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$\text{H}_2$ lines from the first-generation star formation process

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Molecular hydrogen line photons emitted owing to formation events of first-generation stars and their detectability by future observational facilities are explored. The H$_2$ luminosity evolution from the onset of prestellar collapse to the formation of a $\sim$100 M$_{\odot}$ protostar is followed by a simplified model for the dynamical evolution. In particular, the calculation is extended not only the early phase of the runaway collapse but also to the later phase of accretion, whose observational feature has not been studied before. Contrary to the runaway collapse phase, where the pure-rotational lines are always dominant, during the accretion phase prominent emission is owing to rovibrational lines. Also, the maximum luminosity is attained in the accretion phase for strong emission lines. The peak intensity of the strongest rovibrational line reaches $\sim$10$^{-27}$ (W/m$^2$), corresponding to the flux density of 10$^{-5}$ ($\mu$Jy), for a source at the typical redshift of the next-generation infrared satellite, SPICA, _Space Infrared Telescope for Cosmology and Astrophysics_, is ideal for observing the redshifted rovibrational line emission, to exceed the detection threshold, about $10^6$ such forming stars must reach the maximum luminosity simultaneously in a pregalactic cloud. Unfortunately, this situation is excluded by the current theoretical understanding of early structure formation.
We estimate the luminosities of $H_2$ lines, which can be characteristics of the first star formation process, and evaluate the detectability of $H_2$ lines. The luminosities of $H_2$ lines for the runaway collapse phase Ripamonti et al (2002) and Kamaya & Silk (2002) However the luminosities of $H_2$ lines for the main accretion phase haven’t been estimated. we calculate them for both phase.
Model

The thermal and chemical evolution of gravitationally collapsing protostellar clouds is investigated by hydrodynamical calculations for spherically symmetric clouds. (Omukai&Nishi 1998)

The Larson-Penston-type similarity solution, $\gamma = 1.09$ (dotted line), reproduces Omukai&Nishi’s result (solid line) well. It is a good approximation to the actual collapse dynamics.

The evolutionary sequences

The time interval

0 $\rightarrow$ 1 $\sim$ 5.7$\times$10$^5$ yr
1 $\rightarrow$ 2 $\sim$ 8.7$\times$10$^3$ yr
2 $\rightarrow$ 3 $\sim$ 2.8$\times$10$^2$ yr
3 $\rightarrow$ 4 $\sim$ 12 yr
4 $\rightarrow$ 5 $\sim$ 0.32 yr
5 $\rightarrow$ 6 $\sim$ 2.4$\times$10$^2$ yr
6 $\rightarrow$ 7 $\sim$ 4.1$\times$10$^2$ yr

We focus on the central region and calculate the time evolution (e.g., Omukai 2000).

center ---- flat density distribution, runaway collapse
envelope ---- leaving the outer part practically unchanged
1. Dynamics

· The runaway collapse phase

The central evolution the free-fall relation modified by pressure gradient

\[
\frac{d \rho}{dt} = \frac{\rho}{\beta t_{\text{ff}}} , \quad t_{\text{ff}} = \sqrt{\frac{3\pi}{32G\rho}}
\]

\( \rho \) : the central density
\( t_{\text{ff}} \) : free-fall time

the collapse time scale ; \( \beta t_{\text{ff}} \) the flat core size ; \( \alpha \lambda \)

The modification due to the finite pressure gradient force is represented
by the correction factor \( \alpha, \beta \).

For the Larson-Penston-type similarity solution for \( \gamma = 1.09 \),

\[
\delta = \left| \frac{\text{pressure}}{\text{gravity}} \right| \cong 0.78 , \quad \alpha = \sqrt{1+\delta} , \quad \beta = \frac{1}{\sqrt{1-\delta}} , \quad \alpha = 1.33 , \quad \beta = 2.13
\]

· The main accretion phase

approximation, each mass shell free-fall

\[
\frac{dv_r}{dt} = -\frac{GM(<r)}{r^2} , \quad \frac{dr}{dt} = -v_r , \quad \rho \propto r^{-3/2}
\]

\( \rho \) : the density of free-falling mass shell
\( v_r \) : the velocity of free-falling mass shell
\( r \) : the distance from mass shell to the center
The runaway collapse phase

The main accretion phase

Contracting region and mass become more and more small.

