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Letter to the Editor

The H I emission profile of RS Cnc

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Abstract. The H I line at 21 cm has been detected in the direction of the S-type AGB star RS Cnc with the Nançay Radio Telescope (NRT). The profile is composite and similar to the CO rotational line profiles. It is composed of a narrow rectangular component overimposed on a wider Gaussian one, both centred on the stellar radial velocity. The narrow component has a width of 4 km s^{-1} and is unresolved (with the NRT beam size of 4′ in α). The Gaussian component has a width (*FWHM*) of 12 km s^{-1} and seems resolved by the NRT. These components trace at least 2 different episodes of mass loss by RS Cnc.

We argue that the atomic hydrogen responsible for the narrow rectangular profile was likely formed in the stellar atmosphere which could thus be devoid of molecular hydrogen, although we cannot strictly exclude that up to 25% may have been produced by photodissociation of H_2. As predicted 20 years ago by Glassgold & Huggins, such a situation should be common to giants with stellar effective temperature larger than 2500 K. This property is relevant to the atmospheric structure of these sources and probably also to the characteristics of their winds.

Key words. stars: circumstellar matter – stars: mass-loss – stars: individual: RS Cnc – stars: AGB and post-AGB – radio lines: stars

1. Introduction

Most of the matter lost by Asymptotic Giant Branch (AGB) stars is hydrogen, atomic or molecular. It is therefore important to detect this element in their circumstellar shells. In particular it is important to know which is the dominant form of hydrogen. This determines the properties of the stellar atmosphere and of the circumstellar envelope, and the characteristics of the wind coming from the stellar surface. The low level lines of molecular hydrogen are in the infrared range, in a part of the spectrum which is opaque from the ground. On the other hand, atomic hydrogen has a line, nicely located at 21 cm, which has already been widely used to explore the Universe.

However, this line has been searched for in the direction of several late-type stars by Zuckerman et al. (1980) with no success. It suggests that only a small fraction of circumstellar hydrogen is in atomic form. Bowers & Knapp (1988) detected H I emission in the direction of Mira, but the interpretation of this detection is ambiguous because Mira is known to have a hot companion (Karovska 1999) and H I could be produced through H_2 photodissociation by UV photons from this companion.

We have undertaken a new sensitive search for the 21 cm H I emission line in circumstellar shells with the recently upgraded Nançay Radio Telescope (NRT). Up to now we have obtained 6 positive detections (Le Bertre & Gérard, in preparation). In this letter we report on a source which shows an intense emission at 21 cm and whose profile allows to derive important constraints.

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2. Presentation of the source

RS Cnc is a semi-regular variable (SRc?) of period ~120 days. Percy et al. (2001) find that it is irregularly variable with timescales ranging from 50 to 200 days, and possibly more. Its spectral type is M6IIIase (CSS 589 in Stephenson's catalogue of S stars) and *s*-process elements are found to be enhanced (Smith & Lambert 1986). The presence of technetium (e.g. Sanner 1978) in its spectrum indicates that it has gone through at least one thermal pulse. There is no evidence of a hot companion (Ake & Johnson 1988), which supports an intrinsic S-type nature.

The parallax measured by Hipparcos is 8.21 mas which translates to 122 pc, a distance that we adopt hereafter. Wang & Chen (2002) have obtained near-infrared photometry (K = -1.62). Using the bolometric correction of Le Bertre et al. (2001), we derive a bolometric magnitude $m_{\rm bol}$ = 1.08 which corresponds to 4370 $L_{\odot}$ for a distance of 122 pc. This estimate is well above the upper limit for red giants confirming that the star is on the AGB. Finally Dumm & Schild (1998) derive a stellar effective temperature of 3226 K and Perrin et al. (1998), 3110 ± 117 K.

Speck et al. (2000) have obtained (8–13.5 μm) spectrophotometry which shows a typical silicate feature in emission. Dust is therefore forming in the atmosphere of RS Cnc and the star should be surrounded by an expanding circumstellar shell.

The IRAS data shows that this process of mass loss in RS Cnc is not uniform. Indeed, Young et al. (1993) found that there is an excess of flux at 60 μm due to a detached shell. The inner radius of the detached shell is 1.0′, or ∼10^{17} cm at 122 pc. The outer radius is found at 5.8′, but this limit may only be an effect of the low temperature of dust at large distance from the central star. The mass loss rate corresponding to this detached shell is a few 10^{-8} $M_\odot$ yr^{-1}.

