Astron. Astrophys. 317, 883–888 (1997)

ASTRONOMY AND ASTROPHYSICS

Research Note

^{14}C in AGB stars: the case of IRC+10216

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Received 21 February 1996 / Accepted 31 May 1996

Abstract. Observations and stellar evolution computations have been dedicated to the search for ^{14}C in the archetype of AGB stars, IRC+10216/CW Leo. Contrary to Wright's (1994) tentative detection, we see no trace of ^{14}CO in this star down to a 3σ limit R = ^{13}CO/^{14}CO$\geq$ 1400. The new limit is consistent with our stellar evolution computations, which indicate that R should be $>$ 4000. Comparison of the C, N, O, Mg, Si, and S isotopic ratios observed in this source with the calculated ones reinforces our earlier conclusion that CW Leo had a main sequence mass $3\,M_\odot < M_{ZAMS} < 5\,M_\odot$ (see Guélin et al. 1995).

While searching for the ^{14}CO 2–1 line, we detected the $(1\nu_3)$ $9_{36} - 8_{35}$ line of vibrationally excited SiC_2. The latter line pertains to the first vibrational level of the ν_3 bending state and its upper level has an energy of 290 K, lower than the temperature of the dust forming shell. The line has a pyramidal shape and shows acceleration steps, which we interpreted in terms of dust formation.

Key words: stars: AGB – stars: IRC +10216 – nucleosynthesis – stars: abundances – molecular data – radio lines: stars

1. Introduction

The observation of short lived nuclei in the circumstellar (CS) and interstellar (IS) gas can put stringent constraints on stellar nucleosynthesis, as well as on the time scales for mixing and ejection of the synthesized elements. The shorter the nuclei lifetimes, the tighter are the constraints.

^{14}C and ^{26}Al are probably the most promising such 'clocks'. Their lifetimes ($t_{1/2}$ = 5730 yr and 0.7 Myr, respectively) are short compared to stellar ages, but large compared to the ages of most CS envelopes. Live ^{26}Al is known to be present in IS space (Diehl et al. 1994) and, may be, in CS gas (Guélin et al. 1995, hereafter GFVZ). ^{14}C is not observed in the IS medium, but recently Wright (1994) reported the probable detection of its J= 1–0 line in the carbon star envelope IRC+10216. He derived a ^{13}CO/^{14}CO abundance ratio of 224 ± 47.

The presence of so much ^{14}C is surprising. It disagrees with theoretical predictions (see below) and conflicts with the upper limit derived for the inner CS envelope from IR studies (Barnes et al. 1977; see also Harris & Lambert 1987 for limits on other evolved AGB stars). Confirmed, it would call for a major revision of our ideas on intermediate mass AGB stars. We thus decided to check Wright's result and to embark into new stellar evolution computations adapted to CW Leo, the carbon star at the center of IRC+10216.

2. Observations and results

The line reported by Wright (1994) is so weak that it has escaped detection in all previous mm searches. It is therefore difficult to confirm. However, if Wright is correct, the next rotational line of ^{14}CO, the J= 2–1 line, should be much stronger and easier to detect. This is illustrated by Fig. 1, which shows the ^{13}CO 2–1 and 1–0 lines, observed with the IRAM 30m telescope. Both lines exhibit the cusped profile characteristic of optically thin (or near optically thin) lines arising in a resolved expanding shell. The 2–1 line, which is observed closer to the star, hence in a warmer region, is 3 times stronger (in antenna temperature scale) than the 1–0 line in its central part, and twice stronger in the horns where it starts to be optically thick. Corrected for antenna efficiency and atmosphere transparency, these ratios become 4.5 and 3, respectively. Even larger ratios are expected in the case of ^{14}CO, whose lines must be optically very thin.

We have searched for the corresponding J = 1–0 and 2–1 ^{14}CO lines. The observations were made in April 1995 with the IRAM 30-m telescope, using 3 receivers simultaneously: two 1.3 mm receivers, with image sideband rejections $r \simeq 16$ dB and SSB system temperatures above atmosphere T_{sys} = 280–330 K, and one 2.6 mm receiver with r = 30 dB and T_{sys} = 230 K.

