

[C I] and [C II] emission in the circumstellar envelope of IRC +10216

I. Observational data and NLTE modelling of the [C I] emission★

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ABSTRACT

Context. The envelopes of evolved late-type stars on the asymptotic giant branch are characterised by a complex chemistry that is close to thermochemical equilibrium near the stellar surface; however, in the outer envelope, it is dominated by radical reactions, assisted by a photo-chemistry driven by the interstellar radiation field.

Aims. The study at hand aims to describe the distribution of atomic carbon, C⁰, throughout the envelope, in support of an improved understanding of its photo-chemistry. Additionally, we also briefly discuss the observation of [C II] emission towards the star.

Methods. We obtain spectra of the [C I] ³P₁ → ³P₀ fine structure line (at 492.160700 GHz) at projected distances of up to 78'' from the star. The line profiles are characterised by both direct fitting of Gaussian components, and by modelling the observed line of the [C I] triplet. We also report the detection of the ²P_{3/2} → ²P_{1/2} line (at 1900.5369 GHz) from the C⁺ fine structure singlet at the central position and its non-detection at 32'' from the star.

Results. The overall picture of the [C I] emission from IRC +10216 agrees with more limited previous studies. The satisfying agreement between the observed and modelled line profiles, with emission at the systemic velocity appearing beyond one beam (13'' HPBW) from the star, rules out that the C⁰ is located in a thin shell. Given that the bond energy of CO falls only 0.1 eV below the ionisation threshold of C⁰, the absence of observable [C II] emission from sightlines beyond a projected distance of ~10¹⁷ cm (≥20''–30'') from the star (adopting a distance of 130 pc) does not contradict a scenario where the majority of C⁰ is located between that of CO and C⁺, as expected for an external far-ultraviolet radiation field. This conjecture is also corroborated by a model in which the C⁰ shell is located farther outside, failing to reproduce the [C I] line profiles at intermediate sky-plane distances from the star. Comparing a photo-chemical model adopted from literature with the simplifying assumption of a constant C⁰ abundance with respect to the H₂ density (with the 1/r² fall-off of a mass-conserving expansion flow), we constrain the inner boundary of the [C I] emitting shell, located at ~10¹⁶ cm from the star.

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

1. Introduction

Low- to intermediate-mass stars (0.8–8 M_⊙) evolve to the asymptotic giant branch (AGB) when they are close to the end of their lives. These objects go through intense mass loss forming a circumstellar envelope (CSE) around them that contains dust and molecules (Höfner & Olofsson 2018). Many of the 241 molecules that so far have been identified in astronomical sources were detected in the CSEs of AGB or red supergiant stars (McGuire 2022), which therefore efficiently enrich the interstellar medium (ISM).

The abundances of carbon and oxygen at the stellar surface reflect the interplay of nucleosynthesis and convection in the stellar interior. Stars with C/O > 1 are defined as carbon-rich, those with C/O < 1 as oxygen-rich, and those with C/O ≈ 1 are the S-type stars. The abundance of these atoms is mainly due to the third dredge-up, where the material is brought up to the

stellar surface and subsequently ejected into the envelope thanks to thermal pulses (TPs) forming in response to instabilities in the helium-burning shell. The third dredge-up occurs after each TP (except for a few initial ones, depending on the model, e.g. Weiss & Ferguson 2009), influencing the C/O ratio in the envelope (Karakas & Lattanzio 2014, further references therein), while the number of TPs depends on the mass loss experienced by the star before it leaves the AGB.

IRC+10216 (= CW Leonis) is the archetypal carbon-rich AGB star located close to us at a distance between 120 and 140 pc (Crosas & Menten 1997; Groenewegen et al. 2012) and losing its mass at a high rate of 2–4 × 10^{−5} M_⊙ yr^{−1} (Crosas & Menten 1997; De Beck & Olofsson 2018; Fonfría et al. 2022). The star has a luminosity of 8600 L_⊙ determined from the Very Large Array (VLA) imaging of the optically thick radio photosphere (Menten et al. 2012) that, for a photospheric effective temperature of 2750 K (assumed from spectral energy distribution (SED) modelling, Men'shchikov et al. 2001), entails an optical photospheric diameter of 3.8 AU, while measurements of lunar occultations in the H and K bands estimate a near-infrared diameter of 7.1 AU (Richichi et al. 2003).

