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Letter to the Editor

Discovery of water vapour in the carbon star V Cygni from observations with *Herschel*/HIFI⋆

D. A. Neufeld[1], E. González-Alfonso[2], G. Melnick[3], M. Pułecka[4], M. Schmidt[4], R. Szczerba[4], V. Bujarrabal[5], J. Alcolea[6], J. Cernicharo[7], L. Decin[8,9], C. Dominik[9,15], K. Justtanont[10], A. de Koter[9,16], A. P. Marston[11], K. Menten[12], H. Olofsson[10,13], P. Planesas[5,14], F. L. Schöier[10], D. Teyssier[11], L. B. F. M. Waters[9,8], K. Edwards[17], C. McCoey[17], R. Shipman[18], W. Jellema[18], T. de Graauw[19], V. Ossenkopf[20], R. Schieder[20], and S. Philipp[12]

[1] The Johns Hopkins University, 3400 North Charles St, Baltimore, MD 21218, USA
e-mail: neufeld@pha.jhu.edu
[2] Departamento de Física, Universidad de Alcalá de Henares, Campus Universitario, 28871 Alcalá de Henares, Madrid, Spain
[3] Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA
[4] N. Copernicus Astronomical Center, Rabiańska 8, 87-100 Toruń, Poland
[5] Observatorio Astronómico Nacional (IGN), Ap 112, 28803 Alcalá de Henares, Spain
[6] Observatorio Astronómico Nacional (IGN), Alfonso XII No. 3, 28014 Madrid, Spain
[7] CAB, INTA-CSIC, Ctra de Torrejón a Ajalvir, km 4, 28850 Torrejón de Ardoz, Madrid, Spain
[8] Instituut voor Sterrenkunde, Katholieke Universiteit Leuven, Celestijnenlaan 200D, 3001 Leuven, Belgium
[9] Sterrenkundig Instituut Anton Pannekoek, University of Amsterdam, Science Park 904, 1098 Amsterdam, The Netherlands
[10] Onsala Space Observatory, Dept. of Radio and Space Science, Chalmers University of Technology, 43992 Onsala, Sweden
[11] European Space Astronomy Centre, ESA, PO Box 78, 28691 Villanueva de la Cañada, Madrid, Spain
[12] Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany
[13] Department of Astronomy, AlbaNova University Center, Stockholm University, 10691 Stockholm, Sweden
[14] Joint ALMA Observatory, El Golf 40, Las Condes, Santiago, Chile
[15] Department of Astrophysics/IMAPP, Radboud University Nijmegen, Nijmegen, The Netherlands
[16] Astronomical Institute, Utrecht University, Princetonplein 5, 3584 CC Utrecht, The Netherlands
[17] University of Waterloo, and University of Western Ontario, Canada
[18] SRON Netherlands Institute for Space Research, Landleven 12, 9747 AD Groningen, The Netherlands
[19] Atacama Large Millimeter/Submillimeter Array, Joint ALMA Office, Santiago, Chile
[20] KOSMA, I. Physik. Institut, Universität zu Köln, Zülpicher Str. 77, 50937 Köln, Germany

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ABSTRACT

We report the discovery of water vapour toward the carbon star V Cygni. We have used *Herschel*'s HIFI instrument, in dual beam switch mode, to observe the $1_{11}-0_{00}$ para-water transition at 1113.3430 GHz in the upper sideband of the Band 4b receiver. The observed spectral line profile is nearly parabolic, but with a slight asymmetry associated with blueshifted absorption, and the integrated antenna temperature is 1.69 ± 0.17 K km s^{-1}. This detection of thermal water vapour emission, carried out as part of a small survey of water in carbon-rich stars, is only the second such detection toward a carbon-rich AGB star, the first having been obtained by the *Submillimeter Wave Astronomy Satellite* toward IRC+10216. For an assumed ortho-to-para ratio of 3 for water, the observed line intensity implies a water outflow rate $\sim 3-6 \times 10^{-5}$ Earth masses per year and a water abundance relative to H_2 of $\sim 2-5 \times 10^{-6}$. This value is a factor of at least 10^4 larger than the expected photospheric abundance in a carbon-rich environment, and – as in IRC+10216 – raises the intriguing *possibility* that the observed water is produced by the vapourisation of orbiting comets or dwarf planets. However, observations of the single line observed to date do not permit us to place strong constraints upon the spatial distribution or origin of the observed water, but future observations of additional transitions will allow us to determine the inner radius of the H_2O-emitting zone, and the H_2O ortho-to-para ratio, and thereby to place important constraints upon the origin of the observed water emission.

