Collaps of Low Mass Clouds in the Presence of UV Radiation Field

Hajime Susa,1⋆ and Tetsu Kitayama2†

1 Center for Computational Physics, University of Tsukuba, Tsukuba 305, Japan
2 Department of Physics, Tokyo Metropolitan University, Hachioji, Tokyo, Japan

Accepted 2000 April

ABSTRACT

The collapse of marginally Jeans unstable primordial gas clouds in the presence of UV radiation field is discussed. Assuming that the dynamical collapse proceeds approximately in an isothermal self-similar fashion, we investigate the thermal evolution of collapsing central core until H$_2$ cooling dominates photoheating and the temperature drops to below 10$^4$K. Consequently, the mass of the cooled core is evaluated as $M_{\text{cool}} = 3.6 \times 10^6 M_\odot (I_{21}/1)^{-0.32}$. This scale depends only on the incident UV intensity, and provides a lower limit to the mass of collapsed objects in the UV radiation field.

Key words: galaxies: formation — radiative transfer — molecular processes

1 INTRODUCTION

Formation of primordial objects, such as young galaxies and globular clusters, in the early universe is a fundamental problem in modern cosmology. Rapid progress of observations in the last decade has pressed theoreticians to construct the physically correct and proper theory to solve this problem. Recently, formation of primordial objects has been investigated mainly in the following two contexts; one is the formation of "first stars" or "first luminous objects" (e.g. Tegmark et al. 1997, Abel et al. 1998, Omukai & Nishi 1998, Nishi & Susa 1999), and the other is that of "second generation objects" (e.g. Haiman, Rees & Loeb 1997, Kepner, Babul & Spergel 1997, Omukai & Nishi 1999). These two populations are expected to arise in quite different physical environments. For instance, the former is likely to be born from the primordial gas under little influences of the external radiation field, except for that of the cosmic microwave background radiation (CMB). The latter, on the other hand, is largely affected by the external UV radiation produced by the former. The UV photons not only ionize and heat up the pregalactic gas clouds, but also dissociate H$_2$ in the clouds, which is an important coolant in metal-free gas clouds. In this paper, we pay particular attention to the formation of the latter population.

At high redshifts, say $z \sim 5$, ionized bubbles around photon sources, such as young galaxies or AGN's, are still so small that most of the gas in the universe is not ionized and photoheated. In this case, the external radiation affects the formation of primordial objects only via H$_2$ photodissociation (Haiman, Rees & Loeb 1997). On the other hand, gas clouds near the ionizing sources, or those at lower redshifts ($z \lesssim 5$) are ionized and photoheated, before they collapse and cool. Therefore, the formation of population III objects close to the ionizing sources and the formation of galaxies at low redshifts are likely to start from hot ionized media. Kepner, Babul & Spergel (1997) investigated this problem in the context of dwarf galaxy formation under the assumption that pregalactic clouds are in hydrostatic equilibrium. They found that the gas transit from H$^+$ phase to H and H$_2$ ones, as radiative cooling proceeds. Corbelli, Galli & Palla (1997) also found similar phenomena in the rotationally supported hydrostatic gaseous disc. However, gravitational collapse of ionized gas proceeds almost isothermally (Umemura & Ikeuchi 1984, Thoul & Weinberg 1996, Kitayama & Ikeuchi 2000, Susa & Umemura 2000), and such a collapse becomes inevitably dynamical (Larson 1969).

In this paper, we investigate H$_2$ cooling in the dynamically collapsing core in marginally Jeans unstable clouds. If these clouds are self-gravitating, they are likely to collapse almost spherically with the temperature kept nearly at $\sim 10^4$K, until the external radiation field is shielded by the clouds themselves. We thus employ the isothermal Larson-Penston similarity solution (Larson 1969) and solve explicitly non-equilibrium chemical reactions and energy equation to trace the thermal history of a collapsing central core. Consequently, the mass and the size of the cooled core are assessed, and their astrophysical implications are discussed.

