{H_2}(HCN)}{\Sigma_{H_2}(CO)} \right] \]

\[ f_{mol} = \frac{\Sigma_{H_2}}{\Sigma_g} = \frac{R_{mol}}{(1 + R_{mol})} = \left[ 1 + \left( \frac{P_{ext}}{P_0} \right)^{-\alpha} \right]^{-1} \]

\[ R_{mol} \equiv \frac{\Sigma_{H_2}}{\Sigma_{HI}} \]

\[ \epsilon \sim 10 \, \text{Gyr}^{-1} \quad \left[ \frac{\Sigma_{H_2}(HCN)}{\Sigma_{H_2}(CO)} \right] \sim 0.1 \]

\[ \alpha \sim 0.92 \quad P_0 = (4.3 \pm 0.6) \times 10^4 \, \text{K cm}^{-3} \]

Blitz & Rosolowsky (2006)
Blitz’s Pressure SF Criteria

\[ \Sigma_{\text{SFR}} = \frac{\Sigma_g}{1 + \left( \frac{P_{\text{ext}}}{P_0} \right)^{-\alpha}} \text{ Gyr}^{-1} \]

\[ \dot{\rho}_* = \frac{\rho_g}{1 + \left( \frac{P_{\text{ext}}}{P_0} \right)^{-\alpha}} \text{ Gyr}^{-1} \]

(cf. Kravtsov ‘03: \( \dot{\rho}_* \propto \rho_g \))
Pressure-density diagram in cosmological SPH simulation

Blitz’ external ISM pressure \( P_0 \) when the molecular fraction is unity

Test run:

Q3b:
Blitz’s low pressure + S&H (at \( P > P_0 \))
$f(N_{\text{HI}})$ with Blitz SF criteria

- Some overprediction at $\log N_{\text{HI}}>21$. 

\begin{center}
\begin{figure}
\begin{tikzpicture}
\begin{axis}[
width=\textwidth,
height=\textwidth,
axis lines=left,
xlabel={Log $N_{\text{HI}}$ [cm$^{-2}$]},
ylabel={Log $f(N)$},
]
\addplot[blue,mark=triangle] coordinates {
(19, -20)
(20, -22)
(21, -24)
(22, -26)
};
\addplot[red,mark=x] coordinates {
(19, -20)
(20, -22)
(21, -24)
(22, -26)
};
\addplot[green,mark=square] coordinates {
(19, -20)
(20, -22)
(21, -24)
(22, -26)
};
\legend{
Q3b2 $z=4$ (Blitz low P),
Q3b2 $z=3$ (Blitz low P),
Q3 - orig $z=3$
}
\end{axis}
\end{tikzpicture}
\end{figure}
\end{center}
Blitz SF criteria

- slope became closer to 1.4. (encouraging)

green contour: original Q3 run (10 Mpc/h, 2x144^3, S&H SF model)
Problems in Current Cosmological Simulations

• Inadequate resolution
• Angular momentum transfer problem
• Feedback by SNe and BHs
• Radiative Transfer
Future efforts

• Higher resolution: $1000^3 - 2000^3$
• More realistic models of SF and feedback -- multiphase ISM
• Radiative transfer
• Code comparisons: e.g. AMR vs. SPH
  (Adaptive Mesh Refinement vs. Smoothed Particle Hydrodynamics)
Code comparison: SPH vs. AMR

O’Shea, KN + 2005

Dark matter power spectrum

Entropy vs. gas density
Extending the comparison to the runs with cooling & SF

Gadget SPH

Enzo AMR
The End