Water is one of the key molecules in the physical and chemical evolution of star- and planet-forming regions. We here report the first spatially resolved observation of thermal emission of (an isotopologue of) water with the Plateau de Bure Interferometer toward the deeply embedded Class 0 protostar NGC 1333-IRAS4B. The observations of the H$_2^{18}$O $3_13$--$2_0$ transition at 203.4 GHz resolve the emission of water toward this source with an extent of about 0″2 corresponding to the inner 25 AU (radius). The H$_2^{18}$O emission reveals a tentative velocity gradient perpendicular to the extent of the protostellar outflow/jet probed by observations of CO rotational transitions and water masers. The line is narrow, $\approx 1$ km s$^{-1}$ (FWHM), significantly less than what would be expected for emission from an infalling envelope or accretion shock, but consistent with emission from a disk seen at a low inclination angle. The water column density inferred from these data suggests that the water emitting gas is a thin warm layer containing about 25 $M_{\text{Earth}}$ of material, 0.03% of the total disk mass traced by continuum observations.

Key words: astrochemistry -- ISM: abundances -- ISM: individual objects (NGC 1333-IRAS4B) -- protoplanetary disks -- stars: formation

1. INTRODUCTION

Water is one of the most important molecules in star-forming regions: it is a dominant form of oxygen, is important in the energy balance, and is ultimately associated with the formation of planets and emergence of life. Thus, following the water "trail" from collapsing clouds to protoplanetary disks is a fundamental problem in astronomy and astrochemistry. In the cold and quiescent regions, the gaseous water abundance is low, only $10^{-9}$--$10^{-8}$ (e.g., Bergin & Snell 2002), but in regions with intense heating or active shocks, its abundance can reach $10^{-4}$ with respect to H$_2$—comparable to or higher than that of CO (e.g., Harwit et al. 1998). Which mechanism is most important for regulating the H$_2$O abundance in low-mass protostars is still heavily debated. Is it passive heating of the collapsing envelope by the accretion luminosity from forming stars (e.g., Ceccarelli et al. 1998; Maret et al. 2002), or shocks either caused by protostellar outflows (e.g., Nisini et al. 1999) or related to ongoing accretion onto circumstellar disks (Watson et al. 2007)? H$_2$O is also a key molecule in the chemistry in regions of star formation: in large parts of the cold and dense envelopes around low-mass protostars, H$_2$O is the dominant constituent of the icy mantles of dust grains (e.g., Whitet et al. 1988; Boogert et al. 2008). Its evaporation at temperatures higher than 90–100 K determines at what point water itself and any complex organic molecules, formed in these ice mantles, are injected into the gas phase.

This discussion has received new fuel with the detection of surprisingly strong highly excited H$_2$O lines at mid-infrared wavelengths with the Spitzer Space Telescope’s infrared spectrograph (IRS) toward one deeply embedded Class 0 protostar, NGC 1333-IRAS4B, by Watson et al. (2007). Based on the high critical density of the observed lines and temperature ($\approx 170$ K), Watson et al. argue that the water emission observed toward this source has its origin in an accretion shock in its circumstellar disk. Those data could not spatially or spectrally resolve the water emission, however.

In this Letter, we present observations at 203 GHz of the H$_2^{18}$O isotopologue at high angular resolution (0″5) using the Institut de Radioastronomie Millimétrique (IRAM) Plateau de Bure Interferometer (PdBI) to determine the origin of water emission in low-mass protostars. This isotopic line is a useful tracer of H$_2$O as it can be detected and imaged at high angular resolution from the ground under good weather conditions (e.g., Jacq et al. 1988; Gensheimer et al. 1996; van der Tak et al. 2006). Its upper level energy of 203.6 K is well matched to the observed excitation temperature of water seen by Spitzer.

2. OBSERVATIONS

We observed NGC 1333-IRAS4B (hereafter IRAS4B; $\alpha = 03^h29^m12^s00$, $\delta = +31^\circ13'08"$) using the six-element IRAM PdBI. The receivers were tuned to the para-H$_2^{18}$O $3_{13}$--$2_0$ transition at 203.407498 GHz (1.47 mm). The correlator was set up with one unit with a bandwidth of 36 MHz (53 km s$^{-1}$) centered on this frequency providing a spectral resolution on 460 channels of 0.078 MHz (0.11 km s$^{-1}$). The source was observed in two configurations: in the C configuration on 2008 December 2 and in the B configuration on 2009 January 11 and 13. About 11 hr were spent in each configuration (including time used on gain calibrators etc.). When combined, these two configurations cover baselines with lengths from 17.8 to 452 m (12 to 308 k$\lambda$).

