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Publication date:
2003

Permanent link:
https://doi.org/10.3929/ethz-a-004582412

STAR AND STRUCTURE FORMATION : FROM FIRST LIGHT TO THE MILKY WAY
Astrophysics Conference, August 18-22, 2003, ETH Zurich, Switzerland.

H_2 lines from the first-generation star formation process

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Abstract

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 ~ 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 $\sim 10^{-27}$ (W/m^2), corresponding to the flux density of 10^{-5} (μ 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.

Purpose

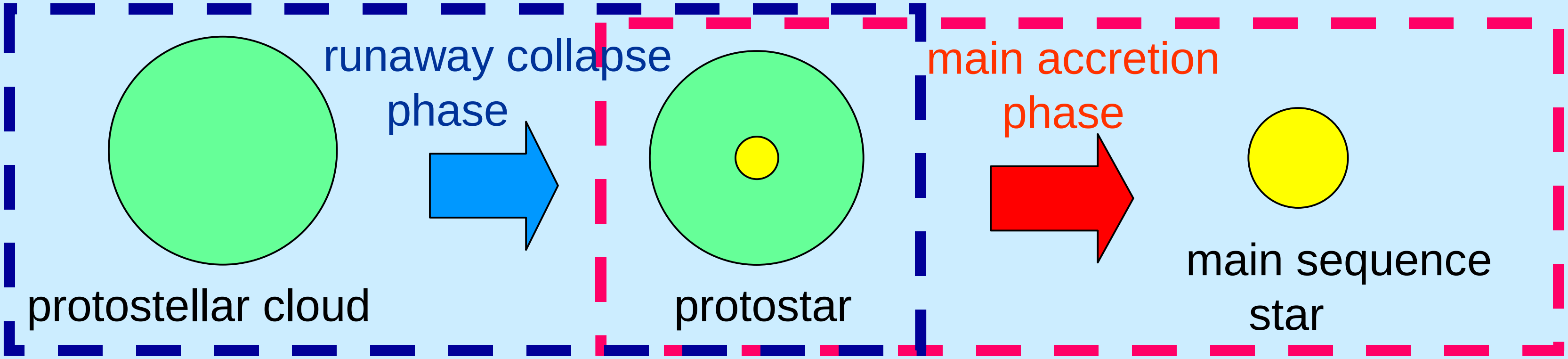
We estimate the luminosities of H_2 lines, which can be characteristics of the first star formation process, and evaluate the detectability of H_2 lines.

The luminosities of H_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 .

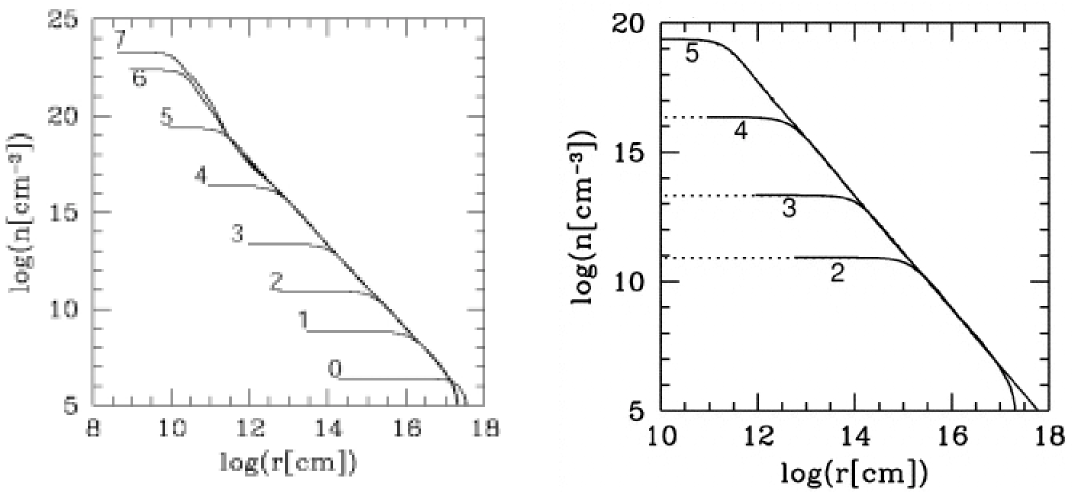


Model

The thermal and chemical evolution of gravitationally collapsing protostellar clouds is investigated by hydrodynamical calculations for spherically symmetric clouds.