Key words. stars: AGB and post-AGB – circumstellar matter – submillimeter: stars

1. Introduction

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_2O, while those of carbon-rich stars are dominated by CO, HCN, and C_2H_2 and contain very little H_2O. Despite this sharp dichotomy in photospheric composition, water vapour has previously been discovered, using the Submillimeter Wave Astronomy Satellite (SWAS), in the circumstellar outflow of the extreme carbon star IRC+10216 (Melnick et al. 2001), for which the C/O ratio is ~1.4. The observation of water vapour in that source, with an inferred abundance relative to H_2 of $\sim 10^{-7}$ (Agúndez & Cernicharo 2006; González-Alfonso et al. 2007), has led to the suggestion of several possible origins for the water vapour, including (1) the vapourisation of icy objects (comets or dwarf planets) in orbit around the star (Ford & Neufeld 2001);

⋆ *Herschel* is an ESA space observatory with science instruments provided by European-led Principal Investigator consortia and with important participation from NASA.

(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. 2010). In both carbon- and oxygen-rich stars, Cherchneff (2006) and Decin et al. (2008) have argued for the importance of shocks in setting non-equilibrium abundances of the molecules CO, HCN, CS, and SiO within the inner envelope, although existing models do not appear to predict a persistent enhancement of H_2O in stars with C/O > 1.

Using the HIFI instrument (de Graauw et al. 2010) on *Herschel* (Pilbratt et al. 2010), it is now possible to search with unprecedented sensitivity for water vapour in carbon-rich stars. As part of the HIFISTARS guaranteed time key program, we will carry out a survey for water vapour in eight carbon-rich stars at distances greater than that (~170 pc) of IRC+10216. Here, we report the detection of water vapour in the very first carbon star targeted in this survey: V Cygni, a Mira variable of spectral type C6 (Wallerstein & Knapp 1998), with an apparent V magnitude varying from 13.9 to 7.7 mag, a period of 421 days, and a distance of ~400 pc (Bieging & Wilson 2001).

2. Observations and results

We observed the lowest transition of para-water, the 1_{11}–0_{00} transition at 1113.3430 GHz line, in the upper sideband of the Band 4b HIFI receiver. This observation, of duration 1167 s including overheads, was carried out on 2010 March 5, using the dual beam switch (DBS) mode and the wide band spectrometer (WBS). The WBS has a spectral resolution of 1.1 MHz, corresponding to a velocity resolution of 0.30 km s^{-1} at the frequency of the 1_{11}–0_{00} transition. The telescope beam, of half-power-beam-width (*HPBW*) ~ 20″, was centered on V Cygni at coordinates α = 20h41m18.3s, δ = 48°08′29″(J2000). The reference positions for this observation were located at offsets of 3′ on either side of the source.

The data were processed using the standard HIFI pipeline to Level 2, providing fully calibrated spectra of the source. The Level 2 data were analysed further using the *Herschel* interactive processing environment (HIPE; Ott 2010), version 2.4, along with ancillary IDL routines that we have developed. Having found the signals measured in the two orthogonal polarizations to be in excellent agreement, we combined them to obtain an average spectrum. Figure 1 shows the WBS spectrum of para-H_2O 1_{11}–0_{00} obtained toward V Cygni, with the frequency scale expressed as Doppler velocities relative to the Local Standard of Rest (LSR) and the intensity scale expressed as antenna temperature. A zeroth-order baseline has been subtracted. The vertical dashed line indicates the LSR velocity of the source, as determined by Bieging & Wilson (2001, hereafter BW01) from observations of the CO J = 2–1 line. The integrated antenna temperature is found to be 1.69 ± 0.17 K km s^{-1}. Our identification of the observed feature with the para-H_2O 1_{11}–0_{00} transition is supported by the absence of any plausible alternative candidate in the JPL (Pickett et al. 1998) or CDMS (Müller et al. 2001) spectral line catalogues.

