Primordial gas cooling behind shockwaves

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Abstract

We investigate thermal evolution of the baryons behind shock waves arising in the process of virialization of dark matter halos. We find the 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 $M = 10^7 M_\odot$ to ~ 0.1 for halos with $M = 2 \times 10^7 M_\odot$ at $z = 20$. We show, however, that further increase of the mass does not lead to a significant growth of f_c: the assymptotic value for $M \gg 2 \times 10^7 M_\odot$ is of 0.2. Also we find the fragmentation of the shocked gas layer can be possible in a cold gas dominated by HD cooling, where the temperature $T < 100$ K.

Introduction

When dark matter halos form in the hierarchy of mergings of small mass minihalos (see review Ciardi & Ferrara 2005), shocks form and compress the baryons. Apparently, all subsequent evolution of baryons in dark halos and their condensation into stars is determined by these shock waves.

Here we present the 1D computations of chemical and thermal evolution of the gas behind shock waves after a head-on collision of two clouds of equal sizes, with a special attention on conditions when HD molecules can be dominant cooling agent in a pregalactic gas (Vasiliev & Shchekinov 2005).

Model

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 the primordial plasma in the 1D Lagrangian hydrodynamics.

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 shock wave was computed in one collision time t_c. The initial baryonic density in colliding halos is taken equal to the virial value $18\pi^2\Omega_b\rho_0(1+z)^3$, while the temperature close to the radiation temperature $T_b = 1.1T_{\rm cmb}$. The fractional ionization x, and the abundances of H_2 and HD molecules before the shock are taken equal to the values $x = 10^{-4}$, $f(H_2) = 10^{-5}$ and $f(HD) = 10^{-9}$, respectively.

Thermal and chemical evolution of postshock gas

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 $t = t_c$, for the halos merged at $z = 20$ with velocity $v_c = 22$ km s^{-1} corresponding to the total mass $M = 1.9 \times 10^7 M_\odot$. Two qualitatively different cooling regimes are clearly seen in the temperature profile: in the temperature range ($200 < T < 10^4$ K) excitation of H_2 ro-vibrational levels dominates, and in the low temperature 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.

Fig. 2a shows fraction of baryons $q(T)$ in several temperature bins: $T < 200$ K, $T < 150$ K, $T < 100$ K, and $T \simeq T_{\rm cmb}$, at one collision time $t = t_c$ as it varies versus halo mass. It is seen that in the temperature bin $T < 200$ K cooled by H_2 cooling $q(T)$ equals 0.06 for the halo mass $10^7 M_\odot$ and asymptotically (at $M \gg 2 \times 10^7 M_\odot$) tends to 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 obvious that

