DETECTION OF WATER AT $z = 0.685$ TOWARD B0218+357

FRANCOISE COMBES
Département de Matière Interstellaire et Radioastronomie Millimétrique, Observatoire de Paris, 61 Avenue de l'Observatoire, F-75014 Paris, France; bottaro@obspm.fr

AND

TOMMY WIKLIND
Onsala Space Observatory, S-43992 Onsala, Sweden; tommy@oso.chalmers.se

Received 1997 April 28; accepted 1997 June 26

ABSTRACT

We report the detection of the H$_2$O molecule in absorption at a redshift, $z$, of 0.68466 in front of the gravitationally lensed quasar B0218+357. We detect the fundamental transition of ortho-water at 556.93 GHz (redshifted to 330.59 GHz). The line is highly optically thick and relatively wide ($15 \text{ km s}^{-1} \text{ FWHM}$), with a profile that is similar to that of the previously detected CO(2–1) and HCO$^+$ (2–1) optically thick absorption lines toward this quasar. From the measured level of the continuum at 330.59 GHz, which corresponds to the level expected from the power-law spectrum $S(\nu) \propto \nu^{-0.25}$ already observed at lower frequencies, we deduce that the filling factor of the H$_2$O absorption is large. It was already known from the high optical thickness of the CO, $^{13}$CO, and C$^{18}$O lines that molecular clouds entirely cover one of the two lensed images of the quasar (all its continuum is absorbed); our present results indicate that H$_2$O clouds are covering a comparable surface. The H$_2$O molecules are therefore not confined to small cores with a tiny filling factor but are extended over parsec scales. The H$_2$O line has a very large optical depth, and only isotopic lines could give us the water abundance. We have also searched for the 183 GHz line in absorption, obtaining only an upper limit; this yields constraints on the excitation temperature.

Subject headings: BL Lacertae objects: individual (B0218+357) — galaxies: abundances — galaxies: ISM — ISM: molecules — quasars: absorption lines — radio lines: ISM

1. INTRODUCTION

Water is believed to be one of the most abundant molecules in the interstellar medium (ISM). It can be formed through gas-phase chemistry in cold, dense, and thick clouds, with an abundance ratio H$_2$O/H$_2$ between $10^{-7}$ and $10^{-5}$, depending on the chemical models, the reactions rates used, and the C/O abundance in the gas phase (Leung, Herbst, & Huebner 1984; Langer & Graedel 1989); in nondissociative shocks the abundance ratio is calculated to be as high as $10^{-4}$ (Draine, Roberge, & Dalgarno 1983; Kaufman & Neufeld 1996a, 1996b). The H$_2$O abundance can also be enhanced through evaporation of grain mantles in star-forming hot cores (Jacq et al. 1988; Brown, Charnley, & Millar 1988; Gensheimer, Mauersberger, & Wilson 1996), so H$_2$O could play a major role in the cooling of molecular clouds and in the oxygen budget of the ISM. Unfortunately, the broad atmospheric water lines prevent direct detection from the ground in our own Galaxy; up to now, no thermal emission from the main isotopomer in its fundamental lines has been detected, and the H$_2$O abundance in the ISM remains poorly known. Attempts have been made to determine the H$_2$O abundance through observations of the isotopomers HDO and H$_2^{18}$O (Henkel et al. 1987; Jacq et al. 1988, 1990; Wannier et al. 1991; Gensheimer et al. 1996) and through observations of the precursor ion H$_3^+$ (Phillips, van Dishoeck, & Keene 1992). Abundances of the normal isotopomer of H$_2$O around 10$^{-7}$ have been deduced. This is also confirmed by the detection in Orion of absorption lines at 2.66 mm with the Kuiper Airborne Observatory (Knacke & Larson 1991). The latter authors found an ortho-para ratio of 1, which confirms that water had no time, after sublimation from grains, to reach the equilibrium high temperature ratio of 3. Also, the deuterated substitute HDO reveals a high degree of fractionation (HDO/H$_2$O = 100 D/H), which implies H$_2$O formation at low temperatures.

Since some of the H$_2$O submillimeter and far-infrared transitions are population inverted, causing maser emission with a very high flux, they can be detected from the ground even at 183 GHz (Cernicharo et al. 1994). Another method of avoiding atmospheric absorption lines is to observe a remote object for which the lines are redshifted outside the broad atmospheric counterpart. Only one tentative detection has been reported so far: the 752 GHz para-water line in the object for which the lines are redshifted outside the broad atmospheric counterpart. Very recently, observations with the Infrared Space Observatory (ISO) satellite of the 2$_{10}$–1$_{0}$ 179.5 mm line of ortho-water in absorption against the continuum of the galactic center (Sgr B2; Cernicharo et al. 1997) have revealed that the H$_2$O molecule is abundant over very extended regions. It has also been detected in absorption in front of massive young stars with strong IR continuum, around 6 mm in the bending vibration series (Helichm et al. 1996; van Dishoeck & Helichm 1996). Abundances of a few $10^{-7}$ are deduced, with a tendency to scale with the amount of warm gas. Even higher abundances ($3 \times 10^{-7}$) have been derived from H$_2$O emission from the stellar wind of W Hya with the ISO short-wavelength spectrometer and long-wavelength spectrometer, but the exact figures depend on the outflow modelization (Barlow et al. 1996; Neufeld et al. 1996).

