Formation of HD molecules in merging dark matter haloes

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ABSTRACT
HD molecules can be an important cooling agent of the primordial gas behind the shock waves originated through mergings of the dark matter haloes at epochs when first luminous objects were to form. We study the necessary conditions for the HD cooling to switch on in the low temperature range $T < 200$ K. We show that these conditions are fulfilled in merging haloes with the total (dark matter and baryon) mass in excess of $M_{\text{cr}} \sim 10^7[(1+z)/20]^{-2} M_\odot$. Haloes with masses $M > M_{\text{cr}}$ may be the sites of low-mass star formation.

Key words: early Universe – cosmology:theory – shock waves.

1 INTRODUCTION
Cooling of primordial gas is determined by molecular hydrogen, which forms in an expanding universe after recombination (Lepp & Shull 1983, Puy et al 1993, Palla, Galli & Silk 1995, Galli & Palla 1998, Stancil, Lepp & Dalgarno 1998). Inside the first virialized dark matter haloes the fraction of $H_2$ can reach $10^{-3}$, which is able to cool gas to 200 K. At lower temperatures energy losses in roto-vibrational $H_2$ lines become insufficient to cool gas further. On the other hand, owing to a low rotational energy and a large dipole moment HD molecules might be an efficient coolant at $T < 200$ K. However, the abundance of HD is fairly sensitive to thermal history of the gas, so that the question of whether HD dominates radiative cooling at low temperatures or its contribution is negligible depends on physical conditions along the evolutionary path. This circumstance is reflected in contradictory conclusions about the role of HD in thermodynamics of primordial gas: for instance, Lepp & Shull (1983), Bromm, Coppi & Larson (2002) point out that HD cooling cannot dominate in primordial gas when the first objects form, while Bougleux & Galli (1997), Puy & Signore (1997, 1998), and more recently Uehara & Inutsuka (2000), Flower (2002), Nakamura & Umemura (2002), Flower & Pineau des Forets (2003) and Machida et al (2005) find that HD molecules form in significant amount and can play a dominant role in thermal evolution of pregalactic gas.

Transformation of $H_2$ molecules into their isotop analog HD is energetically favoured because of higher binding energy of HD molecules. In equilibrium (Solomon & Woolf 1973, Varshalovich & Khersonskii 1976) $\frac{n(\text{HD})}{n(H_2)} = \frac{2n(D)}{n(H)} e^{465}/T$, where factor 2 stems from the difference between the chemical constants of HD and $H_2$ molecules: $\chi_{\text{HD}} - \chi_{H_2} = \ln 2$ (Landau & Lifshitz 1969). It is seen, that at $T \lesssim 150$ K radiative HD cooling can enhance chemical fractionation of deuterated molecules progressively: a small decrease in temperature results in an increase of $n(\text{HD})/n(H_2)$, what in turn increases radiative cooling in HD lines (Shchekinov, 1986). In realistic conditions thermal equilibrium can be reached only in a characteristic time depending on a set of chemical reactions which control the transformation $H_2 \iff \text{HD}$ in primordial gas $H_2$ converges into HD most efficiently in the reaction $H_2 + D^+ \rightarrow \text{HD} + H^+$ (Palla et al. 1995); other channels are unimportant on the Hubble time. The background $H_2$ abundance and the frozen-out post-recombination fractional ionization $x \sim 10^{-4}$ are sufficient to support deuterated $H_2$ only at the level $n(\text{HD}) \lesssim 10^{-3} n(D)$. Thus, a necessary condition for the $H_2 \rightarrow \text{HD}$ convergence to be efficient is that both $H_2$ and electrons are abundant. In a cosmological pregalactic substrate such conditions are most naturally fulfilled behind shock waves associated with formation and virialization of dark matter haloes (Tegmark et al. 1997, Barkana & Loeb 2001). When formed in sufficient amount HD molecules can cool gas down to the temperature of the CMB – the lowest possible temperature, and thus provide conditions for formation of low-mass stars. It is clear that this can occur with shock waves whose parameters (for instance, postshock temperature, total mass involved, and so on) have reached some critical values.

