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<th>Observations of the circumstellar water $^{110}\text{O} \to 110$ and ammonia $^{110}\text{O} \to 00$ lines in IRC $+10216$ by the Odin satellite</th>
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<td>Author(s)</td>
<td>Hasegawa, TI; Kwok, S; Koning, N; Volk, K; Justtanont, K; Olofsson, H; Schöier, FL; Sandqvist, AA; Hjalmarson, Å; Olberg, M; Winnberg, A; Nyman, LÅ; Frisk, U</td>
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OBSERVATIONS OF THE CIRCUMSTELLAR WATER $1_{10} \rightarrow 1_{01}$ AND AMMONIA $1_0 \rightarrow 0_0$ LINES IN IRC +10216 BY THE ODIN SATELLITE

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ABSTRACT

Submillimeter lines of H$_2$O and NH$_3$ have been detected in the carbon star IRC +10216 (CW Leo) with the Odin submillimeter satellite. The detection of the $J_K = 1_0 \rightarrow 0_0$ 572 GHz line of ortho-H$_2$O confirms the earlier detection in the same source with SWAS. The detection of the $J_K = 1_0 \rightarrow 0_0$ 572 GHz line represents the first observation of the ground-state rotational transition of NH$_3$ in a stellar envelope. By fitting a molecular line transfer model to the observed lines, we derive an ortho-H$_2$O abundance of $2.4 \times 10^{-6}$, which is consistent with estimates from the SWAS observation. The derived ortho-NH$_3$ abundance of $1 \times 10^{-9}$ relative to H$_2$ is significantly higher than those derived from 24 GHz inversion transitions and is slightly higher than those from vibrational transitions in the infrared band. The high H$_2$O and NH$_3$ abundances in the carbon-rich star IRC +10216 underscore shortcomings in the conventional gas-phase LTE and non-LTE chemical models.

Subject headings: circumstellar matter — molecular processes — stars: AGB and post-AGB — stars: individual (CW Leo)

1. INTRODUCTION

IRC +10216 (CW Leo) is a carbon-rich asymptotic giant branch (AGB) star that is undergoing extensive mass loss. The dust ejected by the star forms a thick circumstellar envelope (CSE) that obscures the photosphere of the star. Consequently, while it is very bright in the infrared, the star is very faint in the visible due to circumstellar extinction. The CSE is also a site of active chemistry, where more than 50 molecular species have been detected (Glassgold 1996; Olofsson 1999). The very high mass-loss rate inferred from the strengths of the molecular lines suggests that the star is rapidly depleting its hydrogen envelope and is about to leave the AGB to become a planetary nebula. The chemically rich molecular envelope makes IRC+10216 an ideal laboratory for the study of the formation mechanisms of molecules. Since the chemical timescale of molecular formation is limited by the dynamical time ($\sim 10^4$ yr) of the stellar wind, the observations of molecular species give excellent constraints of chemical models.

Ammonia (NH$_3$) was first detected in IRC +10216 in the IR band in absorption of vibrational transitions by Betz et al. (1979). This IR detection was confirmed by Keady & Ridgway (1993), who derived an NH$_3$ abundance of $2 \times 10^{-7}$ (relative to H$_2$), consistent with the earlier estimate by Betz et al. (1979). In a subsequent IR observation, Monnier et al. (2000) obtained a column density of NH$_3$ that is a factor of 4 higher than that by Keady & Ridgway (1993).

In the centimeter band, the 24 GHz inversion transition in the $J_K = 1_0$ rotational state of para-NH$_3$ has been detected in IRC +10216 (Kwok et al. 1981; Bell et al. 1982; Nguyen-Q-Rieu et al. 1984). From the strength of this inversion line, the inferred para-NH$_3$ to H$_2$ ratio is $3 \times 10^{-8}$. If the ortho/para NH$_3$ ratio is unity (a statistical equilibrium value in the high temperature limit), then the abundance from the inversion line is significantly lower than the values from vibrational transitions.

