Low-temperature primordial gas in merging halos

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Thermal regime of the baryons behind shock waves arising in the process of virialization of dark matter halos is governed at certain conditions by radiation of HD lines. A small fraction of the shocked gas can cool down to the temperature of the cosmic microwave background (CMB). We estimate an upper limit for this fraction: at $z = 10$ it increases sharply from about $q_{H} \sim 10^{-3}$ for dark halos of $M = 5 \times 10^{7} M_{\odot}$ to $\sim 0.1$ for halos with $M = 10^{8} M_{\odot}$. Further increase of the halo mass does not lead however to a significant growth of $q_{H}$ – the asymptotic value for $M \gg 10^{8} M_{\odot}$ is of 0.3: We estimate star formation rate associated with such shock waves, and show that they can provide a small but not negligible fraction of the star formation. We argue that extremely metal-poor low-mass stars in the Milky Way may have been formed from primordial gas behind such shocks.

1 Introduction

Formation of the first stars is determined by energy losses in ro-vibrational lines of molecular hydrogen $H_{2}$ and its deuterated analogue HD (Lepp & Shull 1983; Shchekinov 1986; Puy et al. 1993; Palla, Galli & Silk 1995; Galli & Palla 1998, 2002; Stancill, Lepp & Dalgarno 1998; Tegmark et al. 1997; Puy & Signore 1997, 1998; Uehara & Inutsuka 2000; Flower 2002; Nakamura & Umemura 2002; Machida et al. 2005, Nagakura & Omukai 2005). In turn, the amount of $H_{2}$ and HD and their ability to cool gas greatly depend on dynamical and thermal regime of the gas. In particular, shock waves strongly enhance the rate of conversion of atomic hydrogen to its molecular form (Shchekinov & Entel 1983; Suchkov, Shchekinov & Edelman 1983; Shapiro & Kang 1987; Kang & Shapiro 1992; Shchekinov 1991; Ferrara 1998; Yamada & Nishi 1998; Uehara & Inutsuka 2000; Cen 2005; Machida et al. 2005; Shchekinov & Vasiliev 2005; Johnson & Bromm 2005). On the other hand, the first stars have formed from the gas processed by the shock waves unavoidable in the process of virialization of dark matter halos (Shapiro 1993; Haiman, Thoul & Loeb 1996; Tegmark et al. 1997; Abel, Bryan & Norman 2000, 2002). Therefore possible enhancement of $H_{2}$ and HD in these conditions can have important consequences for characteristics of the first stars (Oh & Haiman 2002; Johnson & Bromm 2005; Shchekinov & Vasiliev 2005).

When dark matter halos merge, shock waves form and compress the baryons (see discussion in (Barkana & Loeb 2001; Ciardi & Ferrara 2004)). At sufficiently large velocities of colliding flows ($v > 8$ km s$^{-1}$) fractional ionization in shocked gas increases above the frozen cosmological value, and speeds up chemical kinetics of $H_{2}$ molecules. Collisions with velocities above $v > 8.6[(1 + z)/20]^{-1/6}$ km s$^{-1}$ may lead to a rapid formation of HD and an efficient cooling down to the minimum temperature $T = T_{\text{CMB}}$ = 2.7$(1 + z)$ (Vasiliev & Shchekinov 2005; Johnson & Bromm 2005; Shchekinov & Vasiliev 2005). It is worth noting that HD can also play major role in central regions of collapsing dark halos, where a high-density environment favours transition of D into molecular form, so that even in low-mass halos HD cooling can dominate (Ripamonti 2007).