The data were calibrated and imaged using the CLIC and MAPPING packages from the IRAM GILDAS software. The calibration followed the standard approach: the absolute flux calibration was established through observations of MW C 349, the bandpass by observations of the strong quasar 3c454.3 and 3c542.
Figure 1. Continuum image of IRAS4B and IRAS4B′ from the IRAM PdBI observations (contours shown in logarithmic steps from 0.015 to 0.25 Jy beam$^{-1}$ overlaid on the Spitzer Space Telescope mid-infrared image (Jørgensen et al. 2006; Gutermuth et al. 2008) with 4.5 μm emission shown in blue, 8.0 μm green, and 24 μm red.

Table 1
Parameters for IRAS4B and IRAS4B′ from Elliptical Gaussian Fits to Their Continuum Emission

| Parameter          | IRAS4B   | IRAS4B′  |
|--------------------|----------|----------|
| Flux               | 0.586 Jy | 0.128 Jy |
| R.A. (J2000)       | 03:29:12.01 | 03:29:12.84 |
| Decl. (J2000)      | 31:13:08.07 | 31:13:06.93 |
| Extenta            | 0′.80 × 0′.54 (−65°) | 0′.56 × 0′.45 (−86°) |

Note. a Size of Gaussian from fit in the (u, v) plane (i.e., deconvolved full width at half-maximum (FWHM) size) and position angle of major axes (in parentheses).

Figure 2. Left: integrated emission of the H$_{18}$O line (contours in steps of 5 mJy beam$^{-1}$ km s$^{-1}$ starting at 10 mJy beam$^{-1}$ km s$^{-1}$) plotted over the continuum emission (gray scale). Right: spectrum extracted in the central 0′.6 × 0′.5 beam toward the continuum position for IRAS4B. The detected lines are indicated at the position of their catalog rest frequency corrected for the 7.0 km s$^{-1}$ systemic velocity of IRAS4B. The spectrum has been binned to twice the observed resolution. The inset shows a blow-up of the H$_{18}$O line at the original resolution.

3. RESULTS

Figure 1 shows the continuum image of the observed region around IRAS4B. As seen, both IRAS4B and its nearby companion IRAS4B′ are clearly detected in the image. Table 1 lists the results of elliptical Gaussian fits to the two sources: both are resolved with fluxes in agreement with the results from Jørgensen et al. (2007b) assuming that it has its origin in thermal dust continuum emission with $F_\nu \propto \nu^\alpha$ with $\alpha \approx 2.5–3$. The continuum peak is clearly offset by 5′′–7′′ from the emission at 3.6–24 μm seen in the Spitzer Space Telescope images of IRAS4B; an indication that the Spitzer emission has its origin in material heated by the protostellar outflow even at 24 μm (see also Jørgensen et al. 2007a, and Figure 2 of Allen et al. 2007).

Figure 2 shows the spectrum toward the continuum peak of IRAS4B. A number of lines are clearly detected as listed in Table 2—including the targeted H$_{18}$O 3$_1$–3$_2$ line. For the line identification, we used the JPL (Pickett et al. 1998) and CDMS (Müller et al. 2001, 2005) databases and cross-checked those with the online Splatalogue compilation. Since all of the lines are narrow, little line-blending occurs, in contrast to high-mass star-forming regions. Also, all the assigned lines are centered within 0.1–0.2 km s$^{-1}$ of the systemic velocity of 7.0 km s$^{-1}$ of IRAS4B. Most prominent in the spectrum are lines of dimethyl ether, CH$_3$OCH$_3$, with five identified transitions. In addition, lines of sulfur dioxide, SO$_2$, and water, H$_{18}$O, are...
clear detections with a fainter line of ethyl cyanide, C$_2$H$_2$CN, also present. Concerning the confidence of the assignment of the H$_{18}$O line, according to the Splatalogue compilation no other transitions fall within ±1 km s$^{-1}$ of the location of the H$_{18}$O line. Offsets by 1–2 km s$^{-1}$ are transitions of $^{13}$CH$_2$CHCN, $^{13}$CH$_3$CH$_2$CN, and (CH$_3$)$_2$CO: the two formers can be ruled out because of the lack of additional components which should have been observable at larger velocity offsets, whereas the latter has a very low intrinsic line strength. For each of the detected lines we fit a circular Gaussian in the $(\alpha, \delta)$ plane in the widths of the line emission integrated over the widths of the continuum position in right ascension (R.A.)—with the exception of C$_2$H$_2$CN. The peaks of the molecular emission still fall within the deconvolved extent of the continuum emission, though. The images of the complex organic molecules and SO$_2$ will be discussed elsewhere.