The star has a very extended molecular envelope moving through the ISM. Maun & Huggins (1999) and Dharmawardena et al. (2018) also show that the dust

★ A copy of the reduced spectra is only available at the CDS via anonymous ftp to cdsarc.cds.unistra.fr (130.79.128.5) or via <https://cdsarc.cds.unistra.fr/viz-bin/cat/J/A+A/675/A139>

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continuum emission extends out to $\sim 200''$ or more from the central star. The interphase between the envelope and the ISM is seen in the ultraviolet images taken with the Galaxy Evolution Explorer (GALEX) satellite (Sahai & Chronopoulos 2010), and at far-infrared wavelengths with the Photodetector Array Camera and Spectrometer (PACS) and Spectral and Photometric Imaging Receiver (SPIRE) instruments aboard *Herschel* (Ladjal et al. 2010). A similar interaction between the two environments is also seen in Mira A as the star shows a bow-shock feature in the southward direction, and a tail extending in the north. The star has a space velocity of 130 km s^{-1} (Martin et al. 2007), which is larger than what is seen in IRC +10216 ($\sim 91 \text{ km s}^{-1}$ in Sahai & Chronopoulos 2010). More than 80 molecular species have been detected in the CSE of IRC +10216 so far (see Cernicharo et al. 2000; Agúndez et al. 2014; De Beck & Olofsson 2018; Pardo et al. 2022, and many other publications cited therein). These molecules are important probes of the chemical processes at work in the envelope as different molecules at various levels of excitation trace distinct regions in the CSE: parent molecules such as HCN and C_2H_2 form in the inner, hotter part of the envelope (e.g. Cernicharo et al. 2015; Agúndez et al. 2020, further references therein), whereas the daughter species (i.e. mainly photodissociation products of the former) are found to be present in the outer parts (see Fig. 1 in Li et al. 2014; Millar & Herbst 1994; Millar et al. 2000; Van de Sande et al. 2018 for a further understanding of the circumstellar chemistry).

The distribution of the CO molecule, which is an important tracer of the history of mass loss, is quite widespread in the star's CSE: Observations with the Institut de radioastronomie millimétrique (IRAM) 30 m telescope (Cernicharo et al. 2015) and with the Submillimeter Array (SMA) and Atacama Large Millimeter Array (ALMA) interferometers (Guélin et al. 2018) show almost concentric shells, with strong CO emission up to the photodissociation radius of $180''$ after which there is a sudden drop (best discernible in the single-dish maps, Cernicharo et al. 2015) owing to the molecule's photodissociation yielding atomic carbon which is further ionised to form C^+ (Morris & Jura 1983; Mamon et al. 1988; Schöier & Olofsson 2001; Groenewegen 2017; Saberi et al. 2019).

Emission in the two fine-structure lines of neutral atomic carbon, C^0 , from the $^3\text{P}_1 \rightarrow ^3\text{P}_0$ and $^3\text{P}_2 \rightarrow ^3\text{P}_1$ transitions near 492 and 809 GHz, respectively, was first detected in molecular clouds by Phillips et al. (1980) and Jaffe et al. (1985). [C I] emission¹ is recognised as a valuable tracer for environments characterised by a range of molecular gas fractions occurring in photo-dissociation regions, while either C^+ or CO trace them only partially (Papadopoulos et al. 2004, further references therein). However, for circumstellar envelopes, very few studies exist of these [C I] lines. IRC +10216 has been targeted in the $^3\text{P}_1\text{--}^3\text{P}_0$ line with the Caltech Submillimeter Observatory (CSO) 10.4 telescope and the *James Clerk Maxwell* 15 m Telescope (JCMT; Keene et al. 1993; van der Veen et al. 1998). As suggested by Keene et al. (1993), another important carrier of carbon in C-rich circumstellar envelopes is acetylene (C_2H_2), contributing to the shielding against interstellar UV radiation, and acting as a precursor molecule for the subsequent photo-chemistry (Santoro et al. 2020; Siebert et al. 2022).