Explicit answer of how large is the fraction of cold gas in merging halos can be found only in hydrodynamic simulations. Very recently (Maio et al. 2007) performed 3D SPH simulation of structure formation with accounting of HD chemistry. They found that incorporation of effects from HD cooling increases clumpiness of gas, i.e. clouds are denser and more compact with respect to the case when only $H_{2}$ cooling is considered. However, full 3D simulations are time consuming, and always are made within a particular realization of a random hydrodynamic field. They therefore represent only very limited regions in the space of possible random hydrodynamic fields of a given spectrum. This circumstance restricts the final thermodynamic state of baryons within the domain corresponding to the chosen interrelations between the amplitudes of different wave modes. As a result, estimates of the fraction of the cold baryons able to form stars are biased by such limitations. At such circumstances 1D hydrodynamical simulations of chemistry...
and thermodynamics of shocked primordial gas can play an auxiliary role for understanding of what in principle can be expected in the conditions preceding formation of the first stars. In this paper we use 1D planar computations to model chemical and thermal regime of gas behind the shock waves after a head-on collision of two clouds of equal sizes. This approach is justified by the fact that in supersonic cloud collisions the rarefaction motion transverse to the symmetry axis takes longer than the collision time $t_c = 3R/2v_c$ (Gilden 1984). On the other hand, the estimates of the fraction of baryons cooled down by HD molecules we obtain within this approximation are obviously upper limits.

At the stages when the halos are close to merge their velocities are of the order of the virial value corresponding to the total mass of the halos. We therefore connect the collisional velocities of the clouds to the mass of the halo $M$ formed in this collision

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

$\Omega_m$ is the matter closure parameter, $\rho_c = 3H_0^2/8\pi G$, the critical density.

In Section 2 we describe dominant thermal and chemical processes in shocked gas; in Section 3 we discuss consequences of HD cooling for formation of the first stars; summary is given in Section 4.

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. 2007).

**2 Chemistry and thermal regime behind the shock**

In the center of mass of the colliding baryon components a discontinuity forms at the symmetry plane, and two shock waves begin to move outwards. We assume that during the merging 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. Energy equation includes radiative losses typical in primordial plasma: Compton cooling, recombination and bremsstrahlung radiation, collisional excitation of HI (Cen 1992) H$_2$ (Galli & Palla 1998) and HD (Flower 2000; Lipovka, Núñez-López & Avila-Reese 2005). More accurately The H$_2$ cooling function have been recalculated by Le Bourlot, Pineau des Forests & Flower (1999), which which differs considerably (by factor of 2) from the Le Bourlot, Pineau des Forests & Flower function only at $T > 4000$ K (Glover 2005).

Chemical and ionization composition include a standard set of species: H, H$^+$, e, H$^{-}$, He, He$^+$, He$^{++}$, H$_2$, H$_3^+$, D, D$^+$, D$^{-}$, HD, HD$^+$; The corresponding rates are taken from (Galli & Palla 1998; Stancil et al. 1998); the shock wave was computed on one collision time $t_c$. H$_2$ dissociation rate by atomic hydrogen is taken from Mac Low & Shull (1986) – although this reaction is important only at $T > 6000$ K, it restricts the production of H$_2$ molecules by factor of 1.5.

For our simulations we use a 1D planar Lagrangian scheme similar to that described by Thoul & Weinberg (1995). As a standard resolution we have used 700 zones over the computational region, and found a resonable convergence: several test computations with 1500 zones showed significant deviations only in the very central zones of 1% in mass, while in the rest the deviation is normally less than 10%. We assume a “top-hat” initial baryonic distribution in colliding halos with the density equal to the virialized value $18\pi^2\Omega_b\rho_0(1 + z)^3$, while temperature is taken close to the cosmic microwave background (CMB) temperature $T_b = 1.1T_{CMB}$. This corresponds to a simplified picture when merging halos are already compressed to their virial radii, but not yet virialized, i.e. systematic large scale motions did not converged into thermal energy. This assumption allows to better understand the role which shock compression of the baryons plays in their ionization and chemical state in the course 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 $x = 10^{-5}$, $f(H_2) = 10^{-6}$ and $f(\text{HD}) = 10^{-10}$.