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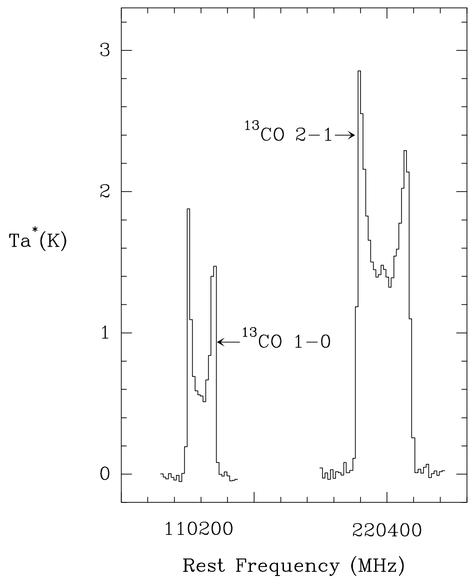

Fig. 1. The J = 2–1 and 1–0 lines of ^{13}CO, observed toward IRC+10216/CW Leo with angular resolutions of 12$''$ and 22$''$. The scale is $T_{MB} = T_a^* \frac{F_{eff}}{B_{eff}}$, the antenna temperature corrected for atmospheric absorption and rear lobes ($\frac{F_{eff}}{B_{eff}}$ = 0.41 and 0.68 for the 2–1 and 1–0 lines, respectively). The image sideband was rejected by $\geq$ 18 dB, insuring a good calibration.

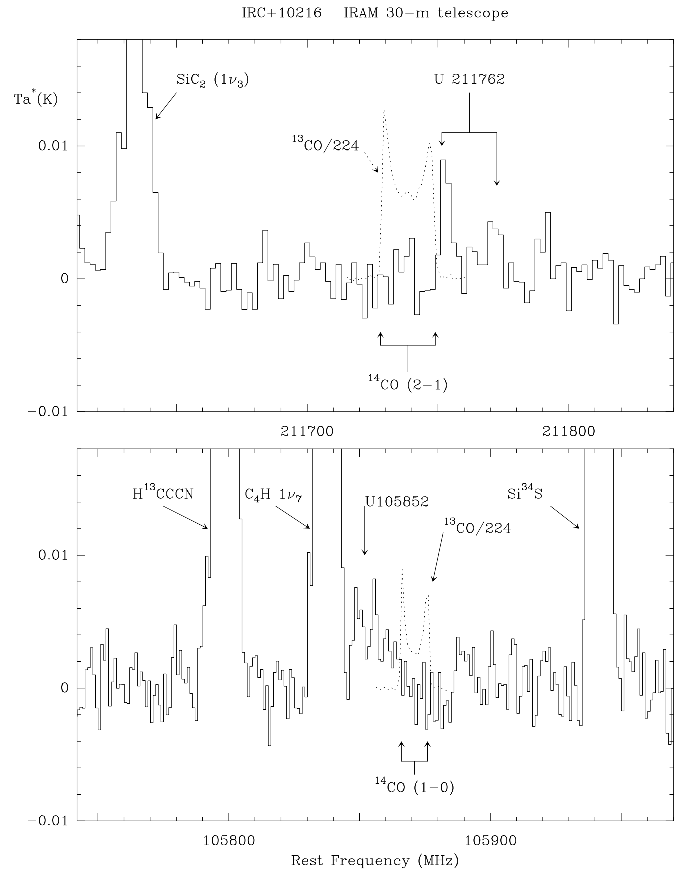

Fig. 2. The J = 2–1 and 1–0 ^{14}CO spectra (full lines) observed toward IRC+10216/CW Leo with the IRAM 30m telescope. The ^{13}CO line profiles of Fig. 1, scaled by 1/224 and shifted to the ^{14}CO transition frequencies, are plotted in dotted lines for comparison. Angular resolution and temperature scale are as in Fig. 1.

The zenith sky opacity was about 0.2 at 218 GHz. The telescope HPBW was 22$''$ for the 1-0 line and 12$''$ for the 2–1 line. Pointing and focusing were checked every two hours on Mars and OJ287, both of which were close to IRC+10216; the receivers were found to be aligned within 3$''$. To insure flat baselines, the subreflector was wobbled at 0.5 Hz with an amplitude of 180$''$. The backend consisted of filterbanks and autocorrelators with resolutions of 1 MHz and 0.32 MHz, respectively.

