HERSCHEL/HIFI SEARCH FOR H$_2^{17}$O AND H$_2^{18}$O IN IRC+10216: CONSTRAINTS ON MODELS FOR THE ORIGIN OF WATER VAPOR*

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ABSTRACT

We report the results of a sensitive search for the minor isotopologues of water, H$_2^{17}$O and H$_2^{18}$O, toward the carbon-rich asymptotic giant branch star IRC+10216 (a.k.a. CW Leonis) using the HIFI instrument on the Herschel Space Observatory. This search was motivated by the fact that any detection of isotopic enhancement in the H$_2^{17}$O and H$_2^{18}$O abundances would have strongly implicated CO photodissociation as the source of the atomic oxygen needed to produce water in a carbon-rich circumstellar envelope. Our observations place an upper limit of 1/470 on the H$_2^{17}$O/H$_2^{16}$O abundance ratio. Given the isotopic H$_2^{17}$/H$_2^{16}$O ratio of 1/840 inferred previously for the photosphere of IRC+10216, this result places an upper limit of a factor 1.8 on the extent of any isotope-selective enhancement of H$_2^{17}$O in the circumstellar material, and provides an important constraint on any model that invokes CO photodissociation as the source of O for H$_2$O production. In the context of the clumpy photodissociation model proposed previously for the origin of water in IRC+10216, our limit implies that H$_2^{17}$O (not H$_2^{13}$O or SiO) must be the dominant source of H$_2$O production, and that the effects of self-shielding can only have reduced the H$_2^{13}$O photodissociation rate by at most a factor ~2.

Key words: circumstellar matter – stars: abundances – stars: AGB and post-AGB

Online-only material: color figures

1. INTRODUCTION

A key Herschel result of relevance to evolved stars has been the discovery of water vapor in the warm inner envelope of the carbon-rich asymptotic giant branch (AGB) star IRC+10216 (a.k.a. CW Leonis). Here, SPIRE, PACS, and Heterodyne Instrument for the Infrared (HIFI) observations of multiple water transitions emitted by the dense outflowing envelope of this star have established (Decin et al. 2010a; Neufeld et al. 2011a) the presence of warm water vapor within a few stellar radii of the stellar photosphere. The presence of water vapor so close to the star definitively rules out a previous suggestion that the origin of the water vapor, originally detected by means of Submillimeter Wave Astronomy Satellite (SWAS) observations of a single water transition (Melnick et al. 2001; Ford & Neufeld 2001), was the vaporization of a Kuiper Belt analog. In addition, and very strikingly, a small HIFI survey for water vapor in eight additional carbon-rich AGB stars has led to the detection of water emission from all eight sources, suggesting that the presence of water in carbon-rich AGB stars is nearly universal (Neufeld et al. 2011b). Moreover, strong similarities in all eight sources between the spectral line profiles of water and those of other species such as CO argue against the water being released from a flattened structure such as a Kuiper Belt analog.

The widespread occurrence of water in these sources is surprising, because the carbon-to-oxygen ratio is the critical determinant of the photospheric chemistry in evolved stars. The photospheres of oxygen-rich stars, with C/O ratios < 1, are dominated by CO and H$_2$O; those of carbon-rich stars, by contrast, are dominated by CO, HCN, and C$_2$H$_2$ and—under conditions of thermochemical equilibrium—are expected to contain very little H$_2$O. The water abundances derived from Herschel observations of carbon-rich AGB stars are typically 3–4 orders of magnitude larger than the photospheric abundance expected under conditions of thermochemical equilibrium. This huge discrepancy, first revealed in IRC+10216 by SWAS, had led to the suggestion of several possible origins for the water vapor, including (1) the vaporization of icy objects (comets or dwarf planets) in orbit around the star (Ford & Neufeld 2001); (2) Fischer–Tropsch catalysis (Willacy 2004); (3) photochemistry within an outer, photodissociated shell (Agúndez & Cernicharo 2006); (4) photochemistry within a clumpy outflow (Decin et al. 2010a; Agúndez et al. 2010); and (5) non-equilibrium chemistry associated with pulsationally driven shock waves (Cherchneff 2011, 2012). At least in the case of IRC+10216, the first three of these suggestions can be ruled out by the relative strengths of the many water transitions detected by Herschel. Here, the large relative strength of high-lying water transitions indicates the presence of warm water vapor close to the star, whereas the models for origins (1)–(3) predict an absence of abundant water within ~100 AU of the star.