4. DISCUSSION
4.1. Velocity Field

The high spectral and spatial resolution offered by the IRAM data reveals a tentative velocity gradient in the H$_{18}$O emission. Figure 3 shows a moment-1 (velocity) map of this emission indicating a change in velocity of a few ×0.1 km s$^{-1}$ over the extent of the source emission. To estimate the magnitude of the velocity gradient, the centroid of the emission was determined channel by channel in the $(\alpha, \delta)$ plane. The derived offsets along and perpendicular to the largest velocity gradient are then plotted as a function of velocity and a linear fit performed (Figure 3). The velocity gradient found in this way is 9.4 km s$^{-1}$ arcsec$^{-1}$ or 7.7 × 10$^3$ km s$^{-1}$ pc$^{-1}$ at a 3.5σ–4σ confidence level. The velocity gradient is about three orders of magnitude larger than the typical gradients observed on arcminute scales in pre-stellar cores (Goodman et al. 1993)—supporting a scenario in which the H$_{18}$O emission has its origin in a more rapidly rotating structure such as a central disk—although it is not possible to address whether the velocity, for example, is Keplerian in nature. The position angle of the largest gradient is ≈75° measured east of north (with an accuracy of ±5°–10° from the gradient measured in the $(\alpha, \delta)$ plane), which, interestingly, is nearly perpendicular to the axis of the protostellar outflow (upper panel of Figure 3) traced by water masers in the north–south direction with a position angle of −29° (Marvel et al. 2008; Desmurs et al. 2009) and thermal line emission on larger scales at a position angle of 0° (e.g., Choi 2001; Jørgensen et al. 2007b).

Besides the tentative velocity gradient, the H$_{18}$O line width is remarkably narrow: its width to zero intensity is about 1.7 km s$^{-1}$ with a FWHM from a Gaussian fit of 1.0 km s$^{-1}$. For comparison, a free-falling envelope toward a central star with even a very small mass of 0.1 $M_\odot$ would have a characteristic infall velocity of 2.5 km s$^{-1}$ at 25 AU—i.e., we would expect a line width significantly larger than that observed in this case. A rotationally supported edge-on disk would show a similar line width, whereas a more face-on disk would provide a lower width in agreement with what is observed, although a disk seen entirely face-on would not produce any observable velocity gradient. Alternatively, an inclined disk with sub-Keplerian rotation (e.g., a “pseudo-disk” Galli & Shu 1993; Hennebelle & Ciardi 2009) or a density enhancement in the inner envelope due to a magnetic shock wall slowing down the infalling material (Tassis & Mouschovias 2005; Chiang et al. 2008) could result in a lower line width—although such phenomena usually occur on larger scales than 25 AU. Watson et al. (2007) argued based on the detected mid-IR emission that the outflow cone must be close to pole-on providing a low-opacity route for the IR emission to escape toward the observer. This would imply a nearly face-on disk. However, the proper motions and radial velocities of H$_2$O masers suggest an outflow directed closer to the plane of the sky (Marvel et al. 2008; Desmurs et al. 2009). Clearly, observations of the dynamical structure of the inner regions of IRAS4B with even higher angular resolution are required to distinguish between these scenarios.

4.2. Column Density, Mass, and Abundance

The strength of the H$_{18}$O transition suggests a significant reservoir of water vapor toward IRAS4B. We estimate the column density of H$_2$O by adopting an excitation temperature for p-H$_{18}$O of 170 K from the modeling results of Watson.