Fig. 2 shows the average ^{14}CO spectra smoothed to a resolution of 2.8 km s^{-1}. The total ON+OFF integration time and r.m.s. noise per velocity channel are 22 h and 1.4 mK for the 2–1 spectrum and 11 h and 1.8 mK for the 1–0 spectrum.

In order to make the comparison with Wright's result easier, we have superimposed on the observed spectra the 'expected' ^{14}CO line profiles, obtained by scaling by 1/224 the ^{13}CO profiles of Fig. 1. Obviously, no line can be seen at either the 2–1 or 1–0 line frequencies. Two weak lines with about the expected strength are present, one 22 MHz below the 2–1 line and the other 11 MHz above the 1–0 line; neither can be assigned to ^{14}CO, whose transition frequencies (and Doppler correction) are accurately known (Rosenblum et al. 1958). A third line is observed at a rest frequency of 211635 MHz, but, in view of its low frequency and triangular profile, it is readily identified with the 9_{36}–8_{35} rotational transition of SiC_2 in its ν_3 = 1 vibrational state (ν_0 = 211634.77, E_u = 290 K, Bogey et al. 1991). Other stronger lines, belonging to vibrationally excited C_4H and to rare isotopomers of SiS and HC_3N are present and allow to check the correctness of the frequency and intensity scales. We have so far no assignment for the two weak lines.

The 3σ limit we can set on the ^{13}CO/^{14}CO line intensity ratio is 600 for the 1–0 line and 1400 for the 2–1 line. The corresponding abundance ratio is thus $\geq$ 1400. It is 6 times higher than Wright's value and three times higher than the double isotopic ratio (^{13}CO/^{12}CO)/(^{12}CO/^{14}CO) $\geq$ 500 derived by Barnes et al. (1977). Wright (1994) has argued that the discrepancy between his result and Barnes' limit could be explained by a recent variation in the ^{14}C production, since the IR and the mm observations sample different regions of the CS shell. Since the 30m telescope beam is much smaller than the 90$''$ beam of the BTL telescope used by Wright, it should be asked whether this argument applies.

The answer is no. As will be seen below, the ^{14}C, which is produced in the thermal pulse tongues, is tightly mixed with the envelope matter prior to reaching the surface. So, although its production rate is highly variable, the dilution in the envelope insures that the ^{14}C abundance increases only slowly at the surface of the star. The same applies to ^{13}C and to the other CNO isotopes. Therefore, except for the ^{14}C radioactive decay, we do not expect any large variation of the ^{13}C/^{14}C abundance ratio (or of the ^{12}C/^{13}C ratio) in the CS envelope over the past 5000 yrs, that is since the 90″ shell sustained by the BTL telescope beam was expelled. As a matter of fact, the ^{12}C/^{13}C isotopic ratio, observed by Wannier & Linke (1978) with the BTL telescope (40 ± 8), is the same as that observed by Kahane et al. (1988) and Cernicharo et al. (1991) with the IRAM 30-m telescope (44 ± 3).

As for the ^{14}C decay, if anything it affects more the matter of the outer CS shell, which was expelled earlier, than that of the convective envelope, which may have benefited from the injection of freshly synthesized ^{14}C. We thus conclude that the ^{13}C/^{14}C ratio could in no way be significantly larger in the outer CS shell than in the inner shell and that Wright is wrong.

3. ^{14}C production by evolved AGB stars

The large ^{12}C abundance observed at its surface attests that CW Leo, like many AGB stars, has become a carbon star. Surface enrichment in C and other He-burning products occurs mostly during the TP-AGB phase, the last thermally pulsing phase of AGB stars. The TP-AGB phase is characterized by strong thermal pulses coupled to a very rich He-burning nucleosynthesis. Following such pulses, the base of the convective envelope, which extends from the surface almost to the H-burning shell, deeply penetrates into the inner regions affected by this rich nucleosynthesis: this is the third dredge-up (DUP). The freshly synthesized products are mixed into the convective envelope and brought up to the surface.