Inner mass shells fall faster than outer mass shells.

\[ \rho \propto r^{-2.2} \]

\[ \rho \propto r^{-3/2} \]

Free-fall determined by
the local density

Free-fall determined by
the gravitational
force of the protostar
2. **Energy equation**

\[
\frac{de}{dt} = - p \frac{d}{dt} \left( \frac{1}{\rho} \right) - L^{(\text{net})}
\]

\[
e = \frac{1}{\gamma - 1} \frac{kT}{\mu m_H}, \quad p = \frac{\rho kT}{\mu m_H}
\]

- \(e\): the energy per unit mass,
- \(p\): the pressure,
- \(T\): the temperature,
- \(\gamma\): the adiabatic exponent,
- \(\mu\): the mean molecular weight,
- \(m_H\): the mass of the hydrogen nucleus

3. **Cooling/Heating processes**

\[
L^{(\text{net})} = L_{\text{rad}} + L_{\text{chem}}, \quad L_{\text{rad}} = L_{\text{line}} (+L_{\text{cont}})
\]

- \(L_{\text{rad}}\): the radiative cooling rate,
- \(L_{\text{chem}}\): the chemical cooling rate or heating rate,
- \(L_{\text{line}}\): the cooling rate of line emission,
- \(L_{\text{cont}}\): the cooling rate of continuum emission

The continuum cooling rate \(L_{\text{cont}}\) is treated with the radiation field from the central protostar which is assumed to be the black body of 6000 K.
· line cooling

\[ L_{H_2} = \frac{1}{\rho} \sum_{i \rightarrow j} n(H_2, i) A_{ij} \varepsilon_{ij} h \nu_{ij} \]

\[ n(H_2, i) \sum_{j \neq i} R_{ij} = \sum_{j \neq i} n(H_2, j) R_{ji} \]

\[ R_{ij} = \begin{cases} A_{ij} \varepsilon_{ij} + C_{ij} (i \geq j) \\ C_{ij} (i \leq j) \end{cases} \]

\[ \varepsilon_{ij} = \frac{1 - e^{-\tau_{ij}}}{\tau_{ij}} \]

\[ \tau_{ij} = A_{ij} c^3 \left[ \sqrt{\frac{n(x, j)}{n(x, i)}} - 1 \right] l_{sh} / (2 \Delta v_D) \]

\[ l_{sh} = \min(\Delta S_{th}, \alpha \lambda_j / 2), \Delta v_D = \sqrt{2kT/(\mu m_H)} \]

The runaway collapse phase;
\[ \Delta S_{th} = 2 \Delta v_D l(dr/dr) = 6 \Delta v_D \beta t_{ff} \]

The main accretion phase;
\[ \Delta S_{th} = 2 \Delta v_D l(dr/dr) = 2 \Delta v_D \left( \frac{GM}{vr^2} \right) = 2 \sqrt{2} \Delta v_D \frac{r^{3/2}}{\sqrt{GM}} \]

\[ n(H_2, i) \quad \text{- the population density of } H_2 \text{ in level } i \]
\[ A_{ij} \quad \text{- the spontaneous transition probability} \]
\[ \varepsilon_{ij} \quad \text{- the escape probability} \]
\[ h \nu_{ij} \quad \text{- the energy difference between levels } i \text{ and } j \]
\[ C_{ij} \quad \text{- the collisional transition rate from level } i \text{ to level } j \]
\[ \Delta v_D \quad \text{- the velocity dispersion} \]
\[ l_{sh} \quad \text{- the shielding length} \]
\[ \tau_{ij} \quad \text{- the optical depth averaged over the line} \]
The main continuum processes as the radiative effect of the protostar

\[ \Lambda_{\text{cont}}(\nu) = 4\pi[\eta_a(\nu) - \kappa_a(\nu)J(\nu)] \]

\( \eta_a(\nu) \) : the thermal part of emission coefficient
\( \kappa_a(\nu) \) : the absorption coefficient , \( J(\nu) \) : the intensity of the central protostar

4. **Chemical reactions** (H\(_2\) formation processes)

\( n_H(\sim 10^8 \text{ cm}^{-3}) \)

\[ \text{H} + \text{e}^- \rightarrow \text{H}^- + \gamma \quad (\text{H}^-\text{process}) \]

\[ \text{H} + \text{H}^- \rightarrow \text{H}_2 + \text{e}^- \]

\( n_H(10^8 \text{ cm}^{-3} \sim 10^{14} \text{ cm}^{-3}) \)

\[ 3\text{H} \rightarrow \text{H}_2 + \text{H} \quad \text{(three-body process)} \]

\[ 2\text{H} + \text{H}_2 \rightarrow 2\text{H}_2 \]
Initial Conditions

The contraction and fragmentation of primordial, metal-free gas clouds is investigated by several authors.
(e.g., Uehara et al. 1996; Abel et al. 2002; Bromm et al. 2002; Nakamura & Umemura 2002)

We adopt the typical values for the star-forming cores from Bromm et al. (2002).

