H_2 and HD cooling in gravitational collapses

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Introduction

The Standard Big Bang Nucleosynthesis (SBBN) theory explains the formation, during the first hundred seconds, of the light nuclei H, D, He, Li, Be and B. For this reason, the primordial chemistry was the chemistry of these light elements. The cosmological recombination allowed the formation of the first molecules. Indeed, the apparition of the first neutral atoms allowed charge exchanges with other, still ionized species. The main primordial molecules are H_2 and HD. These molecules acted a very important role in the formation of the first stars, as they are believed to be the only efficient cooling agent during gravitational collapses of the gas clouds leading to the formation of the Population III stars.

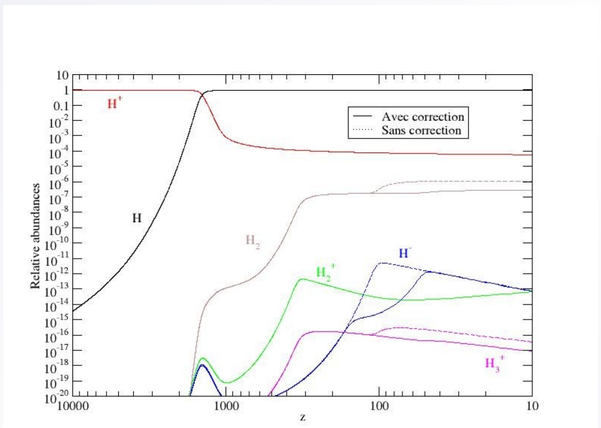
We compute here thermal functions of H_2 and HD using the most recent collision rates in two different scenarios: the SBBN scenario and the non-homogeneous model of Rauscher et al. (1994) in which HD is more abundant than molecular hydrogen. In such a scenario, HD cooling could be more important than H_2 cooling. We also show, using a simple 1D collapse model, the influence of the molecular cooling function on the cloud temperature. In the non-homogeneous case, the total molecular cooling function is much weaker than in the standard scenario.

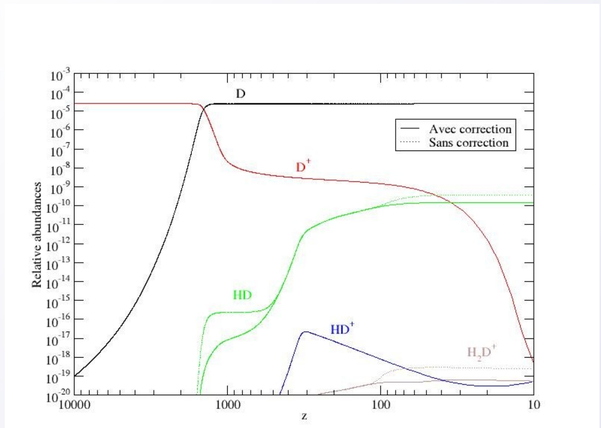
H_2 and HD chemistry

We use the chemical network of Galli & Palla (1998) for H and D, excepted for the recombinations and photoionizations of these two elements (Abel et al. 1997).

We take into account the non-thermal radiation background produced by the cosmological hydrogen recombination (Hirata & Padmanabhan 2006). The main effect is that the final abundance of molecular hydrogen is reduced by a factor about 4 because the recombination photons destroy H^- via photodetachment in a very effective way.

For the first time we compute the deuterium chemistry taking into account this correction. As the main reactions leading to the formation of HD are collisions between D or D+ and H_2, this correction influences the HD abundance. Main result: as for H_2, we see that the final HD abundance is also reduced (by a factor about 2).





