Primordial gas cooling behind shock waves in merging halos

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Abstract

We investigate thermal regime of the baryons behind shock waves arising in the process of virialization of dark matter halos. We find a fraction of the shocked gas cooled by radiation of HD molecules down to the temperature of the cosmic microwave background (CMB): this fraction increases sharply from about $f_c \sim 10^{-3}$ for dark halos of $M = 5 \times 10^7 M_\odot$ to $\sim 0.1$ for halos with $M = 10^8 M_\odot$ at $z = 10$. We show, however, that further increase of the mass does not lead to a significant growth of $f_c$ – the asymptotic value for $M \gg 10^8 M_\odot$ is of 0.2. We estimate star formation rate associated with such shock waves, and show that it can be a small but not negligible fraction of the star formation connected with cooling by HI and H$_2$. We argue that extremely metal-poor low-mass stars in the Milky Way may have been formed from primordial gas behind such shocks.

Key words: cosmology: early universe, galaxies: formation, ISM: molecules, stars: formation, shock waves
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1 Introduction

It is widely believed that molecular hydrogen H$_2$ and its deuterated analogue HD determine thermodynamics of primordial gas and characteristics of the first stars (Lepp & Shull 1983, Shchekinov 1986, Palla et al., 1993, Palla et...
al., 1995, Galli & Palla 1998, Galli & Palla 2002, Stancil et al., 1998, Tegmark et al., 1997, Bougleux & Galli 1997, Puy & Signore 1997, Puy & Signore 1998, Uehara & Inutsuka 2000, Flower 2002, Nakamura & Umemura 2002, Flower 2002, Machida et al., 2005, Nagakura & Omukai 2005). In turn, the amount of H$_2$ and HD and their cooling efficacy greatly depend on dynamical and thermal regime of the gas. In particular, shock waves are argued to strongly enhance the rate of conversion of atomic hydrogen to its molecular form (Shchekinov & Entel 1983, Suchkov et al 1983, Shapiro & Kang 1987, Kang & Shapiro 1987, Shchekinov 1991, Ferrara 1998, Yamada & Nishi 1998, Uehara & Inutsuka 2000, Cen 2005, Machida et al., 2005, Shchekinov & Vasiliev 2006, Johnson & Bromm 2006). On the other hand, first stars have formed from the gas which most likely was processed through shock waves inevitably emerged during virialization of dark matter halos (Shapiro 1993, Haiman et al 1996, Tegmark et al., 1997, Abel et al., 2000, Abel et al., 2002), and therefore possible enhancement of H$_2$ and HD formation in these conditions can have important consequences for characteristics of the first stars (Shchekinov & Vasiliev 2002, Oh & Haiman 2002, Vasiliev & Shchekinov 2003, Shchekinov & Vasiliev 2006, Johnson & Bromm 2006).

When dark matter halos form in the hierarchy of mergings of small mass mini-halos (see review in (Barkana & Loeb 2001, Ciardi & Ferrara 2005)), shocks form and compress the baryons. At sufficiently large velocities of colliding flows ($v > 8$ km s$^{-1}$) fractional ionization in shocked gas increases above the frozen cosmological value, and results in acceleration of chemical kinetics of H$_2$ catalyzed by electrons. Moreover, collisions with velocities above the critical value $v > 8.6[(1 + z)/20]^{-1/6}$ km s$^{-1}$ lead to a rapid formation of HD and an efficient cooling down to the minimum temperature $T = T_{\text{CMB}} = 2.7(1 + z)$ (Shchekinov & Vasiliev 2006, Johnson & Bromm 2006, Vasiliev & Shchekinov 2005a, Vasiliev & Shchekinov 2005b). The latter result is inferred from simplified calculations of a Lagrangian fluid element behind the shock, and can only show principal possibility of the shocked gas to undergo an extreme cooling. Within a 1D code Ripamonti (2006) studied contribution of HD cooling in a contracting halo starting from an already virialized state free of molecular content, and found that a restricted region with baryon mass $\sim 200M_\odot$, where HD cooling is efficient can form even in low-mass halos, $M_h \sim 10^5M_\odot$ at $z = 20$, $v \simeq 3$ km s$^{-1}$. Explicit answer of how big is a fraction of cooled gas can be found only in hydrodynamic simulations. Full 3D simulations are expensive and time consuming. For these reasons they always are made within a specified realization of a random hydrodynamic field, and therefore represent only very restricted regions in the whole space of possible random hydrodynamic fields of a given spectrum. This therefore restricts the final thermodynamic state of baryons within a range corresponding to chosen interelations between the amplitudes of different wave modes. As a result, estimates of the fraction of cold baryons
able to form stars are biased by such limitations. From this point of view 1D hydrodynamical simulations of the chemistry and thermodynamics of a shocked primordial gas are important for a qualitative picture of what we can expect in principle in the conditions preceding formation of the first stars. In this paper we show 1D computations of chemical and thermal regime of the gas behind shock waves after a head-on collision of two clouds of equal sizes. As was pointed by (Gilden 1984), in supersonic cloud collisions the rarefaction time transverse to the symmetry axis is longer than the crossing time $t_c = 3R/2v_c$ – the time for the shock to pass through the entire cloud. In calculations we associate the collisional velocities of the clouds with the mass of the halo $M$ formed in this collision