The surprising detections of NH$_3$ in the carbon star IRC +10216 have not drawn much attention. Detections of other more exotic molecules such as cyanopolyynes (e.g., HC$_9$N) and ring molecules (e.g., c-C$_3$H$_2$) probably overshadowed the significance of the NH$_3$ detections in IRC +10216. In fact, early thermochemical (LTE) models by Tsuji (1964) predicted very low abundances of NH$_3$ in carbon-rich stars. More recent studies of the LTE chemistry in carbon-rich stars (Cherchneff & Barker 1992; Lafont et al. 1982 and references therein) have only enforced the early prediction by Tsuji (1964), where the predicted NH$_3$/H$_2$ ratio is of order $10^{-12}$ or lower. The main reason for the low abundance of NH$_3$ in these models is because most of the nitrogen nuclei are tied up in HCN, CN, and N$_2$. Non-LTE (gas-phase) chemical models for CSEs (IRC +10216, in particular) have been presented by many authors. However, NH$_3$ was not included in models by Glassgold et al. (1986), Cherchneff et al. (1993), or Glassgold (1996). Nejad &

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Millar (1987) and Millar & Herbst (1994) assume a high abundance of NH$_3$ (NH$_3$/H$_2$ = 2 × 10$^{-6}$) as an initial condition at the inner boundary of the model CSE, and the models show no net formation but only photodestruction of NH$_3$.

Willacy & Cherchneff (1998) included shock processing of ejected molecular gas in their models of IRC +10216, but the NH$_3$ abundance in their models only reaches $4 \times 10^{-11}$ in the most favorable case. This discrepancy between theoretical and observational abundances of NH$_3$ (and CH$_4$ and SiH$_4$ as well) was pointed out by Willacy & Cherchneff (1998). This suggests that the conventional gas-phase chemistry models are inadequate, and grain-chemistry is probably needed to account for the observations (Willacy & Cherchneff 1998; Lafont et al. 1982; Keady & Ridgway 1993). The presence of NH$_3$ with rather high abundances in oxygen-rich stars is also a difficult problem (Menten & Alcolea 1995).

The infrared and microwave observations probe different excitation environments and have both advantages and drawbacks. In order to better determine the abundance of NH$_3$ and to further constrain theoretical models, it would be desirable to observe the lowest pure rotational transition $J_K = 1_0 \rightarrow 0_0$ of ortho-NH$_3$. In this paper, we report the observation of this 572 GHz transition in emission using the submillimeter-wave satellite Odin.

Water vapor was first detected in IRC+10216 by the Submillimeter Wave Astronomy Satellite (SWAS; Melnick et al. 2001). Since almost all chemical models predict that most elemental oxygen is tied up in CO in carbon-rich stars, the detection of H$_2$O came as a surprise. Past detections of SiO in carbon-rich stars (and HCN and CN detections in oxygen-rich stars) suggest that the difference in molecular abundances between carbon-rich and oxygen-rich stars is not a clear-cut one but only a general, albeit strong, trend (González-Delgado et al. 2003; Bieging et al. 2000; Bachiller et al. 1997; Bujarrabal et al. 1994; Olofsson et al. 1998). A confirmation of the presence of H$_2$O in IRC +10216 would be yet another challenge to the early dichotomized picture of oxygen-based molecules in IRC +10216 (J.K., K. = 30$^{1}_{0.26}$ → 30$^{2}_{3.27}$) at 572.8771486 GHz every orbit. The H$_2$O observations of IRC+10216 at 556.936 GHz (J$_K$ = 1$_1 \rightarrow 1_0$) were obtained with Odin between orbits 17426 and 17521 in 2004 May. The total integration time including measurements at a sky reference position was 440 minutes in the H$_2$O observing.

The observations were made in a position-switching mode, where the satellite was slewed in a 60 s switching cycle, to observe the target position and a sky reference position +15$^\circ$ in R.A. from the target. At these submillimeter wavelengths, Odin has a beam size (FWHM) of $\sim$2'. Pointing was better than 20" in both cases. Data were obtained using the 1024 channel acoustic-optical spectrometer (AOS) with a channel interval of 0.62 MHz (corresponding to 0.33 km s$^{-1}$ at 556.936 GHz), giving a total frequency coverage of $\sim$1 GHz. The data were processed and calibrated at the University of Calgary Space Astronomy Laboratory using the WinOdin software specifically developed for Odin. The averaged spectra were binned to a frequency resolution of 2.4748 MHz (velocity resolutions of 1.30 and 1.33 km s$^{-1}$ at the NH$_3$ and H$_2$O frequencies, respectively). Twentieth-order polynomial baselines were subtracted from the averaged spectra. For comparison, sixth-order polynomial baselines were also used. There was no noticeable difference between the central sections $[-120 \text{ km s}^{-1} < V_{\text{LSR}} - V_{\text{LSR(source)}} < +120 \text{ km s}^{-1}]$ of the resultant spectra with the different orders of polynomial baselines.