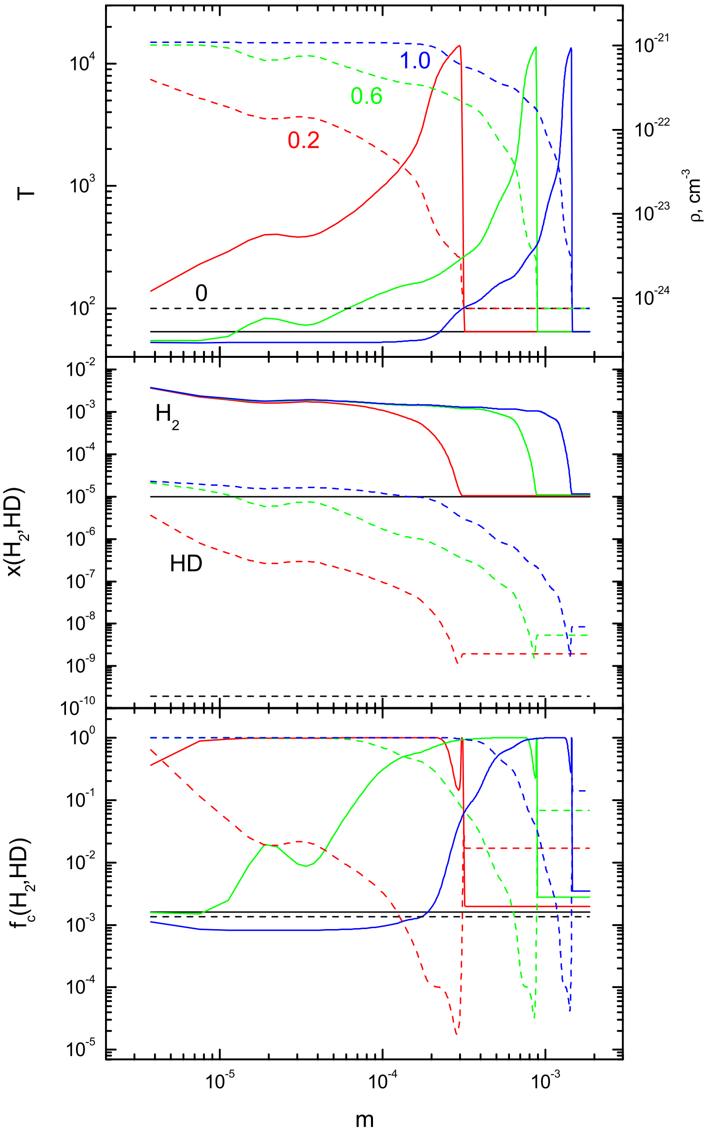

Figure 1: Profiles of density (solid) and temperature (dash) (upper panel), abundances of H_2 (solid) and HD (dash) molecules (middle panel), and their relative contribution to the total cooling (lower panel) for baryons in two colliding halos with the total mass $M = 1.9 \times 10^7 M_\odot$ at $t = 0,\ 0.2,\ 0.4,\ 1.0\ t_c$; the halos merged at $z = 20$.

$q(T)$ in the lower temperature bins ($T < 100$ K, and $T = T_{\bf cmb}$) is a very sharp function of the halo mass: for instance, at redshift $z = 20$ 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 $q(T_{\rm cmb})$ from 10^{-3} to 0.1. At higher masses the dependence becomes more flat and asymptotically in the limit $M \gg 2 \times 10^7 M_\odot$ approaches 0.2. At lower redshifts the gas density decreases and the halo radius increases, as a result the collision time t_c becomes longer and $q(T)$ shifts towards bigger halo masses, approximately by factor of 5 as seen from Fig. 2b for a collision occured at $z = 10$.

Star formation

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

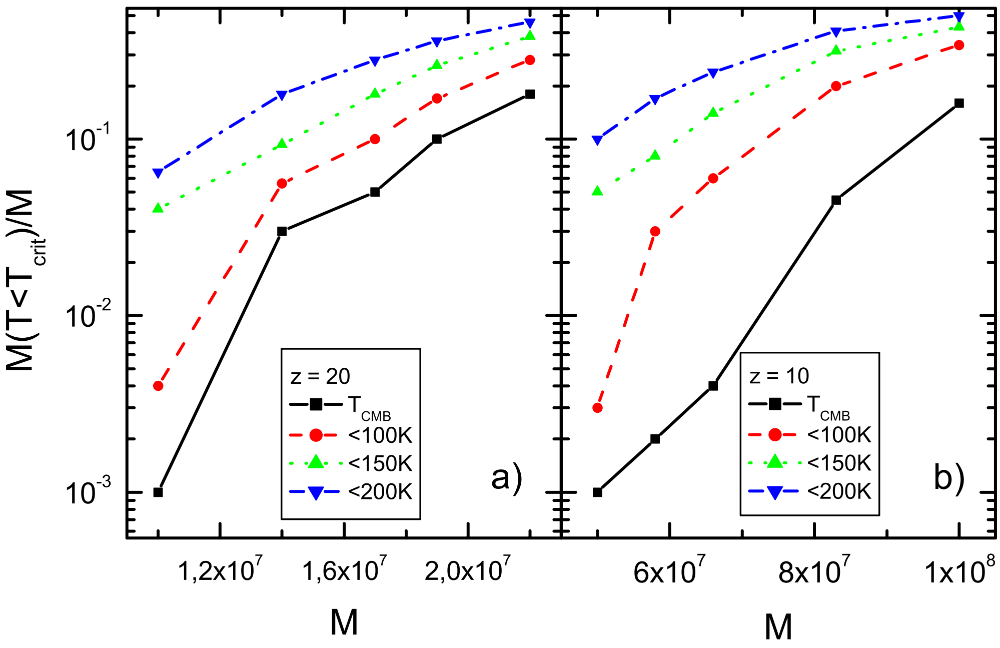

Figure 2: Fraction of baryons cooled below temperature $T < 200$ K, $T < 150$ K, $T < 100$ K, and $T \simeq T_{\rm cmb}$ at $t = t_c$ (from top to bottom).