Thanks to the triple bond between carbon and oxygen, CO has a high bond energy, $11\,109.2 \pm 4.1 \text{ meV}$ (Darwent 1970) that is slightly below the ionisation energy of C^0 ,

$11\,260.2880 \pm 0.0011 \text{ meV}$ (Glab et al. 2018). In an environment characterised by internal or external radiation fields and by gas density gradients, the production of free carbon by photodissociation of CO is therefore accompanied by the production of C^+ (of which minor amounts might arise already before, from the photolysis of carbon-bearing species that dissociate easier than CO). Since the ionisation threshold of carbon falls significantly below that of hydrogen (13.598 eV; Jentschura et al. 2005), the $^2\text{P}_{3/2} \rightarrow ^2\text{P}_{1/2}$ transition from the C^+ fine-structure singlet originates from both the warm ionised gas phase of the interstellar medium and from cold, neutral, and partially molecular gas ($T \sim 10\,000 \text{ K}$ and $\sim 100 \text{ K}$, respectively; Wolfire et al. 2003, with further references therein). Its emission from diffuse gas is therefore widespread. However, despite the interest in the C^+ emission for the analysis of the carbon budget in circumstellar environments, detections of the [C II] line were restricted to post-AGB stars (e.g. Cerrigone et al. 2012; Bujarrabal et al. 2016), before it was found in IRC +10216 (Reach et al. 2022).

Given the importance of atomic and ionised carbon in the circumstellar envelope of IRC +10216, we want to constrain the spatial distribution of the atom. In this publication, we discuss the observations we conducted and the data reduction methods in Sect. 2, followed by the presentation of the obtained spectra and their analysis (Sect. 3). We then discuss the physical constraints we obtained and contextualise them in view of the existing literature in Sect. 4 and conclude our work in Sect. 5. A more detailed model, including dedicated photo-chemical network and radiative transfer calculations, will be presented in a follow-up study (Wiesemeyer et al., in prep., hereafter Paper II), along with the analysis of the variable [C II] emission.

2. Observations and data reduction

2.1. Observations of the [C I] line

We performed observations towards IRC+10216 in the $^3\text{P}_1 \rightarrow ^3\text{P}_0$ fine structure line of atomic carbon with the Atacama Pathfinder EXperiment (APEX) 12 m sub-millimetre telescope². The star was observed under the project ID M-0108.F-9515C-2021 between 2021 November 15 and 30 with the nFLASH460 receiver, a new facility frontend built by the Max-Planck-Institut für Radioastronomie (MPIfR) for APEX, while a fast Fourier transform spectrometer (FFTS; Klein et al. 2006) was used as the backend, providing a spectral resolution of 61 kHz. nFLASH460 is a dual sideband receiver with two polarisations and covers an intermediate frequency (IF) range from 4–8 GHz. We tuned the lower sideband (LSB) to the studied [C I] line at a frequency of 492.160700 GHz (Haris & Kramida 2017). The observations took place in good weather with a precipitable water vapour level below 0.6 mm, translating to sightline system temperatures ranging from 400 to 1200 K. We adopted a forward efficiency (η_f) of 0.95 and a main beam efficiency (η_{mb}) of 0.48³ to calibrate the spectra to the main-beam brightness temperature scale (T_{mb}). At the frequency of 492 GHz, the telescope has a beamwidth of $12.7''$ full width at half maximum (FWHM). The integrations were carried out in a cross along right-ascension and declination offsets, comprising 33 positions, for a total of 9 h equally shared between the target and a reference $1000''$ away, safely outside of the astrosphere. The observed

¹ We denote neutral and ionised carbon as C^0 and C^+ , respectively, while their fine-structure line emission is labelled [C I] and [C II], respectively.

² This publication is based on data acquired with APEX, which is a collaboration between the MPIfR, the European Southern Observatory, and the Onsala Space Observatory.

³ <https://www.apex-telescope.org/telescope/efficiency/>

sky-plane positions are spaced by $6.5''$ out to $26''$ from the star, and by $13''$ beyond, up to a maximum distance of $78''$. Frequent line pointings were performed on the CO(4–3) line, with the secondary wobbling with a throw of $120''$ at a frequency of 1.5 Hz.

We used the CLASS software from the GILDAS⁴ package (Pety 2005) to reduce and further analyse the data. The individual steps consist of masking irrelevant parts of the spectra, subtracting linear baseline fits (with baseline noise figures ranging from 38 mK to 120 mK on T_{mb} scale), and averaging adjacent spectral channels, so as to increase the signal-to-noise ratio while preserving an appropriate velocity resolution of 0.2 km s^{-1} , corresponding to five spectral channels in the unprocessed data. Spectra from equivalent positions (or distances from the centre) are averaged with $1/\sigma^2$ weighting (i.e. the inverse of the squared baseline noise).