* Herschel is an ESA space observatory with science instruments provided by European-led Principal Investigator consortia and with important participation from NASA.
Using the HIFI (de Graauw et al. 2010) on board the Herschel Space Observatory (Pilbratt et al. 2010), we have attempted to distinguish between the remaining origins (4) and (5) above by means of deep searches for the minor isotopologues H$_2^{18}$O and H$_2^{17}$O. Any explanation for the presence of water vapor in a carbon-rich environment must posit the release of oxygen atoms from the strongly bound CO molecule. If that release results from photodissociation by ultraviolet radiation, an enhancement in the abundances H$_2^{18}$O and H$_2^{17}$O might be expected relative to that of H$_2^{16}$O. This possibility follows from the physics of CO photodissociation, which takes place following line absorption to predissociated electronic states. Therefore, once the transitions of relevance become optically thick, CO can shield itself from photodissociation; thus the photodissociation rate for $^{13}$CO, $^{17}$O, and $^{18}$O (per molecule) can significantly exceed that of $^{12}$C$^{16}$O. Similar effects have been proposed, for example, by Lyons & Young (2005) as an explanation for isotopic anomalies in the solar nebula.

This isotope-selective photodissociation of CO preferentially produces $^{17}$O and $^{18}$O, which will then go on to form the minor isotopologues of water vapor. By contrast, an origin for the water vapor that does not involve the photodissociation of CO, as in the shock-driven chemistry model proposed very recently by Cherchneff (2011, 2012), makes the strong prediction that the H$_2^{18}$O/H$_2^{16}$O and H$_2^{17}$O/H$_2^{16}$O ratios should equal the isotopic abundance ratios in the photosphere: 17O/16O = 1/840 and 18O/16O = 1/1260 (Kahane et al. 1992). This prediction follows from the fact that gas-phase reactions are unlikely to provide any significant isotopic fractionation, because the particle kinetic energies at the high temperatures of the inner envelope are much larger than any zero-point energy differences between the relevant molecular isotopologues.

As discussed by Neufeld et al. (2011a), previous observations of IRC+10216 from single-dish spectra have not revealed any clear evidence for water vapor, consistent with the predictions of all four of these models. However, as we shall describe in this Letter, searching for water vapor in the low-to-middle latitude regions of circumstellar disks around the type I protostar IRC+10216 is not a straightforward task, for two reasons. First, the water vapor lines are very narrow (typically < 1 km s$^{-1}$) and will thus be difficult to detect even with the extremely high spectral resolution (100 kHz) available from the HIFI instruments. Second, the water vapor lines are sparsely populated and will thus have weak line strengths, making it difficult to detect water vapor with a high signal-to-noise ratio even if it is present. However, by combining the results of our observations with the predictions of models of circumstellar disks, we are able to place stringent constraints on the presence of water vapor in the circumstellar disk around IRC+10216.

2. OBSERVATIONS AND DATA REDUCTION

The observations of IRC+10216 were carried out on 2011 May 18 in the Open Time program OT2.dneufeld.6. We used HIFI in dual beam switch (DBS) mode to target the 1$_{0,1}$-1$_{0,1}$ rotational transitions of H$_2^{16}$O, H$_2^{17}$O, and H$_2^{18}$O in mixer band 10. These isotopic abundance ratios were determined from single-dish observations of optically thin transitions of $^{13}$CO, $^{17}$O, $^{18}$O, $^{13}$CS, and $^{14}$S within the circumstellar outflow, under the assumption that isotopic fractionation and isotope-selective photodissociation are negligible for these minor isotopologues of CO and CS. Kahane et al. (1992) justified that assumption with reference to theoretical models—which suggest that fractionation is only important in the outermost part of the envelope—and by comparing the observed line profiles, which provide no evidence for any radial dependence in the relative abundances of the various isotopologues.