(Omukai&Nishi 1998)

The evolutionary sequences



The time interval

$0 \rightarrow 1 \sim 5.7\times10^{5}$ yr

$1 \rightarrow 2 \sim 8.7\times10^{3}$ yr

$2 \rightarrow 3 \sim 2.8\times10^{2}$ yr

$3 \rightarrow 4 \sim 12$yr

$4 \rightarrow 5 \sim 0.32$yr

$5 \rightarrow 6 \sim 2.4\times10^{-2}$ yr

$6 \rightarrow 7 \sim 4.1\times10^{-2}$ yr

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

$$\frac{d\rho}{dt} = \frac{\rho}{\beta t_{\mathrm{ff}}} \quad , \quad t_{\mathrm{ff}} = \sqrt{\frac{3\pi}{32 G\rho}}$$

ρ : the central density

t_{ff} :free-fall time

the collapse time scale ; βt_{ff} the flat core size ; $\alpha \lambda_J$

The modification due to the finite pressure gradient force is represented by the correction factor α , β .

For the Larson-Penston-type similarity solution for γ =1.09,

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

・*The main accretion phase*

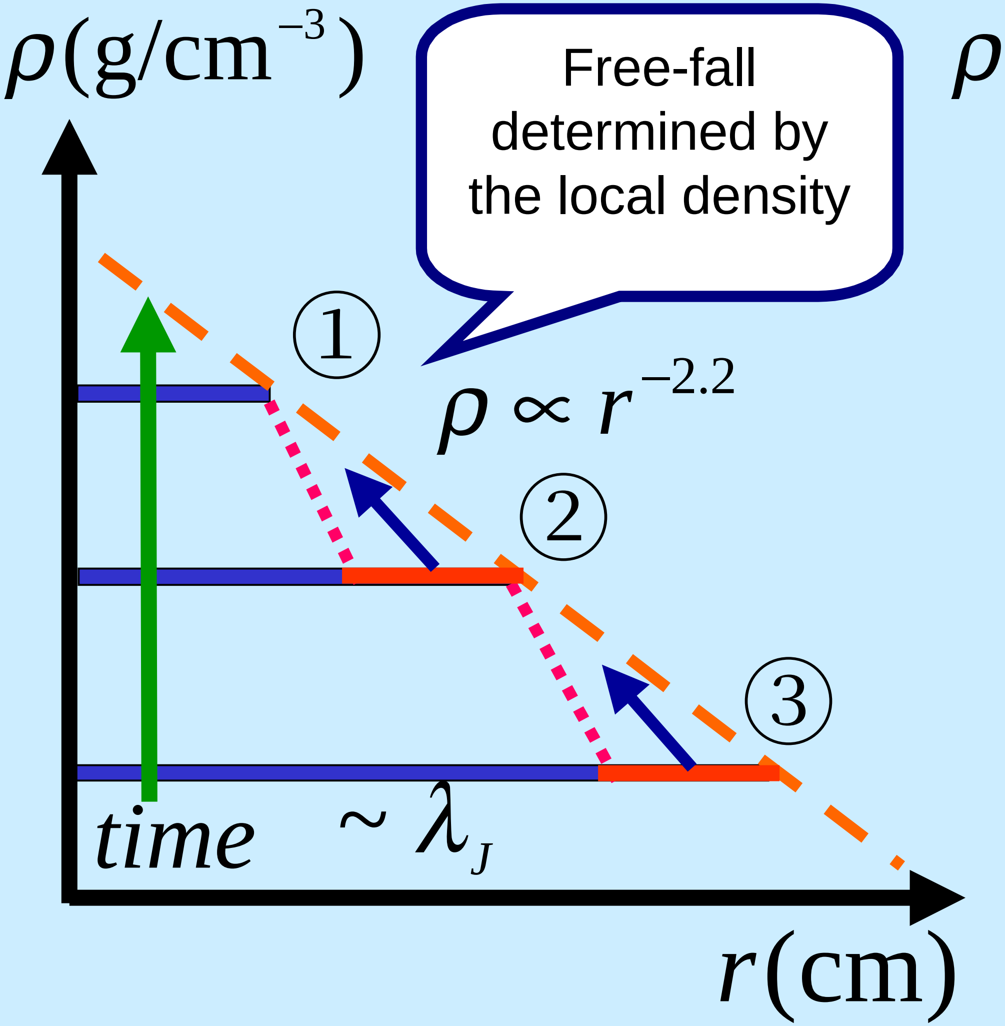
approximation, each mass shell → free-fall