2.2. Observations of the [C II] line

The $^2\text{P}_{3/2} \rightarrow ^2\text{P}_{1/2}$ fine-structure line of ionised carbon, [C II], at 1900.5369 GHz was observed with the upGREAT 7-pixel, dual polarisation receiver array for THz spectroscopy (Risacher et al. 2018) aboard the Stratospheric Observatory For Infrared Astronomy (SOFIA). The [C II] line was tuned to the upper sideband, so as to avoid a contamination by telluric features from the image band of the mixer (operation at THz frequencies precludes sideband separation). The data were acquired on a total of twelve SOFIA flights, spanning 1.4 cycles of the stellar surface pulsation of 630 days (Menten et al. 2012). Two more flights targeting IRC +10216 were conducted in 2021 and 2022. The typical (median) on-sky observing time was 1 h (including calibrations and updates of the gyroscope settings), of which typically 40 min were used for integrating towards the target, equally shared between the on-position and the off-positions on either side (chop-and-nod method, with a throw of $2'$). The data were taken on subscan granularity (40 s including both chop phases) at elevations ranging from 23° to 52° . Median water vapour columns of $10 \mu\text{m}$ (as referred to zenith) and single-sideband receiver temperatures of 1770 K resulted in a median single-sideband system temperature of 1870 K.

The spectroscopic analysis was performed with fast Fourier transform spectrometers (XFFTSs, Klein et al. 2012), covering the instantaneous 4 GHz wide bandpass with 16384 channels, resulting in a channel separation of 244 kHz. Data processing followed steps similar to those applied to the [C I] data; here we removed second-order spectral baselines and averaged them to a spectral resolution of 1.5 km s^{-1} , resulting in a baseline noise of 16 mK (rms value, in Rayleigh-Jeans equivalent main-beam brightness temperature). The conversion from backend count rates to forward-beam antenna temperatures was done using calibration loads at ambient and cold temperature (typically around 295 and 100 K, respectively), and adopting a forward efficiency of 0.97. The beam efficiency was calibrated by frequent observations of Mars, and determined to a coupling ranging from $\eta_{\text{mb}} = 0.65$ to 0.70 (i.e. to the physically possible limit set by the design of the telescope's optics). This interval reflects the inherent calibration uncertainty. At the frequency of the [C II] line, the main beam of the instrument's Airy pattern has a width of $14''$ (FWHM), which is merely 10% wider than the beam at the frequency of the $^3\text{P}_1 \rightarrow ^3\text{P}_0$ [C I] transition and thus facilitates the comparison of the line profiles.

3. Results

3.1. [C I] emission

Since the CO emission from the envelope is largely centrosymmetric (Cernicharo et al. 2015), and C^0 and C^+ are products of photochemistry, we averaged the spectra from the half-beam sampled, equivalent offsets from the star (Fig. 1). Evidence for deviations from this symmetry is discussed below; individual spectra, extending to up to $78''$ from the star, are shown in Fig. A.1. We have analysed the spectra using various methods, from a simple phenomenological description assuming constant excitation to a radiative transfer model of the non-local thermodynamic equilibrium (non-LTE) excitation of [C I] throughout a homogeneous envelope, characterised by constant gradients in temperature and density, and expanding at a constant velocity.

3.2. [C I] emission: Line profile fitting

The emission from the centre and the innermost sightlines (up to a $13''$ projected distance) displays well-separated blue- and red-shifted peaks (horn-shaped line profiles) from the hemispheres expanding towards and away from the observer, respectively. Beyond the $19.5''$ offset, the components start to merge because the sightline-projected expansion velocity decreases. We have fit the observations (up to $26''$ offsets) with individual Gaussian profiles by masking the emission component at the respective opposite velocity. The resulting parameters are reported in Table A.1. At $39''$ significant emission can only be detected after smoothing these spectra to a resolution of 3 km s^{-1} with a rather flat-topped profile of 0.08 K and rms noise of 31.8 mK. For closer inspection, we provide the spectrum of the sightline in Fig. A.2. At the $52''$ offset and beyond, we see no significant emission anymore.