As first investigated by Despain (1977) ^{14}C could well be a by-product of the thermal pulses. More specifically, during the thermal pulses, a convective tongue expands outwards from the He-burning shell. This tongue penetrates the inter-shell region and ingests the nuclear products left by the slowly drifting H-burning shell located just above. These are the CNO cycle products, like ^{13}C and ^{14}N, and the MgAl chain products, like ^{26}Al^{g}, which will play a key role in the thermal pulse nucleosynthesis. ^{13}C fuels the reaction $^{13}\mathrm{C}(\alpha,\mathrm{n})^{16}\mathrm{O}$ that produces neutrons. The neutrons are captured by various nuclides, mostly through (n,γ) and (n,p) reactions. One of those, $^{14}\mathrm{N}(\mathrm{n},\mathrm{p})^{14}\mathrm{C}$, produces ^{14}C. As explained above, the DUP which follows the thermal pulses will later carry this element into the convective envelope. It will be up-heaved to the surface and, finally, expelled into space.

At the end of the TP-AGB phase, the star loses mass at a higher rate. The mass loss makes the convective envelope thinner and reduces the ^{14}C dilution. The resulting higher ^{14}C abundance then provide the best opportunity to observe this isotope.

4. Predictions from stellar evolution calculations

Obviously, the ^{14}C abundance depends not only on the degree of evolution of the AGB star, but also on its total mass. Judging from the slightly bipolar shape of its molecular shell, CW Leo/IRC+10216 seems to have reached the very end of the TP-AGB phase and to have just started its evolution to a PN (see Guélin et al. 1993, Kastner & Wientraub 1994). Judging from its isotopic composition, its main sequence mass should have been in the range $3\,\mathrm{M}_\odot < M_{ZAMS} < 5\,\mathrm{M}_\odot$ (see GFVZ and below).

Evolution models of 3, 4, 5 and $6\,\mathrm{M}_\odot$ stars, with metallicity Z = 0.02, were thus computed from the early pre-main sequence phase up to the TP-AGB phase. The nucleosynthesis has been followed at each time step with a very large set of nuclear reactions, allowing to predict among others the production level of ^{14}C. The reaction network and the complete results will be presented elsewhere (Forestini and Charbonnel, 1996). We review here those concerning ^{14}C.

Despain (1977) already suspected from its envelope calculations that the ^{14}C production was weakened by neutron captures on heavy elements, which would make difficult (if not improbable) the observation of this isotope e.g. in IRC+10216. Our self-consistent evolution models support this view. They make even dimmer the prospects for a detection. Indeed, the reaction $^{14}\mathrm{N}(\mathrm{n},\mathrm{p})$, which was advocated by Despain as the main ^{14}C production channel, does not proceed very efficiently inside the thermal pulses in our model, and this for two reasons:

(1) Other neutron captures shield this reaction. They are, by decreasing order *(i)* $^{12}\mathrm{C}(\mathrm{n},\gamma)$ and the so-called s-process, *(ii)* $^{28}\mathrm{Si}(\mathrm{n},\gamma)$ and $^{26}\mathrm{Al}^{g}(\mathrm{n},\mathrm{p})$, and *(iii)* other (n,γ) reactions involving Ne, Mg and S. Among those, the reaction $^{26}\mathrm{Al}^{g}(\mathrm{n},\mathrm{p})$, not included by Despain, plays an important role in reducing the ^{14}C production.

(2) The competing reaction $^{14}\mathrm{N}(\alpha,\gamma)$ proceeds at a very high rate at the base of the thermal pulses and decreases the ^{14}N abundance in the convective tongue.

During the TP-AGB evolution of a star, the core mass increases and the thermal pulses become stronger and hotter. This favors the depletion of ^{14}N by (2) as well as the destruction of ^{14}C through the parallel reaction $^{14}\mathrm{C}(\alpha,\gamma)$. The process is reinforced in massive AGB stars that have higher core masses. In these massive stars, moreover, the inter-shell region is thinner (in mass), so that less ^{14}N is ingested by the thermal pulses; the convective envelope is also larger, so that the ^{14}C up-heaved to the surface suffers more dilution. All this conspires to reduce the ^{14}C abundance, leaving the less massive stars as the best contenders for ^{14}C studies.

This is illustrated by the numerical results presented in Fig. 3. Since AGB stars lose mass in the course of their evolution, we have plotted for each one of the stellar models mentioned above (M_{ZAMS} = 3, 4, 5 and $6\,\mathrm{M}_\odot$) the ^{13}C/^{14}C ratio in the convective envelope (and at the surface of the star) as a function of the decreasing mass (core+convective envelope). The ^{14}C lifetime being usually comparable than the inter-pulse time, its abundance decreases between two successive DUPs. We have thus represented for each stellar model the isotopic ratio just after the DUPs (solid line) and at the end of the inter-pulse phase (dotted line). The latter ratio takes into account the ^{14}C decay and, for the more massive stars, proton burning (see below).