⋆ e-mail:susa@rccp.tsukuba.ac.jp
† e-mail:tkita@phys.metro-u.ac.jp

© 2000 RAS
The isothermal collapse of a self-gravitating system always tends to converge to the Larson-Penston similarity solution (Larson 1969) because it is a relatively stable solution (e.g. (Hanawa & Nakayama 1997)). We thus assume that the cloud obeys the Larson-Penston solution, which is characterized by the central density

$$\rho_c(t) = \frac{\rho_c(0)}{(t/t_{LP}(0) - 1)^2},$$

and the core radius

$$r_c(t) = (t_{LP}(0) - t)c_s.$$  

Here $t$ denotes the elapsed time from an initial instant characterized by $\rho_c(0)$, $c_s$ is the sound speed in the core, and $t_{LP}$ is defined as $t_{LP}(0) \equiv \sqrt{1.667/4\pi G \rho_c(0)}$ In order to elucidate the thermal history of nearly isothermally collapsing core, we employ an one-zone approximation and integrate numerically the following energy equation:

$$\frac{d\epsilon_c}{dt} = \frac{P_c}{\rho_c^2} \frac{d\rho_c}{dt} - \Lambda - \Gamma,$$

where $P_c$ is the central pressure, $\epsilon_c$ is the specific energy per unit mass, and $\Lambda$ and $\Gamma$ denote the cooling and heating rates, per unit volume, respectively. The cooling rate includes H atom cooling and cooling by rovibrational transition lines, as well as H atomic cooling. We also solve time-dependent non-equilibrium reactions for e, H, H+, H_2^+, H^−, and H_2, to evaluate $\Lambda$. Unless stated explicitly, reaction rates are taken from the recent compilation by Galli & Palla (1998). H_2 photodissociation rate is evaluated using the self-shielding function in Draine & Bertoldi (1996). H^+ photodissociation is also taken into account, based upon the cross section in Stancil (1994). H^- radiative detachment is assessed using the fitting formula for the cross section in Tegmark et al.(1997).

The incident UV intensity is set to be $I_\nu^{in} = I_{21}(\nu/\nu_{Ly}^{-1})^{-10^{-2}}$ erg s$^{-1}$ cm$^{-2}$ str$^{-1}$ Hz$^{-1}$, where $\nu_{Ly}$ is the frequency at the Lyman limit. We take various values for $I_{21}$ in the range $10^{-3} \leq I_{21} \leq 10^{5}$. The power-law approximation of the UV spectrum adopted here is admittedly rather crude. In reality, the UV intensity in the Lyman-Werner bands could be modulated by so-called “sawtoothing effect” and reduced by a factor of $10^{-10}$ at $z = 15$ (Haiman, Abel & Rees 2000). As will be discussed later, however, the two-step photodissociation process is not important in the present case and the spectral change in the Lyman-Werner band will not alter our results.

The photoionization rate is computed taking account of the absorption of ionizing photons as (Tajiri & Umemura 1998, Susa & Umemura 2000):

$$k_{ion} = n_{HI} \int_{\nu_L}^{\infty} I_\nu h\nu \sigma_{\nu} d\Omega d\nu \approx \frac{I_{\nu_L}^{in} \sigma_{\nu_L}}{h} \int \frac{1}{3\tau_{\nu_L}(\Omega)^{4/3}} \gamma(4/3, \tau_{\nu_L}(\Omega)) d\Omega \approx \frac{4\pi}{3} \frac{I_{\nu_L}^{in} n_{HI} \sigma_{\nu_L} \nu_L}{\tau_{\nu_L}} \left[ \frac{\gamma(1, \tau_{\nu_L})}{\tau_{\nu_L}^{1/3}} - \frac{\gamma(4/3, \tau_{\nu_L})}{\tau_{\nu_L}^{4/3}} \right].$$

where $\sigma_{\nu}$ is the photoionization cross section which is proportional to $\nu^{-3}$, $\Omega$ is the solid angle, and $\gamma(a, b)$ represents the incomplete gamma function. The optical depth at the Lyman limit is defined as $\tau_{\nu_L} \equiv n_{HI} \rho_c \sigma_{\nu_L}$, where $\rho_c$ is assessed by equation (2) and $n_{HI}$ denotes the central HI number density. The accreting envelope outside $r_c$ only alters the optical depth $\tau_{\nu_L}$ less than a factor of 2. Similarly, the photoheating rate is expressed as

$$\Gamma = n_{HI} \int_{\nu_L}^{\infty} I_\nu h\nu \sigma_{\nu} (\nu - \nu_{Ly}) d\Omega d\nu \approx \frac{4\pi}{3} \frac{I_{\nu_L}^{in} n_{HI} \sigma_{\nu_L} \nu_L}{\tau_{\nu_L}} \left[ \frac{1}{\tau_{\nu_L}^{1/3}} - \frac{\gamma(4/3, \tau_{\nu_L})}{\tau_{\nu_L}^{4/3}} \right] \text{ [erg s}^{-1}\text{cm}^{-3}].$$

The initial central density is taken as twice the self-shielding critical density $n_{cr}$ derived in Tajiri & Umemura (1997), where $n_{cr}$ represents the density above which the HI fraction exceeds 0.1. Thus, the numerical integrations of the energy equation and chemical reactions start when the cloud center begins to be almost neutral. The initial temperature and chemical abundances are fixed assuming thermal and chemical equilibria. Even if they are perturbed, they immediately converge to equilibrium values. We stop the numerical integrations when the temperature of the core drops to below 5000K and the assumption of an isothermal cloud breaks down.