Fig. 1 shows typical distributions of the temperature, the abundances of H$_2$ and HD and their relative contributions 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 the velocity $v_c = 20$ km s$^{-1}$, corresponding to the total mass $M = 1.4 \times 10^7 M_\odot$. Three qualitatively different cooling regimes can be distinguished in the temperature profiles: 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; in the lowest temperature range ($T < 200$ K) 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. At later times, $t \sim t_c$ a non-monotonous behaviour of temperature is due to the fact that at these stages gas enters the shock front with lower velocities, so that the post-shock temperature becomes below the limit when collisional dissociation of H$_2$ molecules is important. As a result, all molecular hydrogen formed behind the front survives and stimulates rapid cooling.

In this particular case a small fraction ($q \simeq 0.1$ by mass) of the shocked baryons close to the symmetry plane cools to the minimum possible value $T \simeq T_{CMB} = 2.7(1 + z)$ due to cooling in rotational lines of HD. In general, the fraction of compressed baryons cooled down to a given temperature 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. 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 $T \simeq T_{CMB}$ after one crossing time $t = t_c$. In
the temperature range $T < 200$ K where cooling in H$_2$ lines is dominant, $q_T(M)$ increases from 0.1 for the halo mass $10^7 M_\odot$ to the asymptotical (at $M \gg 2 \times 10^7 M_\odot$) value 0.6. Compressed baryons can have temperature below 150 K only due to contribution from HD cooling. In the lower temperature ranges ($T < 100$ K, and at $T = T_{\text{CMB}}$) $q_T(M)$ 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 $3 \times 10^{-3}$ to 0.3. At higher masses the dependence flattens and asymptotically in the limit $M \gg 2 \times 10^7 M_\odot$ approaches 0.4. At lower redshifts gas density decreases and the radiation cooling time becomes longer. As a result, $q_T(M)$ shifts towards larger halo masses, approximately as $(1 + z)^{-3/2}$; Fig. 2b shows $q_T(M)$ for collisions occurred at $z = 10$.

3 Star formation

Baryons cooled below $T < 200$ K are thought to be able to fragment and initiate star formation. In gas layers compressed by shock waves gravitational instability of the cold gas occurs naturally when the thickness of the layer equals the Jeans length. In order to estimate the range of masses expected to form through the gravitational instability we apply (Gilden 1984) criterion for the shock-compressed gas, which implies 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: when the halos merge with low relative velocities (corresponding to lower halo masses), only a small fraction of the compressed baryon mass can cool down to sufficiently low temperatures to form an unstable layer. Mergings with higher relative velocities increase the fraction of gravitationally unstable baryons. Fig. 3 shows the redshift dependence of the halo masses with a given fraction of the compressed baryons unstable in Gilden sense. Each line is marked with symbols corresponding to a given fraction of the baryon mass $q_f$ unstable against fragmentation: for instance, when halos with masses corresponding to the upper line $M = 2.5 \times 10^7 [(1 + z)/20]^{-2.2} M_\odot$ merge, half of their mass becomes compressed in a cold layer with temperature $T \leq 100 - 150$ K unstable in Gilden sense. Coincidently, the thermal evolution is governed by HD cooling, when the temperature falls below 150 K. At the latest stages the unstable layers are dominated by HD cooling, so that fragments 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 $M_J \leq 1.3 \times 10^4 M_\odot^{-1/3} M_\odot$. This means that when halos with masses $M > 10^4 M_\odot$ merge more than

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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 $M = 1.4 \times 10^7 M_\odot$ at $0.2 t_c$, $0.6 t_c$, $t_c$; 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).
The fraction of baryons in the universe able to cool below $T = 150$ K and to form presumably low-mass stars behind shock waves in mergings can be estimated as

$$f_c = \epsilon_\perp \int_{M_c}^{M_{\text{max}}} q_{\text{vir100}} (M, z) MF(M) \, dM,$$