3. RESULTS

Figures 1 and 2 show the spectra targeting H$_2^{17}$O and H$_2^{18}$O obtained from the data reduction procedure described in Section 2 above. The underlying noise ~1 mK (rms in the smoothed spectra) is consistent with the predictions of the HSpot time estimator, but the spectra are clearly characterized by a high density of emission features. For lines with peak antenna temperatures exceeding ~10 mK (~5 Jy), plausible identifications were readily obtained from standard catalogs and are marked in Figures 1 and 2; here the width of each mark indicates the uncertainty in the line frequency (or, in the case of AlCl, the
Figure 1. Spectrum targeting the 110–101 transition of H$_{2}^{17}$O in IRC+10216. The LSR velocity scale is for the 552.021 GHz rest frequency of that transition. Vertical dotted lines indicate the velocity centroid (−26.5 km s$^{-1}$) and outflow velocity (14.5 km s$^{-1}$) determined from observations of other lines. Purple marks indicate probable line identifications obtained from standard catalogs (see the text), with the width of each mark indicating the uncertainty in the line frequency, or—in the case of ALCL—the frequency spread of the hyperfine components. (A color version of this figure is available in the online journal.)

Figure 2. Spectrum targeting the 110–101 transition of H$_{2}^{18}$O in IRC+10216. The LSR velocity scale is for the 547.676 GHz rest frequency of that transition. Vertical dotted lines indicate the velocity centroid (−26.5 km s$^{-1}$) and outflow velocity (14.5 km s$^{-1}$) determined from observations of other lines. Purple marks indicate probable line identifications obtained from standard catalogs (see the text), with the width of each mark indicating the uncertainty in the line frequency, or—in the case of ALCL—the frequency spread of the hyperfine components. (A color version of this figure is available in the online journal.)

Figure 3. Same as Figure 1, but on an expanded velocity scale. Magenta histogram: H$_{2}^{16}$O 110–101 line scaled by a factor of 1/220. (A color version of this figure is available in the online journal.)

Figure 4. Same as Figure 2, but on an expanded velocity scale. Magenta histogram: H$_{2}^{16}$O 110–101 line scaled by a factor of 1/220. (A color version of this figure is available in the online journal.)

frequency spread of the hyperfine components). However, for lines weaker than ∼5 Jy, no plausible identification was obvious. Many of these weak unidentified lines are relatively narrow, implying expansion velocities $\lesssim$6 km s$^{-1}$ and suggesting an origin close to the star. In this respect, the spectrum is rather similar to that obtained in the 345 GHz spectral survey of IRC+10216 carried out by Patel et al. (2011), which revealed a new population of weak, narrow, and mainly unidentified emission features that the authors attributed to uncataloged transitions within vibrationally excited states. Given the density of emission features in the spectra that we obtained, the incompleteness of current line catalogs unfortunately limits our ability (more so than the intrinsic signal-to-noise ratio) to identify very weak emissions from H$_{2}^{17}$O and H$_{2}^{18}$O unequivocally. (On the other hand, improvements in the limits derived below may be possible as line catalogs become more complete, allowing weak interlopers to be identified and their relative line strengths modeled.)

In Figures 3 and 4, we show the spectra targeting H$_{2}^{17}$O and H$_{2}^{18}$O (black histograms) on an expanded velocity scale, with vertical dotted lines indicating the velocity centroid (−26.5 km s$^{-1}$) and outflow velocity (14.5 km s$^{-1}$) inferred from observations of other spectral lines. For the H$_{2}^{17}$O transition (Figure 3), there is no evidence for excess emission at the LSR velocity of the source, although our sensitivity is clearly limited by unidentified emission features at nearby velocities. The magenta histogram in this figure shows the H$_{2}^{18}$O line scaled by a factor of 1/220; this being the strongest feature that could be accommodated under the observed spectral profile, we adopt 1/220 as an upper limit on the H$_{2}^{17}$O/H$_{2}^{18}$O line ratio. We note
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Figure 4. Same as Figure 2, but on an expanded velocity scale. Red histogram: prediction for the HNC $v_2 = 1$ $J = 6$–5 line. Blue histogram: data after subtraction of the emission attributable to HNC $v_2 = 1$ $J = 6$–5.

(A color version of this figure is available in the online journal.)

Here that the H$_{18}$O line profile is considerably broader than the narrow unidentified emission features discussed above; its breadth is typical of other transitions within the ground vibrational states of circumstellar molecules, and is consistent with the predictions of excitation models for the H$_{16}$O 1$10$–1$01$ line (e.g., González-Alfonso et al. 2007).