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

ρ : the density of free-falling mass shell

v_r : the velocity of free- falling mass shell

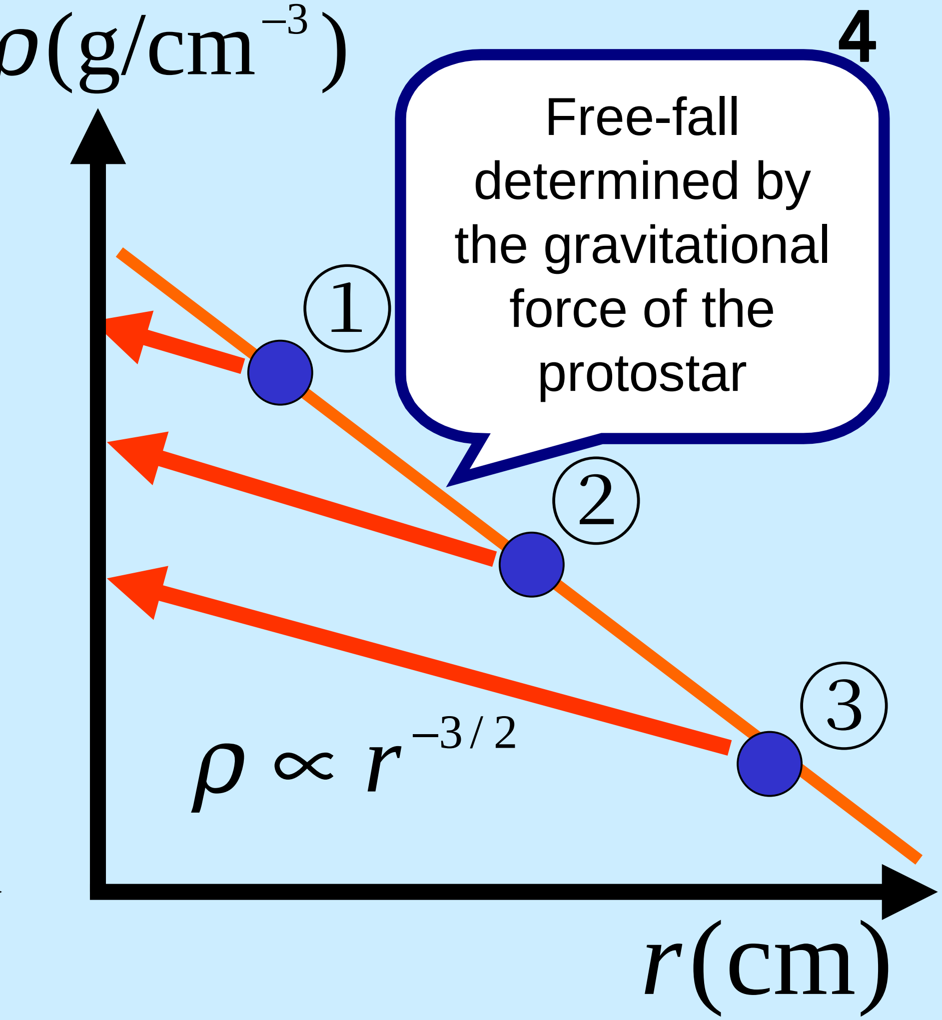
r : the distance from mass shell to the center



Free-fall determined by the local density

The runaway collapse phase

Contracting region and mass become more and more small.



Free-fall determined by the gravitational force of the protostar

The main accretion phase

Inner mass shells fall faster than outer mass shells.

2. Energy equation

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

$$e = \frac{1}{\gamma - 1} \frac{kT}{\mu m_{\mathrm{H}}}, \quad p = \frac{\rho kT}{\mu m_{\mathrm{H}}}$$

e : **the energy per unit mass** , p: **the pressure** , T : **the temperature** ,
γ : **the adiabatic exponent** , μ : **the mean molecular weight** ,
m_{H}: **the mass of the hydrogen nucleus**

3. Cooling/Heating processes

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

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*

$$L_{\mathrm{H}_2} = \frac{1}{\rho}\sum_{i\to j} n(\mathrm{H}_2, i)\, A_{ij}\, \varepsilon_{ij}\, h\nu_{ij}$$

$$n(\mathrm{H}_2, i)\sum_{j\neq i}^{n} R_{ij} = \sum_{j\neq i}^{n} n(\mathrm{H}_2, j)\, R_{ji}$$

