Search for LiH in the ISM towards B0218+357

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Abstract. We report a tentative detection with the IRAM 30m telescope of the LiH molecule in absorption in front of the lensed quasar B0218+357. We have searched for the $J = 0 \rightarrow 1$ rotational line of lithium hydride at 444 GHz (redshifted to 263 GHz). The line, if detected, is optically thin, very narrow, and corresponds to a column density of $N(\text{LiH}) = 1.6 \times 10^{12}$ cm$^{-2}$ for an assumed excitation temperature of 15 K, or a relative abundance LiH/H$_2$ $\sim 3 \times 10^{-12}$. We discuss the implications of this result.

Key words: ISM: general, abundances, molecules; Galaxies: ISM; Quasars: absorption lines; Radio lines: ISM

1. Introduction

Primordial molecules are thought to play a fundamental role in the early Universe, when stellar nucleosynthesis has not yet enriched the interstellar medium. After the decoupling of matter and radiation, the molecular radiative processes, and the formation of HD, HD and LiH contribute significantly to the thermal evolution of the medium (e.g. Puy et al 1993, Haiman, Rees & Loeb 1996). Even at the present time, it would be essential to detect such primordial molecules, to trace H$_2$ in the low-metallicity regions (e.g. Pfenniger & Combes 1994, Combes & Pfenniger 1997). Unfortunately, the first transition of HD is at very high frequency (2.7 THz), and the first LiH line, although only at 444 GHz, is not accessible from the ground at $z = 0$ due to H$_2$O atmospheric absorption. This has to wait the launching of a submillimeter satellite.

Although the Li abundance is low ($10^{-10}$–$10^{-9}$), the observation of the LiH molecule in the cold interstellar medium looks promising, because it has a large dipole moment, $\mu = 5.9$ Debye (Lawrence et al. 1963), and the first rotational level is at $\approx 21$ K above the ground level, the corresponding wavelength is 0.67 mm (Pearson & Gordy 1969; Rothstein 1969). The line frequencies in the submillimeter and far-infrared domain have been recently determined with high precision in the laboratory (Plummer et al 1984, Bellini et al 1994). Because of the great astrophysical interest of this molecule (e.g. Puy et al 1993), an attempt has been made to detect LiH at very high redshifts ($z \sim 200$) with the IRAM 30m telescope (de Bernardis et al 1993). It has been proposed that the LiH molecules could smooth the primary CBR (Cosmic Background Radiation) anisotropies, due to resonant scattering, or create secondary anisotropies, and they could be the best way to detect primordial clouds as they turn-around from expansion (Maoli et al 1996, see also Stancil et al 1996, Bouleux & Galli 1997).

There has recently been some controversy about the abundance of LiH. The computations of Lepp & Shull (1984) estimated the LiH/H$_2$ abundance ratio in primordial diffuse clouds to be as high as $10^{-6.5}$. With H$_2$/H $\sim 10^{-6}$, the primordial LiH/H ratio is $\sim 10^{-12.5}$. More recently, Stancil et al. (1996) computed an LiH/H abundance of $< 10^{-15}$ in the postrecombination epoch, since quantum mechanical computations now predict the rate coefficient for LiH formation through radiative association to be 3 orders of magnitude smaller than previously thought from semi-classical methods (Dalgarno et al 1996). In very dense clouds, however, three-body association reactions must be taken into account, and a significant fraction of all lithium will turn into molecules. Complete conversion due to this process requires gas densities of the order $\sim 10^9$ cm$^{-3}$, rarely found in the general ISM. However, taken other processes into account, such as dust grain formation, an upper limit to the LiH abundance is the complete conversion of all Li into molecular form, with LiH/H$_2$ $\lesssim 10^{-10}$–$10^{-9}$. With a LiH column density of $10^{12}$ cm$^{-2}$, or N(H$_2$) = $10^{22}$ cm$^{-2}$, the optical depth of the LiH line will reach $\sim 1$, in cold clouds of velocity dispersion of 2 km s$^{-1}$. The line should then be easily detectable in dense dark clouds in the present interstellar medium (like Orion where the column density reaches $10^{23}$–$10^{24}$ cm$^{-2}$). This is a fundamental step to understand the LiH molecule formation, in order to interpret future results on primordial clouds, although the primordial abundance of Li could be increased by about a factor 10 in stellar nucleosynthesis (e.g. Reeves 1994). Once the Li abundance is known as a function of redshift, it could be possible to