### 2.2 Numerical Results

The numerical results are presented in Figs. 4 and 5. In Fig. 4, the time evolution of the core temperature (upper panel) and the chemical compositions (lower panel) are plotted for four different values of the incident intensity. In every case, the temperature evolves nearly isothermally after the collapse calculation starts. This ensures that the density evolution approximately follows the isothermal Larson-Penston similarity solution. After the isothermal collapse, core temperature drops dramatically, with the time-scale much faster than the collapse time, and the loci on the $T$-$n$ plane become nearly vertical. This corresponds to the transition from

---

5 The sawtoothing effect could also suppress destruction of H_2^+ by the UV photons, which could in turn enhance the H_2 abundance. The assumption of a power-law spectrum should thus provide the limiting case in which H_2 formation is maximally suppressed. In practice, however, this has only minor impacts on our present results (see also Section 3).
the H phase to the H$_2$ one mentioned in Kepner, Babul and Spergel (1997). The increased cooling rate by H$_2$ overwhelms the photoheating rate which is reduced due to strong self-shielding. In the lower panel of Fig. 2, fractions of electron and H$_2$ are plotted. At $T > 10^4$ K, the electron fraction is kept at $\sim 10^{-1}$ by ionizing UV photons. At $T \lesssim 10^3$ K, the photons are self-shielded and recombination proceeds. However, the radiative cooling time becomes shorter than the recombination time, and the electrons become out of equilibrium. Significant amount of free electrons thus “freeze out” as the system cools via Ly-α and H$_2$ ro-vibrational transitions. The ionization degree still remains at the level of $\sim 10^{-2}$, even at $T \sim 5000$K. Fedded these relic electrons, H$_2$ molecules are formed to the level of $\sim 10^{-3}$. Remark that the similar phenomena have been found in the post-shock region of primordial gas (Shapiro & Kang 1987; Kang & Shapiro 1992; Susa et al. 1998; Nishi et al. 1998).

In Fig. 2, various time-scales are plotted for $I_{21} = 0.1$ and 10$^2$. The upper panel shows time-scales related to the energy equation, i.e., the collapse time ($t_{\text{col}}$), the H$_2$ cooling time ($t_{\text{cool}}$), and the photoheating time ($t_{\text{UV}}$). It is clear that temperature is determined by thermal equilibrium, because the condition $t_{\text{UV}} \approx t_{\text{col}}$ is well satisfied. The transition from the H phase to the H$_2$ one takes place as H$_2$ cooling dominates UV heating. We remark that the collapse time-scale $t_{\text{col}}$ is much longer than the other thermal time-scales. Therefore, hydrostatic equilibrium assumption is a poor one owing to the cooling instability.

In the lower panel of Fig. 2, time-scales related to H$_2$ formation/destruction are plotted. Chemical equilibrium is achieved throughout the evolution because the H$_2$ dissociation time is almost equal to the H$_2$ formation time ($t_{\text{dis}} \approx t_{\text{for}}$). It is clear that two-step photodissociation (Solomon process; $t_{\text{dis}}$) is not important during this calculation. Dissociation of H$_2$ is dominated by a collisional process (H$_2^+ +$ H $ightarrow$ H$_2^+ +$ H) at such high temperature (Corbelli, Galli & Palla 1997; Susa & Umemura 2000).

3 PROPERTIES OF COOLED CORE

As shown in the previous section, the runaway collapsing core cools rapidly as soon as H$_2$ cooling becomes effective. The core will probably cool down to $\sim 100$ K, which is the lowest temperature achievable by H$_2$ cooling. The cooled core will then be a free-falling sphere, since the cooling timescale is much shorter than the collapse time (Fig. 2). Consequently, violent collapse of the cooled core will lead to subsequent star formation in the cloud center.