$$v_c = (3^4\pi^3\Omega_m\rho_c)^{1/6}G^{1/2}M^{1/3}(1+z)^{1/2},$$

$\Omega_m$ is the matter closure parameter, $\rho_c = 3H_0^2/8\pi G$ is the critical density. We assume therefore that the minihalos move with the relative velocity equal to the virial velocity of the larger halo.

In Section 2 we describe dominant thermo-chemical processes of a shocked gas; Section 3 contains description of the postshock thermodynamics as 1D calculations predict; in Section 4 we discuss consequences for formation of the first stars; the discussion and summary of the results are given in Section 5.

Throughout the paper we assume a $\Lambda$CDM cosmology with the parameters $(\Omega_0, \Omega_\Lambda, \Omega_m, \Omega_b, h) = (1.0, 0.7, 0.3, 0.045, 0.7)$ and deuterium abundance $2.6 \times 10^{-5}$, consistent with the most recent measurements (Spergel et al. 2006).

## 2 Chemistry and thermal regime behind the shock

In the center of mass of the colliding baryon components of two merging minihalos a discontinuity forms at the symmetry plane, and two shock waves begin to move outward. We assume that collisionless dark matter components occupy considerably bigger volume and neglect gravitational forces on baryons. Therefore we describe propagation of the shock by single-fluid hydrodynamic equations with radiative energy losses appropriate for primordial plasma: Compton cooling, recombination and bremsstrahlung radiation, collisional excitation of HI (Cen 1992), $H_2$ (Hollenbach & McKee 1979, Le Bourlot et al., 1999) and HD (Flower 2000, Lipovka et al., 2005). Chemical and ionization composition include a standard set of species: H, H$^+$, H$^-$, He, He$^+$, He$^{++}$, $H_2$, $H_2^+$, D, D$^+$, D$^-$, HD, HD$^+$, $e$. The corresponding rates are taken from (Galli & Palla 1998, Stancil et al., 1998); the shock wave was computed in one crossing time $t_c$. We assumed a “top-hat” initial baryonic distribution.
in colliding haloes with density equal to the virialized value $18\pi^2\Omega_b\rho_0(1+z)^3$, while temperature is taken to be close to the cosmic microwave background (CMB) temperature $T_b = 1.1T_{\text{CMB}}$. This corresponds to a simplified picture when merging halos are already compressed to their virial radii, but not virialized yet. On the other hand, such assumptions about the initial thermal state of the colliding halos allow to better understand the role which shock compression of baryons plays in their ionization and chemical state in the process of virialization. The fractional ionization $x$, and the abundances of H$_2$ and HD molecules before the shock are taken equal to their background values $x = 10^{-4}$, $f$(H$_2$) = $10^{-5}$ and $f$(HD) = $10^{-9}$, respectively. Note, that adjustment of baryons to gravitational potential of dark matter and the corresponding steepening of density profiles in dark matter haloes occurs on timescales shorter than the time between mergers. In these conditions merging haloes may have already strongly stratified temperature distribution under efficient cooling in H$_2$ and HD lines (Ripamonti 2006). Thermal structure of baryons behind the shocks in merging nonuniform haloes will be described in a separate paper.