The wind from RS Cnc has also been detected in the rotational lines of CO. Knapp et al. (1998) have obtained high-resolution spectroscopy of the CO (2–1) and CO (3–2) lines. The data show composite profiles which indicate that the star is surrounded by 2 winds with expansion velocities 2.6 and 8.0 km s^{-1}, carrying mass loss at rates 2.3×10^{-8} and 1.0×10^{-7} $M_\odot$ yr^{-1}, respectively, for an estimated distance of 122 pc. They suggest that the narrow components trace a new episode of mass loss after some changes in the stellar properties. It should be noted that these winds cannot be easily related to the detached shell detected by IRAS. Indeed, the CO photodissociation radii corresponding to these 2 winds are 1.1 and 1.8×10^{16} cm, respectively, and are therefore much smaller than the inner radius of the IRAS detached shell. Neri et al. (1998) have mapped the CO emission from RS Cnc with the IRAM interferometer. They find a size of the order of 10″, in good agreement with the photo-dissociation radius determined by Knapp et al. (1998). They find also evidence of departure from spherical symmetry with a possible resemblance to X Her (Kahane & Jura 1996).

CO line profiles with half full-width smaller than 5 km s^{-1} are rare but not exceptional; they have been found for several AGB sources, mostly semi-regular variables. Winters et al. (2000) have developed models of winds from dust-forming long-period variables. They find a regime denoted “B” for which the winds are slow (<5 km s^{-1}), and the mass loss rates low (<3 × 10^{-7} $M_\odot$ yr^{-1}). Such regime develops preferentially in models with low luminosity or high stellar temperature. Recently, the outflow from the semi-regular red giant, L_2 Pup, has been described as a counterpart of B-type models with an expansion velocity ∼3 km s^{-1} (Jura et al. 2002; Winters et al. 2002).

The narrow component of composite profiles has also been interpreted as due to a long-lived reservoir of orbiting molecular gas (Jura & Kahane 1999). Such a situation could arise in a binary system, but there is presently no evidence of a companion to RS Cnc. Also, we prefer the 2 winds model of Knapp et al. (1998) for RS Cnc because, from IRAS, we have independent evidence that the mass loss process in this source is episodic.

The OH radical was once detected by Rudnitskii (1976) at 1667 MHz with a peak flux density of 0.22 Jy. However, we recently observed the source with the NRT at 1612, 1665, 1667 and 1720 MHz and did not detect any of the 4 lines at a 3 σ level of 10 mJy (Aug. 8, 2002). There is no other known radio lines, although they have been searched for (H_2O, SiO, HCN, H_2S, SO_2, etc.). Finally, RS Cnc has not been detected in the radio continuum neither at 2.6 mm (Neri et al. 1998), 2 cm (Drake et al. 1991) or 6 cm (Spergel et al. 1983).

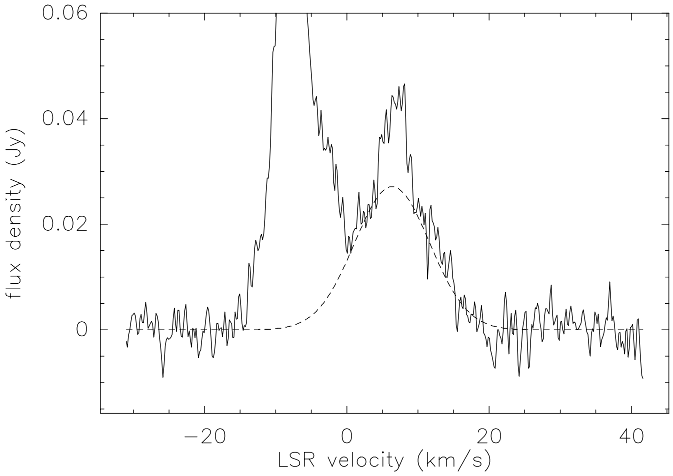

Fig. 1. Average of all the spectra obtained in the position-switch mode. The resolution is 0.16 km s^{-1} and the rms noise, ∼3.5 mJy. A Gaussian fit to the broad feature is shown as a dashed line.

3. Observations

The 21 cm observations have been conducted at the NRT between May and October 2002. The half-power beamwidths at 21 cm are 4′ in right ascension (α) and 22′ in declination (δ). We used a strategy similar to the one in our previous work on IRC +10216 (Le Bertre & Gérard 2001). The data were acquired in the position-switch mode by doing cycles of 4 min, 80 s on the source, then 80 s off East, and finally 80 s off West. The off-positions were selected at ±1 NRT beam (i.e. 4′), ±1.5 beams (6′), ±2 beams (8′), and ±3 beams (12′).