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

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

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

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

The runaway collapse phase ;

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

The main accretion phase ;

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

$n(\mathrm{H}_2, i)$ --- the population density of H_2 in level i

A_{ij} --- the spontaneous transition probability

ε_{ij} --- the escape probability

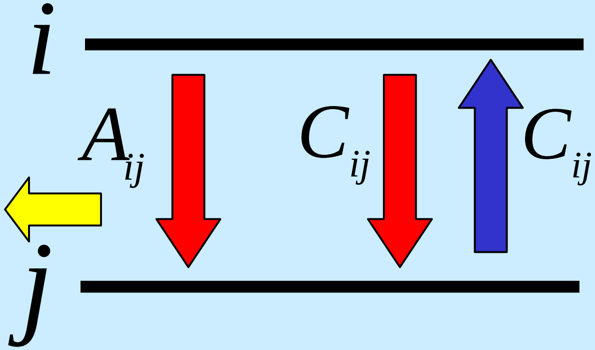
$h\nu_{ij}$ --- the energy difference between levels I and j

C_{ij} --- the collisional transition rate from level I to level j

Δv_{D} --- the velocity dispersion

l_{sh} --- the shielding length

τ_{ij} --- the optical depth averaged over the line



･*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

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

$\eta_a(\nu)$: 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)

$n_{\mathrm{H}}(\sim 10^8\,\mathrm{cm}^{-3})$

$$\mathrm{H} + \mathrm{e}^- \rightarrow \mathrm{H}^- + \gamma$$

$$\mathrm{H} + \mathrm{H}^- \rightarrow \mathrm{H}_2 + \mathrm{e}^-$$

（H^-process)

$n_{\mathrm{H}}(10^8\,\mathrm{cm}^{-3} \sim 10^{14}\,\mathrm{cm}^{-3})$

$$3\mathrm{H} \rightarrow \mathrm{H}_2 + \mathrm{H}$$

$$2\mathrm{H} + \mathrm{H}_2 \rightarrow 2\mathrm{H}_2$$

（three-body process）

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)

$$M_{\mathrm{J}} \sim 10^3\,\mathrm{M_{sun}} \qquad M_{\mathrm{J}}\ \text{: Jeans mass}$$

$$n_{\mathrm{H}} = 10^4(\mathrm{cm}^{-3}), T = 500(\mathrm{K}), y(\mathrm{H}_2) = 10^{-3}, y(\mathrm{e}^-) = 10^{-8}$$

$y(\mathrm{H_i}) = n(\mathrm{H}_i)/n(\mathrm{H})$: the concentration of the i-th species