In the hierarchical scenario dark matter haloes of larger mass form through mergings of smaller objects – mini-haloes (see for review Barkana & Loeb 2001, Ciardi & Ferrara 2004). In these conditions the baryonic component of dark
haloes is compressed by shock waves. Apparently, all subsequent evolution of baryons in dark haloes and their condensation into stars is determined by these shock waves. Furthermore, one can consider that the virial state of dark matter haloes and their baryons is reached through formation of shocks. It is clear, that the physical state of the baryons processed by shocks depends on many factors, such as geometry of a shock front, duration of a compressing flow etc. However, basics characteristic features can be understood in the framework of a head-on collision of two clouds of equal masses (Suchkov, Shchekinov & Edelman 1983, Shapiro & Kang 1987). In the context of the hierarchical scenario a possible role of shock waves in enhancing H$_2$ cooling and stimulation of primordial star formation was studied by Yamada & Nishi (1998), and more recently by Cen (2005). Radiative cooling in H$_2$ lines was indeed found extremely efficient in decreasing the postshock temperature to $\sim 100$ K. In spite of the fact that HD molecules are expected to form at this temperature, HD chemistry was not taken into consideration in this analysis. The main goal of our study are the conditions when HD molecules can be the dominant cooling agent in a pregalactic gas.

In Section 2 we describe a simple thermo-chemical model of a shocked gas; in Section 3 the conditions for HD molecules to be the dominant cooling agent are analyzed; in Section 4 we discuss qualitatively a possibility of a cold compressed layer to fragment; the discussion and summary of the results are given in Section 5.

Throughout the paper we assume a ΛCDM cosmology with the parameters $(\Omega_m, \Omega_{\Lambda}, \Omega_b, \Omega_c, h) = (1.0, 0.71, 0.29, 0.047, 0.72)$ as inferred from the Wilkinson Microwave anisotropy Probe (WMAP), and deuterium abundance $2.62 \times 10^{-5}$ (Spergel et al. 2003).

## 2 THERMO-CHEMISTRY OF POSTSHOCK GAS

For simplicity, we assume a head-on collision of two identical minihaloes, which are virialized at redshift $z$ and have density of matter $18\pi^2 \Omega_m \rho_c (1+z)^3$, $\rho_c$ being the critical density; the collision is assumed to take place at the same redshift $z$. The minihaloes move with the relative velocity $v_c = \sqrt{3} \sigma$, where $\sigma$ is a 1D velocity dispersion of the larger halo

$$\sigma^2 = \frac{GM}{2R} = GM^2/3(3\pi^3 \Omega_m \rho_c)^{1/3}(1+z).$$

(2)

In the center of mass a discontinuity forms at the symmetry plane, and two shocks propagate outwards. The time for the shock to pass through the entire minihalo is $t_c = 3R/2v_c$. As it was pointed out by Gilden (1984) for supersonic rarefactions the rarefaction time in transverse direction is greater than the collision time, which means that a 1D scheme describes the overall picture qualitatively correct. We assume the postshock flow to be isobaric (Suchkov et al. 1983, Shapiro & Kang 1987, Anninos & Norman 1996). The initial post-shock temperature is

$$T_0 = \frac{1}{3} \frac{m_p v_c^2}{k}.$$  

(3)

where the post-shock gas is assumed to be isothermal, i.e. temperatures of the electrons, ions and neutrals are kept always equal $T_e = T_i = T_n$.