For the H$_{18}$O spectrum (Figure 4), a feature is clearly apparent close to the expected frequency of the H$_{18}$O transition, with an integrated antenna temperature $\sim 71$ mK km s$^{-1}$ that exceeds our upper limit on the H$_{17}$O line. Given the $^{17}$O/$^{16}$O isotopic ratio $\sim 1.5$ in IRC+10216 (Kahane et al. 1992), it would be surprising to find a 1$10$–1$01$ line of H$_{18}$O that was stronger than that of H$_{17}$O. A careful search of available line catalogs revealed an interloper transition of vibrationally excited HNC, the $v_2 = 1$ $J = 6$–5 line, which has a frequency offset (relative to H$_{17}$O 1$10$–1$01$) of only $\sim 6$ MHz, corresponding to a velocity offset $\sim 3$ km s$^{-1}$. Based upon a model for the excitation of HNC, constrained by Herschel observations of the ground vibrational state (Daniel et al. 2012) along with ALMA observations of transitions of lower frequency within the $v_2 = 1$ state (F. Daniel et al. in preparation), we expect a velocity-integrated antenna temperature of $62$ mK km s$^{-1}$ for this HNC transition (with the line strength and profile shown in red). After subtraction of the expected HNC emission, the observed spectrum (blue) shows no clear evidence for any residual that could be attributed to H$_{17}$O.

4. DISCUSSION

Because our sensitivity to H$_{18}$O is limited by the precision with which we can model the interloper HNC $v_2 = 1$ $J = 6$–5 line, and given the inferred photospheric isotopic ratio of $^{17}$O/$^{18}$O $\sim 1.5$, we will focus on the H$_{17}$O line intensity limit as a constraint on the extent of any isotope-selective enhancement in the minor isotopologues of water. Using the model of González-Alfonso et al. (2007) for the excitation of water in IRC+10216, we found that the observed line intensity limit, H$_{17}$O 1$10$–1$01$/ H$_{16}$O 1$10$–1$01$ $< 1/220$, implies an abundance ratio limit H$_{17}$O/H$_{16}$O $< 1/470$ (the latter being smaller than the former on account of optical-depth effects for H$_{15}$O). Comparing this with the isotopic $^{17}$O/$^{16}$O ratio of 1/840, we can place a conservative upper limit of 1.8 on the factor, $f_e$, by which the minor isotopologues are enhanced.

This limit on $f_e$ places a strong constraint on any model in which the photodissociation of CO is the source of atomic oxygen to form water in IRC+10216. For example, were $^{13}$CO the primary source of $^{16}$O and C$^{17}$O that of $^{17}$O, then the expected enhancement factor (Neufeld et al. 2011a) would be $f_e \sim$ C$^{17}$/$^1$C $= 45$ (Cernicharo et al. 2000). Such a large enhancement factor is entirely inconsistent with the data reported here, and would argue against the clumpy photodissociation model and in favor of the alternative model proposed by Cherchneff (2011, 2012). However, as noted by Neufeld et al. (2011a), this large predicted enhancement might be decreased if photodissociation of $^{12}$CO or SiO contributed significantly to $^{16}$O production. Moreover, the photodissociation of $^{12}$CO in vibrationally excited states that are populated close to the star might further reduce the enhancement factor. A proper account of these effects will require an extensive theoretical study, beyond the scope of this Letter, in which the clumpy photodissociation model is investigated fully with detailed treatments of radiative transfer and of the photodissociation of vibrationally excited CO.

In any such model, photodissociation of $^{13}$C$^{16}$O would necessarily have to be the primary source of $^{16}$O. Barring any gas-phase fractionation effects, which would have to be extremely minor at the high gas temperatures in the inner envelope, the observed upper limit on H$_{16}$O/H$_{17}$O would imply that $^{16}$O must be produced at least 470 times as fast (per unit volume) as $^{17}$O. Since the latter is produced by photodissociation of $^{12}$C$^{17}$O, the photodissociation of $^{13}$C$^{16}$O is the only photodissociation process that could possibly provide $^{16}$O at a sufficient rate; no other oxygen-bearing molecule is abundant enough to yield the required $^{16}$O production rate as a result of its photodissociation.$^{12}$

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$^{12}$ Although SiO has an unshielded photodissociation rate that is $\sim 6$ times as large as that of $^{13}$C$^{17}$O (van Dishoeck et al. 2006; Visser et al. 2009), its abundance is only $\sim 10^{-7}$ relative to H$_2$ (Decin et al. 2010b), i.e., even less than that of $^{13}$C$^{17}$O.
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