3. Derivation of the water outflow rate and abundance

In modeling the water emission from V Cygni, we have used the methods described by González-Alfonso et al. (2007, hereafter GNM). To determine the H_2O rotational populations and

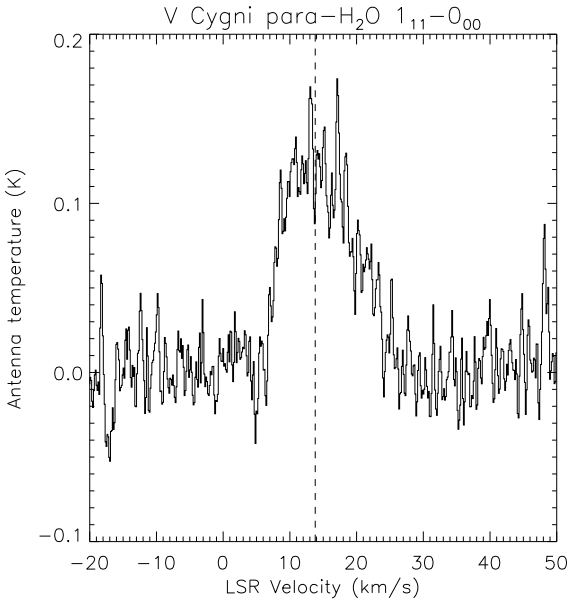

Fig. 1. Continuum-subtracted spectrum of para-H_2O 1_{11}–0_{00} obtained toward V Cygni. The vertical dashed line indicates the LSR velocity of the source, as determined by BW01 from observations of the CO J = 2–1 line.

Table 1. Assumed parameters for V Cygni.

Distance: 400 pc
Stellar luminosity: 8500 $L_\odot$
Effective temperature: 2500 K
Stellar radius: 3.42×10^{13} cm
Systemic LSR velocity: +13.8 km s^{-1}
Terminal outflow velocity: 11.8 km s^{-1}

the resultant H_2O emission spectrum, we included the effects of radiative pumping – through the ν_2 = 1 and ν_3 = 1 vibrational states – and of collisional excitation by H_2, together with a treatment of radiative transfer based upon that discussed by González-Alfonso & Cernicharo (1997).

The assumed parameters for the source are summarized in Table 1 and discussed below. A variety of distance estimates for V Cygni have appeared in the literature. BW01 obtained values of 406 pc and 456 pc respectively by using the $P - K$ (period – absolute K magnitude) and $P - L$ (period – bolometric luminosity) relationships presented by Groenewegen & Whitelock (1996, hereafter GW96). However, our own fit to the spectral energy distribution (SED), shown in Fig. 2, implies that a distance of 342 pc is required to fit the GW96 $P - L$ relationship. Here, we used a dust radiative transfer model to fit a combination of flux measurements from *Tycho*, *Hipparcos*, *MSX*, 2MASS, *ISO*, *IRAS*, and JCMT. This model, full details of which will be presented in a future publication (Schmidt et al., in prep.), assumes a power-law distribution of grain radii with index −3.5 between 0.005 and 0.25 μm, a maximum dust temperature of 1050 K, an inner radius for the dust shell of 2×10^{14} cm, and a total optical depth A_V = 9.45 mag. A smaller distance estimate (370 pc) than those of BW01 was also obtained by Schöier & Olofsson (2000). All of the values mentioned above are consistent with the *Hipparcos*-measured parallax of 3.69 ± 1.77 mas, which implies a 1σ distance range of 180–520 pc. Accordingly, we adopt a value of 400 pc for the estimated distance of V Cygni, with a likely uncertainty ~20%.