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### Table 2

| Molecule   | Transition | Frequency (GHz) | $E_u$ (K) | $\mu^2S$ | Flux$^a$ (Jy km s$^{-1}$) | Offset ($\Delta\alpha, \Delta\delta$) $^b$ | Size$^c$ ($^\prime\prime$) |
|------------|------------|----------------|----------|----------|--------------------------|--------------------------------|-------------------|
| H$_{18}$O  | 3$_1$–2$_0$ | 203.407498     | 203.7     | 0.344    | 0.081                    | (−0.11; −0.02)                | 0.026             |
| CH$_3$OCH$_3$ | 3$_1$–2$_1$ EA | 203.407799   | 18.12     | 9.29     | 0.055                    | (−0.14; −0.07)                | 0.048             |
|            | 3$_3$–2$_1$ EE | 203.410112   | 18.12     | 31.1     | 0.088                    | (−0.14; −0.02)                | 0.046             |
|            | 3$_3$–2$_1$ AE | 203.414131   | 18.12     | 20.0     | 0.044                    | (−0.12; −0.02)                | 0.031             |
|            | 3$_1$–2$_1$ AA | 203.418656   | 18.12     | 33.4     | 0.12                     | (−0.12; +0.03)                | 0.067             |
|            | 3$_3$–2$_1$ EE | 203.420253   | 18.12     | 22.3     | 0.094                    | (−0.16; +0.00)                | 0.025             |
| C$_2$H$_2$CN | 2$_2$–2$_1$  | 203.396581    | 122.3     | 338      | 0.045                    | (+0.02; +0.00)                | 0.037             |
| SO$_2$     | 12$_0$–11$_1$,1$_{11}$ | 203.391550$^d$ | 70.12     | 22.5     | 0.12                     | (−0.11; −0.02)                | 0.041             |

**Notes.**

$^a$ Total flux from fitting circular Gaussian to integrated line emission in the $(\alpha, \delta)$ plane. For conversion to brightness temperatures, the gain of the interferometric observations with the current beam size is 0.0126 Jy K$^{-1}$—i.e., implying an integrated line strength for the H$_{18}$O line of 6.5 K km s$^{-1}$.

$^b$ Peak offset with respect to the continuum peak estimated from the Gaussian fit.

$^c$ Extent of emission (FWHM) from the Gaussian fit.

$^d$ Catalog frequency uncertain (accuracy ±0.1 MHz). The observed SO$_2$ peak indicates a frequency higher by 0.1 MHz than the tabulated one.
et al. (2007) and assume that the emission is optically thin and uniform over its extent. With these assumptions, we estimate a column density for $p$-$\text{H}_2^{18}$O of $4 \times 10^{15}$ cm$^{-2}$, which translates into a total H$_2$O column density of $9 \times 10^{18}$ cm$^{-2}$ assuming a $^{18}$O/$^{16}$O ratio of 560 and an ortho–para ratio for H$_2$O of 3 (i.e., an ortho–para ratio established at high temperatures). For comparison, the column density estimated based on the Spitzer detections by Watson et al. (2007) is two orders of magnitude lower, $9.2 \times 10^{16}$ cm$^{-2}$, over an emitting area of $0.24 \times 0.24$—i.e., comparable to the deconvolved size of the H$_2^{18}$O emission here. Our inferred column density is almost unchanged if the excitation temperature is lowered to 100 K and increases by up to a factor 5 if the temperature is increased to 1000 K. These temperatures cover the range of conditions expected for any of the scenarios for the origin of the H$_2$O emission discussed in Section 1.

The total mass contained in the detected H$_2$O is $6.0 \times 10^{-8} M_\odot$, or 0.02 $M_{\text{Earth}}$. Assuming a typical H$_2$O abundance relative to H$_2$ of $10^{-4}$, corresponding to sublimation of the H$_2$O-rich dust ice mantles (e.g., Pontoppidan et al. 2004), the total H$_2$O mass of the H$_2$O-emitting material (dust+gas) is $7.5 \times 10^{-7} M_\odot$ or $25 M_{\text{Earth}}$. For comparison, the mass of the compact disk around IRAS4B inferred from the modeling of high angular resolution dust continuum observations is $0.24 M_\odot$ (Jørgensen et al. 2009). Thus, if the H$_2^{18}$O emission has its origin in this disk, it arises in a small fraction $\approx 0.03\%$ of the material in the disk.