$n(\mathrm{H})$: the number density of the hydrogen nucleus

Results

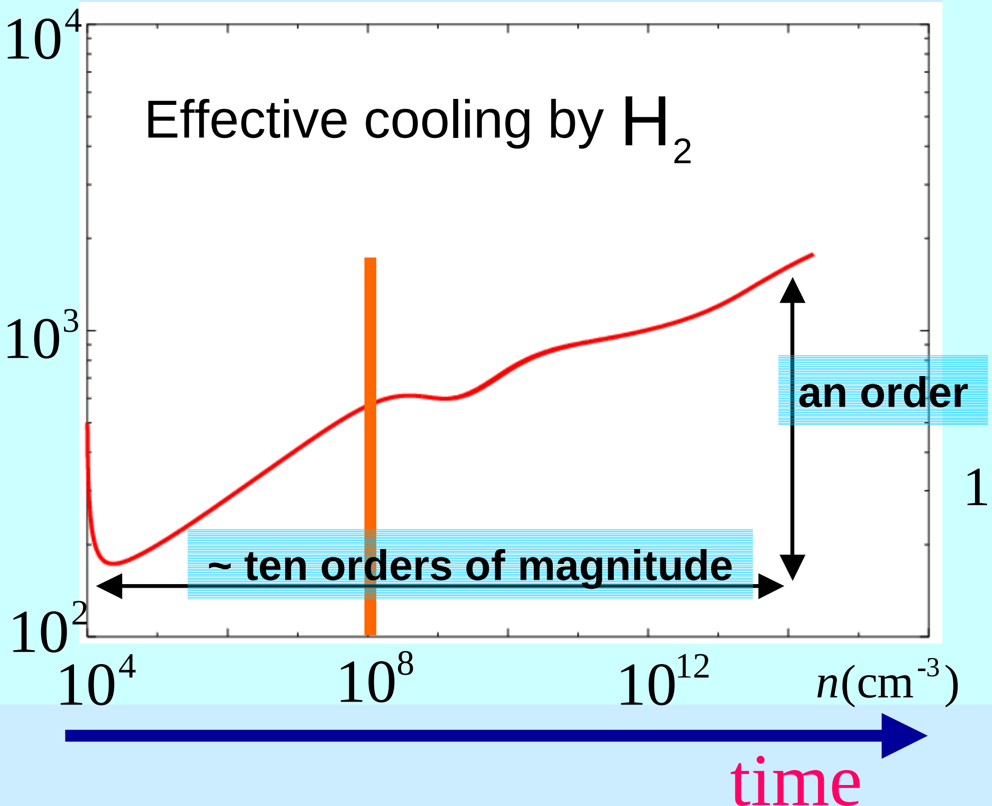
☆ ***Notice!***

temperature, abundance of H_2,
luminosities of the H_2 lines

The runaway collapse phase

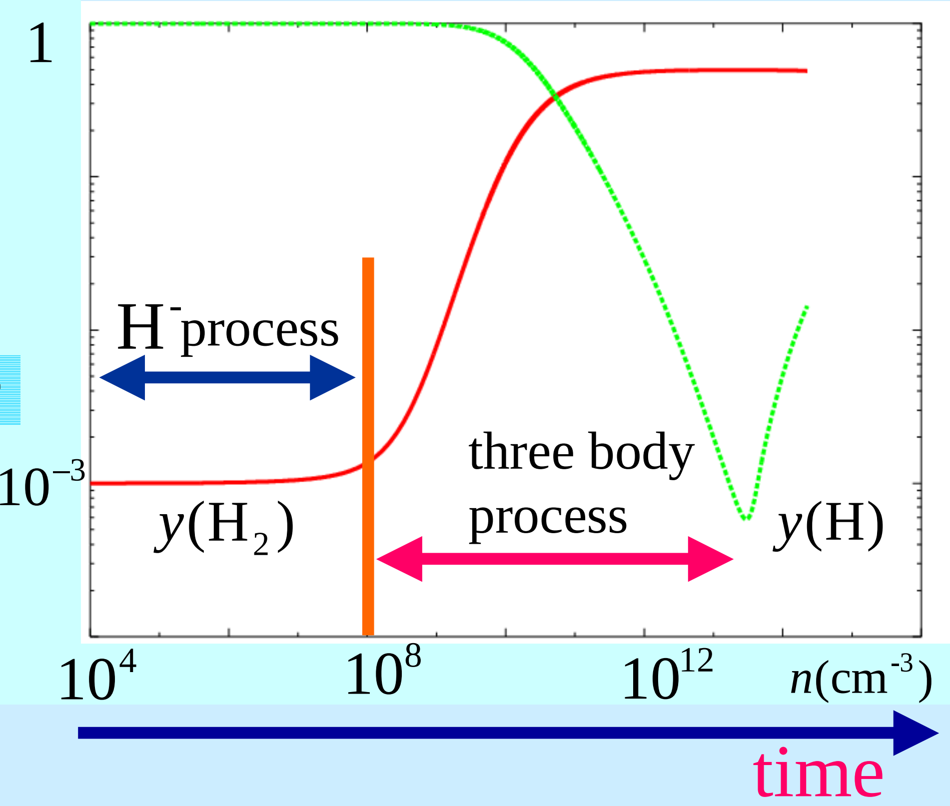
The time evolution of
the central temperature

T(K)