In Fig. 3, the mass and the radius of the cooled core are plotted against the incident UV intensity. The upper panel shows the cooled mass, which is approximately fitted by $M_{\text{cool}} \propto 3.6 \times 10^8 M_\odot (I_{21}/1) ^{-0.32}$. Remark that this scale depends only on the incident intensity $I_{21}$. This dependence can be understood essentially as follows. $M_{\text{cool}}$ is roughly estimated from three conditions at the onset of H$_2$ cooling: 1) $M_{\text{cool}} \simeq M_I (T = 10^4 K)$, 2) $H \simeq \lambda H_2$, and 3) $y_{H_2} \simeq 10^{-4} - 10^{-3}$. Condition 1) simply dictates that the core mass is comparable to the Jeans mass. Condition 2) means that the thermal equilibrium is achieved until the onset of H$_2$ cooling. Condition 3) is based on the fact that the H$_2$ fraction (denoted as $y_{H_2}$) at this moment roughly converges to a fixed level (Fig. 3). These three conditions yield $M_{\text{cool}} \propto I_{21}^{-1/3}$, which is slightly steeper than our numerical results. This difference is caused by two reasons. The first one is the destruction of H$_2^+$ and H$^-$ by the UV flux which are neglected in the above simplified estimation. For large $I_{21}$, the fractions of H$_2^+$ and H$^-$ are reduced, and the amount of H$_2$ produced and H$_2$ cooling rate both become smaller. In order to achieve the balance between cooling rate and photoheating rate, the system has to collapse even further. As a result, the cooled mass becomes slightly smaller than the analytic estimation and the $M_{\text{cool}} - I_{21}$ correlation becomes steeper for large $I_{21}$. The other reason is the relatively short free-fall time compared to the cooling time at lower density. For low $I_{21}$, H$_2$ cooling starts to operate at low density (Fig. 2) when the difference between the free-fall time and the cooling time scale is small. This makes gentler the drop of the temperature as a function of density at the onset of H$_2$ cooling (Fig. 2, upper panel). Consequently, the cooled mass becomes larger and the $M_{\text{cool}} - I_{21}$ correlation becomes shallower for small $I_{21}$.

In the limit of very strong UV field, H$_2$ formation is completely suppressed as H$^-$ and H$_2^+$ are both destroyed by the UV photons. We find that this happens at the threshold intensity of $I_{21} \simeq 3.6 \times 10^4$ in the case of $\alpha = 1$.

The radius of the cooled core is also plotted for various $I_{21}$ in the lower panel. It also has the same dependence on $I_{21}$ as $M_{\text{cool}}$, $r_{\text{cool}} \propto I_{21}^{-0.32}$. Note that the absolute values of cooling radius shown in Fig. 3 are larger than the Jeans length of the cooled objects, since they are assessed just at the onset of H$_2$ cooling. In reality, the temperature drops rapidly from $\sim 10^4$K to $\sim 100$K due to H$_2$ cooling. Therefore, the corresponding Jeans length should be reduced by a factor $\sim 10^2$, provided the cooled core mass is constant during the free-fall collapse. This Jeans length will provide the actual size of the cooled object.

For $1 \lesssim I_{21} \lesssim 10^2$, the cooled mass is $\sim 10^3 - 10^4 M_\odot$. Such high intensity is realized near the luminous Population III objects, such as young galaxies or quasars. For instance, $I_{21} = 10^2$ roughly corresponds to the intensity at 10kpc away from the center of active galactic nuclei whose luminosity is $10^{44}$ erg s$^{-1}$. In this case, the cooled mass in Fig. 3 should provide a lower limit to the mass of the cooled objects around or inside the young galaxies/quasars. The mass ($\sim 10^6 M_\odot$), compactness ($\sim$ a few pc, 100 times smaller than $r_{\text{cool}}$ in Fig. 3) and location ($\sim$ 10 kpc) of the cooled core roughly account for those of globular clusters (Binney & Merrifield 1998). This result implies that the globular clusters might be formed in the runaway collapsing core around luminous host galaxies.

For $10^{-3} \lesssim I_{21} \lesssim 1$, the cooled mass $M_{\text{cool}} \sim 10^7 - 10^8 M_\odot$, and cooling radius $r_{\text{cool}} \lesssim 1$kpc. These in
The tensile correspond to the UV background radiation field inferred from so-called the proximity effect of Lyα forests (Bajtlik, Duncan & Ostriker 1988; Giallongo et al. 1996). The actual mass of the cooled gas is determined by some mechanism (SN, radiation feedback) which halts the mass accretion from the envelope onto the cooled core. In this sense, these mass scales provide a lower limit to the mass of cooled objects under the UV background radiation field. HST (Pascarelle et al. 1996) and SUBARU (Yamada 1999) in fact found the “building blocks” which are very compact (< 1kpc), although the mass is still unsettled. The creation mechanism of low mass compact objects discussed in this paper might be able to explain the formation of such objects. Finally, let us remark on influences of dissipationless dark matter on the present results especially in case we apply them to the formation of dwarf galaxies. If the dark matter dominates the gravity of the collapsing core, the collapse will not follow the Larson-Penston similarity solution. The dark matter distribution at the center of a pregalactic cloud is still highly uncertain, but the cooled mass in Fig. is likely to be reduced by the dark matter gravity. This point will be discussed in more detail in our future publications (Kitayama, Susa, Umemura & Ikeuchi 2000).

