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Absorption Measurement of Hydrogen Molecules in the Early Universe

By

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Abstract: The observability of Hydrogen molecules in absorption is investigated. For solar abundances, such as in the Galaxy, the absorption measurement is very difficult because the absorption efficiency of the Hydrogen molecular absorption lines is significantly smaller than that of dust grains. On the other hand, in the metal-poor condition as expected in the early Universe, the absorption efficiency of the Hydrogen molecules become comparable with or larger than that of the dust grains. If we could use bright infrared sources behind the molecular gas clouds, the absorption measurement of the Hydrogen molecules would be an important technique to analyze the primordial gas clouds that are contracting into first-generation objects. The SPICA (Space Infrared Telescope for Cosmology and Astrophysics) will be sensitive enough to detect a molecular gas could of 10^{24} cm^{-2} against an infrared source of 10 mJy flux. These observations would be able to reveal the distribution of the primordial molecular gas clouds in the early Universe.

1. INTRODUCTION

The original purpose of this paper was to propose or review important sciences in the field of interstellar gaseous content to be pursued and solved by the SPICA (HII/L2) project (Nakagawa 2000). However, two general reviews by Serabyn (2000) and Onaka (2000) cover a wide variety of topics in this field. We can also download a good review article written for the NGST project by Bally et al. (2000) from its web site. Therefore, I concentrate on a particular topic, the observability of absorption lines of Hydrogen molecules in the infrared region.

Molecular Hydrogen is the predominant constituent of the dense gas in the Universe. In particular, molecules containing heavy elements, such as CO, H_2O, CH, OH, are expected to be significantly depleted in the early Universe and in primeval galaxies. Therefore, these molecular lines may not be useful for analyzing star- and galaxy-formation in the early Universe. We need to have a technique for detection of the molecular Hydrogen directly. We also want to be able to observe atomic and ionized Hydrogen. However, they are thought to be important only for the study of the ambient or thinner gas and not for the dense gas clouds that are forming the first-generation objects in the early Universe.

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Table 1: Transitions of molecular Hydrogen.

Transition	Wavelength	A-coefficients	Comment
ionization and dissociation	UV	large	
vib-rotational transitions	NIR (2 μm)	small	
rotational transitions	MIR (28, 17, ...μm)	small	
rotational transitions of HD	FIR (112, 56, ...μm)	medium	low abundance

Table 1 shows important transitions of the Hydrogen molecule. The transitions of ionization and dissociation have ultra-violet lines near 10 eV, and their transition probabilities (Einstein's A-coefficients) are significantly large. Therefore, they are useful for detecting thin-layers and small amounts of the molecular gas, but useless for detecting dense gas clouds.

On the other hand, the molecular Hydrogen has well-known vibrational and rotational transitions in the infrared region, as shown in the Table 1. In the rest frame, vib-rotational transitions are in the near-infrared region and pure-rotational transitions are in the mid-infrared regions. Their transition probabilities are very small because the Hydrogen molecule, a diatomic molecule of two identical nuclei, has no allowed dipole transitions but has allowed quadra-pole transitions. An isotopic specie, HD, has pure rotational transitions in the far-infrared region and the transition probabilities are significantly larger than those of the molecular Hydrogen, because they are allowed dipole transitions.

These transitions of the Hydrogen molecule may have both emission and absorption. Vib-rotational and rotational line emission from Hydrogen molecules are widely detected in star-forming regions, shocked regions, HH objects, and some starburst galaxies and are useful tools to analyze dense (> 10 cm^{-3}) and hot (> 300 K) gas. However, it is difficult to detect those emission lines from contracting gas clouds of the first-generation objects with available techniques in the near future because the expected line intensities are generally very weak (Ciardi & Ferrara 2000).

On the other hand, if there is a strong infrared continuum source behind or in the molecular gas cloud, absorption measurements of these transition lines may be obtainable. The absorption measurement has the great advantage that the column density to the source can be derived with less assumptions. The absorption measurement of the Hydrogen molecule in the early Universe is one of the best ways to ascertain the amount of the molecular gas clouds that are collapsing to form the first-generation objects. The main scope of the present paper is to investigate the possibility of the absorption measurement of the Hydrogen molecules in the early Universe.