Chemical kinetics and thermal evolution of the gas are described by the following set of equations

$$\dot{x}_i = F_i(x, T, n) - D_i(x, T, n),$$

$$\dot{T} = \frac{2}{3k} \sum_i (\Gamma_i(x, T, n) - \Lambda_i(x, T, n)) - \frac{2T}{3n},$$

(4)

(5)

where $k$ is the Boltzmann constant, $x_i$ is the fraction of $i$-th species, $F_i(x, T, n)$, $D_i(x, T, n)$ are respectively the formation and destruction rates, $\Gamma_i(x, T, n)$, $\Lambda_i(x, T, n)$ are the heating and cooling rates; $x$ includes 14 species: H, H$^+$, H$^-$, He, He$^+$, He$^{++}$, H$_2$, H$_2^+$, D, D$^+$, D$^-$, HD, HD$^+$, e. In the energy equation (5) all relevant cooling processes (such as collisional excitation and ionization, Compton cooling, recombination and bremsstrahlung radiation, cooling by HI, H$_2$ and HD line emission) are accounted for. For the cooling functions of H$_2$ and HD we adopted the expressions given by Hollenbach & McKee (1979), and Flower et al. (2000), respectively; note, that the Hollenbach & McKee H$_2$ cooling function practically coincides with the one calculated by le Bourlot, Pineau des Forets & Flower (1999). The most recent calculations of the HD cooling function by Lipovka, Núñez-López, & Avila-Reese (2005) show that in the temperature range of interest ($T < 10^4$ K) it coincides with that found by Flower et al. (2000). At higher temperatures, where Lipovka et al. (2005) predict an order of magnitude enhanced cooling from HD, the abundance of HD molecules is too low to contribute significantly. The other cooling functions connected with excitation and ionization of H and He are taken from Cen (1992). In general, radiation from a hot shocked gas can heat the gas, however, for the shock waves with the velocity $\lesssim 60$ km s$^{-1}$ (Shull & McKee 1979, Shull & Silk 1979) its contribution to ionization and heating is unimportant, therefore in our calculations we assume $\Gamma_i(x, T, n) = 0$. The chemical reaction rates are taken from Galli & Palla (1998).

The thermo-chemical equations (4), (5) are solved in one collisional time $t_c$; $t_c$ is much shorter than the age of the universe at any redshift $z$.

Fig.1 shows an example of physical characteristics of the postshock gas versus temperature in the collision of two minihaloes with the total masses $M = 10^7 M_\odot$ each at $z = 20$. The fractional ionization $x$ and H$_2$ abundance behind the shock are taken equal to their background values $x = 10^{-4}$ and $f(H_2) = 10^{-5}$, $f(HD) = 10^{-9}$. Immediately behind the shock concentration of H$_2$ increases very rapidly and reaches its maximum value $\sim 2 \times 10^{-3}$ promoting cooling of gas to $T \sim 200$ K. If H$_2$ cooling decreases the gas temperature below $T = 150 – 160$ K the abundance of HD molecules grows fast and HD cooling becomes dominant. It sets a runaway cooling on. At $T < 100$ K almost all the deuterium is converted into molecular form, and in one collisional time gas cools down to $T \approx 60$ K.

Haiman, Rees, & Loeb (1997) showed that the very first stars emit a large amount of photons in Lyman-Werner band (LW), which produces a hostile UV background for HD molecules. The characteristic time of photodissociation of HD can be estimated as $t_{diss} = 10^4/J_{LW}$ yr, where $J_{LW}$ is the LW flux in units of $10^{-21}$ ergs s$^{-1}$ cm$^{-2}$ Hz$^{-1}$ sr$^{-1}$ (Le Petit, Roueff, & le Bourlot, 2002, Johnson & Bromm,
Figure 1. Thermo-chemical evolutionary state vs temperature of a postshock gas parcel in the collision of minihaloes with the mass $M = 10^7 M_\odot$ each at $z = 20$: in the upper panel abundances of the species: electrons (solid), $H_2$ (dashed) and HD (dotted) lines – are shown; the lower panel shows the relative contribution of $H_2$ (solid) and HD (dashed) molecules to the total cooling rate.