where $F(M) = dN/dM$ is the Press-Schechter mass function, $M_c$ is the halo mass at a given redshift presumably formed through merging of two $M_c/2$ halos, where the fraction of cold ($T \leq 150$ K) baryons is equal to 1%. $M_{\text{min}}$, the minimum halo mass at a given redshift. We assume that the halos with the fraction of cold baryons less than 1% do not significantly contribute to $f_c$ or the star formation rate. Here we introduced factor $\epsilon_\perp = 0.05$ 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 $t_{KH} \sim R/v_\parallel$ must be longer than the dynamical (collision) time $t_d \sim 2R/v_\perp^{-1} \epsilon_\perp > t_d$. This gives $v_\parallel/v_\perp < 1/2$, and as a result, only a fraction $\epsilon_\perp \simeq \Delta \Omega/4\pi \simeq 0.05$ of mergers where the flows are approximately head-on. In Introduction we stressed that the estimate of the cold baryon fraction $f_c$ within the approximation of head-on collisions is an upper limit. Introducing the factor $\epsilon_\perp$ attempts to quantify more accurately the fraction $f_c$. However, the estimate (2) still has a meaning of an upper limit, particularly because $i)$ in (2) we assumed explicitly that the spectrum $F(M)$ above $M_c$ is formed through merging of equal masses, and $ii)$ we do not account here (negative) feedback from the stars have already formed during the merging.

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. Independent on $M_{\text{min}}$, the total fraction of baryons in the universe able to cool below $T = 150$ K and form stars approaches $f_c \sim 0.1 \epsilon_\perp$ at $z = 10$. This fraction may increase if the halos are clustered as suggested by Barkana & Loeb (2004) and Cen (2005). For comparison we show in Fig. 4 the fraction of baryons in the universe cooled by H$_2$ molecules and hydrogen atoms with the lower limit $M_c$ in the integral (2) corresponding to the virial mass $M_c = M_\epsilon$ at $T_{\text{vir}} = 400$, $10^4$ 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 $M_{\text{min}} = 10^4 M_\odot$.

Characteristic star formation time inside the formed fragments is determined by the baryon density in there $t_{sf} = t_{\text{Jeans}}/\epsilon$, where $t_{\text{Jeans}} = \sqrt{3\pi/32G\rho}$ is the baryon Jeans time in cold layers, $\epsilon \ll 1$ is the star formation efficiency. Gas density $\rho_f$ in cold layers when they fragment can be found from the condition $\rho_f v_f^2 = k \rho_f T_{\text{CMB}}/m_H$, which gives

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

where $M_7$, $(1 + z)^3$ is the star formation efficiency.

Fig. 3 Lines with symbols depict halo masses vs redshift, where the fraction of baryon mass unstable in Gildem sense is at given level: 1%, 7%, 25%, 50% from bottom to top; straight thin solid line corresponds to a 3σ peak mass, dashed line shows the minimum mass obtained by (Tegmark et al. 1997), thick solid line shows the minimum mass from (Shchekinov & Vasiliev 2006).
For star formation efficiency \( \varepsilon > 0.03 \) the characteristic time \( t_{\varepsilon} \) 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 – the characteristic time between subsequent mergers. In these conditions star formation rate is proportional to the merger rate of the halos with the total mass above the critical value \( M_c(z) \) (Barkana & Loeb 2000; Santos, Bromm & Kameikowski 2002)

\[
\dot{M}_s = \frac{\Omega_m}{2 \Omega_b} (1 + z)^{-3/2} t_{\varepsilon} \int_{M_{\text{min}}}^{M_c} dM_1 F(M_1) \int_{M_c}^{M_1} dM_2 q_f(M_2, z) M_2 \frac{d^2P}{dM_2 dz},
\]