The resulting average of all the data is shown in Fig. 1. The H I line is clearly detected with a peak intensity above 40 mJy. It is centred at $V_{\rm lsr} = 6.5$ km s^{-1}, which corresponds to the stellar velocity derived from the CO rotational line profiles. The H I profile is composed of 2 components: a broad Gaussian feature of width (*FWHM*) ∼12 km s^{-1}, plus a narrow rectangular feature of width ∼4 km s^{-1}. The emission which is observed around −8 km s^{-1} is an artefact coming from residual interstellar H I emission (Fig. 2), not perfectly cancelled with the position-switch mode of observation. In our sample, this composite profile is exceptional: the 5 other sources, in which we have detected H I in emission, do not show such a narrow rectangular feature.

We analysed also separately the data corresponding to the different off-positions. In all cases we obtained the same kind of composite profile. The narrow component is stable, but we suspect that the broad one varies with the amplitude of the beam-throw. The results of the fits are reported in Table 1. The narrow feature is displayed in Fig. 3 together with a rectangular fit; the corresponding mass of atomic hydrogen within the central beam of the NRT is $M_{\rm HI}$ ∼ 2.7 × 10^{-4} $M_\odot$. The mass of atomic hydrogen corresponding to the broad feature, also within the central beam of the NRT, is ∼1.25×10^{-3} $M_\odot$.

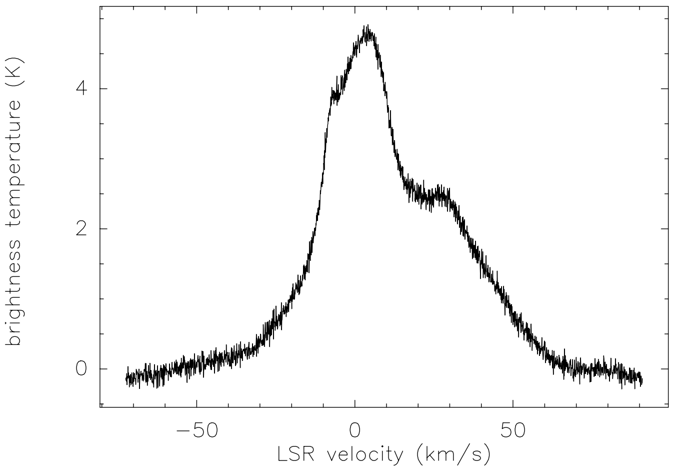

Fig. 2. On-source spectrum obtained in the frequency-switch mode. The resolution is 0.08 km s^{-1} and the rms noise, ~0.08 K. The emission comes essentially from interstellar atomic hydrogen on the line of sight.

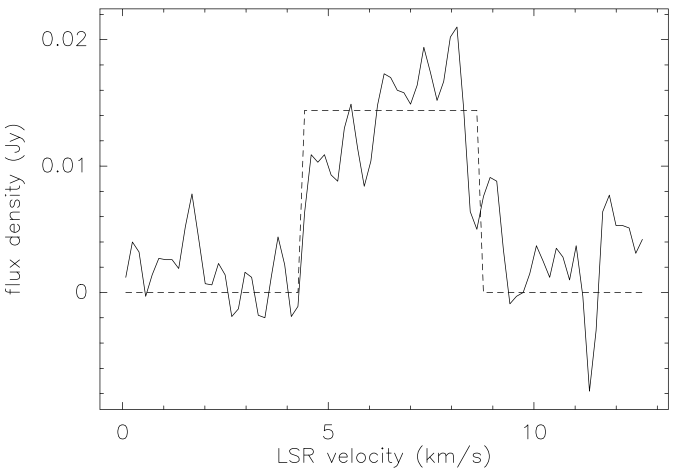

Fig. 3. Same as Fig. 1, but after subtraction of a Gaussian with $FWHM = 12.43$ km s^{-1} and $F_{\rm peak} = 0.027$ Jy. A rectangular fit is shown as a dashed line.

4. Interpretation

The H I profile at 21 cm shows obvious similarities with the CO profiles obtained by Knapp et al. (1998). All three can be decomposed in 2 components: a narrow one and a broad one. However, the 2 CO components are quasi-parabolic whereas the H I components are rectangular and Gaussian, respectively.

The rectangular profile of the narrow H I component is an indication of an unresolved, optically thin (at 21 cm), isotropic and steady wind. It seems reasonable to ascribe it to the same wind producing the narrow component observed in CO. The broad H I component has a width comparable to the CO broad component. However, its emission is spatially more extended: it seems resolved at the scale of the NRT (4′), whereas the CO photodissociation radius of the broad component is $\sim 1.8 \times 10^{16}$ cm, or 0.16′. Also the red wing of the H I velocity profile suggests the presence of material flowing out at velocities larger than deduced from the CO profile (8.0 km s^{-1}). We note that a part of the IRAS extended emission fits within the NRT beam which is elongated in the North-South direction.