2005). One can assume that the LW flux is by an order of magnitude equal to the ionizing flux from the first stars $J_{\text{LW}} \approx J_{21} \sim \exp[-(z - 5)]$ in the range $5 \leq z \leq 20$ (Ciardi et al., 2000). On the other hand, the characteristic formation time of HD is $t_{\text{form}} \sim 3 \times 10^6$ yr at $z = 10 - 20$. Thus, practically in the whole range of redshifts considered here photodissociation from the very first stars can be neglected: $t_{\text{disc}}$ becomes comparable to $t_{\text{form}}$ only at $z \lesssim 10$. At lower $z$ self-shielding seems to come into play. Indeed, for the masses of merging haloes $M > 10^6 M_\odot$ the characteristic column density of HD molecules in the shocked layer at final stages can be as high as $\sim 3 \times 10^{15}$ cm$^{-2}$, which is factor of 3 greater than the column density needed to provide optical depth in LW band of the order of one $\sim 10^{15}$ cm$^{-2}$ (Le Petit et al., 2002).

3 HD BEHIND SHOCK WAVES

Haloes of small masses ($M < 5 \times 10^6 M_\odot$) merge with slow relative velocities, and the post-shock temperature is so low that fractional ionization remains equal to its post-recombination value $x \sim 10^{-4}$. As a result, $(x, T)$ diagrams connecting $x(t)$ and $T(t)$ along evolutionary paths very weakly depend on halo masses, as seen from Fig. 2. Mergings of more massive haloes produce shocks with temperature $T \gtrsim 10^4$ K, so that fractional ionization can be as high as $x \sim 10^{-2}$. Immediately behind the shock $x$ starts growing from its pre-shock value to the corresponding equilibrium. However, as the characteristic collisional ionization time is longer than the cooling time, gradual increase of fractional ionization is accompanied by cooling, which in turn weakens the rate of collisional ionization. As a result, fractional ionization remains always lower that the equilibrium value determined by collisional ionization and radiative recombination. At temperature $T \gtrsim 10^4$ K $x$ reaches the maximum which depends on the postshock temperature, and
then goes down as shown in Fig. 2. This behavior restricts the efficiency of molecule formation: as seen from Fig. 1 H₂ saturates at $T \lesssim 10^3$ K when fractional ionization begins to decrease sharply. HD instead monotonously grows until practically all deuterium is converted into molecular form. The abundance of H₂ molecules at the end of baryon compression increases with the mass of the merging haloes, and the minimum temperature reached at this stage becomes lower. When it reaches $T \gtrsim 150$ K a rapid fractionation of HD molecules sets on. For larger halo masses HD cooling dominates and cools baryons down to the temperature of the CMB radiation. Fig. 3 connects variations of temperature and molecular concentrations (H₂ and HD) along the evolutionary paths for different masses of the haloes merging at $z = 20$. Their contribution to the total cooling is shown in Fig. 4 where open circles show the ending stage after one collision time $t_c$: while immediately after crossing the shock front the contribution from HD (left curve) is negligible, it increases in the course of gas cooling, and the transition to the regime with a predominance of HD cooling is clearly seen at $M \simeq 10^7 M_\odot$. The critical mass corresponding to the onset of a predominantly HD cooling is $M_{\text{crit}}^{\text{HD}} \sim 5 \times 10^8 (1 + z/20)^{-2} M_\odot$ as shown in Fig. 5. This value is factor of 5 higher than the minimum mass of the first objects found by Tegmark et al. (1997). One may conclude therefore, that at the lower end of masses the primordial gravitationally bound baryonic condensations stop cooling at relatively high temperature $T \sim 200$ K due to H₂ radiation, and HD molecules do not form in sufficient amount to cool the baryons further. However, soon later, at $z \approx 18$ more massive haloes can form and merge with a clear predominance of HD cooling, and in principle with lower masses of possible stars. Note, that the critical mass $M_{\text{crit}}^{\text{HD}}$ is fairly insensitive to the choice of cooling function. In particular, for the cooling function of Galli & Palla (1998), who included the collisional rates from Martin, Schwarz & Mandy (1996) and Forrey et al. (1997), in which the temperature range $T \sim 10^{10}$ K is approximately factor of 3 higher than H₂-cooling function of Hollenbach & McKee in our calculations, $M_{\text{crit}}^{\text{HD}}$ increases only by 10–15% in comparison with that shown in Fig. 5.