Except for $M_{ZAMS} = 3\,\mathrm{M}_\odot$, the ^{13}C/^{14}C abundance ratio is always > 4000, i.e. larger than the lower limit derived from our

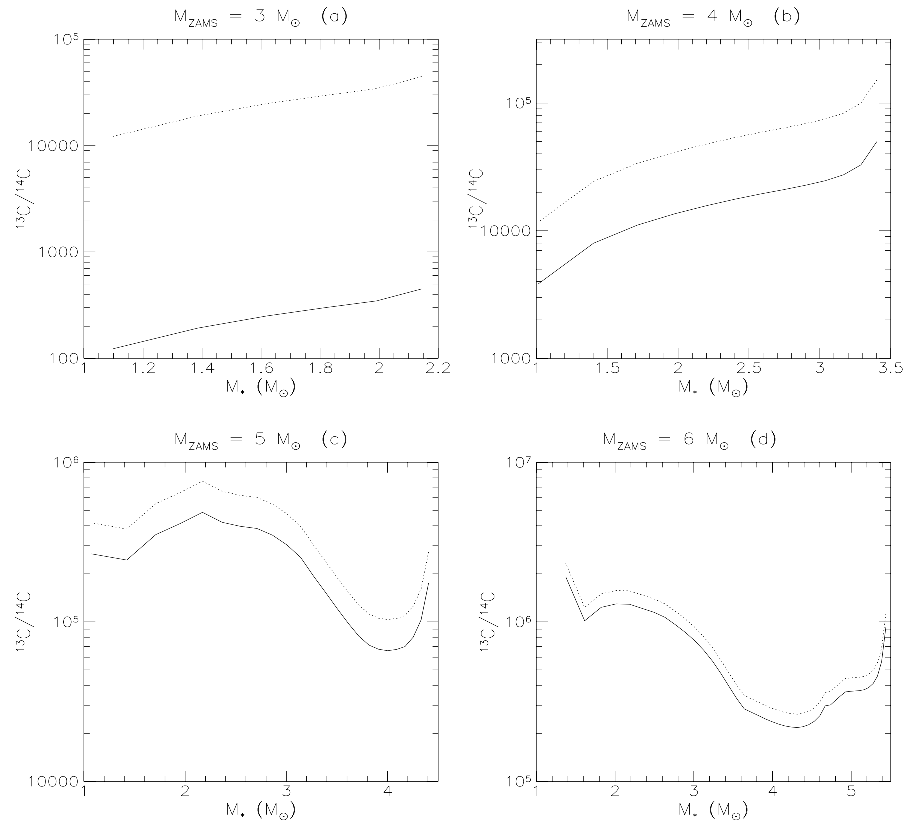

Fig. 3. The ^{13}C/^{14}C isotopic ratio calculated for 4 different stellar models (M_{ZAMS} = 3, 4, 5 and 6 $M_{\odot}$), as a function of the current stellar mass (which decreases with time). The solid line is the ratio shortly after the thermal pulses and DUPs, and the dotted line the ratio at the end of the inter-pulse phase, resulting from the sole ^{14}C decay. The typical inter-pulse durations are 38000, 9200, 3700 and 1600 yr for the 3, 4, 5 and 6 $M_{\odot}$ models, respectively.

mm observations. In the case of stars with $M_{ZAMS} \simeq 3\,M_{\odot}$, this ratio stays below 1000 for about half of the inter-pulse phase.

5. Uncertainties and prospects

Considering what we know about IRC+10216/CW Leo, what abundance ratio do we predict and could ^{14}C be detectable with more sensitive observations?

The ^{13}C abundance relative to ^{14}C decreases with time, as we have seen, mainly because the convective envelope becomes less massive and the dilution less important. This is in favor of CW Leo. On the other hand, as we will see now, the M_{ZAMS} of CW Leo is relatively large, which reduces the chances of observing this isotope. GFVZ compared the calculated C, N, O (as well as Mg, Si and S) isotopic ratios, to those observed in this star. They showed that the observed high ^{14}N/^{15}N ratio implies a stellar mass significantly larger than 3 $M_{\odot}$, whereas the relatively low ^{16}O/^{18}O and high ^{12}C/^{13}C isotopic ratios precludes a mass larger than 5 $M_{\odot}$. With these constrains, Fig. 3b&c teaches us that the ^{13}C/^{14}C ratio must be > 4000.