The individual spectra (Fig. A.1) observed at the same distance from the star show no strikingly remarkable differences. The central sightline features a slightly asymmetric double-peak profile, which can be attributed to a weak absorption in the blue wing, because in the corresponding hemisphere the sightline crosses layers of decreasing excitation. We note, however, that the blue- and red-shifted fractions of the line area display the opposite behaviour. The same holds for the observations of Keene et al. (1993) at $15''$ (FWHM) resolution, who reported peak temperatures of less than 0.4 K, falling 0.3 K below ours. While the discrepancy may be partly due to the individual coupling of the [C I] emission to the different main beams or due to residual pointing or calibration errors, we note that our line flux of 3.1 K km s^{-1} is in agreement with that of Keene et al. (1993). We concede that with the ≈ 30 yr time span between these observations and ours, the [C I]-emitting shell has expanded by almost 90 AU (or $0.7''$ at the adopted distance of 130 pc). While such a distance is too short to be noticeable in the beams of single-dish sub-millimetre telescopes, it may be long enough (17 pulsation periods of 630 days, Menten et al. 2012) to possibly alter the line profiles if the shell and its photochemistry are not in a steady state. From the asymmetry of the line profile, which is weak at most, we conclude that opacity effects cannot be very important in the formation of the line. At offsets of $-19''$ and $-26''$ (in either right ascension or declination), the spectra show more centre-filling emission than the direct fits do (i.e. around the systemic velocity of -26.5 km s^{-1}).

3.3. C^0 excitation modelling

Given the ad hoc approach of the direct fitting, we now use a more sophisticated method to model the excitation of [C I]

⁴ <https://www.iram.fr/IRAMFR/GILDAS/>

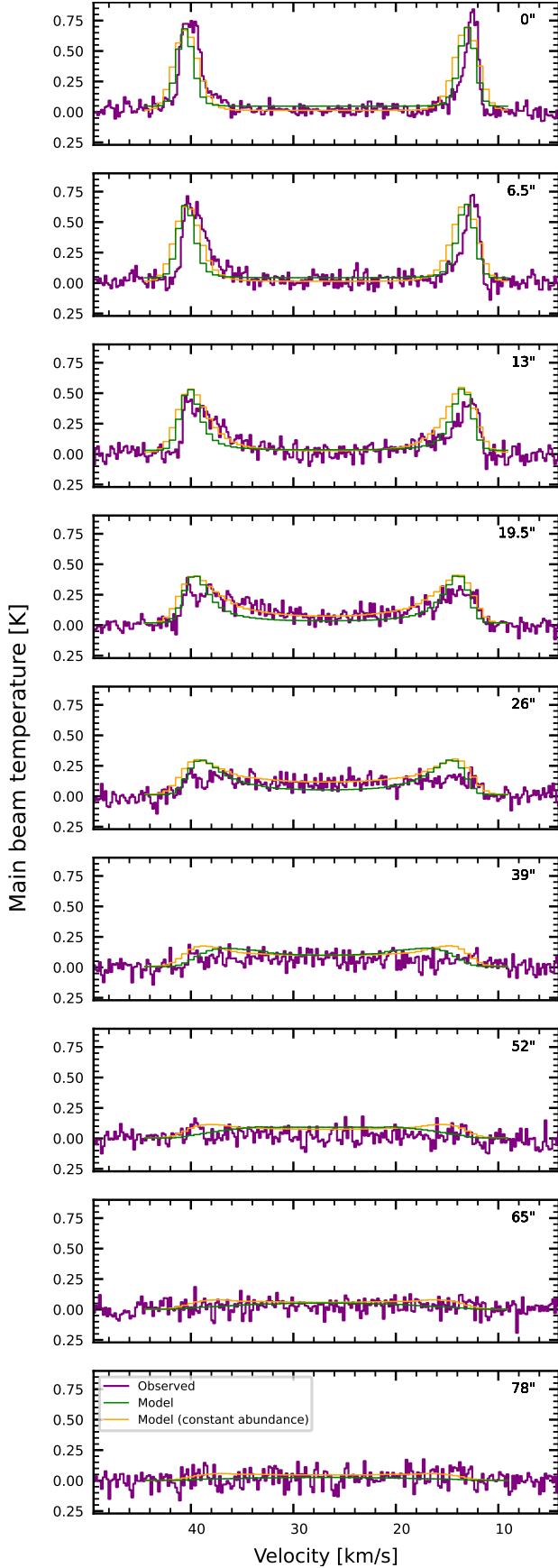


Fig. 1. [C I] $^3P_1 \rightarrow ^3P_0$ averaged spectra towards nine offsets from the star (in purple) overlaid with the RATRAN model for variable abundance (in green) and constant abundance (in orange).