However, because of heavy extinction by dust grains, many attempts for detecting the absorption lines of the Hydrogen molecule have failed with the exception of Lacy et al. (1994). The authors detected the absorption line of $v = 1 - 0\ S(0)$ at 2.12 μm toward NGC2024 - IRS2. The maximum optical depth of the line was 1%. Even in this case, the dust optical depth for extinction at 2 μm is an order of 10.

Fortunately, in the early Universe, we can expect a significantly lower heavy element abundance. The primordial gas is expected to consist of Hydrogen and Helium, and does not contain heavy elements that are the main constituents of the dust grains. Detection of the absorption lines of is Hydrogen molecule is easier than in the Galaxy, if we have a strong infrared source in the early Universe.

Table 2: Parameters assumed for the present calculation.

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HD/H2	10^{-5}
Intrinsic Flux of Source	10 mJy
Line width	100 km s^{-1}
Detection Limit (5σ) [a]	5×10^{-21} W m^{-2}
Detectable Line Optical Thickness	> 0.01
Dust Extinction Model	Mathis (1990)

[a] Expected Detection Limit of the SPICA Mission (Ueno et al. 2000)

Table 3: Parameters of the Line Transitions.

Transition	Wavelength (μm)	A-Coefficient (s^{-1})	(A_λ/A_V)
H_2 v = 1-0 S(1)	2.12	3.47×10^{-7}	0.11
H_2 v = 1-0 S(0)	2.22	2.53×10^{-7}	0.11
H_2 v = 0-0 S(1)	17	4.77×10^{-10}	0.020
H_2 v = 0-0 S(0)	28	2.95×10^{-11}	0.011
HD v = 0-0 R(0)	112	2.54×10^{-8}	0.0011

2. CALCULATION

The calculation of the expected line absorption is simple, as follows. Assuming a uniform, cool gas cloud ($kT_{ex} \ll h\nu$), the optical thickness of the line absorption, $\tau(line)$ is written by

$$\tau(line) \simeq \frac{\lambda^3}{8\pi}\left(\frac{g_u}{g_l}\right) A_{ul} N_l \frac{1}{\Delta v}, \tag{1}$$

where u and l indicate the upper and lower levels of a transition, g_u and g_l are the degeneracy of each state, respectively, A_{ul} is the Einstein's A-coefficient, N_l is the column density of the molecules in the lower state, and Δv is the line width in velocity. As is well known, in the optically thin case, the column density can be directly derived from the equivalent width, which nearly equals to the product of the $\tau(line)$ and the Δv.

The absorption line flux in the extinction free case, $I_0^{abs}(line)$, is obtained by

$$I_0^{abs}(line) = S\Delta\nu(1 - \exp(-\tau(line))), \tag{2}$$

where $\Delta\nu$ is the line width in frequency and S is the intrinsic continuum flux of the infrared source behind the cloud in case of no extinction/absorption. The line width and the source flux are assumed to be 100 km$\,s^{-1}$ and 10 mJy, respectively. The width assumed here is a relevant one, but the assumed source flux corresponds to a considerably luminous object in the early Universe. We can scale the results of this calculation for other source fluxes. Assumed parameters are listed in Table 2.

Next, we have to consider about the dust extinction, which is denoted by

$$\tau(dust) = 1.087 A_\lambda = 1.087\left(\frac{A_\lambda}{A_V}\right)\left(\frac{A_V}{N_H}\right)_\odot Z N_H. \tag{3}$$