With present state of the art telescopes, it seems difficult to improve our limit ^{13}C/^{14}C > 1400 by new mm/submm measurements. As concerns IR observations, the ^{14}C limit stems more from the stellar spectrum modeling than from their sensitivity level, since the ^{14}CO lines are blended (with CN lines, with other CO lines, and with telluric lines) and since the derived ratio is temperature dependent (Barnes et al. 1977). In fact, no limit on ^{12}CO/^{14}CO larger than 3×10^4 (which, for IRC+10216, would correspond to ^{13}C/^{14}C $\simeq$ 1000) was set so far for any star by this method (see Harris & Lambert 1987). The prospects for detecting ^{14}CO look therefore very dim.

Of course, the results of the calculations have to be considered with some caution, particularly for very evolved AGB stars. Calculations of complete evolutionary tracks with extended nuclear reaction networks take a large amount of CPU time and are not quite finished. Our new computations have not yet reached the very end of the TP-AGB phase, and we had to extrapolate the relevant parameters (the total radius, luminosity, mass loss rate, temperature and density at the base of the convective envelope, core mass, . . .) to reach the AGB tip. Let us emphasize that these calculations are stopped at the last third dredge-up for which the envelope mass is still $> 0.2\,M_{\odot}$. This is mainly justified by the facts that *(i)* these last $0.2\,M_{\odot}$ are typically ejected during the planetary nebula phase and *(ii)* the last thermal pulse (and accompanying third dredge-up) most probably occurs well before the convective envelope is completely lost. Nucleosynthesis and time-dependent convective mixing have been followed together in detail. The depth reached by the convective envelope has been assumed such as the upper third of the thermal pulse convective tongue is brought to the envelope – probably the maximum possible, considering the DUP calculations. Although these assumptions seem justified in view of the regularity and roughly linear structural evolution of TP-AGB stars, let us finish by briefly mentioning the changes in the ^{13}C/^{14}C ratio predictions for the end of the TP phase which could occur. We divide them in two classes: those in favor of a larger ^{14}C abundance and those of a lower.

(1) The major process neglected here, which could result in more ^{14}C, is the s-process. Observations indicate that evolved AGB stars show significant surface enhancement in heavy nuclides, whose production probably requires a neutron flux at least ten times greater than predicted by the current models (see e.g. Sackmann & Boothroyd 1991). This is generally interpreted as a model insufficiency in producing enough ^{13}C for the reaction $^{13}C(\alpha, n)$. Ten times more ^{13}C, however, does not necessarily mean that the reaction $^{14}N(n, p)^{14}C$ would run ten times faster but, possibly, would tend to decrease the ^{13}C/^{14}C ratio. Furthermore, the AGB stars for which the s-process is inferred are significantly less massive than CW Leo.

The very hot pulses characterizing very evolved massive AGB stars could also produce neutrons through the $^{22}Ne(\alpha, n)$ reaction. Such pulses, however, would also be very efficient in destroying ^{14}N by the $^{14}N(\alpha, \gamma)$ reaction and ^{14}C through $^{14}C(\alpha, \gamma)$.

In summary, not much can be expected for boosting the ^{14}C production in CW Leo.

(2) At the opposite, the extrapolation of nucleosynthesis calculations to the final AGB stage could well lead to an underestimation of the ^{13}C/^{14}C ratio. Indeed, as just mentioned, the last thermal pulses are hotter hence likely to destroy completely the ^{14}C and the ^{14}N. As, moreover, the base of the convective envelope becomes also hotter with time, the nuclear burning occuring there (the so-called hot-bottom burning, or HBB) can partially convert ^{12}C in ^{13}C through the CN cycle. Especially for very massive AGB stars, this will increase the ^{13}C/^{14}C ratio, as seen in Fig. 3. CW Leo, however, cannot be experiencing efficient HBB, since its ^{12}C/^{13}C ratio (44 $\pm$ 3 according to Cernicharo et al. 1991) is much larger than 3, the CN cycle equilibrium value.