Fig. 1 shows typical distributions of temperature, fractional concentrations of H$_2$ and HD and their contribution to the total cooling behind the shock front at $t = (0.2, 0.6, 1)t_c$, for the halos merged at $z = 20$ with $v_c = 22$ km s$^{-1}$ corresponding to the total mass $M = 1.9 \times 10^7M_\odot$. Three qualitatively different cooling regimes can be distinguished in the temperature profile: in the high temperature range (1500 $< T <$ 7000 K) excitation of ro-vibrational levels of H$_2$ dominates, while in the intermediate range (200 $< T <$ 1500 K) only rotational lines contribute to the cooling, and in the lowest range ($T <$ 200 K) rotational cooling from H$_2$ molecules exhausts and only HD rotations support cooling – it is seen in the lower panel from comparison of the relative contributions of H$_2$ and HD cooling.

In this particular case a small fraction ($q \simeq 0.1$ by mass) of the shocked baryons close to the symmetry plane has cooled to the minimum possible value $T \simeq T_{\text{CMB}} = 2.7(1+z)$ due to cooling in rotational lines of HD. In general, the fraction of compressed baryons cooled down to a certain level depends on the relative velocities of the colliding clouds $v_c$: the larger the collisional velocity $v_c$, the stronger the gas compression after cooling, and the higher the contribution from HD cooling (Shchekinov & Vasiliev 2006). Fig. 2 shows the fraction of baryons $q_T(M)$ contained in several temperature ranges versus the halo mass: $T <$ 200 K, $T <$ 150 K, $T <$ 100 K, and at $T \simeq T_{\text{CMB}}$, at one crossing time $t = t_c$. It is seen that in the temperature range $T <$ 200 K cooled by H$_2$ radiation, $q_T(M)$ is equal to 0.06 for halo mass $10^7M_\odot$ and asymptotically (at $M \gg 2 \times 10^7M_\odot$) approaches 0.5. One should stress that compressed baryons can have temperature below 150 K only due to a dominant contribution from HD cooling. It is readily seen that $q_T(M)$ in the lower temperature range ($T <$ 100 K, and at $T = T_{\text{CMB}}$) is a very sharp function of the halo mass:
for instance, at redshift $z = 20$ (Fig. 2a) a two-fold increase of the mass from $10^7 M_\odot$ to $2 \times 10^7 M_\odot$ results in a two-order of magnitude increase of $q(T_{\text{CMB}})$ from $10^{-3}$ to 0.1. At higher masses the dependence flattens and asymptotically in the limit $M \gg 2 \times 10^7 M_\odot$ approaches 0.2. At lower redshifts gas density decreases and halo radius increases, as a result the collision time $t_c$ becomes longer and $q_T(M)$ shifts towards bigger halo masses, approximately by factor of 5 as seen from Fig. 2b for a collision occurred at $z = 10$. 

### 3 Star formation

Baryons cooled below temperature $T < 200$ K are normally thought to be able to fragment and initiate star formation. In gas layers compressed by shock waves gravitational instability of the cooled gas occurs naturally when the thickness of the layer equals the Jeans length. In order to understand the range of masses expected to form through the instability we applied Gilden (1984) criterion for a shock-compressed gas which 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. The corresponding critical mass $M_{\text{cr}}$ depends on the average temperature and density in the layer under consideration. Therefore, when halos merge with small relative velocities (corresponding to lower halo masses), smaller fraction of the compressed baryon mass cools down to sufficiently low temperatures to form an unstable layer, while mergings with higher relative velocities increase the fraction of gravitationally unstable baryons. Fig. 3 shows dependence of the halo masses with a given fraction of the compressed baryons unstable in Gilden sense vs redshift $z$. Each line is marked with symbols corresponding to a fraction of baryon mass $f_c(M, z)$ unstable against fragmentation: for instance, when halos with masses corresponding to the upper line $2.6 \times 10^7[(1 + z)/20]^{-2.4} M_\odot$ merge, half of their mass becomes compressed in a layer of a cold gas with temperature $T < 100$ K unstable in Gilden sense. The fraction of mass unstable against fragmentation increases with the mass of merging halos, approximately as $f_c(M, z) \simeq \exp[-(2.24/m_0)^{2.5}]$, where the halo mass is taken in the form $M_h = m_0[(1 + z)/20]^{-2.4} 10^7 M_\odot$. At the latest stages the unstable layers of $f_c(M, z)$ are dominated by HD cooling, so that fragments being formed in these conditions can reach the minimum possible temperature $\simeq T_{\text{CMB}}$. The corresponding Jeans mass in the unstable layer is $M_J \leq 2.3 \times 10^3 M_\odot v_{10}^{-1}[(1 + z)/20]^{1/2}$, which is considerably smaller than the baryonic mass of this layer; here $v_{10} = v_c/10$ km s$^{-1}$. With accounting (1) the Jeans mass in the unstable layer is $M_J \leq 1.3 \times 10^4 M^{-1/3} M_\odot$. This means that when halos with masses $M > 10^4 M_\odot$ merge more than one cold and dense clouds in the unstable layer can form and give rise to formation of stars.