clouds. The corresponding critical mass $M_{\rm cr}$ 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 some fraction of the compressed baryons unstable in the Gilden sense. Each line is marked with symbols corresponding to a fraction of baryon mass $f(M)$ unstable againts 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 the Gilden sense. At the latest stages the unstable layers of $f(M)$ are dominated by HD cooling, so that fragments being formed in these conditions can reach the minimum possible temperature $\simeq T_{\rm cmb}$. 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 the unstable layer; here $v_{10} = v_c/10$ km s^{-1}.

Whether such fragments are the protostellar condensations evolving further in a single massive star, or they are the nestles where in the process of hierarchical (Hoyle 1953) fragmentation a cluster of less massive stars is formed, depends sensitively on details of gravitational contraction of the fragments (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 (2005) 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: $M_{\rm J} \sim (0.03-0.1)M_\odot$.

Conclusions

In this paper we showed that

- the fraction of the shocked gas cooled by radiation of HD molecules down to the CMB temperature can be a significant part of the whole baryonic mass of merging halos: $f_c \sim 10^{-3} - 0.2$;

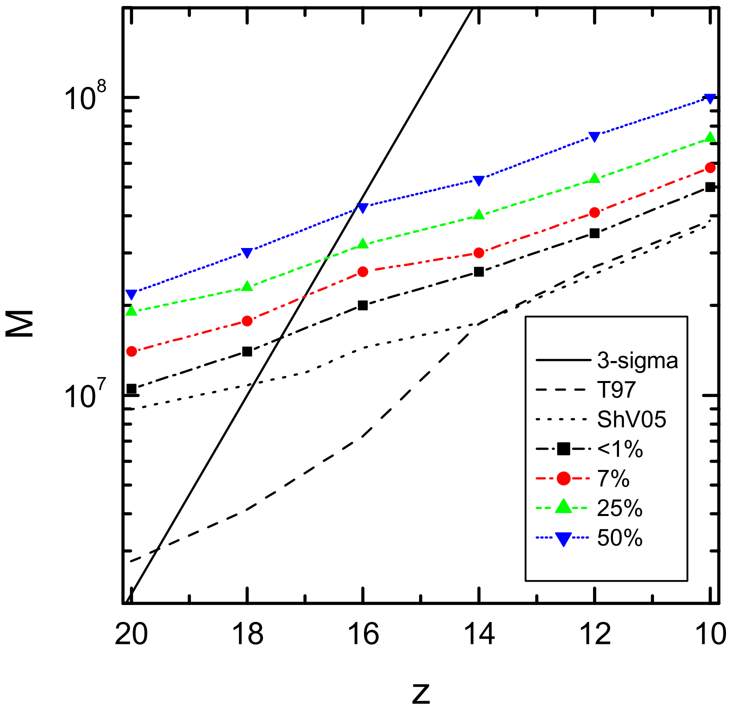

Figure 3: Mass of halo, where fraction of gravitationally unstable baryonic mass is 1%, 7%, 25%, 50% (lines with symbols from bottom to top). The 3σ peaks line (solid), critical masses Tegmark et al 1997 (dashed) and Shchekinov & Vasiliev 2005 (dotted).

- the fragmentation of the shocked gas layer can be possible in a cold gas dominated by HD cooling, where the temperature $T < 100$ K;
- the Jeans mass of fragments in the shocked gas can reach the value $M_J \leq 2.3 \times 10^3 M_\odot v_{10}^{-1}[(1+z)/20]^{1/2}$.

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