The physical condition of fragments (protopstellar clouds)

\[ M_J \sim 10^3 M_{\odot} \quad M_J : \text{Jeans mass} \]

\[ n_H = 10^4 \text{(cm}^{-3} \text{)}, T = 500 \text{(K)}, y(H_2) = 10^{-3}, y(e^-) = 10^{-8} \]

\[ y(H_i) = n(H_i)/n(H) \quad : \text{the concentration of the i-th species} \]

\[ n(H) : \text{the number density of the hydrogen nucleus} \]
Results

*Notice!*

temperature, abundance of $\text{H}_2$, luminosities of the $\text{H}_2$ lines

The runaway collapse phase

The time evolution of the central temperature

The time evolution of the central abundance of $\text{H}, \text{H}_2$

Effective cooling by $\text{H}_2$

$\text{H}^-$ process

three body process

$y(\text{H}_2)$

$y(\text{H})$

$\sim$ ten orders of magnitude

an order
Comparison between runaway collapse phase and main accretion phase

For the accretion phase, the evolutionary trajectories of the mass shells of $M / M_{\text{sun}}$ ($M$: protostellar mass) = 0.5, 1, 5, 10, 50, 100 are shown.
The time evolution of the $H_2$ line luminosities

Pick up: four of the strongest $H_2$ lines

- **Red**: $(1,1) \rightarrow (0,1)$
- **Green**: $(1,1) \rightarrow (0,3)$
- **Blue**: $(0,6) \rightarrow (0,4)$
- **Purple**: $(0,5) \rightarrow (0,3)$

Rest frame: 2.34 $\mu$m, 2.69 $\mu$m, 8.27 $\mu$m, 10.03 $\mu$m

**Before**
(vibrational level, rotational level) \rightarrow (vibrational level, rotational level)

**Peak luminosity**

The central protostar
$\sim 26M_\odot$

Runaway collapse phase

Main accretion phase

Rotational lines

Rovibrational lines
Detectability

For mid-infrared region (\( \lambda \sim 40\mu m \)), SPICA (ISAS), a large (3.5m), cooled (4.5K) telescope, is the best. (better than JWST and ALMA)

The line detection limit of SPICA is about \( 10^{-20} (W/m^2) \) in \( \lambda \sim 40\mu m \).

In this region, the high background of the zodiacal light limits the sensitivity of SPICA to \( 10^{-(21-22)} (W/m^2) \) (private communication H. Matsuhara).

\[
(1,1) \rightarrow (0,1), \text{ rest frame } : \lambda = 2.34(\mu m) \\
\text{ redshifted } (1+z=20) : \lambda = 46.8(\mu m)
\]

\[
F_{\text{peak}} = \frac{L_{\text{peak}}}{4\pi D_{z=19}^2} \sim 10^{-27} (W/m^2) \quad D_{z=19} : \text{The luminosity distance to } z=19 \\
L_{\text{peak}} : \text{The peak luminosity}
\]

If there are more than \( 10^{5-6} \) sources with their luminosity near the peak value, SPICA is able to observe a cluster of forming first-generation stars.

The total cloud mass reaches Galactic scale.

The metalicity in the pregalactic clouds must be lower than \( \sim 10^{-4} Z_{\odot} \) (Omukai 2000).

Formation of Galactic scale with such low metalliccy is clearly excluded in the context of standard cosmology (e.g., Scannapieco, Schneider, & Ferrara 2003).
Summary

- We estimate the $H_2$ line luminosities from the first-generation star formation process.
- The luminosities of both rovibrational lines and rotational lines become maximum value at the main accretion phase.
- For the runaway collapse phase, the strongest lines are rotational lines. But for the main accretion phase, some rovibrational lines overwhelm them.
- For the peak, rovibrational lines are stronger than rotational lines.

For observation of the first-generation star, rovibrational lines are important.

- Unfortunately, detecting $H_2$ line emission from forming first star by SPICA is highly improbable.