Odin has a main beam efficiency ($\eta_{\text{MB}}$) of 0.9. The internally calibrated intensity scale was expressed as the antenna temperature ($T_{\text{a}}$), but all intensity scales in this paper are expressed as the main beam brightness temperature ($T_{\text{MB}}$), where $T_{\text{MB}} = T_{\text{a}}/\eta_{\text{MB}}$.

3. RESULTS

The final averaged Odin spectra of NH$_3$ and H$_2$O lines in IRC+10216 are shown in Figure 1 (without baseline removal) and Figure 2 (after baseline removal). The H$_2$O profile has a single-peak, round-top shape consistent with other molecular line spectra of IRC +10216 obtained with a large beam. The peak intensity $T_{\text{MB}}$(peak) is 0.060 ± 0.017 K at the frequency resolution of 2.5 MHz. The integrated intensity is 1.11 ± 0.11 K km s$^{-1}$ for a velocity interval from −16 to +16 km s$^{-1}$ with respect to the systemic velocity. The intensity of the Odin H$_2$O spectrum is consistent with that of the SWAS H$_2$O spectrum $T_{\text{A}}$(peak) = 0.02 K; Melnick et al. 2001) if one takes into account the larger beam size of 3.3′ × 4.5′ and the main beam efficiency of 0.90 of SWAS.

The NH$_3$ spectrum has a peak intensity of 0.093 ± 0.023 K (2.5 MHz), an integrated intensity of 1.31 ± 0.15 K km s$^{-1}$, and a width of about 30 km s$^{-1}$ at the detection limit. The width and the overall spectral shape of the NH$_3$ line are similar to those of
Fig. 1.—NH$_3$ ($J = 1_0 \rightarrow 0_0$) (top) and H$_2$O ($J = 1_0 \rightarrow 1_0$) (bottom) spectra obtained with Odin in IRC +10216. The baselines have not been removed from the spectra. The frequency resolution is 0.62 MHz in this figure. The NH$_3$ spectrum has been offset by 0.35 K.

Fig. 2.—NH$_3$ ($J = 1_0 \rightarrow 0_0$) (top) and H$_2$O ($J = 1_0 \rightarrow 1_0$) (bottom) spectra obtained with Odin in IRC +10216. The baselines have been removed. The frequency resolution is 2.5 MHz in this figure. The NH$_3$ spectrum has been offset by 0.1 K.
H2O and other molecular lines in IRC +10216. The present NH3 profile, however, shows a depression at the systemic velocity ($V_{LSR} = -26$ km s$^{-1}$). Since the signal-to-noise ratio is only 4 for $T_{MB}(\text{peak})$ in the NH3 spectrum, the observed profile may have simply been distorted by noise, and the actual profile may well be similar to that of H2O. On the other hand, if the observed depression is real, then such a central depression is unusual for a molecular spectrum in an evolved star unless the emitting region is significantly larger than the beam size (which is unlikely).

The NH3 (10 000) line consists of three hyperfine components (Townes & Schawlow 1955), but the hyperfine lines lie within 2 km s$^{-1}$ in velocity, which is much smaller than the observed line width. Thus, the hyperfine lines should not affect the observed line shape and can be safely regarded as degenerate. Every effort was made to eliminate instrumental effects and distortions from the observation. Since the AOS was routinely used in H2O and NH3 observations by Odin at different times, the spectrometer should not be a cause of distortion. The stability of the local oscillator was checked by observing the telluric O3 line every orbit. The observed O3 profiles were inspected; their peak positions (determined with Gaussian fitting) in spectrometer channel are plotted as a function of orbit number in Figure 3. After inspection and rejection of bad data, we include only reliable data in the averaged NH3 spectrum in Figure 2. Since absorption by cooler outer parts of the molecular envelope should appear at a velocity significantly blueshifted from the systemic velocity, absorption within the expanding envelope is ruled out as a cause for the depression at the systemic velocity. One possible explanation for a double peak profile is an unresolved torus (or a disk). Ford et al. (2003), in their attempt to interpret their OH spectrum, suggest such a geometry and present a model double-peaked profile. Given the low signal-to-noise level of our NH3 spectrum, however, an exploration of such a possibility should wait another, better quality NH3 spectrum.