(4)

where \( P = P(M_1, M_2, z) \) is the probability that a halo with mass \( M_1 \) merges to a halo of mass \( M_2 > M_1 \) at redshift \( z \) (Lacey & Cole 1993); we explicitly assume here that only fraction of baryons \( q_f(M, z) \) cooled after merging below 200 K is able to form stars. Therefore, if we substitute here the fraction \( q_f \leq 150(M) \) of baryons cooled to \( T < 150 \) K, equation (5) will describe the contribution to the total star formation rate from the merging halos where thermodynamics is governed by HD cooling, and where low mass stars may form. It is obvious that mergers of halos of masses \( M_{\text{min}} \lesssim M_c \) with the halo of critical (or overcritical) mass, involve too small baryon mass fraction into sufficiently strong compression where HD molecules can cool gas. Moreover, in this limit the compressed region deviates significantly from planar geometry, and Gilden criterion is not applicable. Therefore, in our estimates of star formation rate we assume for \( M_{\text{min}} \) two values: \( M_{\text{min}} = 0.5 M_c \) and \( M_{\text{min}} = 0.9 M_c \) with \( M_c \) defined as above as the mass where the fraction of cold baryons \( (T \leq 150 \) K) after merging is equal to 1%; at equal densities of merging halos their sizes differ in the first case by \( \approx 20\% \), while in the second only by 4\%. Therefore, in the estimates of the star formation rate with a predominance of HD in thermodynamics, we neglect contribution from mergers of masses significantly smaller than the critical mass. On the other hand, it is seen from Fig. 3 that halos with \( \approx 2M_c \) have already \( \approx 50\% \) of their mass colder than \( T < 150 \) K and unstable in Gilden sense. This means that the upper limit \( 2M_c \) in the second integral of (5) counts practically all halos whose star formation is regulated by HD cooling. With this proviso, the two cases: \( M_{\text{min}} = 0.5 M_c \) and \( M_{\text{min}} = 0.9 M_c \), are shown in Fig. 5 by two solid lines – the region between them can be a reasonable estimate of the star formation rate governed by HD cooling.

For comparison in Fig. 5 we add two lines for which \( M_c \) in (5) is replaced by the virial mass \( M_* \) 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 (although not negligible) fraction of all mergers: at \( z \) between 10 and 16 star formation governed by HD varies from 15 to 30\% of the one connected with \( 10^4 \) K halo mergers (the lower dashed line), and 0.5 to 10\% of star formation in 400 K mergers (the upper dashed line); in Fig. 5 for all low-mass mergers dominated by HD cooling \( q_f(M, z) = q_f, H_2 = 0.08 \) is assumed following (Abel et al. 1998). 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 think that in numerical simulations the regions with HD cooling are apparently missed.

It is therefore seen that a small fraction of baryons in mergers cools down to the lowest possible temperature \( T \approx T_{\text{CMB}} \), and can give rise to formation of the first generation stars of low masses – lower than the masses formed under the conditions when \( H_2 \) controls thermal evolution of baryons. This fraction increases with the total mass of merging halos, and thus in massive galaxies the population of low-mass stars of the first generation can be considerable. One should stress though that massive galaxies, formed in the hierarchical scenario through mergers, are quite expected to have been already experienced 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. Simple arguments suggest the opposite.

Fig. 4 Fraction of baryons \( f_c \) in the universe cooled below 150 K. According to Gilden criterion these baryons can give rise to the formation of stars. Solid curves show the fraction \( f_c \) for \( M_{\text{min}} = 10^5 M_\odot, 10^6 M_\odot, 10^7 M_\odot \) (bottom to top) in eq. (2). Dashed curves depict two cases when the lower limit in the r.h.s. of (2) is equal to the virial mass \( M_v = M_c \) with \( T_{\text{vir}} = 400, 10^4 \) K (top to bottom); the lower limit \( M_{\text{min}} \) in the denominator of the r.h.s. of (2) is taken for these two curves to be \( 10^4 M_\odot \).
can be estimated as the characteristic mixing time for the whole galaxy to the collision time.

The existence of low mass Pop III stars is suspected from the observational point of view: recently discovered extremely metal-poor and low-mass stars, as for instance a slow mixing.

Although some of the absorbed low mass halos can have been also experienced star formation episodes before being merged, and thus can be already metal enriched (Scannapieco, Schneider & Ferrara 2003), however a non-negligible fraction of them may have pristine composition due to a slow mixing.

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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