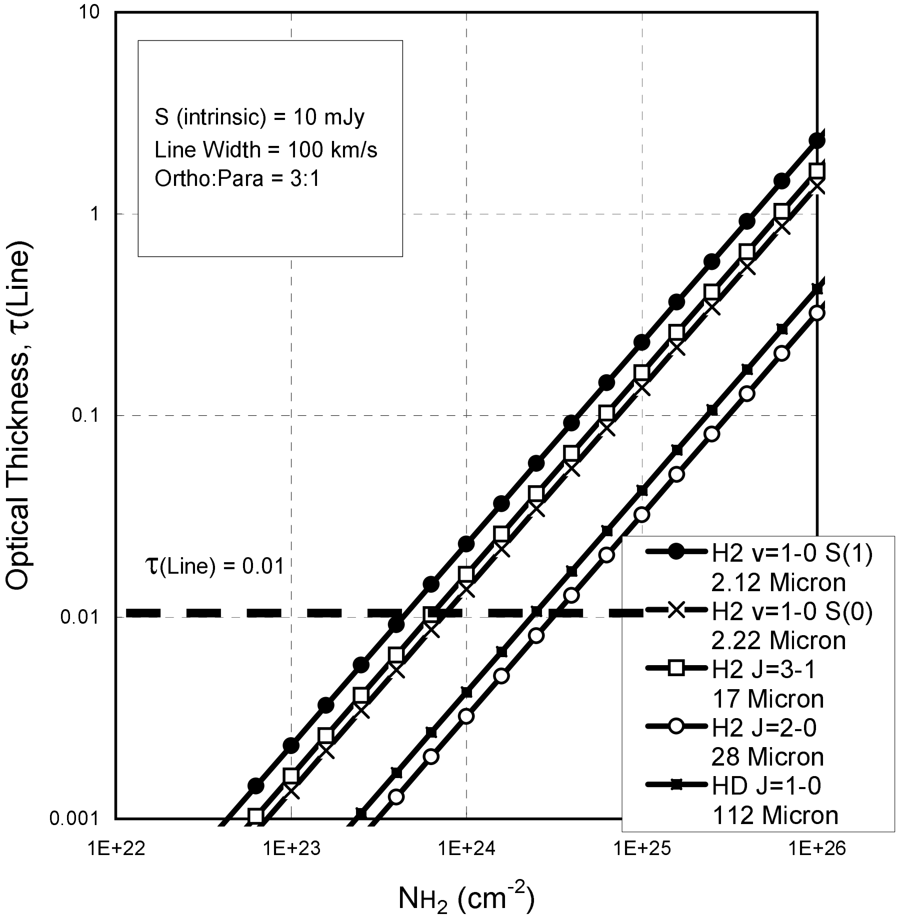

Fig. 1: Optical thickness of the absorption lines with the column density of molecular Hydrogen.

The extinction spectrum of Mathis (1990) is adopted for (A_λ/A_V), and the extinction efficiency is assumed to be proportional to the relative heavy element abundance, Z ($Z = 1$ for the local abundance), and $(A_V/N_H)_\odot$ is the conversion factor from A_V to N_H for the local abundance listed in Table 2.

Finally, we obtained the absorption line flux with extinction, $I^{abs}(line)$, by

$$I^{abs}(line) = I_0^{abs}(line) \times \exp(-\tau(dust)) = S\Delta\nu(1-\exp(-\tau(line)))\exp(-\tau(dust)). \quad (4)$$

3. RESULTS

The calculation was made for the five lines as listed in Table 3. Parameters used here are from Turner, Kirby-Docken, & Dalgarno (1977). First, it is interesting to compare the optical thickness of the line absorption and the dust extinction. In case of $\Delta v = 100$ km s^{-1} and the local heavy element abundance, the ratio of the line optical thickness to the dust optical thickness is 10^{-4} for vib-rotational lines in NIR, 10^{-3} for pure rotational line in MIR, and 10^{-2} for pure rotational lines of HD in the FIR. It means that the absorption measurement is certainly difficult against the large extinction in the Galaxy. However, this ratio increases as