4. ANALYSIS

Model profiles were fitted to the observed spectra of NH3 and H2O. The model profiles were calculated with excitation and radiative-transfer codes for NH3 and H2O. Both of the NH3 and H2O codes employ the large velocity gradient (LVG) algorithm (or Sobolev approximation) in a spherically symmetric geometry for radiative transfer calculations (Deguchi & Nguyen-Q-Rieu 1990). We assumed a constant radial expansion for the model envelope. Local line broadening with a width of 1 km s$^{-1}$ (FWHM) was taken into account when a model profile was calculated. We included, in the excitation calculations, IR illumination from a central star that was approximated as a blackbody with an assumed radius and an assumed surface temperature, consistent with an assumed luminosity of the model central star. Local IR radiation from dust within the molecular envelope was not considered in the present work.

The ortho-H2O (o-H2O) excitation calculations include the $(\nu_1, \nu_2, \nu_3) = (0, 0, 0)$ (ground state), $(0, 1, 0)$ (first excited bending mode), and $(0, 0, 1)$ (antisymmetric O-H stretch) vibrational states with 61 rotational levels in each vibrational state. The ortho-NH3 (o-NH3) excitation calculations only included the $K = 0$ ladder ($J = 0$ through 11) of o-NH3 in the ground vibrational state. The omission of the $K = 0$ levels only through collisional transitions. The $J_K = 3_3$ level, the lowest of the omitted o-NH3 levels, is higher than the $J_K = 2_0$ level in excitation energy. Thus, the inclusion of the $K = 3n$ ($n \geq 1$) levels will have an effect on the excitation of the $J_K = 1_0 \rightarrow 0_0$
TABLE 1

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<td>Distance $D$</td>
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<td>Outer boundary $R_2$</td>
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<td>Gas temperature $T_1$ at $R_1$</td>
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<tr>
<td>Stellar luminosity</td>
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<tr>
<td>Star radius $R_{star}$</td>
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Derived Abundance

$X$(o-NH$3$)$^b$                        | $6.3 \times 10^{-7}$ |
$X$(o-H$2$O)$^a$                        | $2.4 \times 10^{-6}$ |

$^a$ $f_{He}$ is the relative abundance of He to H.
$^b$ Underestimated by ~30%–50% (see text).

The best-fit spectral line profiles are shown in Figure 4. Although the model gives an excellent fit to the observed profile of H$_2$O, the fit to the NH$_3$ profile is less satisfactory. Unless the assumed density $n_1$ (H$_2$) is very high (of the order of $2 \times 10^5$ cm$^{-3}$ or higher, corresponding to a mass-loss rate of $\sim 4 \times 10^{-4}$ $M_\odot$ yr$^{-1}$ or higher), a model profile with a flat top or a central depression cannot be generated for a source smaller than the beam size.

In the best-fit models, the ground rotational transitions of o-NH$_3$ and o-H$_2$O are both subthermally excited. The $T_{ex}/T_k$ ratio is 108/500 K at the inner boundary for the 1$_{01}$--1$_{00}$ transition of o-H$_2$O. The corresponding ratio for the 1$_{10}$--0$_{10}$ transition of o-NH$_3$ is 115/500 K. The $T_{ex}/T_k$ ratio drops to 0.1 or much lower in the outer regions for both of the transitions. Since collisional deexcitation is insignificant in the best-fit models, the estimated abundances from the present models are dependent on the adopted collisional excitation rates and the assumed IR radiation field.

From the integrated line strengths, we can derive the abundances of H$_2$O and NH$_3$ relative to H$_2$. These derived abundance values scale approximately as $X \propto M^{-2}D^2$, where $D$ is the assumed distance to IRC +10216. Assuming a distance of 130 pc and a mass-loss rate of $M = 1.4 \times 10^{-5}$ $M_\odot$ yr$^{-1}$, we obtain a relative abundance of $2.4 \times 10^{-6}$ for o-H$_2$O in IRC +10216. Our result from the Odin observation is consistent with the abundance

![Fig. 4.—Model NH$_3$ and H$_2$O spectra of IRC+10216 (thick lines) plotted together with the observed spectra (histograms).](image-url)
of $2.5 \times 10^{-6}$ (at 170 pc with $\dot{M} = 2.0 \times 10^{-5} M_\odot$ yr$^{-1}$) from the SWAS observation (Melnick et al. 2001). The H$_2$O abundance is comparable to those of CH$_4$, CS, CCH, and CN in IRC +10216 (cf. Table 1 in Glassgold 1996).