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derive its true primordial abundance, a key factor to test Big Bang nucleosynthesis (either homogeneous or not). Up to now, due to atmospheric opacity, no astrophysical LiH line has been detected, and the abundance of LiH in the ISM is unknown. The atmosphere would allow to detect the isotopic molecule LiD (its fundamental rotational line is at 251 GHz), but it has not been seen because of the low D/H ratio, and the expected insufficient optical depth of LiH \[1\].

Another method to avoid atmospheric absorption lines is to observe a remote object, for which the lines are redshifted into an atmospheric window. Here we report about the first absorption search for a LiH line at high redshift: the latter allows us to overcome the earth atmosphere opacity, and thanks to the absorption technique we benefit of an excellent spatial resolution, equal to the angular size of the B0218+357 quasar core, of the order of 1 milli-arsec (Patnaik et al 1995). At the distance of the absorber (redshift \( z = 0.68466 \), giving an angular size distance of 1089 Mpc, for \( H_0 = 75 \) km/s/Mpc and \( q_0 = 0.5 \)), this corresponds to 5pc. We expect a detectable LiH signal, since the H\(_2\) column density is estimated to be \( N(\text{H}_2) = 5 \times 10^{23} \) cm\(^{-2}\). Menten & Reid (1996) derive an \( N(\text{H}_2) \) value ten times lower than this, using the H\(_2\)CO(2\(_1\)-1\(_2\)) transition at 8.6 GHz. At this low frequency the structure and extent of the background continuum source may be quite larger than at 100–200 GHz and the source covering factor smaller. This means that their estimate of the column density is a lower limit.

\[1\] The LiD line at 251 GHz is not covered in the 247-263 GHz survey of Orion by Blake et al 1986, but was observed at the McDonald 5m-telescope, Texas, see Lovas 1992; we ourselves checked with the SEST telescope that no line is detected towards Sagittarius-B2 at this frequency. The 3\(\sigma\) upper limit to the LiD abundance towards SgrB2 is \( 1 \times 10^{11} \) cm\(^{-2}\).

| Table 1. Parameters for the tentative LiH line |
|-----------------|-----------------|
| \( J_u-J_l \) | 1–0 |
| \( \nu_{ab} \) GHz | 443.953 |
| \( \nu_{obs} \) GHz | 263.527 |
| Forward eff. | 0.86 |
| Beam eff. | 0.32 |
| \( T_A \) | 7 mK |
| \( T_{cont} \) | 15 mK |
| FWHM | 3.2 km/s |
| \( \sigma \) | 1.8 mK |
| noise rms with \( \Delta v \) 2.3 km/s |

\( \alpha(1950) = 02h 18m 04.1s \)  
\( \delta(1950) = 35^\circ 42^\prime 32^\prime \prime \)

3. The molecular absorption line system towards B0218+357

We select the ISM in front of the B0218+357 BL Lac object, because it revealed the highest molecular column densities in all cases of molecular absorption at high redshift (Wiklind & Combes 1995, Combes & Wiklind 1996). The remote quasar is gravitationally lensed by a foreground galaxy at \( z = 0.68466 \), which produces the absorption. The radio image of the quasar is composed of two distinct flat-spectrum cores (A and B component), with a small Einstein ring surrounding the B image, of 335 milli-arcsecond (mas) in diameter (Patnaik et al 1993). Since the ring has a steeper spectrum, it is interpreted as the image of a jet component, or in fact a hot spot or knot in the jet that happens to be just in the line of sight of the lens center.

