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## Formation of $H_2$ and Galaxies in the Hot Universe

Hidenori TAKEDA, Humitaka SATŌ
and Takuya MATSUDA

*Department of Physics
Kyoto University, Kyoto*

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In the hot universe model, the recombination of the plasma causes the decoupling of matter from the primeval radiation and the uniform gas starts to fragment into gravitationally contracting clouds.[1] If the cloud contracts adiabatically, hydrogen atoms in it are soon collisionally ionized again and the cloud is finally dispersed by radiation pressure.[2] Therefore, some kind of cryogen is necessary to form a bound system. Since the primeval gas does not contain the heavy elements like carbon,[3] the $H_2$ molecule is the sole possibility of a primeval cryogen. In this way, the formation of $H_2$ is closely connected to the generation of astronomical objects like galaxies.

In this letter, we show the evolution of $H_2$ abundance in the uniform medium in contrast with the works by Saslaw et al.[4] and Peebles et al.,[5] in which they calculated the products of $H_2$ in dense clouds. Our aim is to find the critical epock before which the formation of $H_2$ has been prevented even in the dense cloud by the photo-dissociation.

Here, we consider the following processes,

$$(\mathrm{A})\quad\begin{cases}\mathrm{H}+e\rightleftarrows\mathrm{H}^-+h\nu\,, & (1)\\ \mathrm{H}^-+\mathrm{H}\rightarrow\mathrm{H}_2{}^-\rightarrow\mathrm{H}_2+e\,, & (2)\end{cases}$$

$$(\mathrm{B})\quad\begin{cases}\mathrm{H}+\mathrm{H}^+\rightleftarrows\mathrm{H}_2{}^++h\nu\,, & (3)\\ \mathrm{H}_2{}^++\mathrm{H}\rightarrow\mathrm{H}_2+\mathrm{H}^+, & (4)\end{cases}$$

and

$$\mathrm{H}_2+h\nu\rightarrow\mathrm{H}_2{}^*\rightarrow\mathrm{H}+\mathrm{H}\,. \qquad (5)$$

In the processes (A) and (B), electron and proton work as a kind of catalyzer. Reaction rate $\alpha$ in $\mathrm{cm}^{-3}$ sec and photodissociation rate $\beta$ in $\mathrm{sec}^{-1}$ are taken as $\alpha(\mathrm{H}, e) = 6.1\times10^{-19}T_m$,[6] $\alpha(\mathrm{H}, \mathrm{H}^+) = 5.0\times10^{-24} T_m{}^2$,[4] $\alpha(\mathrm{H}^-, \mathrm{H}) = \alpha(\mathrm{H}_2{}^+, \mathrm{H}) = 1.3\times10^{-9}$,[5] and $\beta(\mathrm{H}^-) = 1.5\times10^{-2}T_r{}^{2.4}\exp(-8750/T_r)$,[4] where $T_m$ and $T_r$ are matter and radiation temperatures in °K respectively. The remaining $\beta(\mathrm{H}_2{}^+)$ and $\beta(\mathrm{H}_2)$ are not so simply given, because the populations among the vibrational levels depend on their formation processes.

If all of $\mathrm{H}_2{}^+$ were in the vibrationally ground states, the process (B) might be more frequent than the (A) and the product of $H_2$ amounts to $\mathrm{H}_2/\mathrm{H}\simeq10^{-4}$ at $T_r \simeq 3000$°K. However, such an assumption is wrong and we must assume a broad distribution among the vibrational levels like Frank-Condon distribution,[8] in the case of which the process (A) is always more frequent than the (B). The ambiguity of $\beta(\mathrm{H}_2)$ does not affect the evolution of $H_2$ abundance in the stage such as $T_r<2000$°K, as shown in the figure.

Evolution of the abundances is shown in the figure. Final abundances of $\mathrm{H}^+$ [9] and $H_2$ are also given in the table. After the critical epock when the photo-dissociation of $\mathrm{H}^-$ becomes inefficient, the sufficient quantity of $H_2$ can be formed in the contracting dense cloud.[10] Therefore, the first generation of the bound system is postponed from the stage of plasma recombination ($t\simeq10^{5.1}$ years, $T_r\simeq4000$°K

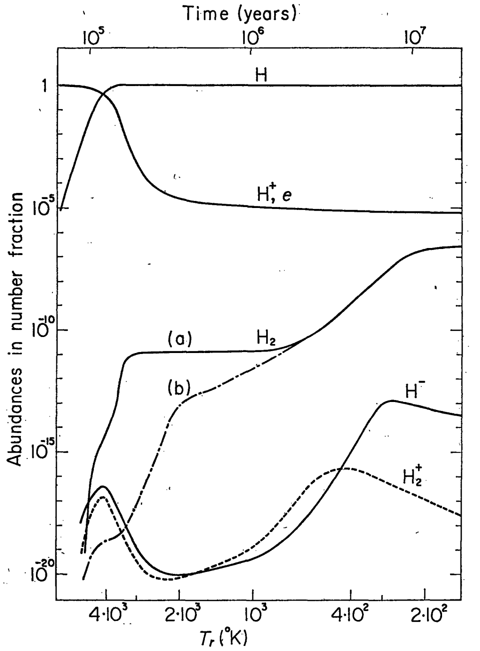

Fig. Evolution of the abundances of $H^+$, H, $H^-$, $H_2^+$ and $H_2$ for the flat universe model $q_0 \doteq 1/2$. (a) and (b) denote the two extreme cases: (a) $\beta(H_2, v=0) = 5.1\times10^7 \exp(-1.44\times10^5/T_r)$ and (b) $\beta(H_2, v=14) = 2.1\times10^7 \exp(-9.19\times10^4/T_r)$.[7] Abundance of $H_2^+$ is drawn assuming the cross section $\sigma = 3\times10^{-19}\,\mathrm{cm}^2$ and the threshold at $\lambda = 10^4$ Å.[8]

Table. Final abundances for the Universe models with the present density $\rho_{m0} = 1.86\times10^{-29}(2q_0)\,\mathrm{g/cm}^3$.

| $2q_0$ | $\log(H^+/H)$ | $\log(H_2/H)$ |
|---|---|---|
| 10 | −5.83 | −6.72 |
| 1 | −5.24 | −6.57 |
| $10^{-1}$ | −4.64 | −6.43 |
| $10^{-2}$ | −3.93 | −6.43 |

and redshift parameter $z \simeq 10^{3.1}$ in the case $q_0 = 1/2$) to the stage of $H_2$ formation ($t \simeq 10^{6.9}$ years, $T_r \simeq 3000$°K and $z = 10^2$). These primeval bound systems with mass bigger than $10^6 M_\odot$ are not necessarily galaxies themselves but pregalactic supermassive stars.[2],[5]

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