ACKNOWLEDGMENTS

We thank the referee, Tom Abel, for helpful comments, Masayuki Umemura and Taishi Nakamoto for continuous encouragement, and Ryoichi Nishi and Yukiko Tajiri for useful remarks. The analysis of this paper has been made with computational facilities at the Center for Computational Physics in University of Tsukuba. This work is supported in part by Research Fellowships of the Japan Society for the Promotion of Science for Young Scientists, No. 2370 (HS) and 7202 (TK).

REFERENCES

Abel T., Anninos, P., Norman M. L. & Zhang, Yu. 1998, ApJ, 508, 518
Bajtlik, S. Duncan, R. C., & Ostriker, J. P. 1988, ApJ, 327, 570
Binney, J., & Merrifield, M. 1998, “Galactic Astronomy”, Princeton University Press
Corbelli E., Galli, D & Palla, F. 1997, ApJ, 487, 53L
Galli D. & Palla F. 1998, A&A, 335, 403
Giallongo, E., Cristiani, S., D’Odorico, S., Fontana, A., & Savaglio, S. 1996, ApJ, 466, 46
Haiman, Z., Abel, T. & Rees, M. J. 2000, ApJ, in press
Haiman, Z., Rees, M. J., & Loeb, A. 1997, ApJ, 476, 458
Hanawa, T. & Nakayama, K. 1997, ApJ, 484, 238
Kang, H., & Shapiro, P. 1992 , ApJ, 386, 432
Kepner, J., Babul, A., & Spergel, N. 1997, ApJ, 487, 61
Kitayama, T., Susa, H., Umemura, M., & Ikeuchi, S. 2000, in preparation
Kitayama, T., & Ikeuchi, S. 2000, ApJ, in press
Larson, R. 1969, MNRAS, 145, 271
Navarro, J. F., Frenk, C. S., & White, S. D. M. 1997, ApJ, 490, 493
Nishi, R. & Susa, H. 1999, ApJ, 523, L103
Nishi, R., Susa, H., Uehara, H., Yamada M. & Omukai K. 1998, Prog. Theor. Phys., 100, 881
Omukai K., & Nishi R. 1998, ApJ, 508, 141
Omukai K. & Nishi R. 1999, ApJ, 518, 64
Pascarelle, S.M., Windhorst, R.A., Driver, S.P., & Ostrander, E.J., 1996, ApJ, 456, L21
Shapiro, P. R. & Kang H. 1987, ApJ, 318, 32
Stancil, P.C. 1994, ApJ, 430, 360
Susa H., Uehara H., Nishi R. & Yamada M. 1998, Prog. Theor. Phys., 100, 63
Susa H. & Umemura, M. 2000, ApJ, in press, astro-ph/000110
Tajiri, Y., & Umemura, M. 1998, ApJ, 502, 59
Tegmark M., Silk J., Rees M. J, Blanchard A., Abel T. & Palla F. 1997, ApJ, 474, 1
Thoul, A. A., & Weinberg, D. H., 1996, ApJ, 465, 608
Umemura, M., & Ikeuchi, S. 1984, Prog. Theor. Phys., 72, 47
Yamada, T. 1999, private communication
Figure 1. Time evolution of the physical quantities in the collapsing core for four different values of the incident UV intensity $I_{21}$. The upper panel shows the evolution of temperature, while the lower panel that of electron fraction (solid lines) and H$_2$ fraction (dotted lines).
Figure 2. Various time-scales during the evolution for $I_{21} = 0.1$ and $10^2$. The upper panel shows the collapse time of the Larson-Penston similarity solution (solid line; $t_{LP}$), the total cooling time (short dashed; $t_{cool}$), the H$_2$ radiative cooling time (long dashed; $t_{cool,H_2}$), and the photoheating time (dotted; $t_{UV}$). In the lower panel, time-scales related to H$_2$ formation and dissociation are plotted; the H$_2$ photodissociation time (dotted; $t_{Sol}$), the H$_2$ collisional dissociation time (solid; $t_{dis}$), and the H$_2$ formation time (short dashed; $t_{for}$).
Figure 3. Mass (upper panel) and radius (lower panel) of the core at $T_{\text{core}} = 5000$ K, i.e. at the onset of H$_2$ cooling, as a function of the incident UV intensity $I_{21}$. 

© 2000 RAS, MNRAS 000, 000-000