Here we report the first detection of an H$_2$O line in
absorption at high redshift. The high redshift allows us to avoid the high opacity of the terrestrial atmosphere near the rest frequency, and because absorption is against a small continuum source, excellent spatial resolution is achieved, equal to the angular size of the B0218+357 quasar core, which is only of the order of 1 mas (Patnaik, Porcas, & Browne 1995). At the distance of the absorber (\( z = 0.68466 \)), giving an angular distance of 1089 Mpc, for \( H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1} \) and \( q_0 = 0.5 \), this corresponds to only 5 pc.

### 2. OBSERVATIONS

The observations were made with the Institut de Radio Astronomie Millimétrique (IRAM) 30 m telescope at Pico Veleta near Granada in Spain in 1997 March. Table 1 displays the observational parameters. Several SIS receivers were used simultaneously: at 3 mm, the receiver was tuned to the \( \text{H}_2\text{O} 3_{13}-2_{12} \) para line at 183 GHz, redshifted to 108.811 GHz to obtain an estimate of the excitation temperature (the lower level of this transition corresponds to a temperature of 190 K). The single-sideband (SSB) system temperature was 180 K, and the rejection level of the image sideband was \( \sim 30 \text{ dB} \). At 0.8 mm, the \( \text{H}_2\text{O} 1_{0-1} \) para line at 557 GHz, redshifted to 330.592 GHz, was observed. The receiver was operating in single sideband, with a rejection level of a factor 4 (6 dB measured on Orion); its SSB receiver temperature was 90 K, and the system temperature was between 400 and 2000 K, depending on the atmospheric humidity, with an average of 700 K. Two 512 \( \times \) 1 MHz filter banks and an autocorrelator back end were used. Here only the 1 MHz resolution spectra are presented, binned to a velocity resolution of a few km s\(^{-1}\).

The observations were done with a nutating subreflector, with a beam throw of 1′ in azimuth and a switching frequency of 0.5 Hz. The temperature scale was calibrated every 10 minutes by a chopper wheel on an ambient temperature load and on liquid nitrogen. Pointing was checked on broadband continuum sources. The relative pointing offsets between the two receivers were of the order of 4′. The frequency tunings and rejection levels were checked by observing known molecular lines toward Orion, DR 21, and IRC +10216. The integration times were 8 and 20 hr on the 183 GHz and 557 GHz lines, respectively, and noise levels of 1.1 and 1.3 mK in the \( T_A^* \) antenna temperature scale were obtained, with a velocity resolution of 9 km s\(^{-1}\). The forward and beam efficiencies at each frequency are displayed in Table 1.

In order to derive the continuum flux, B0218+357 was observed regularly with a continuum back end and in a fast switching mode (4 times higher than in the line-observing mode). The continuum level from line observations obtained under good sky conditions was also used. The two estimates of the continuum flux agree.

The BL Lac object B0218+357 was selected for this first search for \( \text{H}_2\text{O} \) in absorption because it is the absorbing system at high redshift with the highest column density (Wiklind & Combes 1995). The remote quasar (\( z \approx 0.9 \); see, e.g., Browne et al. 1993) 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), with a small Einstein ring of 335 mas in diameter surrounding the B image (Patnaik, Browne, & King 1993). Since the ring has a steep spectrum, it is best interpreted as the image of a jet component or as a hot spot or knot in a jet that happens to lie in the line of sight to the center of the lens. Owing to its steep spectral index, the Einstein ring gives a negligible contribution to the continuum flux at millimeter wavelengths. The intensity ratio between the two images (A/B) is \( \approx 3-4 \) at several radio wavelengths, but the B component has varied in flux by \( \approx 10\% \) in a few months (O’Dea et al. 1992; Patnaik et al. 1993). Since the depth of the molecular absorption is less than the continuum level, but the absorption is optically thick, it follows that the absorbing material does not cover the whole surface of the continuum source. It is likely that only one image of the quasar is covered by molecular clouds, since the two images, A and B, are separated by 1.8 kpc at the absorber distance. The fraction of the total continuum that is absorbed is \( \approx 33\% \).