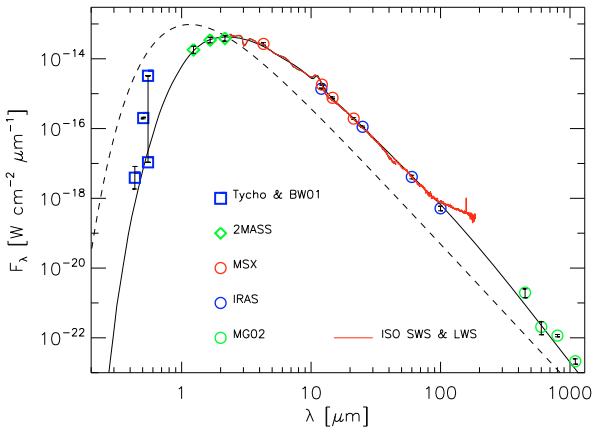

Fig. 2. Spectral energy distribution of V Cygni. A dust radiative transfer model (see text) has been used to fit the fluxes measured by *Tycho*, *MSX*, 2MASS, *ISO*, *IRAS*, and JCMT. The dashed curve shows the unattenuated photospheric emission, while the solid curve shows the total emission from the attenuated photosphere and surrounding dust.

This estimate of the distance then requires a bolometric luminosity of 8500 $L_\odot$ to match the observed SED shown in Fig. 2, and a stellar radius of 3.42×10^{13} cm, given an assumed effective temperature of 2500 K. The values given in Table 1 for the systemic velocity of the source and the terminal velocity of the outflow were based upon *Herschel*/HIFI observations of the CO $J = 6-5$ transition at 691.473 GHz (Schmidt et al., in prep.) and are in excellent agreement with previous determinations by BW01. To obtain an estimate of the total mass-loss rate in the outflow, we have modeled the fluxes observed by *Herschel*/HIFI for the CO $J = 6-5$, $J = 10-9$ and $J = 16-15$ transitions. Full details of the observations and modeling of CO will be given by Schmidt et al., in prep.). Our best estimate of the gas mass-loss rate in the inner envelope is 4.6×10^{-6} $M_\odot$ yr^{-1}, a factor ~3 larger than that obtained by Schöier & Olofsson (2000) from a fit to the CO $J = 2-1$ transition, and the derived CO/H_2 ratio is 10^{-3}. Indeed, we find that a constant mass-loss rate model that fits the CO $J = 6-5$, $J = 10-9$ and $J = 16-15$ transitions substantially overpredicts the flux in the CO $J = 2-1$ transition. This discrepancy suggests some variability in the mass-loss rate, with a larger value applying to the inner envelope where the higher-lying transitions of CO originate. We obtained a satisfactory fit to both the CO rotational line fluxes and the continuum spectrum by assuming a gas and dust density that decreases as radius$^{-2.15}$, instead of the radius^{-2} density profile expected for an envelope with a constant mass loss rate and outflow velocity. The gas-to-dust mass ratio in this model is 510.

Fortunately, given the significant uncertainties in many of the assumed parameters listed in Table 1, the derived water outflow rate is not strongly dependent upon any of them. As discussed in GNM, unless the mass-loss rate is extremely large, the excitation of water is dominated by radiative pumping via the 6 μm ν_2 band. Thus, for a given water outflow rate, the observed water line fluxes scale linearly with the observed 6 μm continuum flux. Since the latter is an observed (rather than a derived) quantity, our estimate of the water outflow rate is largely independent of the distance or total outflow rate assumed for the source.

In modeling the water line strength and profile observed toward V Cygni, we have investigated two models for the spatial distribution of the observed water. In Model A, we assume that water is present at radii as small as 4.5×10^{14} cm, while in Model B, we adopt an inner radius $R_{\rm in} = 2 \times 10^{15}$ cm at which the water is injected into the outflow. In both cases, we assume

Table 2. Derived parameters for V Cygni.

Model A: Water inner radius = 4.5×10^{14} cm
Para-water abundance relative to H_2: 5.3×10^{-7}
Total water abundance[a] relative to H_2: 2.1×10^{-6}
Total water outflow rate: 3×10^{-5} Earth mass/yr
Model B: Water inner radius = 2×10^{15} cm
Para-water abundance relative to H_2: 1.0×10^{-6}
Total water abundance[a] relative to H_2: 4.2×10^{-6}
Total water outflow rate: 6×10^{-5} Earth mass/yr

Notes. [(a)] For an assumed ortho-to-para ratio of 3.

