Radiative Regulation of Population III Star Formation

☆Kenji Hasegawa (University of Tsukuba)
collaborators
Masayuki Umemura (University of Tsukuba)
Hajime Susa (Konan University)

14-16 Jan. 2009, Italo-Japanese Mini-Workshop @ University of Tsukuba
Introduction
✓ Population (Pop) III stars
✓ Radiative feedback
Methodologies
✓ Simulation code
✓ Setup
Results
Summary
Pop III stars

- **Very Massive Stars of >100M☉**
  - e.g., Abel, Bryan & Norman 2000; Bromm, Coppi & Larson 2001; Nakamura & Umemura 2001; Yoshida et al. 2006
  - $H_2$ cooling $\rightarrow T \sim 100K$

- **Less Massive Star ~10M☉-100M☉**
  - Variation of cosmological density fluctuation (O'Shea & Norman 2007)
  - Enhanced $H_2$ cooling (via virial shock with $T_{\text{vir}} > 10^4K$)
    - (eg., Shapiro & Kang 1987; Susa et al. 1998; Oh & Haiman 2002)
  - HD cooling in fossil HII region (often called Pop III.2 star)

Pop III stars are massive!

UV radiation from Pop III stars affects star formation around the stars.
Radiative Feedback Effects

**Negative Feedback**
- Photoionization ($h\nu > 13.6\text{eV}$)
- Photodissociation ($11.2\text{eV} < h\nu < 13.6\text{eV}$)
  - Lyman-Werner (LW) band radiation
- Gas temperature reaches $\sim 10^4\text{K}$
- Destruction of coolants ($\text{H}_2$)

**Positive Feedback**
- Increase of electron fraction
- Enhancement of $\text{H}_2$ formation
- $\text{H}_2$ formation process
  - $\text{H} + e^- \rightarrow \text{H}^- + \gamma$
  - $\text{H}^- + \text{H} \rightarrow \text{H}_2 + e^-$
- Negative feedback
- Positive feedback

**Shock induced by the ionization**
- Blowouts a gas cloud.
Pop III stars are Massive

UV radiation from the stars affects surrounding medium!!

**Pop III minihalos**

- Alvarez, Bromm & Shapiro 2006
- One star per halo
- Distance between halos \( \sim 200 \text{pc} \)

Suwa, Umemura & Susa in prep.
(Umemura-san’s talk)

- Multiple star
- Distance between peaks \( \sim 60-70 \text{pc} \)

**First Galaxies**

Stars can form from metal-free component in interstellar gas.
(e.g., Tornatore, Ferrara & Schneider 2007)

Feedback from Pop III stars is important.
Ionizing radiation alleviates the negative effect by LW radiation.

The H$_2$ shell can shield the cloud core from the LW radiation emitted by the source star.

These studies focus on the radiative feedback from a very massive Pop III star with \( M_* = 120M_\odot \).
Radiative feedback from less massive PopIII stars on neighboring cores have not been investigated in detail so far...

The feedback tends to be more negative?

We perform 3D RHD simulations in order to

✓ Investigate dependence of the radiative feedback on the mass of source star.
✓ Derive the radiative feedback criterion.
\[\frac{d\rho}{dt} = -\rho \nabla \cdot v\]
\[\frac{d^2 r}{dt^2} = -\frac{1}{\rho} \nabla P - \nabla \phi + f_{\text{rad}}\]
\[\frac{du}{dt} = \frac{P}{\rho} \nabla \cdot v + \frac{\Gamma - \Lambda}{\rho}\]
\[P = (\gamma - 1) \rho u = \frac{k_B \rho_b T}{\mu m_p}\]

Radiative transfer (Susa 2006)
\[\frac{dI_v}{d\tau_v} = I_v + \Sigma_v\]

- **Photoionization rate**
  \[k_{\text{ion}} = \int dv \int d\Omega \frac{a_v I_v}{hv}\]

- **Photoheating rate**
  \[\Gamma_{\text{ion}} = \int dv \int d\Omega \frac{(hv - hv_L)a_v I_v}{hv}\]

- **Photodissociation rate**
  \[k_{\text{H2dis}} = 1.13 \times 10^8 F_{\text{LW0}} f_{\text{sh}} [\text{s}^{-1}]\]
  \[f_{\text{sh}} = \min[1, (N_{\text{H2}}/10^{14})^{-0.75}]\]

Draine & Bertoldi (1996)