### 3. RESULTS AND DISCUSSION

Figure 1 presents our \( \text{H}_2\text{O} \) detected spectrum, compared with those of \( \text{HCO}^+ (2–1) \) and \( \text{CO}(2–1) \) previously detected with the IRAM 30 m telescope (Wiklind & Combes 1995; Combes & Wiklind 1995). The line widths are very similar, respectively, 15, 16, and 15 km s\(^{-1}\) for \( \text{H}_2\text{O} \), \( \text{HCO}^+ (2–1) \), and \( \text{CO}(2–1) \), as determined by Gaussian fits. This is a strong indication that the \( \text{H}_2\text{O} \) line is optically thick, as the \( ^{13}\text{CO} \) and \( ^{18}\text{O} \) isotopic lines have been detected, with progressively reduced line widths (Combes & Wiklind 1995). The \( 3_{13}-2_{12} \) para line at 183 GHz was not detected. The 3 \( \sigma \) upper limits presented in Table 1 were derived by assuming the same line widths for the two \( \text{H}_2\text{O} \) lines.

The redshift of the absorbing molecular gas, \( z = 0.68466 \pm 0.00001 \) (Wiklind & Combes 1995), puts the redshifted \( \text{H}_2\text{O}(1_{0-1}) \) line at 330.593 GHz, which is close to the frequency of the \(^{13}\text{CO}(3–2) \) transition at \( z = 0 \) of 330.588 GHz (see, e.g., Lovas 1992). The difference in velocity is only 4.1 km s\(^{-1}\). Nevertheless, it is highly unlikely that the absorption line seen at 330.59 GHz is caused by a Galactic \(^{13}\text{CO}(3–2) \) transition. First of all, the depth of the absorption and the width of the \( \text{H}_2\text{O} \) line are the same as those of the lines of redshifted \( \text{CO}(2–1) \). \(^{13}\text{CO}(2–1) \), \(^{18}\text{O}(2–1) \), and so on (Combes & Wiklind 1996)—in itself a strong indication that our new line is from redshifted water. Second, a search through all our spectra, covering several gigahertz, does not reveal any molecular transition at \( z = 0 \), although several relatively strong lines should be present [e.g., \( \text{SO}(3–2) \), SiO(3–2) \( \nu = 0 \)]. Third, B0218+357 is situated at Galactic coordinates \( l = 142^\circ 6, b = -23^\circ 5 \). This means that
unless Galactic absorption occurs very locally, Galactic rotation would displace the $z = 0$ line of $^{13}$CO(3–2) to negative velocities. If there is local gas, it is likely to be extended on scales of 1′ (the throw of our telescope beam), and the observing procedure with a nutating subreflector would effectively cancel Galactic absorption.

Figure 2 displays our continuum measurements, together with a compilation of previous results in the literature for lower frequencies. Within the 1σ error bars, the continuum spectrum can be fitted with a power law with a slope of −0.25. From our previous detection of the $^{13}$CO(2–1) line with an optical depth of 23 (Combes & Wiklind 1995), we deduced an optical depth of 1500 for the 12CO(2–1) line. Since the H$_2$O abundance is likely to be only 10 times lower than that of CO, while its dipole moment, $\mu = 1.8$ D, is 18 times higher, we expect an H$_2$O optical depth that is $\sim 30$ times higher than CO for cold gas, since $\tau/N$ scales as $\mu^2$. This clearly prevents any estimation of the H$_2$O abundance; however, the line strength, $S$, is about 10 times lower for the 183 GHz line, so the upper limit on the 183 GHz line provides a constraint on the excitation temperature.

The total column density of the H$_2$O 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 is

$$N_{\text{H}_2\text{O}} = \alpha f(T_e) \frac{\nu^2 \tau \Delta v}{g_u A_u},$$

where $\alpha$ is a constant ($8\pi/c^3$), $\nu$ is the frequency of the transition, $g_u$ is the statistical weight of the upper level $(2J_u + 1)$, $A_u$ is the Einstein coefficient of the transition, $T_e$ is the excitation temperature, and

$$f(T_e) = \frac{Q(T_e) \exp \left( E_s/kT_e \right)}{1 - \exp \left( -h\nu/kT_e \right)},$$

where $Q(T_e)$ is the partition function. The factor $s_l$ is the nuclear spin statistical weight, equal to $\frac{5}{2}$ for ortho states and $\frac{3}{2}$ for para states.

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 H$_2$O lines. Also, we assume an ortho/para ratio of 3. Replacing in the above formula the molecular parameters from de Lucia, Helminger, & Kirchhoff (1974), and assuming the abundance of H$_2$O/CO $\approx 0.1$, or H$_2$O/H$_2$ $\approx 10^{-5}$, which is found for the galactic ISM, we can predict the optical depths of the two observed H$_2$O lines as displayed in Figure 3. The $3\sigma$ upper limit to the 183 GHz line then constrains $T_x$ to be lower than 20 K.