The derived abundance for o-NH$_3$ is $6.3 \times 10^{-7}$. Since our NH$_3$ excitation code includes only the $K = 0$ rotational states, and $\chi$(o-NH$_3$) in Table 1 is underestimated by 30% to 50%, we estimate that the actual abundance of o-NH$_3$ is $1 \times 10^{-6}$. This value is significantly higher than $3 \times 10^{-8}$ for para-NH$_3$ derived from the 24 GHz observations (Nguyen-Q-Rieu et al. 1984; Kwok et al. 1981). Abundance estimates for NH$_3$ (ortho and para) from IR observations range from $2 \times 10^{-7}$ to $8 \times 10^{-7}$ (Betz et al. 1979; Keady & Ridgway 1993; Monnier et al. 2000). An accuracy in mass-loss rate of $\pm$50% propagates to a range of $(0.5-2) \times 10^{-6}$ for the (o-NH$_3$) abundance estimate in the present work. Given these uncertainties in the abundance estimate, the present estimate is in line with those from IR observations. The IR absorption spectra in Keady & Ridgway (1993) show no hint of an abundance disparity of order 30 between the ortho- and para-NH$_3$. The difference in excitation requirements (and hence difference in probed gas volume). The present o-NH$_3$ abundance estimate has a very weak dependence on $R_2$ (the outer boundary). If the $R_2$ value is twice the value in Table 1, $\chi$(o-NH$_3$) decreases by only 3%. If the $R_2$ value is half the value in Table 1, $\chi$(o-NH$_3$) increases by only 8%. Thus, if $\chi$(o-NH$_3$) dramatically decreases from $1 \times 10^{-6}$ to $3 \times 10^{-8}$ outward for $r > 2 \times 10^{16}$ cm [$n$(H$_2$) $< 3.5 \times 10^4$ cm$^{-3}$], the present $\chi$(o-NH$_3$) estimate approximately stands. Meanwhile, the thermalization density for the 24 GHz transitions is about $10^4$ cm$^{-3}$, and the 24 GHz lines can easily be excited in the outer part ($r > 2 \times 10^{16}$ cm), where the gas temperature is 50–80 K in the model in Table 1.

5. DISCUSSION

The present Odin observation of the H$_2$O line eliminates any doubt about the SWAS detection of this molecule and firmly establishes the presence of a significant amount of water vapor in the CSE of this carbon-rich late-AGB star. Since the conventional (LTE and non-LTE) gas-phase chemical models all fail to predict the presence of H$_2$O, Melnick et al. (2001) have proposed a scenario in which Kuiper belt objects (comets) are vaporized in the CSE. While this is a very exciting hypothesis, other formation processes such as grain-related processes need to be explored.

Willacy (2004), for example, has shown that under certain conditions, the Fischer-Tropsch (F-T) catalytic processes are able to generate H$_2$O and CH$_4$ in sufficient quantities to explain observed H$_2$O in IRC +10216. The high abundance of H$_2$O also leads to a detectable amount of OH through photodissociation of H$_2$O. The proposed F-T mechanism was first employed to explain the observed molecular abundances in the solar nebula during the planet formation (including the pristine comet composition; Kress & Tielens 2001). It would therefore be difficult to differentiate the formations of H$_2$O and CH$_4$ through the F-T catalysis during the AGB mass-loss phase from the evaporation of H$_2$O and CH$_4$ from comets the composition of which is explained by the F-T process during the pre-main-sequence phase. The weakness with the F-T based model is that the F-T process possibly produces alkanes, alkenes, carbon dioxide, and alcohols, in particular, as well as water and methane (Willacy 2004), but a sensitive search for CH$_3$OH has set a strong upper limit to CH$_3$OH abundance (CH$_3$OH/H$_2$O $< 7.7 \times 10^{-5}$) (Ford et al. 2004). A future F-T model will need to explicitly include the (thus far omitted) CH$_3$OH production channel and yet satisfy the observational constraint on the CH$_3$OH abundance.

The present estimate of $1 \times 10^{-6}$ for NH$_3$/H$_2$ in IRC +10216 reiterates another challenge to chemical models. The LTE chemical models for the atmosphere of a carbon-rich star all predict $\chi$(NH$_3$) less than $1 \times 10^{-10}$ at $P/k = n$(H$_2$) $T = 4.8 \times 10^{16}$ K cm$^{-3}$ for elemental abundance C/O = 1.1–3.5 (Cherchneff & Barker 1992). The only case in Cherchneff & Barker (1992) in which $\chi$(NH$_3$) is as high as $1 \times 10^{-7}$ is under the extreme condition $T = 1008$ K and $n$(H$_2$) = 4.8 $\times 10^{16}$ cm$^{-3}$.