4 FRAGMENTATION OF THE COLD GAS LAYER

When cooled the shocked gas layer can fragment due to gravitational instability (Stone 1970, Elmegreen & Elmegreen 1978, Gilden 1984). For a layer formed in a collision of two clouds the necessary conditions for instability imply that $i)$ the characteristic growth time is shorter than the collision time, and $ii)$ the critical wavelength is shorter than the initial size of the clouds (Gilden 1984). The dotted line in Fig. 5 depicts the critical mass $M_{\text{crit}}^G$ of a merging halo gravitationally unstable in Gilden sense: merging haloes with individual masses above this line are unstable against fragmentation; $M_{\text{crit}}^G$ is approximated as $M_{\text{crit}}^G \simeq 10^7 [(1 + z)/20]^{-2} M_\odot$. It is readily seen that $M_{\text{crit}}^G$ is practically coincident with the mass corresponding to the transition to a predominance of HD cooling $M_{\text{crit}}^{\text{HD}}$. The explanation of this coincidence can be found in the fact that the shock compressed layers become unstable in Gilden sense only when HD molecules cool the compressed gas below $T \simeq 150$ K (Vasiliev & Shchekinov 2005). It is obvious therefore that all masses $M > M_{\text{crit}}^G$ at the latest stages are dominated by HD cooling, and as a consequence the fragments compressed by mutual action of ram pressure and gravitation are able to cool further down to $T < 100$ K. In the layer formed in a collision of two haloes with masses $M = 10^7 M_\odot$ the corresponding Jeans mass is $M_J = 10^3 M_\odot$, which is less than 1% of the baryonic mass involved into collision. Fig. 6 shows the dependence of Jeans mass in unstable layers on the mass of merging haloes and the redshift $z$ when the haloes merge: thick dotted white line delimits the haloes whose compressed layers are gravitationally unstable – all masses above this line are unstable. The thin solid lines are the iso-Jeans masses in compressed layers. When temperature in the compressed layer goes to the CMB value the Jeans mass becomes independent on redshift. Clarke & Bromm (2003) have estimated a lower limit of the masses of fragments formed in similar conditions, with baryons confined by ram pressure from shocks and gravitation. However, for the primordial gas they assumed the lower temperature limit $T = 200$ K determined by H₂ cooling. As a result, the masses of the fragments are systematically higher compared to our estimates. In order to obtain smaller values of the masses they had to assume that the compressed gas has cooled down to the CMB temperature due to cooling provided by CO molecules only after the gas is pre-enriched with metals.

The lower panel of Fig. 6 shows the gas temperature at the latest stages of gas compression, i.e. at $t = t_c$, for mergings of haloes with masses $M$ at redshift $z$. It is clearly seen that the compressed gas can cool down to the lowest temperature $T_{\text{CMB}}(z)$ in haloes with masses $M > M_{\text{crit}}^{\text{HD}}$ as their cooling is dominated by HD molecules. Note, that this result does not contradict the conclusions drawn from numerical simulations by Abel et al. (2000, 2002) and Bromm et al. (2002), because these simulations have been done for halo masses close to the minimum mass expected for first objects.

Fragmentation of a compressed gas layer can be initiated by thermal instability at the stages when H₂ and HD begin to dominate radiative cooling. In Fig. 7 (upper panel) temperature dependence of the effective cooling function $\Lambda(T)$ and its logarithmic derivative $\Phi = (\partial \ln \Lambda/\partial \ln T)_n$ are shown in the temperature interval $T < 10^4$ K, where HI radiative energy losses become unimportant and molecular cooling sets on. The curves corresponding to different masses are plotted in temperature interval from the initial value immediately behind the shock to the lowest value at $t = t_c$. In a non-steady cooling medium without external heating the condition for the isobaric mode to be unstable reads as $\Phi < 2$ (e.g., Shchekinov 1978). It is evident that this condition is fulfilled at $T \gtrsim 9000$ K due to cooling of H₂ molecules, and in the lower temperature end at $T \lesssim 100$ K where HD cooling dominates. The characteristic length of thermally unstable perturbations is $\lambda_R \sim c_s \tau_R$, where