Non equilibrium chemistry (Kitayama et al. 2001)
\[\frac{dn_i}{dt} = \sum_j \sum_k k_{jk} n_j n_k + \sum_l \sum_m \sum_n k_{lmn} n_l n_m n_n\]

⇒ determines **fractions of species** and **radiative cooling rate**
Setup

3D-RHD simulation
1. Purely baryonic primordial cloud
   \( n_H = 14 \text{cm}^{-3} \) (uniform),
   \( M = 8.3 \times 10^4 M_\odot \), \( T_i = 100\text{K}, 350\text{K} \)

   \[ \text{Gravitational contraction} \]

2. When the density of cloud core exceeds a certain value \( n_{\text{on}} \), the core is irradiated by the source star with mass of \( M_\ast \), which placed \( D \) pc away from the core.

   \[ \text{We also perform simulations with NO ionizing radiation to investigate the effect of ionizing radiation.} \]

---

**Parameters**

- \( n_{\text{on}} \): 30 - 10^4 \text{ cm}^{-3} \\
- \( D \): 10-200pc \\
- \( M_\ast \): 25, 40, 80, 120M_\odot
**Result:** $M_* = 80 M_\odot$, $D = 40 \text{pc}$, $n_{\text{on}} = 10^3 \text{cm}^{-3}$

- Dotted: **LW only**
- Solid: **LW + ION**

Various physical quantities along the symmetry axis at 1Myr after the ignition:

- **Time variations of density profiles**

LW: Self-shielding by the core is not sufficient.
LW + ION: The H$_2$ shell enhances $N_{\text{H}_2}$

Fails to collapse (a hydrostatic core is formed)

The cloud is able to collapse
Result: \(M_*=25M_\odot\), \(D=14\) pc, \(n_{on}=10^3\) cm\(^{-3}\)

The LW flux is the same as that in the previous case.

Various physical quantities along the symmetry axis at 1Myr after the ignition

Time variations of density profiles

Ionizing radiation cannot alleviates the negative feedback of photodissociation.
The shielding effect by H$_2$ shell becomes weak as the source star becomes less massive.
Summary of Numerical Runs

- Collapses, \( \triangle \text{Collapses with the aid of ionizing radiation} \), \( \times \text{failed collapse} \)

Model A (High \( T_C \))

- The shielding effect by \( \text{H}_2 \) shell becomes weak as the source star becomes less massive.
- Resultant critical distance does not so strongly depend on the mass of source star.
LW radiation is mainly shielded at the two part of a cloud

**Core**
- Core radius ~ Jeans scale
- \(N_{H_2,\text{core}} = 4.5 \times 10^{15} \left( \frac{F_{LW,0}}{5 \times 10^{23} \, \text{ergs}^{-1}} \right)^{-4} \left( \frac{n_c}{10^4 \, \text{cm}^{-3}} \right)^4 \left( \frac{T_c}{300 \, \text{K}} \right)^6\)

**Chemical equilibrium**
- \(\gamma_{H_2} = \frac{n_H y_e k_H^-}{k_{dis}}\)

**H\(_2\) shell**
- \(N_{H_2,\text{sh}} = 5.8 \times 10^{14} \left( \frac{N_{\text{ion}}}{10^{50} \, \text{s}^{-1}} \right)^4 \left( \frac{L_{LW}}{5 \times 10^{23} \, \text{ergs}^{-1}} \right)^{-4}\)

**Susa 2007: collapse criterion**
- \(t_{\text{ff}} = t_{\text{dis}}\)

**Critical distance** (KH, Umemura & Susa 2009)
- \(D_{\text{cr,sh}} = 147 \, \text{pc} \left( \frac{L_{LW} f_{s,\text{sh}}}{5 \times 10^{23} \, \text{ergs}^{-1}} \right)^{1/2} \left( \frac{n_c}{10^3 \, \text{cm}^{-3}} \right)^{-7/16} \left( \frac{T_c}{300 \, \text{K}} \right)^{-3/4}\)

**Strongly depends on** \(N_{\text{ion}} / L_{LW} \)**!!**
- \(f_{s,\text{sh}} = \min\{1, (N_{H_2,\text{sh}} / 10^{14} \, \text{cm}^{-2})^{-0.75}\}\)

**Shielding function** (Draine & Bertoldi 1996)
- \(N_{\text{ion}}: \) number of ionizing photos emitted per second
Summary of Numerical Runs