Whether such fragments are the protostellar condensations evolving further in
a single massive star, or they are the nestles, where in the process of sequential (hierarchical, (Hoyle 1953)) or of a one-step (Nakamura & Umemura 1999) fragmentation a cluster of less massive stars is formed, depends sensitively on details of gravitational contraction and thermal evolution of the fragments (see discussion in (Coppi et al., 2001, Glover 2004)). However, both the mass of a central protostellar core in the former case, and the minimum mass of the protostellar condensation in the latter case are determined by the opaqueness of the contracting gas. (Vasiliev & Shchekinov 2005a) estimated this mass as \( M_J \sim 10^{-3}(1 + z)^{3/2} M_\odot \), what gives for \( z = 10 - 20 \) a relatively low mass limit: \( M_J \sim (0.03 - 0.1) M_\odot \). Therefore stars formed in such cold layers with a predominance of HD cooling on later stages, are anticipated in general to be less massive than those expected when thermodynamics of primordial gas is determined by \( \text{H}_2 \) cooling (Shchekinov & Vasiliev 2006).

The fraction of baryons in the universe able to cool below \( T = 100 \) K and form presumably low-mass stars behind shock waves in mergings can be estimated as

\[
f_c = \frac{\int_{M_c}^{M_{\text{max}}} MF(M) dM}{\int_{M_{\text{min}}}^{M_{\text{max}}} MF(M) dM},
\]

where \( M_c \) is the halo mass at a given redshift, where the fraction of cold \( (T \leq 100 \) K) baryons is equal to 1%, \( F(M) = dN/dM \) is the Press-Schechter mass function, \( M_{\text{min}} \), the minimum halo mass at a given redshift; Fig. 4 depicts \( f_c \) versus redshift. For \( M_{\text{min}} \) we have taken \( 10^3 M_\odot \), \( 10^4 M_\odot \) and \( 10^5 M_\odot \), however, only the last value seems meaningful, because for lower halo masses their baryonic content is too small and likely can be easily removed in tidal interactions. Independend on \( M_{\text{min}} \) the total fraction of baryons in the universe able to cool below \( T = 100 \) K and form stars approaches \( f_c \sim 0.1 \) at \( z = 10 \). For comparison we show in Fig. 4 fraction of baryons in the universe cooled by \( \text{H}_2 \) molecules and hydrogen atoms with \( M_c \) corresponds to \( T_{\text{vir}} = 400 \), \( 10^4 \) K, for both cases we assume that in virialized halos 8% of baryons can have temperature \( 200 \) K as calculated by (Abel et al., 1998), and integrate over the halo mass spectrum from \( M_{\text{min}} = 10^4 M_\odot \).