In general, we have no real limit on the duration of the winds revealed by the CO emission lines because these lines probe a region limited by the CO photo-dissociation radius. However, in the case of RS Cnc, a limit on the duration of the low-velocity wind is given by the timescale for the photo-dissociation radius of the high-velocity CO wind which is 710 years (Knapp et al. 1998). On this basis we can derive a mass loss rate of 3.5×10^{-7} $M_\odot$ yr^{-1} from the fit of the H I rectangular profile, a factor 15 larger than the estimate obtained from the CO line fitting by Knapp et al. (1998). One should not overemphasize the magnitude of this factor because our estimate of the amount of atomic hydrogen responsible for the rectangular feature depends on the fit of the Gaussian profile to the observed spectrum and because Knapp et al. assume that the slow wind has filled the sphere corresponding to its CO photodissociation radius.

The atomic hydrogen in the slow wind could be the product of the photodissociation of molecular hydrogen in the outflowing wind or could originate directly from the stellar surface. The rectangular profile indicates an expanding, isotropic and steady wind. Adopting for this wind a mass loss rate of 2.3×10^{-8} $M_\odot$ yr^{-1} (which is an underestimate, possibly by a factor ~15) and a duration of at most 710 years (which is an upper limit), we obtain a density at the outer boundary of $\sim 1.3 \times 10^{-20}$ g cm^{-3}. This would translates to a molecular hydrogen density of 4000 cm^{-3}, large enough for H_2 to be self-protected throughout the wind notwithstanding the additional protection provided by dust (Glassgold & Huggins 1983). Therefore the atomic hydrogen responsible for the narrow component of the H I line should originate in the stellar atmosphere.

Furthermore, Morris & Jura (1983) estimate the total number of hydrogen atoms in an initially molecular circumstellar shell as 1.8×10^6 $r^3_{\rm max}/V_{\rm exp}$, assuming a UV flux typical of the solar neighborhood. An upper limit to $r_{\rm max}$, the maximum size of the emitting region, is given by the size of the NRT beam which translates to 2.2×10^{17} cm at 122 pc. With $V_{\rm exp}$ = 2 km s^{-1}, the mass in atomic hydrogen would be $\sim 7.5 \times 10^{-5}$ $M_\odot$, four times smaller than our estimate. More serious however, the timescale would be 3.5×10^4 years, much too large to account for the CO broad component which would have disappeared. Therefore to explain the intensity of the narrow HI feature by photo-dissociation would require an interstellar radiation field much larger than the local one, which is unlikely, considering the distance to RS Cnc.

Following Knapp et al. (1998), we assumed a model with spherical symmetry in which the 2 winds follow each other in time. Should they expand simultaneously within a bipolar structure, e.g. as reported for X Her (Kahane & Jura 1996), then we may apply the same reasoning as above to the broad component. The number of hydrogen atoms would correspond to $\sim 2 \times 10^{-4}$ $M_\odot$ six times smaller than our estimate. Likewise, the timescale of the narrow component would no longer be constrained. In this case, one cannot exclude that a significant fraction of the atomic HI in both winds (perhaps up to 25%) comes from the photodissociation of H_2.

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Table 1. Results of the fits to the H I line profiles. The broad components are fitted with Gaussians and the narrow ones, with rectangles. Only 2 hours were obtained at ±12′ (E–W) and the corresponding fits have not much significance.

off-positions	broad $V_{cent.}$ km s^{-1}	feature *FWHM* km s^{-1}	F_{peak} mJy	narrow $V_{cent.}$ km s^{-1}	feature width km s^{-1}	F_{peak} mJy	σ mJy	integration time hours
±4′ (E–W)	7.0	17.6	44	6.8	4.8	18	8	5
±6′ (E–W)	6.3	13.7	20	6.7	4.5	12	5	15
±8′ (E–W)	6.2	14.0	25	6.5	4.6	19	7	7
average	6.37	12.43	27	6.54	4.24	17	3.5	29

The Gaussian feature comes probably from the addition of winds with different expansion velocities. Adopting an average expansion velocity of ~10 km s^{-1}, we get a crossing time for the NRT beam of ~7000 years which translates to an average flux of atomic hydrogen of about 1 to 2 × 10^{-7} $M_\odot$ yr^{-1}. This estimate is crude but compatible with what we know from other respects (Sect. 2). A mapping with a sensitive interferometer (e.g. EVLA) would certainly be very useful in this context. One could confirm whether the narrow HI component indeed coincides with the narrow CO component and whether the broad HI component is a spatial extension of the broad CO component. As H I is not easily photo-ionized by the normal interstellar UV field, the 21 cm line can be used as a probe of past stellar winds.