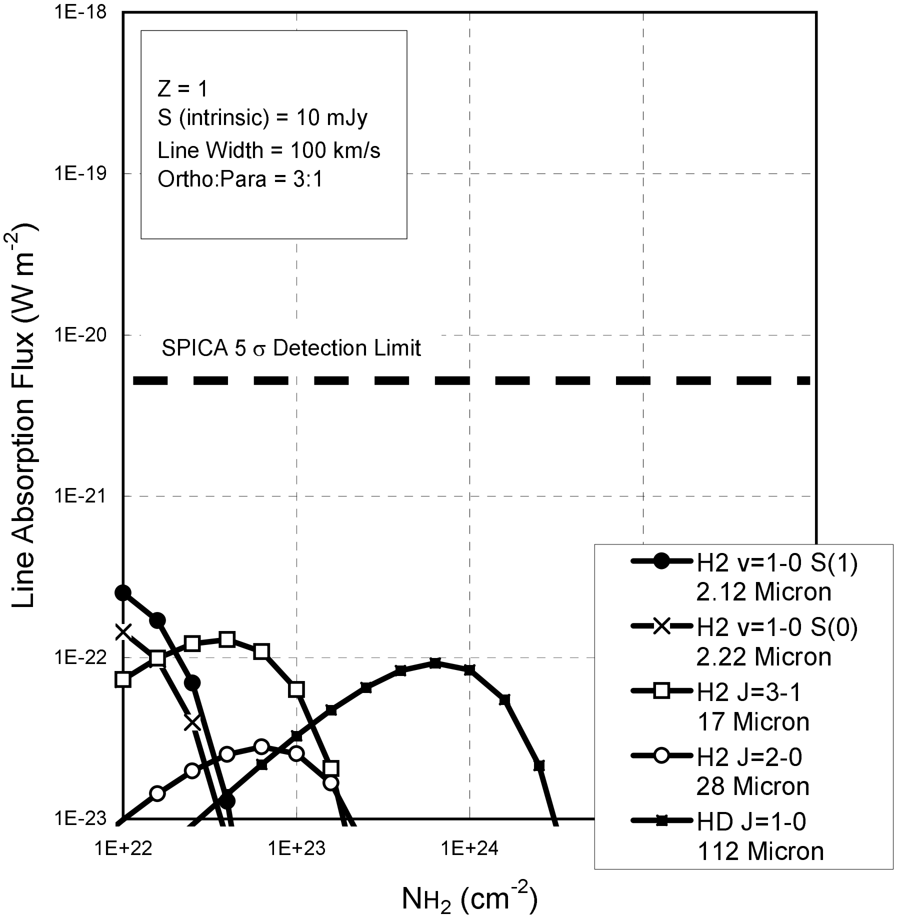

Fig. 2: Absorption line flux expected for a cloud of the local heavy element abundance ($Z = 1$) in front of a 10 mJy source.

the inverse of the heavy element abundance. Therefore, in the lower heavy element abundance case, we can expect reasonably higher ratios.

Figure 1 shows the optical thickness of the absorption lines with the column density of molecular Hydrogen. It can be seen that the optical thickness of the lines become larger than 1 % when the column density is larger than 10^{24} cm^{-2}. It is quite difficult to detect absorption lines whose optical thickness is less than 1 %. Therefore, only the clouds whose column density is larger than 10^{24} cm^{-2} can be detected in absorption.

Figure 2 shows the absorption line flux expected for a cloud with the local heavy element abundance in front of a 10 mJy source. The absorption fluxes are far smaller than the 5σ expected sensitivity of the SPICA mission (Ueno et al. 2000). On the other hand, Figure 3 shows the result for the case in which the heavy element abundance is 1% of that of the local one. All five lines are well above or near the limit.

Figure 4 shows the result of the same calculation, but for the H_2 $v = 0-1$ $S(1)$ line in various values of the heavy element abundance. In case that both conditions of $N_{H_2} > 10^{24}$ cm^{-2} and $Z < 0.01$ are satisfied, the absorption line can be detected.