In non-LTE gas-phase chemical models, NH$_3$ is in most cases either assumed to be initially present (Millar & Herbst 1994) or not considered at all (Cherchneff et al. 1993; Glassgold et al. 1986; Glassgold 1996). Nejad & Millar (1987) and Millar & Herbst (1994 and references therein) assume a high abundance of NH$_3$ (NH$_3$/H$_2$ = 2 $\times 10^{-6}$) as an initial condition at the inner boundary of the model CSE together with $\chi$(CO) = $1 \times 10^{-4}$, $\chi$(C$_2$H$_2$) = $2 \times 10^{-3}$, $\chi$(HCN) = $6 \times 10^{-6}$, $\chi$(CH$_4$) = $2 \times 10^{-6}$, and $\chi$(N$_2$) = 1.84 $\times 10^{-5}$. With these initial (inner boundary at $r = 1 \times 10^{16}$ cm) conditions, the NH$_3$/H$_2$ ratio remains at $5 \times 10^{-7}$ for $r < 6 \times 10^{16}$ cm, beyond which NH$_3$/H$_2$ drops drastically below $1 \times 10^{-16}$ at $r = 2 \times 10^{17}$ cm as a result of photodissociation without net formation. The present work supports the high initial values of NH$_3$ abundance assumed in the models by Millar and collaborators, but the origin of such high abundance is still unexplained. From the infrared absorption studies, Keady & Ridgway (1993) suggest that most of the IR absorption by NH$_3$ occurs near $r = 3 \times 10^{16}$ cm.

Willacy & Cherchneff (1998) considered a shock chemistry in addition to the usual quiescent gas chemistry in the outward-moving gas. Although NH$_3$ is considered in their model, NH$_3$ is not generated in abundance in the model. They suggest a possibility (also suggested by Keady and Ridgway 1993) that these simple hydrogenated species are ejected when gas molecules condense into grains. The possibility that grain surface reactions may be responsible was proposed by Lafont et al. (1982). For example, H atoms may be adsorbed or directly react with grain surface materials, and carbonaceous grain surfaces may generate CH$_4$ in the gas phase. These possibilities should be explored more specifically and quantitatively.

In comparison with H$_2$O and CH$_4$, the present estimate for NH$_3$ abundance is significantly higher in IRC +10216 than in comets in the solar system. The NH$_3$/H$_2$O ratio in IRC +10216 is about 0.4 in the present work. The observed NH$_3$/H$_2$O ratios in comets are about 0.007 (Hale-Bopp), 0.004 (Hyakutake), and 0.01 (1P/Halley) (Iro et al. 2003; Bochkéllé–Morel and et al. 2000). If these low ratios apply to all Kuiper belt objects, the evaporation of comets may not be sufficient to explain the observed NH$_3$/H$_2$O ratio in IRC +10216. In addition, there is a growing body of evidence for a strong depletion of elemental nitrogen in comets, and the low NH$_3$ and N$_2$ abundances (relative to H$_2$O in particular) seem widespread among comets (Iro et al. 2003). The extrasolar comets may have very different chemical compositions, however. Meanwhile, it is not clear whether the Fischer-Tropsch (or a similar) process enhances the abundance of NH$_3$. There have been suggestions that NH$_3$ may be formed from N$_2$ through a process similar to Fischer-Tropsch catalysis in the solar nebula (Kress & Tielens 2001). While the N$_2$ dissociation process may be difficult to happen, an experiment is highly desirable (Kress & Tielens 2001). Theoretical studies incorporating an enhanced production of NH$_3$ through Fischer-Tropsch catalysis or similar catalytic processes would substantially advance our
understanding of the origin of NH\textsubscript{3} and H\textsubscript{2}O in carbon-rich AGB stars.

6. CONCLUSIONS

We have detected the ground-state rotational transitions of water and ammonia in the circumstellar envelope of IRC+10216 and derived their relative abundances from line-transfer models. The high abundances of both ammonia and water is a mystery as current LTE and non-LTE gas-phase chemistry models have failed to produce the observed abundance. While the hypothesis of comet vaporization is very attractive in explaining the origin of water in IRC+10216, it does not account for the equally high abundance of ammonia. These results show that our theoretical understanding of circumstellar chemistry is rudimentary, and some (unspecified) fundamental processes are still missing in the models.

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