This result implies that the bulk of the H$_2$O molecules that we detect in absorption are not coming from hot dense cores but are more widely spread and mixed with the molecular gas absorbing in CO. This is consistent with the high covering factor observed and the fact that the absorption technique selects preferentially cold gas (see, e.g., Combes & Wiklind 1996; Wiklind & Combes 1997). Also, the absorbing gas is situated in an intervening cloud that happens to be on the line of sight of the remote quasar. It is thus not necessarily an actively star-forming region, as is the case for emission line observations of distant galaxies. It should be emphasized, however, that this result is based on the assumption of H$_2$O galactic abundance, which is poorly known; another solution could be a lower H$_2$O abundance, which will release the constraint of low temperature. However, even with an abundance of H$_2$O/H$_2$ $= 10^{-6}$ (or H$_2$O/CO $= 0.01$), the excitation temperature should be lower than 30 K (see Fig. 3). A higher H$_2$O abundance is not likely, unless we release the hypothesis of a constant $T_x$ over the rotational ladder.

The present H$_2$O line detection at 331 GHz could not have been done without the enthusiastic support from the Institut de Radio Astronomie Millimétrique staff at Pico Veleta. Bibliographic and photometric data have been retrieved from the NED database.

REFERENCES

Barlow, M. J., et al. 1996, A&A, 315, L241
Brown, P. D., Charnley, S. B., & Millar, T. 1988, MNRAS, 231, 409
Browne, I. W. A., Patnaik, A. R., Walsh, D., & Wilkinson, P. N. 1993, MNRAS, 263, L32
Casoli, F., Gerin, M., Encrenaz, P., & Combes, F. 1994, A&A, 287, 716
Cernicharo, J., et al. 1997, A&A, 323, L25
Cernicharo, J., González-Alfonso, E., Alcolea, J., Bachiller, R., & John, D. 1994, ApJ, 422, L59
Combes, F., & Wiklind, T. 1995, A&A, 303, L61
———. 1996, in Cold Gas at High Redshift, ed. M. Bremer, H. Rottgering, P. van der Werf, & C. L. Carilli (Dordrecht: Kluwer), 215
de Lucia, F. C., Helminger, P., & Kirchhoff, W. H. 1974, J. Phys. Chem. Ref. Data, 3, 211
Draine, B. T., Roberge, W. G., & Dulgarino, A. 1983, ApJ, 264, 485
Encrenaz, P. J., Combes, F., Casoli, F., Gerin, M., Pagani, L., Horellou, C., & Gac, C. 1993, A&A, 273, L19
Gensheimer, P. D., Mauersberger, R., & Wilson, T. L. 1996, A&A, 314, 281
Helmich, F. P., et al. 1996, A&A, 315, L173
Henkel, C., Mauersberger, R., Wilson, T. L., Snyder, L. E., Menten, K. M., & Wouterloot, J. G. A. 1987, A&A, 182, 299
Jacq, T., Jewell, P. R., Henkel, C., Walmsley, C. M., & Baudry, A. 1988, A&A, 199, L5
Jaqq, T., Walmsley, C. M., Henkel, C., Baudry, A., Mauersberger, R., & Jewell, P. R. 1990, A&A, 228, 447
Kaufman, M. J., & Neufeld, D. A. 1996a, ApJ, 456, 250
———. 1996b, ApJ, 456, 611
Knacke, R. F., & Larson, H. P. 1991, ApJ, 367, 162
Langer, W. D., & Graedel, T. E. 1989, ApJS, 69, 241
Leung, C. M., Herbst, E., & Huebner, W. F. 1984, ApJS, 56, 231
Lovas, F. J. 1992, J. Phys. Chem. Ref. Data, 21, 181
Neufeld, D. A., et al. 1996, A&A, 315, L237
O'Dea, C. P., Baum, S. A., Stanghellini, C., Dey, A., van Bruegel, W., Deustua, S., & Smith, E. P. 1992, AJ, 104, 1320
Patnaik, A. R., Browne, I. W. A., & King, L. J. 1993, MNRAS, 261, 435
Patnaik, A. R., Porcas, R. W., & Browne, I. W. A. 1995, MNRAS, 274, L5
Phillips, T. G., van Dishoeck, E. F., & Keene, J. 1992, ApJ, 399, 533
van Dishoeck, E. F., & Helmich, F. P. 1996, A&A, 315, L177
Wannier, P. G., et al. 1991, ApJ, 377, 171
Wiklind, T., & Combes, F. 1995, A&A, 299, 382
———. 1997, A&A, 324, 51