

# H<sub>2</sub> lines from the first generation star formation process

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#### *H*<sub>2</sub> lines from the first-generation star formation process

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#### Abstract

Molecular hydrogen line photons emitted owing to formation events of firstgeneration 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 ~100 M\_sun 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 roviblational line reaches ~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<sup>6</sup> 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.

### Purpose

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<sub>2</sub>lines for the runaway collapse phase Ripamonti et al (2002) and Kamaya & Silk (2002)

However the luminosities of H<sub>2</sub> 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.



The Larson-Penston-type similarity solution,  $\gamma = 1.09$  (dotted line), reproduces Omukai&Nishi'result (solid line) well.

It is a good approximation to the actual collapse dynamics.

**center** ---- flat density distribution, runaway collapse

envelope ---- leaving the outer part practically unchanged

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

#### 1. Dynamics

· The runaway collapse phase

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

$$\frac{d\rho}{dt} = \frac{\rho}{\beta t_{\rm ff}} \quad , \quad t_{\rm ff} = \sqrt{\frac{3\pi}{32 \, G \rho}} \qquad \qquad \rho \quad : \text{the central density} \\ t_{\rm ff} : \text{free-fall time}$$

the collapse time scale;  $\beta t_{\rm ff}$  the flat core size;  $\alpha \lambda_J$ 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  $\gamma = 1.09$ ,

$$\delta = \left| \frac{\text{pressure}}{\text{gravity}} \right| \approx 0.78 \text{ , } \alpha = \sqrt{1+\delta} \text{ , } \beta = \frac{1}{\sqrt{1-\delta}} \text{ , } \alpha = 1.33 \text{ , } \beta = 2.13$$

The main accretion phase

approximation, each mass shell free-fall  $\frac{dv_r}{dt} = -\frac{GM(\langle r)}{r^2} , \quad \frac{dr}{dt} = -v_r , \quad \rho \propto r^{-3/2}$ : 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



become more and more small.

2. Energy equation

$$\frac{de}{dt} = -p \frac{d}{dt} \left(\frac{1}{\rho}\right) - L^{(net)}$$
$$e = \frac{1}{\gamma - 1} \frac{kT}{\mu m}, \ p = \frac{\rho kT}{\mu m}$$

e : the energy per unit mass , p: the pressure , T : the temperature ,  $\gamma$  : the adiabatic exponent ,  $\mu$  : the mean molecular weight ,

 $\mathcal{M}_{
m H}$ : the mass of the hydrogen nucleus

3. Cooling/Heating processes

$$L^{(net)} = L_{rad} + L_{chem}$$
,  $L_{rad} = L_{line}(+L_{cont})$ 

 $L_{rad}$  : the radiative cooling rate,  $L_{chem}$  : the chemical cooling rate or heating rate,  $L_{line}$  : the cooling rate of line emission,  $L_{cont}$  : the cooling rate of continuum emission The continuum cooling rate  $L_{cont}$  is treated with the radiation field from the central protostar which is assumed to be the black body of 6000 K.

• *line cooling*  

$$L_{H_{2}} = \frac{1}{\rho} \sum_{i \to j} n (H_{2}, i) A_{ij} \varepsilon_{ij} h v_{ij}$$

$$n (H_{2}, i) \sum_{j \neq i}^{n} R_{ij} = \sum_{j \neq i}^{n} n (H_{2}, j) K$$

$$R_{ij} = \begin{cases} A_{ij} \varepsilon_{ij} + C_{ij} (i \ge j) \\ C_{ij} (i \le j) \end{cases}$$

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

$$\tau_{ij} = \frac{A_{ij} c^{3}}{8\pi v_{ij}^{3}} \left[ n(x, j) \frac{g_{i}}{g_{j}} - n(x, i) \right] l_{sh} / (2\Delta v_{D})$$

$$l_{sh} = \min(\Delta S_{th}, \alpha \lambda_{J} / 2), \Delta v_{D} = \sqrt{2kT / (\mu m_{H})}$$