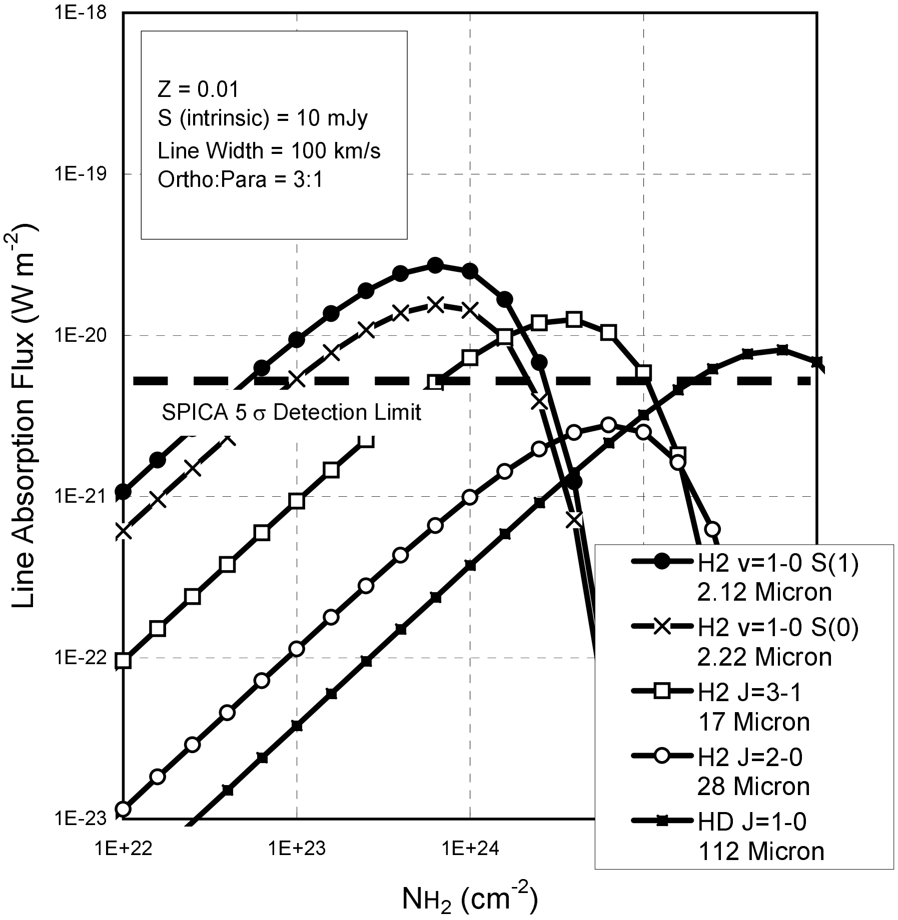

Fig. 3: Absorption line flux expected for a cloud of the low heavy element abundance ($Z = 0.01$) in front of a 10 mJy source.

4. DISCUSSION

One of the most important questions in current astrophysics is how the first generation objects formed from the primordial gas that was not contaminated with heavy elements. Recent theoretical work (e.g. Omukai & Nishi 1998) proposes the following scenario. The collapsing primordial gas must radiate its gravitational energy before the first generation objects are born from it. However, the gas consisting of only Hydrogen and Helium atoms cannot cool efficiently below a few thousand K because their constituents do not have radiative transitions corresponding a few tens to a few thousands K. Therefore, a much more efficient cooling process must be working at this stage of the Universe. The most plausible cooling process is vib-rotational and pure rotational lines of molecular Hydrogen. If the molecular Hydrogen is effectively produced in the collapsing primordial gas at a few thousands K, the expected time scale of the gas contraction is remarkably reduced. Galli & Palla (1998) indicated that so called relic electrons would work there as effective catalyst to produce primordial molecular clouds.