○ Collapses, △ Collapses with the aid of ionizing radiation, × failed collapse

Model B (Low $T_C$)

Susa 2007

KH+ 2009
Summary of Numerical Runs

○ Collapses, △ Collapses with the aid of ionizing radiation, × failed collapse

Model A (High $T_C$)

- $D$ [pc] vs. $n_{\text{on}}$ [cm$^{-3}$]
- Masses: 40, 80, 120 $M_{\text{sun}}$
- Lines represent different initial conditions and temperatures.
We have found

i) The critical distance below which a neighboring cloud cannot collapse does not so strongly depend on the mass of source star.

ii) H$_2$ column density of the H$_2$ shell sensitively depends on the relative intensity of the ionizing radiation to LW radiation \( \propto (N_{\text{ion}}/L_{\text{LW}})^4 \).

If \( M_\ast \) is less than \( \sim 25M_\odot \), ionizing radiation cannot suppress the negative feedback of LW radiation.
We have found

iii) The feedback criterion is well expressed as

\[
D_{\text{cr}} = 147 \text{pc} \left( \frac{L_{\text{LW}} f_{s,sh}}{5 \times 10^{23} \text{ erg s}^{-1}} \right)^{1/2} \left( \frac{n_c}{10^3 \text{ cm}^{-3}} \right)^{-7/16} \left( \frac{T_c}{300 \text{K}} \right)^{-3/4}
\]

where \(f_{s,sh}\) is a factor regarding the shielding effect by H\(_2\) shell.

Using above formula (\(f_{s,sh}=1\)), \(F_{\text{LW,cr}}\) is given by

\[
F_{\text{LW,cr}} = 3.01 \times 10^{-17} \text{ erg cm}^{-2} \text{s}^{-1} f_{\text{dyn}}^{-2} \left( \frac{n_c}{10^3 \text{ cm}^{-3}} \right)^{7/8} \left( \frac{T_c}{300 \text{K}} \right)^{3/2}
\]

This criterion is available for LW background radiation.
Research Interests

First Galaxies
formed via mergers of Pop III minihalos
Properties? (e.g., Metallicity, star formation rate, stellar population)

Radiative Feedback
Local feedback
Global feedback (LW background radiation)

SN Feedback
Mechanical: heating, compression.
Chemical: metal enrichment $\Rightarrow$ cooling function, PopIII$\rightarrow$II

RHD simulations including SN feedback.
Dynamical effect

\[ f_{\text{dyn}} \equiv \frac{D_{\text{cr,num}}}{D_{\text{cr,analy}}} \]

High initial temperature

Low initial temperature

W: gravitational energy  U: internal energy
Effects of Dark Matter

Static NFW potential
\[ M_{\text{vir}} = 5 \times M_b = 4.15 \times 10^5 M_\odot \]
\[ R_{\text{vir}} = 160 \text{pc} (z_c = 15), 240 \text{pc} (z_c = 10) \]

where:
- \( f_{\text{dyn}} \equiv \frac{D_{\text{cr,num}}}{D_{\text{cr,analy}}} \)
- \( W \): gravitational energy
- \( U \): internal energy
If a source star is less massive, $L_{\text{LW}}/N_{\text{ion}}$ increases!!
Result: $M_* = 80 M_\odot$, $D = 40$ pc, $n_{on} = 10^3$ cm$^{-3}$

Dotted: LW only  
Solid: LW + ION  
Low $T_c$ case

Various physical quantities along the symmetry axis at 1Myr after the ignition

Time variations of density profiles

LW: Self-shielding by the core  
LW + ION: The $H_2$ shell enhances $N_{H_2}$

Fails to collapse
Positive feedback by shock

In the low core density cases, shocks positively work.
Estimate of the thickness of H$_2$ shell

- **H$_2$ fraction in the shell**
  - determined by $F_{\text{LW}}$, $n_{\text{sh}}$, and $T_{\text{sh}}$ (chemical equilibrium)

- **Thickness of the shell**
  - ~ the amount of ionized gas in the envelope.