The runaway collapse phase ;

$$\Delta S_{\rm th} = 2\Delta v_{\rm D} / (dv / dr) = 6\Delta v_{\rm D} \beta t_{\rm ff}$$

The main accretion phase ;

$$\Delta S_{\rm th} = 2\Delta v_{\rm D} / (dv/dr) = 2\Delta v_{\rm D} / \left(\frac{GM}{vr^2}\right) = 2\sqrt{2}\Delta v_{\rm D} \frac{r^{3/2}}{\sqrt{GM}}$$

 $n(\mathrm{H_2},i)$  --- the population density of  $H_2$  in level i --- the spontaneous transition probability --- the escape probability  ${\cal E}_{_{ij}}$ --- the energy difference  $h v_{_{ii}}$ between levels I and j - the collisional transition rate from level I to level j  $\Delta \mathcal{V}_{\mathrm{D}}\,$  --- the velocity dispersion  $l_{
m sh}$  --- the shielding length  ${ au}_{ii}$  --- the optical depth averaged over the line

ji

#### continuum cooling/heating

The main continuum processes as the radiative effect of the protostar bound-free absorption of  $H^-$ , free-free absorption of  $H^-$ ,  $H_2$  collision induced absorption

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

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

4. Chemical reactions ( $H_2$  formation processes)  $n_{\rm H}$  (~10<sup>8</sup> cm<sup>-3</sup>)

$$\begin{array}{c} \mathrm{H} + \mathrm{e}^{-} \rightarrow \mathrm{H}^{-} + \gamma \\ \mathrm{H} + \mathrm{H}^{-} \rightarrow \mathrm{H}_{2} + \mathrm{e}^{-} \end{array} \quad (\mbox{ H}^{-}\mbox{process}) \\ n_{\mathrm{H}} (10^{8} \mbox{cm}^{-3} \sim 10^{14} \mbox{cm}^{-3}) \\ 3\mathrm{H} \rightarrow \mathrm{H}_{2} + \mathrm{H} \\ 2\mathrm{H} + \mathrm{H}_{2} \rightarrow 2\mathrm{H}_{2} \end{array} \quad (\mbox{three-body process}) \end{array}$$

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# 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)

$$M_{\rm J} \sim 10^3 \,\rm M_{sun}$$
  $M_{\rm J}$  : Jeans mass  
 $n_{\rm H} = 10^4 (\rm cm^{-3}), T = 500 (\rm K), y(\rm H_2) = 10^{-3}, y(e^-) = 10^{-8}$ 

 $y(H_i) = n(H_i) / n(H)$ : the concentration of the i-th species

n(H) : the number density of the hydrogen nucleus

### Results

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#### 10 Comparison between runaway collapse phase and main accretion phase

For the accretion phase, the evolutionary trajectories of the mass shells of  $M / M_{sun}$  (M: protostellar mass) = 0.5, 1, 5, 10, 50, 100 are shown.





### 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<sup>2</sup>) 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<sup>2</sup>) (private communication H.Matsuhara).

$$(1,1) \rightarrow (0,1), \text{ rest frame}: \lambda = 2.34 (\mu m) \\ \text{redshifted}(1 + z = 20): \lambda = 46.8 (\mu m) \\ F_{\text{peak}} = \frac{L_{\text{peak}}}{4\pi D_{z=19}^2} \sim 10^{-27} (W/m^2) \qquad \begin{array}{l} D_{z=19} \\ D_{z=19} \\ L_{\text{peak}} \end{array} \text{The luminosity distance to } z=19 \\ L_{\text{peak}} \end{array}$$

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 ~  $10^{-4} Z_{sun}$  (Omukai 2000).

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

# Summary

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- We estimate the H<sub>2</sub> 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, **rovibratinal lines** are stronger than rotational lines.

rotational lines ----- low density region such as envelope of the protostellar clouds rovibrational lines ----- high density region such as final stage of star formation process rovibrational lines ------ the evidence of the first-generation star formation

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

 Unfortunately, detecting H<sub>2</sub> line emission from forming first star by SPICA is highly improbable.