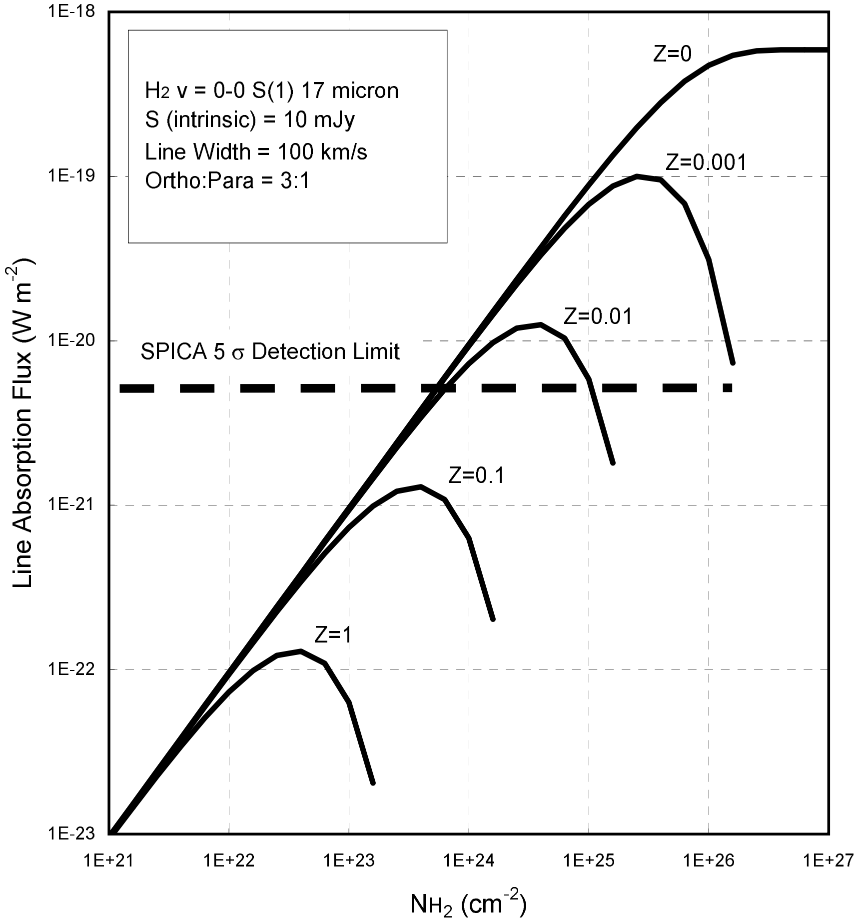

Fig. 4: Result of the same calculation, but for the H_2 $v = 0 - 0$ $S(1)$ line in various values of the heavy element abundance.

This scenario proposed theoretically in the early epoch of the Universe should be confirmed by observations and developed in order to establish a much more realistic story of the first generation objects in the Universe. For example, the following questions arise; size, density, and temperature of the primordial molecular clouds and the uniformity of the cloud distribution in the Universe. Answering these questions will be important to establish the story of first generation objects.

Emission line intensities of molecular Hydrogen expected for the primordial gas clouds in the early universe were calculated by Ciardi & Ferrara (2000). According to their result, direct measurement of the emission lines of molecular Hydrogen is very difficult due to their weakness. On the other hand, absorption measurements of the molecular Hydrogen lines have the advantage that we would be able to achieve a high sensitivity in detecting molecular Hydrogen gas clouds if we could have a number of luminous point sources behind the clouds concerned.

The most crucial problem is the dust extinction. The absorption by dust in the cloud is usually larger than the absorption by H_2 molecules. Therefore, the continuum level becomes more weak as the H_2 column density larger, and the measurement is very difficult due to smaller signals. This is the common situation in the metal-rich interstellar matter, such as that in the Galaxy.

Fortunately, it can be expected that the metal abundance is significantly lower in earlier epochs of the Universe, and the dust absorption is considerably smaller than that in the Galaxy. Assuming the metal poor interstellar matter, which means low dust absorption, fundamental Hydrogen molecular lines can be detected as absorption against bright infrared sources. As shown in Figure 3, if we can use a source whose intrinsic flux is 10 mJy as the light candle, the absorption lines can be detected for a cloud of $N_{H_2} = 10^{24}$ - 10^{26} cm^{-2}, which corresponds to $A_V = 10^3$ - 10^5 mag.

At present, we have a not so concrete idea of the uniformity of the Universe in the era of first-object formation. A very few strong sources might exist in a relatively diffuse molecular and atomic Hydrogen (and Helium) gas clouds. The absorption measurement of Hydrogen molecules with the next-generation infrared space telescope, SPICA, is expected to bring the most valuable information on the first-object formation phenomena in the early Universe.

5. CONCLUSION

The absorption measurement is possible in the metal-poor condition as expected in the early Universe, the absorption efficiency of the Hydrogen molecules becomes comparable with or larger than that of the dust grains. If we could use bright infrared sources behind the molecular gas clouds, the absorption measurement of the Hydrogen molecule would be an important technique to analyze the primordial gas clouds that are contracting into first-generation objects. The SPICA will be sensitive enough to detect a molecular gas could of 10^{24} cm^{-2} against an infrared source of 10 mJy flux. These observations will be an effective and unique tool to reveal the distribution of the primordial molecular gas clouds in the early Universe.

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