$$\tau_R \sim \frac{3 kT}{2 \Lambda},$$

is the characteristic radiative cooling time, $c_s$ is the sound speed. The corresponding masses $M_R \sim \rho_R (\lambda_R/2)^3$, estimated for the parameters of a shocked gas, are shown in the lower panel of Fig. 7; here $\rho_R$ is the baryon density at the
Figure 2. The evolutionary paths connecting fractional ionization and gas temperature behind shocks in collisions of minihaloes of masses $10^6$, $2 \times 10^6$, $3 \times 10^6$, $5 \times 10^6$, $8 \times 10^6$, $10^7$ (from left to right) at $z = 20$. The arrows show the direction of evolution of a gas parcel starting from its state immediately behind the shock; paths for the first four masses practically coincide.

Figure 3. The evolutionary paths connecting variations of temperature and concentrations of $H_2$ and HD molecules for the same masses as in Fig. 2 (from left to right).
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Figure 4. The relative contribution of $H_2$ (right curve) and HD (left curve) into the total cooling for the same set of models shown in Fig. 2: increasing numbers correspond to the increasing masses in Fig. 2; open circles mark the state after one collision time $t_c$.

Figure 5. The mass-redshift diagram delimitating interval of halo masses, where HD molecules dominate in cooling at low temperatures (this is the range above the dash-dotted line), and halo masses with the postshock baryon layer being gravitationally unstable and subjected to further fragmentation (these masses above the dotted line). The thick solid line shows the $3\sigma$ fluctuations in the $\Lambda$CDM cosmology; the dashed line shows the minimum mass limit found by Tegmark et al (1997).

Stage when thermal instability begins. For the haloes of large masses the mass of fragments which can form through thermal instability is lower than the total mass of baryons and Jeans mass practically in the whole temperature range of compressed gas layers. This means that in these conditions thermal instability stimulates subsequent fragmentation of the compressed gas. The minimum mass of fragments expected from thermal instability $M_R \approx 10^{26} M_\odot^{-0.5} M_\odot$ can be as small as $M_R < 10 M_\odot$ for halo masses $M_h > 1.2 \times 10^7 M_\odot$. However, thermal instability does not work in the haloes of smaller masses when $M_R$ exceeds their baryon mass. As it seen from Fig. 7 this occurs at $M_h \approx 9 \times 10^6 M_\odot$. The
clouds formed under thermal instability are pressure supported, but not necessarily gravitationally bound – it is seen from Fig. 6 that thermal instability forms gravitationally bound clouds of stellar masses only in mergings of massive haloes \( M > (1 - 3) \times 10^7 M_\odot \). Therefore not always thermal instability can give rise directly to star formation, however collisions of clouds formed through it can be a stimulating factor.