The intensity ratio between the two images is A/B \( \approx 3.3 \) at several radio wavelengths, and it can vary slightly (the B-component has varied in flux by \( \approx 10\% \) in a few months, O'Dea et al. 1992, Patnaik et al. 1993). A large variety of molecules has been detected in absorption towards B0218+357, among them several of the isotopes of CO, HCN, HCO\(^+\), HNC, H\(_2\)O etc. (Wiklind & Combes 1995, Combes & Wiklind 1995, 1997). Since the depth of the molecular absorption is less than the continuum level, while being optically thick, we deduced that the absorbing material does not cover the whole surface of the...
Fig. 1. Spectrum of LiH in its fundamental line (1–0) at 444 GHz, redshifted at 263 GHz, in absorption towards B0218+357, compared to the highly optically thick CO(2–1) line previously detected. The tentative LiH line is slightly shifted from the center by about 5 km/s, but is still comprised within the CO(2–1) velocity range. Its width is compatible with what is expected from an optically thin line. Spectra have been normalised to the absorbed continuum level and the velocity resolution is 2.3 km/s.

4. Results and discussion

Figure 1 presents our LiH spectrum, compared to that of CO(2–1) previously detected with the IRAM 30m-telescope (Wiklind & Combes 1995, Combes & Wiklind 1998). There is only a tentative detection of LiH at \( \sim 3 \sigma \). The line is very narrow, but is compatible to what is expected from an optically thin line. The CO(2–1) is highly optically thick, with \( \tau \sim 1500 \). This optical depth is determined from the detection of \(^{13}\)C\(^{18}\)O(2–1), which is moderately thick, and the non-detection of \(^{13}\)C\(^{17}\)O(2–1). The center of the tentative line is shifted by 5 km/s from the average center of other lines detected towards B0218+357. This shift cannot be attributed to uncertainties of the line frequency, since it has been measured in the laboratory (e.g. Bellini et al 1994), and the error is at most 0.24 km/s at \( 3\sigma \), once redshifted. But the scatter of the line centers is \( \sim 3 \) km/s, and the width of most of the lines is \( \sim 15 \) km/s (cf Wiklind & Combes 1998). The velocity shift is therefore insufficient to reject the line as real.

Combining our own continuum data with that of lower frequencies (obtained from the NASA Extragalactic Database NED), we have previously found that the continuum spectra of B0218+357 can be fitted with a power law of slope \(-0.25\) (Combes & Wiklind 1997). This would imply a continuum level of 15.5 mK at 263 GHz, which is in accord with the measured level. Since only 70\% of the continuum is covered by molecular gas, the continuum level to be used for our LiH observations amounts to 11 mK.

We can write the general formula, concerning the total column density of the LiH molecule, observed in absorption between the levels \( l \rightarrow u \) with an optical depth \( \tau \) at the center of the observed line of width \( \Delta v \) at half-power:

\[
N_{\text{LiH}} = \frac{8\pi}{c^3} f(T_x) \frac{\nu^5 \tau \Delta v}{g_u A_u}
\]

where \( \nu \) is the frequency of the transition, \( g_u \) the statistical weight of the upper level \( (= 2J_u + 1) \), \( A_u \) the Einstein coefficient of the transition, \( T_x \) the excitation temperature, and

\[
f(T_x) = \frac{Q(T_x) \exp(E_l/kT_x)}{1 - \exp(-h\nu/kT_x)}
\]

where \( Q(T_x) \) is the partition function. For the sake of simplicity, we adopt the hypothesis of restricted Thermodynamical Equilibrium conditions, i.e. that the excitation temperature is the same for all the LiH ladder. Since the line is not optically thick, but the optical thickness reaches \( \tau = 1.3 \) at the center of the line, we have derived directly from the spectrum, through a Gaussian fit of the opacity, the integrated \( \tau \Delta v = 3.64 \) km/s. From the formulæ above, and assuming an excitation temperature of \( T_x = 15 \) K (see Table 2 for variation of this quantity), we derive a total LiH column density of \( 1.6 \times 10^{12} \) cm\(^{-2} \) towards B0218+357. Compared to our previously derived \( \text{H}_2 \) column density of \( 5 \times 10^{23} \) cm\(^{-2} \), this gives a relative abun-
Since $6$ increased significantly the Li abundances. Bang, this ratio indicates that cosmic ray spallation has two velocity components in optical absorption lines Lemoine et al (1995) find towards molecule the dense clumps. It is also interesting to observe the rarer that the spatial resolution is enough to avoid dilution of should be easy with a submillimeter satellite, provided LiH in emission towards dense clouds in the Milky Way gas, and the black-body temperature at the redshift of the though the absorption technique selects preferentially cold of the more diffuse parts, LiH is photodissociated (e.g. Kirby & Dalgarno 1978). Also, some regions of the cloud could have a higher excitation temperature, in which case our computation under-estimates the LiH abundance (al- though the absorption technique selects preferentially cold gas, and the black-body temperature at the redshift of the absorbing molecules is $T_{bg} = 4.6$ K).