High fraction of baryons cooled down \( \leq 150 \) K in collisions of large halos gives high luminosity in HD lines. Earlier studies (Shchekinov 1986, Shchekinov 1991, Kamaya & Silk 2003, Mizusawa et al., 2005) mainly pay attention to the emission of clusters of dense clouds formed in very large proto-galaxies, \( M \geq 10^8 M_\odot \). As it was shown in the previous section during head-on collisions of smaller halos, \( M \sim 10^7 M_\odot \), a big fraction of baryonic mass can cool down to the conditions, where the emission in HD lines is the main process of energy losses. The luminosity in HD lines is estimated as \( L_{\text{HD}}^{\text{tot}} \sim \Lambda_{\text{HD}} M_{\text{HD}} x_{\text{HD}} / (\mu m_p) \), where \( \Lambda_{\text{HD}} \) is the cooling rate per molecule, \( M_{\text{HD}} = f_c (\Omega_b / \Omega_m) M_h \), \( x_{\text{HD}} \) is the
abundance of HD. For the final phases ($t = t_c$) of the collision of halos with the total mass $1.9 \times 10^7 M_\odot$, when the density in a compressed layer is $n \sim 400$ cm$^{-3}$ (see Fig. 1), the expected luminosity in HD lines can reach $\sim 5 \times 10^{35}$ erg s$^{-1}$. This is an upper limit for the luminosity from protogalaxies at the stages before their fragmentation. Further collapse and fragmentation increase the luminosity. This makes plausible detection of radiation in HD rotational lines from forming protogalaxies (Kamaya & Silk 2003).

Characteristic star formation time inside the formed fragments is determined by the baryon density in the fragments $t_{sf} = t_J/\varepsilon$, where $t_J$ is the Jeans time corresponding to the baryon density in cold layers $\rho_f$, $\varepsilon \ll 1$ is the star formation efficiency. Gas densities in cold layers when they fragment can be found from the condition $\rho_i v_c^2 = k \rho_f T_{\text{CMB}}/m_H$, which gives

$$n_f \simeq 0.02 M_7^{2/3} (1 + z)^3 \text{ cm}^{-3},$$

and

$$t_J = 5 \times 10^8 M_7^{-1/3} (1 + z)^{-3/2} \text{ yr},$$

so that for star formation efficiency $\varepsilon > 0.03$ characteristics time $t_{sf}$ remains shorter than the Hubble time for the halo masses $M_h > 10^7 M_\odot$. This means that star formation rate in merging halos is determined by the longest time — characteristic time between subsequent mergings. In these conditions star formation rate is proportional to the merger rate of the halos with the total mass above a critical value $M_{\text{crit}}(z)$ (Barkana & Loeb 2000, Santos et al., 2002)

$$\dot{M}_* = \frac{1}{2} \frac{\Omega_b}{\Omega_m} f_c \int M_{\text{crit}}^{M_1} F(M_1) dM_1 \int M_{\text{crit}}^{M_1+M_2} f_c(M_2, z) M_2 \frac{d^2P}{dM_2 dt},$$