The compressed layers gravitationally unstable against fragmentation, \( M > M_{\text{Gcr}} \), lie in the halo mass range where HD cooling can keep gas isothermal with temperature close to \( T_{\text{CMB}} \). Therefore, once the fragments are formed, they can afterwards either collapse homogeneously or brake further on smaller masses as prescribed by the hierarchical fragmentation scenario (Hoyle 1953). The possibility of the fragmentation cascading down to lower scales still remains under debate (see, e.g., discussion in Coppi et al. 2001, Glover 2005). An essential condition for such a cascading process is a pressure-free contraction regime. In practice, gravitational collapse turns out to settle onto a slow quasi-hydrostatic regime, which results in an efficient subsonic damping of perturbations (Abel et al. 2002, Bromm et al. 2002), and therefore a strong suppress of further fragmentation. The mass of dense clumps which can be reached in the hierarchical fragmentation scenario gives, however, an estimate of the lower mass limit of protostellar condensations expected at given physical conditions – the opacity limit for fragmentation (Low & Lynden-Bell 1976, Rees 1976). This mass is determined by a maximum density when the forming fragments become optically thick in the lines providing dominant radiative cooling. When HD molecules are the main cooling agent, a hierarchical fragmentation becomes optically thick in HD rotational lines, i.e the optical depth of a fragment at line centre becomes \( \tau_{\text{HD}} = 1 \), at densities \( \sim 10^9 - 10^{10} \text{ cm}^{-3} \). Even though at these densities most of hydrogen converts to molecular form in three-body collisions (Palla et al. 1983) its contribution to the total cooling remains negligible because of low temperatures. The corresponding Jeans mass at this stage is \( M_J \sim 30 T_{\text{CMB}}^{-2} n^{-1/2} M_\odot \sim 10^{-3} (1 + z)^{3/2} M_\odot \) (Vasiliev & Shchekinov 2005). For \( z = 10 - 20 \) this gives a relatively low mass limit: \( M_J \sim (0.03 - 0.1) M_\odot \). A similar estimate...
for the mass of fragments formed behind the shock waves with velocities $\geq 300$ km s$^{-1}$ from supernovae explosions was obtained by Uehara & Inutsuka (2000). One should stress though, that the condition $\tau_{HD} = 1$ implies that photons from HD rotational lines experience in average only one scattering, which seems insufficient to lock radiation inside a contracting cloud and stop further decrease of Jeans mass. From this point of view, the condition $\tau_{HD} = 3 - 5$ equivalent to about 10 scatterings of photons (Ivanov, 1973), gives apparently more accurate estimate of the opacity mass limit: the corresponding Jeans mass is $M_J \sim (0.01 - 0.03)M_\odot$.

For comparison, the estimates of the opacity mass limit of the fragments determined by $\mathrm{H}_2$ cooling vary from $3M_\odot$ to about $10^2 M_\odot$ (Nakamura & Umemura 1999) depending on the initial $\mathrm{H}_2$ abundance. Note, that the exact value of the opacity limit depends on dynamical regime of a collapsing cloud: the optical depth of a contracting cloud decreases with the velocity gradient as $|dv/dr|^{-1}$ (Sobolev, 1960). In numerical simulations $|dv/dr| \simeq 2v_T/R_J$ at late stages of the contraction (Abel et al. 2002), here $R_J$ is the Jeans length. Abel et al. (2002) stop their simulation when optical depth at line centre is 10. With accounting the factor 2 in the velocity gradient this corresponds to the effective optical depth of $5 - 10$ at the beginning of the stage when radiation becomes locked inside the contracting fragment.

5 CONCLUSIONS

In this paper we showed that

(i) In the hierarchical scenario of galaxy formation mergings of massive dark matter haloes, $M \gtrsim 8 \times 10^6(1 + z)/20^2 M_\odot$ develop dense baryon layers, where practically all the deuterium becomes confined into HD molecules, which then provide a very efficient radiative cooling;
(ii) Only slightly higher is the critical mass of the merging haloes when the shocked baryon layers can be unstable against gravitational fragmentation \( M > 10^7(1+z)/20 \) \( M_\odot \).

(iii) In these conditions the shocked baryons can cool down to the lowest temperature \( T \simeq T_{\text{CMB}} = 2.7(1+z) \) K;

(iv) The fragments formed through instability evolve then practically isothermally with \( T \sim T_{\text{CMB}} \), and can in principle undergo further sequential fragmentation, which stops when the minimum mass \( M_\odot \sim 10^{-3}(1+z)^{-3/2}M_\odot \) is reached.

(v) This minimum mass is smaller than the one expected when \( \text{H}_2 \) molecules control radiative cooling (Nakamura & Umemura 2002, Ciardi & Ferrara 2005). This means that the first stars can be less massive in galaxies with masses \( M > 8 \times 10^6(1+z)/20^{-2}M_\odot \), where HD cooling dominates.

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