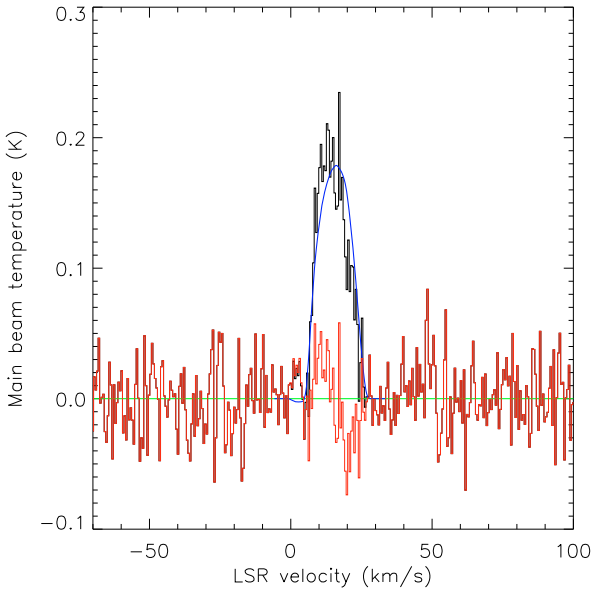

Fig. 3. Continuum-subtracted and smoothed spectrum of the $1_{11}-0_{00}$ transition of para-water at 1113.3430 GHz (black), compared with the the best fit from Model B (blue). The residuals are shown in red. Here, the vertical axis is the main beam brigthness temperature, obtained by dividing the antenna temperature by an assumed main beam efficiency of 0.67.

an outer radius of $R_{\rm out} = 1 \times 10^{16}$ cm, the estimated photodissociation radius for water[1].

The distribution assumed in Model B is expected if the vapourisation of icy objects is the origin of the observed water vapour, since all such objects at smaller distances from the star will have been vapourised already (Ford & Neufeld 2001, GNM). In both models, we adopted the profile given by Goldreich & Scoville (1976) for the outflow velocity as a function of radius. For Model B, this velocity profile was found to give a better fit to the observed line shape than an alternative velocity profile, based upon the work of Skinner et al. (1999), which entails a more rapid acceleration of the outflowing material. A clear asymmetry in the line profile, apparently associated

[1] The mean lifetime against photodissociation for a water molecule in the unshielded mean Galactic ultraviolet radiation field is 1.2×10^9 s (Roberge et al. 1991), corresponding to a distance of 1.4×10^{15} cm at the terminal outflow velocity of the V Cygni outflow. Shielding by dust in the outflow increases this distance by a factor of several, leading to photodissociation radii ranging from ~$5-10 \times 10^{15}$ cm^{-2} for radiation fields within a factor of two of the mean Galactic value. We adopt the upper end of this range, in order to obtain a conservative estimate of the water outflow rate. To account for the observed water line strength, smaller values of $R_{\rm out}$ would require larger values of the water abundance.

with blueshifted absorption, suggests a significant turbulent velocity width, of order 1.3 km s^{-1}. *Equally good fits can be obtained for models A and B, implying that our current observations (of a single line) cannot be used to provide useful constraints on the spatial distribution or origin of the water vapour in V Cygni.* The best-fit parameters are given in Table 2, for each of the two models, and the fit for Model B is shown in Fig. 3. For an assumed water ortho-to-para ratio of 3, the required water outflow rates are 3×10^{-5} and 6×10^{-5} Earth masses per year for models A and B respectively.