where $M_0$ is the minimum mass of a smaller (absorbed) halo, $P = P(M_1, M_2, z)$ is the probability that a halo with mass $M_1$ merges with a halo of mass $M_2 > M_1$ at redshift $z$ (Lacey & Cole 1993); we explicitly assume here that only fraction of baryons $f_c(M, z)$ cooled down after merging is able to form stars. Therefore, if we substitute here the fraction $f_c$ of baryons cooled to $T < 150$ K as shown in Fig. 2, equation (5) will describe the contribution to the total star formation rate from the halos where thermodynamics of star forming mergers is controlled by HD cooling, and where low mass stars can, in principle, form. The critical mass for such mergings can be identified with the mass $M_{\text{HD}}$, where $f_c, \text{HD} \geq 0.01$. In Fig. 5 this contribution is shown by the dotted line. Mergings of halos with mass $M_0 \ll M_{\text{crit}}$ with the halo of critical (or overcritical) mass, involve obviously too small baryon mass fraction into sufficiently strong compression where HD molecules can cool gas
down to low temperature. Moreover, the compressed region deviates significantly from planar geometry, and Gilden criterion is not applicable to these conditions anymore. Therefore, in our estimates of star formation rate we assumed for \(M_0\) two values: \(M_0 = 0.5 \, M_{\text{crit}}\) and \(M_0 = 0.9 \, M_{\text{crit}}\). In addition we introduced in (5) factor \(f_{\perp} = 0.05\) accounting only approximately head-on collisions. Indeed, our conclusions about the role of HD cooling are based on the assumption of a head-on collision of merging halos, and can be valid only in a restricted range of the impact parameter when the shear motion is less important than the converging flow and the corresponding diverging shock waves. For this condition to be fulfilled the characteristic time of the Kelvin-Helmholtz instability of the shear flow \(t_{\text{KH}} \sim R/v_{\|}\) must be longer than the dynamical (crossing) time \(t_d \sim 2R/v_{\perp}\), where \(v_{\|}\) and \(v_{\perp}\) are the relative velocity component parallel and perpendicular the contact discontinuity: \(t_{\text{KH}} > t_d\). This gives \(v_{\|}/v_{\perp} < 1/2\), and as a result, only a fraction \(f_{\perp} = \Delta \Omega / 4\pi \simeq 0.05\) of mergers where the flows are approximately head-on. With this proviso, the two cases: \(M_0 = 0.5 \, M_{\odot}\) and \(M_0 = 0.9 \, M_{\odot}\), are shown in Fig. 5 by dotted and dot-dashed lines, respectively – the region between the two lines can be reasonable estimate of the star formation rate where thermodynamics of baryons is dominated by HD cooling. For comparison we add two lines corresponding to the critical mass of a halo with \(T_{\text{vir}} = 400, 10^4\) K (see, Barkana & Loeb 2000). It is obvious, that the number of mergers where HD cooling dominates, is only a small but not negligible fraction of all mergers: at \(z\) between 10 and 16 HD dominated star formation varies from 10 to 30 % of the one connected with \(10^4\) K halo mergers (dashed line), and from 3 to 20 % of star formation in 400 K mergers; in Fig. 5 for all low-mass mergers dominated by H\(_2\) cooling \(f_c(M, z) = f_{c, \text{H}_2} = 0.08\) has been assumed following (Abel et al., 1998). Note, however, that at earlier stages, \(z = 18 - 20\), mergers with a predominance of HD cooling contribute less than 0.5% compared to the 400 K mergers. From this point of view one can expect that in numerical simulations the regions with HD cooling can be missed.

It is therefore seen that a small fraction of baryons in mergers cools down to the lowest possible temperature \(T \simeq T_{\text{CMB}}\) and can give rise to formation of the first generation stars of low masses – lower than the masses formed under the conditions when H\(_2\) cooling controls thermal evolution of baryons. This fraction increases with the total mass of merging halos, and therefore in massive galaxies the population of low-mass first generation stars can be considerable. One should stress though that massive galaxies, formed in the hierarchical scenario through mergers of less massive systems, are quite expected to have been experienced already star formation episodes with the interstellar gas polluted by metals. However, it remains unclear whether the metals can become well mixed in a galaxy before it absorbs a new halo in next merger event, and simple arguments suggest the opposite. Indeed, the characteristic mixing time for the whole galaxy can be estimated as \(t_{\text{mx}} \sim \langle \delta e_j \rangle R/c_s\), where \(\langle \delta e_j \rangle > 1\) is mean density contrast between SNe ejecta and diffuse in-
terstellar gas, $R$ is the galaxy radius, $c_s$ is the sound speed or the velocity dispersion in diffuse gas; note that $R/c_s \sim t_c$. The characteristic time scale for the halo mass growth $t_m = [M_2 d^2 P(M_1, M_2, z)/dM_2 dt]^{-1}$, where $P(M_1, M_2, z)$ is the probability that a halo of mass $M_2$ absorbs a smaller halo $M_1$ (Lacey & Cole 1993). For the halos $M_2 \sim 10^7 M_\odot$ and $M_1 \sim 0.9M_2$ at $z = 20$, $t_m$ is about $\sim 8 \times 10^{14}$ s, which is comparable to the collision time $t_c = 3R/2v_c$, and is therefore $< t_{mx}$. Although some of the absorbed low mass halos can have been experienced star formation episodes before being merged, and thus can be already metal enriched (Scannapieco et al 2003), however a non-negligible fraction of them may have pristine composition. (Wyithe & Cen 2006) studied the star formation history before reionization and found that the era of Pop III star formation can be significantly prolonged. From this point of view one can expect possible important contribution from primordial star formation at redshifts $z \sim 3 – 4$ (Jimenez & Haiman 2006).