The present observations suggest that the detection of LiH in emission towards dense clumps in the Milky Way should be easy with a submillimeter satellite, provided that the spatial resolution is enough to avoid dilution of the dense clumps. It is also interesting to observe the rarer molecule $6$LiH, which in some clouds might be of same order of abundance as the main isotopic species. Through optical absorption lines Lemoine et al (1995) find towards two velocity components in $\zeta$-Oph, $^7$Li/$^6$Li = 8.6 and 1.4. Since $^6$Li is formed only in negligible amounts in the Big Bang, this ratio indicates that cosmic ray spallation has increased significantly the Li abundances.

**Table 2. Derived LiH column density**

| $T_x$ (K) | 5 | 10 | 15 | 20 |
|-----------|---|----|----|----|
| N(LiH) ($10^{12}$ cm$^{-2}$) | 0.4 | 0.9 | 1.6 | 2.4 |
| LiH/H$_2$ ($10^{-12}$) | 0.8 | 1.8 | 3.2 | 5 |

dance of LiH/H$_2$ $\sim 3 \times 10^{-12}$. Note that there is a possible systematic uncertainty associated with this measure, due to the velocity difference between the maximum opacity of the CO, HCO$^+$ and other lines with that of LiH.

To interpret this result, comparison should be made with the atomic species. First, it is likely that the molecular cloud on the line of sight is dense and dark, and all the hydrogen is molecular, $f$(H$_2$) = 0.5. The Li abundance (main isotope $^7$Li) at $z = 0.68466$ (i.e 5-10 Gyr ago) can be estimated at Li/H $\sim 10^{-9}$, since its abundance in the ISM increases with time. The primordial Li abundance must be similar to that in metal deficient unevolved Population II stars, Li/H = 1-2 $10^{-10}$ (Spite & Spite 1982), but Li could be depleted at the stellar surface by internal mixing. In meteorites and unevolved, unmixed Pop I stars, Li/H $\sim 10^{-9}$, representative of the Li abundance some 4 Gyr ago. The present abundance in the ISM is estimated around 3 $10^{-9}$ (Lemoine et al 1993).

We therefore deduce LiH/Li $\sim 1.5 \times 10^{-3}$. The uncertainty associated with the derived abundances are large, but the low LiH/Li ratio seems to exclude complete transformation of Li into LiH, as would be expected in very dense clouds (e.g. Stancil et al 1996, although the Li chemistry is not yet completely understood in dark clouds). However, it is likely that the cloud is clumpy, and in some of the more diffuse parts, LiH is photodissociated (e.g. Kirby & Dalgarno 1978). Also, some regions of the cloud could have a higher excitation temperature, in which case our computation under-estimates the LiH abundance (although the absorption technique selects preferentially cold gas, and the black-body temperature at the redshift of the absorbing molecules is $T_{bg} = 4.6$ K).

The present observations suggest that the detection of LiH in emission towards dense clouds in the Milky Way should be easy with a submillimeter satellite, provided that the spatial resolution is enough to avoid dilution of the dense clumps. It is also interesting to observe the rarer molecule $^6$LiH, which in some clouds might be of same order of abundance as the main isotopic species. Through optical absorption lines Lemoine et al (1995) find towards two velocity components in $\zeta$-Oph, $^7$Li/$^6$Li = 8.6 and 1.4. Since $^6$Li is formed only in negligible amounts in the Big Bang, this ratio indicates that cosmic ray spallation has increased significantly the Li abundances.

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