- **H$_2$ column density of the shell**

- **$D_{\text{sh}}$**
  - $D_{\text{sh}} \propto L_{\text{LW}} / D_{\text{SH}}^2$

- **$L_{\text{LW}}$ and $D$**

---

**Graphical Representation**

- Plot with axes: $n_H$ [cm$^{-3}$] on the y-axis and Distance [pc] on the x-axis.
- Legend showing data points at different distances.
- Annotations indicating key parameters and relationships.
Parameters:
Cloud $M_b$, distance $D$

- $M_* = 120 M_\odot$
- $T_{ini} = 350K$
- $n_{on} = 10^3 \text{cm}^{-3}$
- $M_b = 8.3 \times 10^4 M_\odot, 1.6 \times 10^5 M_\odot, 3.3 \times 10^5 M_\odot$

Distance

Cloud $M_b$
Dependence of the cloud mass

Critical distance

analytic simulation

~190pc ~180pc

~150pc ~60pc

~130pc ~10pc

WHY ? ? ?

Temperature

H2 fraction

\[ M_j = 8.3 \times 10^4 M_{\odot} \]

\[ M_j = 1.66 \times 10^5 M_{\odot} \]

\[ M_j = 3.32 \times 10^5 M_{\odot} \]
Dependence of the cloud mass

\[ M_{\text{cloud}} = 3.32 \times 10^5 M_\odot, \quad D = 10 \text{pc}, \quad T_i = 350 \text{K}, \quad n_{\text{on}} = 10^3 \text{cm}^{-3} \]
Q: Can UV photons drive the star formation in mini-halo which is destined to fail to collapse.

\[ M_{\text{cloud}} = 2.77 \times 10^4 M_\odot \] (Cannot collapse)

100pc, 200pc, 300pc
Preliminary result

Collapsing models:
- $D = 100\text{pc}$
- $t_{\text{life}} = 2\text{Myr}$
- $t_{\text{life}} = \text{infinity}$
- $D = 200\text{pc}$
- $D = 300\text{pc}$

Central density (cm$^{-3}$)

Time (Myr)

No feedback
\[ \tau_{\text{target}} = \tau_{n1} + \Delta \tau \]

\[ N_{H2,\text{target}} = N_{H2,n1} + \Delta N_{H2} \]

\[ k_{\text{ion}}, \Gamma_{\text{ion}} \text{ and } k_{H2} \text{ are obtained} \]
Test calculations (Static)

Radiation source Source:
$N_{\text{ion}} = 5 \times 10^{48} \text{s}^{-1}$, $T_{\text{eff}} = 10^5 \text{K}$
Structure: uniform
$N = 10^{-3} \text{cm}^{-3}$, $T = 100 \text{K}$
Number of particles: $64^3$
Test calculations (dynamic)

Radiation Source:
\( N_{\text{ion}} = 5 \times 10^{48} \text{s}^{-1}, T_{\text{eff}} = 10^5 \text{K} \)
Structure: uniform
\( N = 10^{-3} \text{cm}^{-3}, T = 100 \text{K} \)
Number of particles: 64^3
UV feedback by PopIII stars

✓ **H$_2$-dissociating radiation (LW radiation)**

Omukai & Nishi (1999): Uniform virialized halo is assumed

* H$_2$ molecules are totally dissociated by LW radiation from a single massive star

Subsequent star formation is NOT feasible in the halo.

✓ **LW + ionizing radiation**


The H$_2$ shell can shield the cloud core from the LW radiation emitted by the source star.

Ionizing radiation alleviates the negative effect by LW radiation.
The escapes fraction of LW photons are larger than those of the ionizing radiation.

Kitayama et al. 2004
Dynamical Effect

$M_*=80M_\odot$, $D=40$pc, $n_{on} = 10^3$cm$^{-3}$

$H_2$ fraction at the core (Susa 2007)

$$y_{H_2} = 2.33 \times 10^{-5} \left( \frac{F_{Lw}}{2 \times 10^{-17} \text{ cgs}} \right)^4 \left( \frac{n_c}{10^4 \text{ cm}^{-3}} \right)^{7/2} \left( \frac{T_c}{10^3 \text{ K}} \right)^{15/2}$$

Intense LW radiation

$\Rightarrow$ adiabatic evolution

$T_c \propto n_c^{2/3}$ and $y_{H_2} \propto n_c^{17/2}$

$H_2$ fraction is quickly recovered, and $H_2$ column density becomes large.

Finally, $t_{ff} < t_{\text{dis}}$ is satisfied
Evolution of Clouds without Radiative Feedback

Low $T_c$ model: high initial temperature $\Leftrightarrow$ high U/W
High $T_c$ model: low initial temperature $\Leftrightarrow$ low U/W