4. Discussion

Our detection of thermal water vapour from V Cygni is only the second such detection from the circumstellar envelope of a carbon-rich AGB star, the first having been obtained toward IRC+10216.The water outflow rate in V Cygni, $3-6 \times 10^{-5}$ Earth masses per year, is 4–8 times that in IRC+10216, even though the total mass outflow rate of 4.6×10^{-6} $M_\odot$ yr^{-1} is smaller by a factor ~8. Thus the water line luminosity in V Cygni implies a water abundance ~30–60 times as large as that inferred for IRC+10216. The large H_2O abundance $\sim 3-6 \times 10^{-6}$ that we infer is at least a factor of 10^4 larger than that predicted in models for the photospheres of C-rich stars in thermochemical equilibrium (e.g. Cherchneff 2006). As in IRC+10216, the inferred abundance raises the intriguing *possibility* that the water is produced by the vapourisation of orbiting comets or dwarf planets. In this picture (Ford & Neufeld 2001), a collection of orbiting icy objects in a Kuiper-belt analogue are vapourised as the star ascends the asymptotic giant branch and its luminosity gradually increases; to match the observed water outflow rate in V Cygni, this scenario would require a reservoir of ~10 Earth masses of water ice available for release during the AGB phase.

Observations of the single water line observed to date, however, do not permit us to place strong constraints upon the spatial distribution or origin of the observed water, but future observations of additional transitions will allow us to determine the inner radius, $R_{\rm in}$, of the H_2O-emitting zone, as well as the H_2O ortho-to-para ratio. The radius, $R_{\rm in}$, is a critical diagnostic, because the comet vapourisation model predicts a value $\sim 2 \times 10^{15}$ cm (Model B), all orbiting icy objects within that radius having already been vapourised. In Table 3, we present predictions for the strengths of various emission lines lying within the spectral range accessible to the HIFI, SPIRE and PACS instruments on *Herschel*. In the HIFI (and SPIRE) spectral range (upper section of Table 3), results are given as integrated antenna temperatures; in the PACS spectral range (lower section), the values given are fluxes, in units 10^{-16} W m^{-2}. The predictions presented here are for an assumed ortho-to-para ratio of 3. Several lines, such as the 916.171 GHz $4_{22}-3_{31}$ transition observable by HIFI and the $6_{16}-5_{05}$ 82.031 μm transition observable by PACS, show a strong dependence upon $R_{\rm in}$ and should provide an excellent discriminant between different models.

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Table 3. Predicted line strengths for V Cygni.

Transition	Frequency (GHz)	Wavelength (μm)	Line strength $\int T_{\rm MB}\,{\rm d}v$ in K km s^{-1} [a]	
			Model A	Model B
$1_{11}-0_{00}$	1113.343	269.272	2.53[a]	2.53[b]
$2_{02}-1_{11}$	987.927	303.456	2.46	2.79
$2_{11}-2_{02}$	752.033	398.643	1.18	1.17
$2_{20}-2_{11}$	1228.789	243.974	0.56	0.56
$4_{22}-3_{31}$	916.171	327.223	0.47	0.02
$1_{10}-1_{01}$	556.936	538.289	1.16	1.06
$2_{12}-1_{01}$	1669.905	179.527	6.40	5.90
$2_{21}-2_{12}$	1661.008	180.488	1.92	1.79
$3_{03}-2_{12}$	1716.770	174.626	5.43	4.93
$3_{12}-2_{21}$	1153.126	259.982	1.37	0.85
$3_{12}-3_{03}$	1097.365	273.193	1.67	1.49
$3_{21}-3_{12}$	1162.911	257.795	0.65	0.59
$4_{32}-5_{05}$	1713.882	174.920	0.64	0.03
Transition	Frequency (GHz)	Wavelength (μm)	Line strength (10^{-16} W m^{-2})	
			Model A	Model B
$2_{11}-2_{02}$	2968.748	100.983	1.27	0.82
$3_{31}-2_{20}$	4468.572	67.089	1.16	0.42
$2_{21}-1_{10}$	2773.976	108.073	2.20	1.67
$3_{21}-2_{12}$	3977.045	75.381	2.61	1.11
$4_{14}-3_{03}$	2640.473	113.537	1.70	0.70
$3_{30}-2_{21}$	4512.385	66.438	2.51	1.12
$4_{32}-3_{12}$	3807.256	78.742	1.72	0.23
$5_{05}-4_{14}$	3013.199	99.493	1.23	0.22
$4_{32}-3_{21}$	5107.284	58.699	1.73	0.35
$6_{16}-5_{05}$	3654.602	82.031	1.20	0.02

Notes. [(a)] Integrated main beam temperature; [(b)] observed line strength.

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