Alternatively, in the absence of such a disk, it is possible that the emission has its origin in the hot inner region of the protostellar envelope where the temperature is $\gtrsim 100$ K: for a simple power-law envelope density profile reproducing the submillimeter continuum emission for IRAS4B on scales larger than $\sim 1000$ AU (2.8 $M_\odot$ within 8000 AU; Jørgensen et al. 2009), the mass within 25 AU (where the temperature is higher than about 100 K) is about $5 \times 10^{-4} M_\odot$, implying a H$_2$O abundance of about $1.5 \times 10^{-5}$. However, such a model is not self-consistent on small scales: to fit the observed compact dust continuum emission seen by the interferometer a strong increase in the envelope density on small scales by two orders of magnitude is required—above the already increasing radial density profile (e.g., Jørgensen et al. 2009). However, if such a density enhancement was due to a magnetic field wall as discussed above (Chiang et al. 2008), the H$_2$O abundance would be lower by the same amount, dropping to about $1.5 \times 10^{-7}$. This abundance is low compared to the expectation from the full desorption of the H$_2$O mantles and also lower than the constraints on the H$_2$O abundance in the outer envelopes of the IRAS4 sources where H$_2$O is frozen out based on ISO-LWS results (Maret et al. 2002). A low H$_2$O abundance in the region of grain–mantle desorption may reflect destruction of H$_2$O by X-rays (Stäuber et al. 2006), but the H$_2$O abundance would need to be reduced to the levels of the outer cold envelope where H$_2$O is frozen out and thus could not provide the compact emission observed here.

Models of the chemistry in more evolved disks around pre-main-sequence stars (where the envelope has dissipated) show a warm upper layer where H$_2$O gas can exist. Although these models are not fully appropriate for disks in the embedded phase, where UV photons may not be able to freely reach the disk surface and heat the gas, they provide a useful reference point for comparison. If the H$_2$O gas-phase abundance is just determined by the balance of photodesorption of H$_2$O ice and
freeze-out, typical gaseous H₂O column densities at 10–25 AU are a few \(10^{18}\ \text{cm}^{-2}\), dropping rapidly at larger radii in these models (e.g., Öberg et al. 2009), only slightly lower than those found here. Alternatively, the temperatures in the upper layers of the disk may be hot enough to drive an active gas-phase chemistry. Woitke et al. (2009) find a layer of irradiated hot water at altitudes \(z/R = 0.1–0.3\) extending out to 30 AU where temperatures are 200–1500 K and densities are \(10^8–10^{10}\ \text{cm}^{-3}\), comparable to the conditions deduced here (see also Glassgold et al. 2009). The H₂O mass in this layer is \(\sim 10^{-4}M_{\text{Earth}}\) in their model, about two orders of magnitude lower than that derived on basis of the H¹⁸O observations presented in this Letter. Because their H₂O/H₂ abundance is only \(10^{-6}–10^{-5}\), the inferred total warm H₂ mass is comparable.

The discrepancy between the column densities from these data and those from the Spitzer mid-infrared observations (Watson et al. 2007) remains significant, though. A possible explanation is that the mid-infrared observations are limited by extinction and thus do not probe the total water column density. Alternatively, a lower temperature of the H₂O emitting gas of \(\sim 100\ \text{K}\) could with an unchanged column density keep the observed H¹⁸O line intensity at the same level while decreasing the mid-IR line flux predicted by the model.

It also remains a question why IRAS4B is the only source with strong H₂O lines at mid-infrared wavelengths (Watson et al. 2007). Watson et al. proposed that IRAS4B was either seen in a particularly favorable geometry—with the H₂O mid-infrared emission from disks around other sources being masked by optically thick envelopes—or that the release of H₂O into the gas phase constituted a particularly short-lived stage in the evolution of embedded protostars. These scenarios could easily be distinguished by further observations of H¹⁸O emission from embedded protostars at sub/millimeter wavelengths where the envelopes are optically thin, and water should thus be detectable if present at similar levels as in IRAS4B. Future observations with the Atacama Large Millimeter Array in Band 5 will fully open this topic up for ground-based observations of large samples of embedded protostars in the same lines.

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