In conclusion, the simplifications in the model are more likely to lead to an underestimation, than to an overestimation of the ^{13}C/^{14}C abundance ratio in CW Leo, which is therefore very probably > 4000. ^{14}C appears thus beyond detection in this star.

What about other stars? Combining the ^{12}C/^{14}C limits and the ^{12}C/^{13}C ratios measured by Lambert and co-workers for 25 stars, we note that limits on ^{13}C/^{14}C larger than 1400 (i.e. larger than our limit for IRC+10216) and up to ¿3200 can already be set for 4 AGB stars (RY Dra, Y CVn, WZ Cas and T Lyr). How do these limits relate to the theoretical ratios presented in Fig. 3? The 4 stars, in fact, are all J stars with ^{12}C/^{13}C ratios close to the CN cycle equilibrium value of ~ 3. Such low ratios clearly indicate these objects are experiencing strong HBB and are therefore massive ($> 5\,M_\odot$). From Fig. 3, we then expect $^{13}C/^{14}C \gg 10^4$, so that these IR limits are hardly meaningful. It could however be interesting to investigate (both on grounds of new IR observations and low-mass evolutionary models) the case of other low-mass AGB stars for which $^{13}C/^{14}C < 1000$ ratios could be expected.

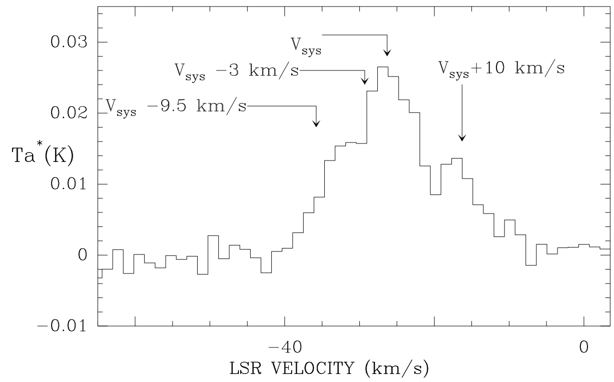

Fig. 4. The $9_{36} - 8_{35}$ line of the $\nu_3 = 1$ bending state of SiC_2, observed toward CW Leo with a 1.4 km s^{-1} resolution.

6. Vibrationally excited SiC_2

The line at 211635 MHz is the first detection of vibrationally excited SiC_2 in an astronomical source. This line is shown in Fig. 4 at a resolution of 1.4 km s^{-1}. It has a pyramidal shape quite uncommon for IRC+10216 and is slightly asymmetrical. The line-width is much narrower than the standard line-width of 29 km s^{-1} in the upper part of the line (Δv = 7 km s^{-1}), and increases abruptly to 20 km s^{-1} at 2/3 of the height. Further down, it increases slowly to the standard value.

It is tempting to see in the line shoulders the acceleration of the gas by dust. More specifically, SiC_2 is expected to be relatively abundant in the hot stellar atmosphere and to be slowly expelled with CO, SiS, and other stable compounds into the CSE. The gas from the hot atmosphere, presumably driven outwards by acoustic waves, cools down and partly condenses into grains, a process which becomes quite rapid as soon as the first dust seeds are formed. The newly formed dust grains are accelerated by radiation pressure and start to drag the gas on their way. According to Keady et al. (1988), who modeled the profile of the CO (v=0–2) IR lines, the gas expansion velocity actually observed increases abruptly from 3 to 10 10 km s^{-1} in the dust formation region (R = 3–4 R_*).

The bulk of the SiC_2 expelled by the star is expected to condense onto the grains. This is probably observed on the high resolution interferometric maps (Lucas et al. 1995), as attested by the point-like SiC_2 source present at the position of the central star. Because it requires high excitation conditions (E_u = 290 K), the ν_3 = 1 line of Fig. 4 arises essentially from this hot and dense central source and its profile is modeled by the acceleration process. The narrow top of the line must arise from the quiet region interior to the dust formation shell, and the line shoulders from the gas acceleration region. A detailed analysis of the shape and excitation of this line – and of other transitions of vibrationally excited SiC_2 – should provide some insight into the dust formation process. It is, however, out of the scope of the present paper.

Acknowledgements. Part of the computations presented in this paper were performed at the "Centre de Calcul Intensif de l'Observatoire de

Grenoble". Most of them have been realized at "IMAG" on a IBM SP1 computer financed by the MESR, CNRS, and Region Rhône-Alpes.

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