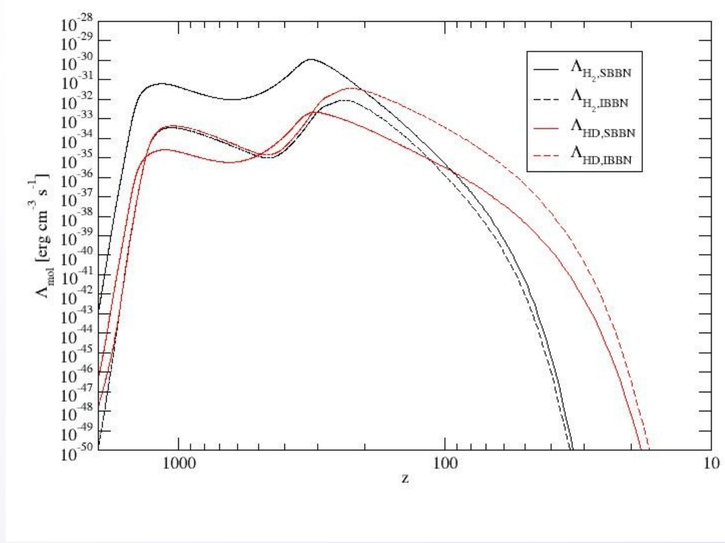
H_2 and HD thermal functions

We define the thermal molecular function Ψ_{mol} as the difference between the heating function Γ_{mol} (radiative excitation followed by collisional deexcitation)and the cooling function Λ_{mol} (collisional excitation followed by radiative deexcitation). The rotational level populations are calculated at each time step using the method described in Puy & Signore (1997).

Ψ_{H2} : rotational levels up to J=20. Collisions with H atoms and He atoms. Collision rates between H_2 and H: Wrathmall, Gusdorf & Flower (2007). Collision rates between H2 and He: Le Bourlot et al. (1999).

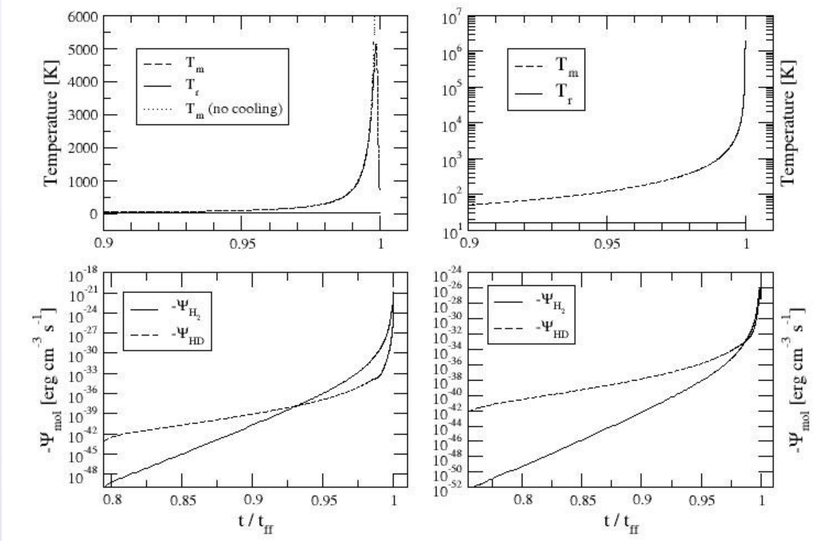
Ψ_{HD}: rotational levels up to J=8. Collisions with atomic H, atomic He and H_2. Collision rates: Flower & Roueff (1999).

We consider two nucleosynthesis scenarios:
- The SBBN model with H_0 = 71 km s^{-1} Mpc^{-1}, $\Omega_b h^2$ = 0.0224, Ω_Λ = 0.73, Y_p = 0.2484 and an initial relative abundance of deuterium $n_D/n_H = 2.74 \times 10^{-5}$ (Cyburt, Fields & Olive 2003).
- The non-homogeneous scenario of Rauscher et al. (1994). In that model, the formation of heavy nuclei is a consequence of primordial inhomogeneities. Indeed, heavy elements are synthesized by neutron capture in neutron rich regions. In that particular case, the most abundant element is not H, but He, followed by H and D. The initial abundances are: $n_H/n_b = 10^{-2}$, $n_D/n_b = 7.9 \times 10^{-4}$ and $n_{He}/n_b = 0.9892$.



H_2 and HD cooling functions in both scenarios. SBBN: Ψ_{HD} dominates for redshifts smaller than about 90. Non-homogeneous model: Ψ_{HD} is always greater than Ψ_{H2}.

Thermal functions and collapses



Evolution of temperature and thermal functions in a 10^{10} solar masses spherical and homogeneous cloud, undergoing gravitational collapse (Lahav 1986, Puy & Signore 1999). The left column is the standard case, the right one the non-homogeneous scenario.

- Standard collapse: Ψ_{HD} dominates at the beginning, then Ψ_{H2} is the main cooling agent for $T_m \geq 60$ K. Shortly before one free-fall time, molecular cooling is important enough to decrease the cloud temperature.

- Non-homogenous collapse: T_m never decreases. Indeed, molecular cooling (dominated by Ψ_{HD}) is less efficient by a factor about 2000.

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