The existence of low mass Pop III stars is suspected from the observational point of view: recently discovered extremely metal-poor low-mass stars, as for instance a 0.8 $M_\odot$ star HE 0107-5240 (Christlieb et al. 2002, Christlieb et al. 2004) with [Fe/H]$= -5.3$, may be the first-generation stars. The question of whether stars with [Fe/H]$< -5$ are indeed Population III stars is still under discussion, partly because of overabundant carbon and nitrogen: [C/Fe]$= 4$, [N/Fe]$= 2.3$ in HE 0107-5240 (Bessell et al. 2004). From this point of view HE 0107-5240 can be a Population II star formed in already enriched interstellar gas (Umeda & Nomoto 2003). However, the possibility that this star has formed of pristine gas cannot be excluded: (Shigeyama et al. 2003) conclude that HE 0107-5240 is a Pop III star with the surface polluted by accreted interstellar gas already enriched with metals. In this scenario overabundant C and N in the envelope can be produced during the core helium flash as suggested by (Weiss et al. 2004, Schlattl et al. 2002).

4 Conclusion

In this paper we have shown that

- A small fraction of baryons in merging halos can cool down to very low temperatures close to the temperature of the cosmic microwave background;
- This fraction increases with the halo mass, and can reach $\approx 0.2$ for masses $M > 2 \times 10^7 M_\odot$ at $z = 20$ and for $M > 10^8 M_\odot$ for $z = 10$;
- Such cold gas is unstable against gravitational fragmentation, with the mass of the primary fragments decreasing for mergers of higher masses $M: M_f \leq 1.3 \times 10^4 M^{-1/3} M_\odot$; masses of protostars formed in gas cooled down by HD molecules are in general lower than those formed in conditions when H$_2$ cooling dominates;
• The contribution to the cosmic star formation rate of the mergers with a predominance of HD cooling, and therefore with presumably low mass first stellar objects, increases from less than 0.5% at redshift $z = 18-20$ to 10-30% at $z = 10$. Extremally metal-poor low mass stars in the Milky Way may have been formed in mergers dominated by HD cooling.

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Fig. 1. Upper panel: profiles of temperature (solid) and density (dash); middle panel: relative concentration of H$_2$ and HD molecules; lower panel: their relative contribution to the total cooling (H$_2$ – solid and HD – dashed), for baryons in two colliding halos with the total mass $M = 1.9 \times 10^{7} M_{\odot}$ at $0.2t_{c}$, $0.6t_{c}$, $t_{c}$; halos merged at $z = 20$. 
Fig. 2. Fraction of baryons cooled below temperature $T < 200$ K, $T < 150$ K, $T < 100$ K, and $T = T_{\text{CMB}}$ from top to bottom at $z = 20$ (left), and $z = 10$ (right).
Fig. 3. Lines with symbols depict halo masses vs redshift, where the fraction of baryon mass unstable in Gilden sense is at given level: 1%, 7%, 25%, 50% from bottom to top; straight thin solid line corresponds to a $3\sigma$ peak mass, dashed line shows the minimum mass obtained by (Tegmark et al., 1997), thick solid lines shows the minimum mass from (Shchekinov & Vasiliev 2006).
Fig. 4. Fraction of baryons $f_c$ in the universe cooled below 100 K. According to Gilden criterion these baryons can give rise to the formation of stars. Solid curve shows the fraction $f_c$ for $M_{\text{min}} = 10^3 M_\odot$ in eq. (2), dashed curve $- M_{\text{min}} = 10^4 M_\odot$, dotted $- M_{\text{min}} = 10^5 M_\odot$ dot-dashed and dot-dot-dashed curves correspond to $M_c$ with $T_{\text{vir}} = 400, 10^4$ K.
Fig. 5. Cosmic star formation rate: solid and dashed lines correspond to the halos with $T_{\text{vir}} = 400, 10^4$ K; dotted – the halos with mass $M_{\text{crit}} = M_{\text{HD}}$, where $f_{\text{c, HD}} \sim 0.01$ and $M_0 = 0.5M_{\text{crit}}$, and dot-dashed line – $M_0 = 0.9M_{\text{crit}}$ (see text for details); in all cases $\varepsilon = 0.1$. 