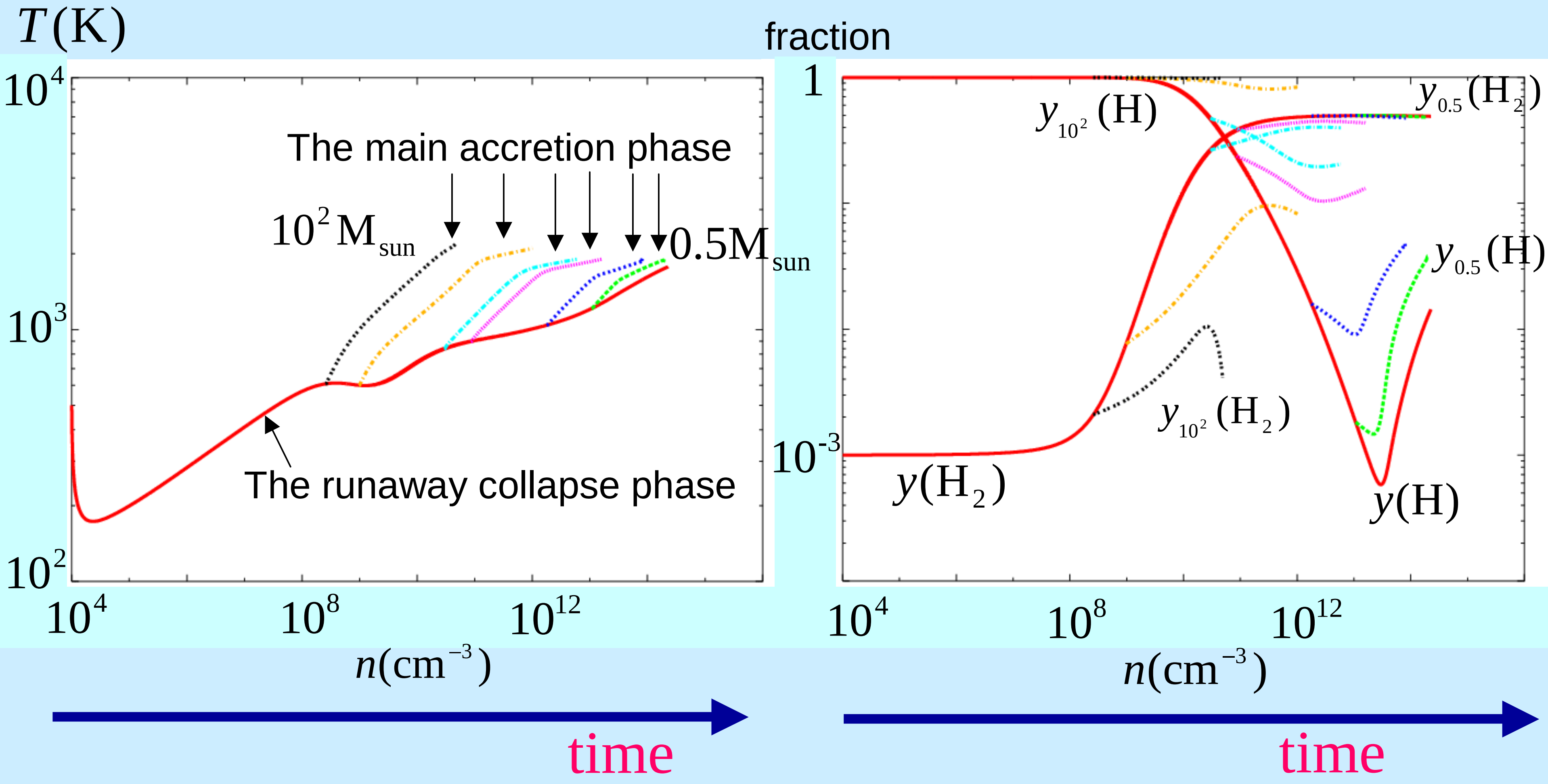
fraction

The time evolution of
the central abundance of H,H_2



Comparison between runaway collapse phase and main accretion phase

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



The time evolution of the H_2 line luminosities

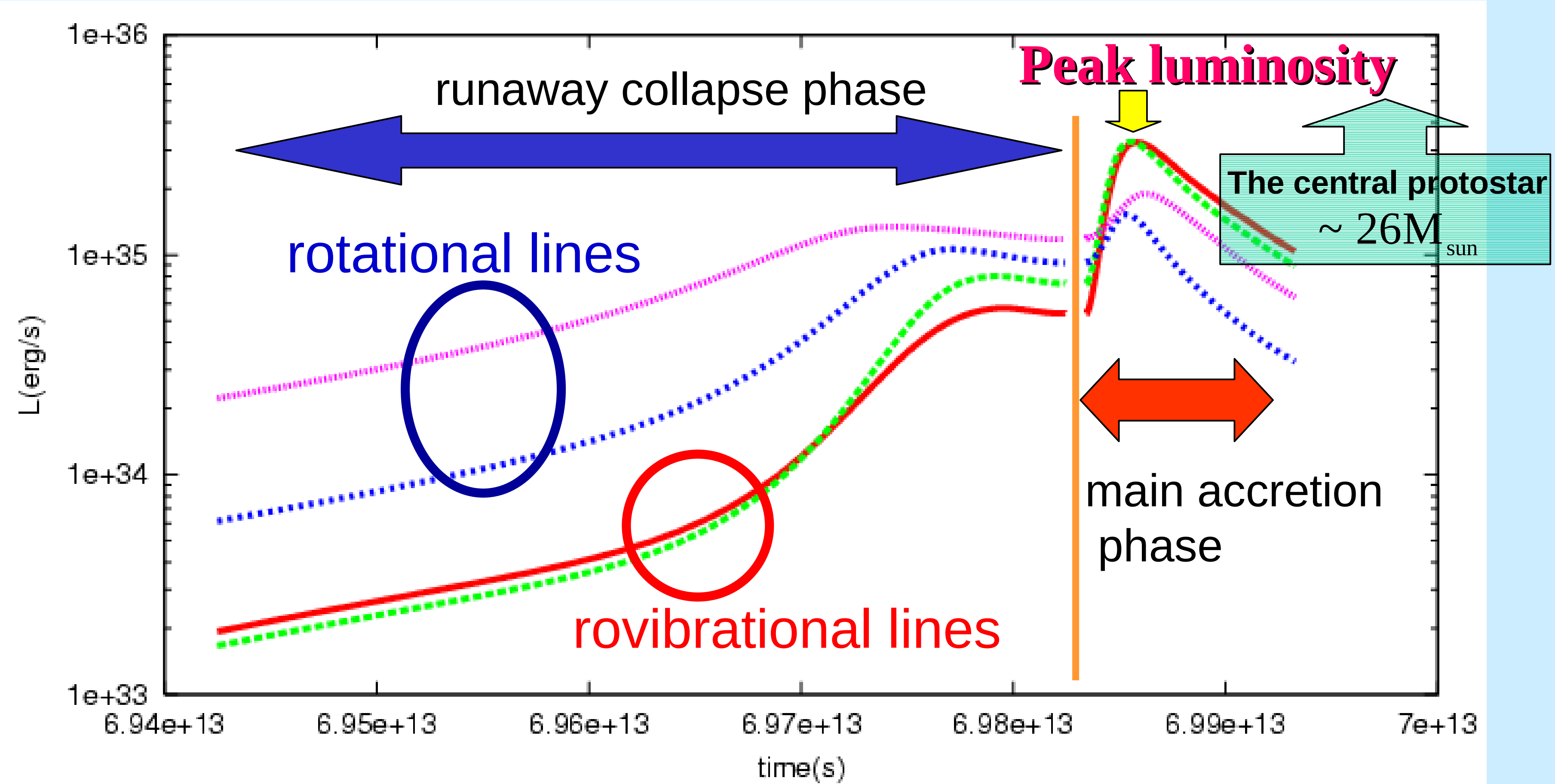
Pick up : four of the strongest H_2 lines

red : (1,1)→(0,1), **green**:(1,1)→(0,3), **blue** : (0,6)→(0,4), **purple** : (0,5)→(0,3)

rest frame : 2.34 μm , 2.69 μm , 8.27 μm , 10.03 μm

before **after**

(vibrational level, rotational level)→(vibrational level, rotational level)



Detectability

For mid-infrared region($\lambda \sim 40\,\mu\mathrm{m}$), 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 $10^{-20}\,(\mathrm{W/m^2})$ in $\lambda \sim 40\,\mu\mathrm{m}$.
In this region, the high background of the zodiacal light limits the sensitivity of SPICA to $10^{-(21-22)}\,(\mathrm{W/m^2})$ (private communication H.Matsuhara).

$(1,1) \to (0,1)$, rest frame: $\lambda = 2.34(\mu\mathrm{m})$
redshifted $(1+z=20)$: $\lambda = 46.8(\mu\mathrm{m})$

$$F_{\mathrm{peak}} = \frac{L_{peak}}{4\pi D_{z=19}^2} \sim 10^{-27}\,(\mathrm{W/m^2})$$

$D_{z=19}$:The luminosity distance to z=19

L_{peak} :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 $\sim 10^{-4}\,Z_{\mathrm{sun}}$ (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

- 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, **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_2 line emission from forming first star by SPICA is highly improbable.