The narrow HI component might also arise in a disk with a rotational speed of ~2 km s^{-1} (Jura & Kahane 1999). For a 1 $M_\odot$ central star, the orbital velocity is 2.1 km s^{-1} at 200 a.u., or 3 × 10^{15} cm (1.6″). The beam dilution is such however that even with an optically thick HI disk of 100 K, a minimum projected face-on radius of 700 a.u. would be needed to account for the 17 mJy flux density. Hence an optically thick HI disk would not explain the narrow HI feature. With an optically thin disk, the 2.1 km s^{-1} velocity should correspond to the projected velocity at the inner boundary of an extended HI disk which could extend from 50 up to 3000 a.u. more or less like the Kuiper belt around the Sun. Such a possibility could already be tested with the VLA. However, we note that for CO the rotational speed of ~2 km s^{-1} would correspond to the outer boundary which seems difficult to reconcile with the HI-disk hypothesis.

5. Discussion

Glassgold & Huggins (1983) have discussed the distribution of atomic and molecular hydrogen in the expanding envelopes of late-type stars. They find that for stars with effective temperature, T_{eff}, larger than 2500 K most of the hydrogen should be in atomic form in the stellar atmosphere, and that it should stay atomic in the outflowing wind. On the other hand, for stars with $T_{eff} \leq 2500$ K, hydrogen should be molecular in the stellar atmosphere and stay as such in the wind out to the point where it would be photodissociated by the interstellar radiation field or by UV radiation from a hot companion. The stellar effective temperature of RS Cnc being clearly above 3000 K (Sect. 2), our result is in agreement with the Glassgold & Huggins' model.

The detection of H I at 21 cm indicates also that the formation of H_2 on circumstellar grains is not proceeding efficiently in the RS Cnc outflow. This is again in agreement with Glassgold & Huggins (1983) who find that the conversion to H_2 is not effective below a minimum mass loss rate of the order of 10^{-5} $M_\odot$ yr^{-1}.

Despite this model, till now it has been generally assumed that in the outflows from late-type giants all hydrogen is molecular (from e.g. Kwan & Hill 1977, to recently e.g. Olofsson et al. 2002). This prescription was supported by the non-detection of atomic hydrogen in AGB stars and in particular in IRC +10216 (Zuckerman et al. 1980; Bowers & Knapp 1987). Recently, we confirmed the non-detection of H I in emission from this source, but rather we detected an absorption from an extended region of ~0.1 pc signing the presence of atomic hydrogen far from the star (Le Bertre & Gérard 2001). The only AGB star for which an H I emission was previously detected is Mira (Bowers & Knapp 1988), but as it has a hot companion the origin of the atomic hydrogen was not clear, so that the problem was left open. In fact, the absence of atomic hydrogen close to the central star of IRC +10216 is in agreement with the Glassgold & Huggins' model because the stellar effective temperature of this source is ≤2200 K (Cohen 1979; Bergeat et al. 2001) and the mass loss rate ~2 × 10^{-5} $M_\odot$ yr^{-1} (e.g. Truong-Bach et al. 1991).

Reid & Menten (1997) have found that mass losing red giants may have a radio-photosphere at a temperature of 1500 K. RS Cnc has not been detected in radio continuum (e.g. Drake et al. 1991), but if such structure did exist in its atmosphere, it would mean that the hydrogen is already "frozen-out" at this level.

The presence of atomic hydrogen instead of molecular hydrogen is important for the chemistry operating in stellar atmospheres and in circumstellar shells. It may have an impact on the dust formation processes which depend partly on the chemistry. It should also affect the hydrodynamic structure of the atmospheres of variable stars, and therefore also the development of winds from these objects. It will therefore be important to determine better under which form hydrogen is present in the different classes of mass-losing giants.

6. Conclusion

We have detected the 21 cm H I line in emission from the AGB star RS Cnc. After Mira, RS Cnc is the second AGB star for which this emission is reported. The H I line profile shows 2 components tracing different episodes of mass loss.

Our data suggests that atomic hydrogen is present in the stellar atmosphere and in the expanding circumstellar shell of an AGB star with $T_{\rm eff} \geq 3000$ K. These results are in agreement with the model of Glassgold & Huggins (1983). Observations of the H I line at 21 cm towards AGB sources should bring new informations on their circumstellar shells and their mass loss history, and constraints on their modelling.

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