Table 1. Input parameters for the RATRAN model of the [C I] emission.

D (pc)	$\dot{M}$ ($M_\odot \text{ yr}^{-1}$)	r_{in} (cm)	r_{out} (cm)	$n_{\text{H}_2}(r_{\text{in}})$ (cm^{-3})	$T(r_{\text{in}})$ (K)	v_{exp} (km s^{-1})	Δv (km s^{-1})
130	2×10^{-5}	2.3×10^{16}	1.9×10^{18}	4.5×10^4	156	14.0	1.0

Notes. The [C I] abundance profile is taken from Fig. 3 of [Reach et al. \(2022\)](#). A second model uses a constant abundance (with respect to hydrogen nuclei) of $n(\text{C}^0)/n(\text{H}) = 4 \times 10^{-5}$ and $r_{\text{in}} = 4 \times 10^{16}$ cm. We note that D is the distance to the source, r_{in} and r_{out} are the inner and outer radius of the shell, respectively, v_{exp} is the expansion velocity, and Δv is the line width ($1/e$ half-width). The power-law indices for the fall-off of density and kinetic temperature (gas and dust temperature are assumed to be equal) with distance from the star are -2 and -0.50 , respectively. For comparison, the temperature power-law index for purely adiabatic cooling at a constant expansion velocity would be $-4/3$ ([Crosas & Menten 1997](#)).

throughout an envelope characterised by density, abundance, and temperature gradients. We performed radiative transfer modelling to describe the observed spectral lines and determine the abundance and temperature profiles. We used the 1D radiative transfer code RATRAN⁵ ([Hogerheijde & van der Tak 2000](#)), where a spherically symmetric model is assumed. For the model, we take a distance of 130 pc to the star with a mass-loss rate of $2 \times 10^{-5} M_\odot \text{ yr}^{-1}$ ([Cernicharo et al. 2015](#); [Reach et al. 2022](#); [Fonfria et al. 2022](#)). Furthermore, the gas is expanding at a velocity of 14 km s^{-1} . The line profile function is Gaussian with a $1/e$ width of 2.0 km s^{-1} . Under a turbulent contribution of 1.5 km s^{-1} (based on observations of CO and C₂H, [De Beck et al. 2012](#)), the resulting thermal width of $(\sqrt{2.0^2 - 1.5^2} = 1.3) \text{ km s}^{-1}$ would be too large to be accounted for by our temperature profile. We note, however, that non-thermal line broadening in circumstellar envelopes is poorly constrained, and that magnetohydrodynamic turbulence cannot be ruled out on grounds of CN Zeeman measurements revealing significant deviations from a homogeneous magnetic field structure ([Duthu et al. 2017](#)). In such a picture, the fact that the emissions of CO and [C I] trace spatially distinct envelope regions could then reconcile the different estimates of turbulent line broadening. The excitation model accounts for far-infrared pumping by the dust emission (with an assumed gas-to-dust ratio of 100), and assumes that the temperatures of gas and dust are tightly coupled.

[Reach et al. \(2022\)](#) assume that the abundances of C⁺ and C⁰ in the outer envelope derive entirely from the photo-dissociation of CO (see their Fig. 3). The abundance of the latter is parameterised by the photo-destruction radius r_{phot} and steepness parameter α ,

$$n(\text{CO})/n(\text{H}_2) = [\text{C}/\text{H}_2] \exp(-\ln 2(r/r_{\text{phot}})^\alpha). \quad (1)$$

Here we adopt their model with $r_{\text{phot}} = 3.5 \times 10^{17}$ cm, and $\alpha = 3.0$ (cf. [Saber et al. 2019](#)), for an underlying elemental abundance of $[\text{C}/\text{H}_2] = 8 \times 10^{-4}$, of which at the inner boundary of the model 75% is contained in CO, while the remainder accounts for acetylene (C₂H₂) and HCN. The model parameters are summarised in Fig. 4 and Table 1. While this model provides a satisfactory description of the azimuthally averaged spectra (Fig. 1, baseline noise 67–128 mK rms) or on individual positions (Fig. A.1), we have to test whether it entails uniqueness or not. We therefore overlay the corresponding spectra obtained from adjusting the spectra obtained from a constant-abundance

⁵ <https://personal.sron.nl/~vdtak/ratran/frames.html>

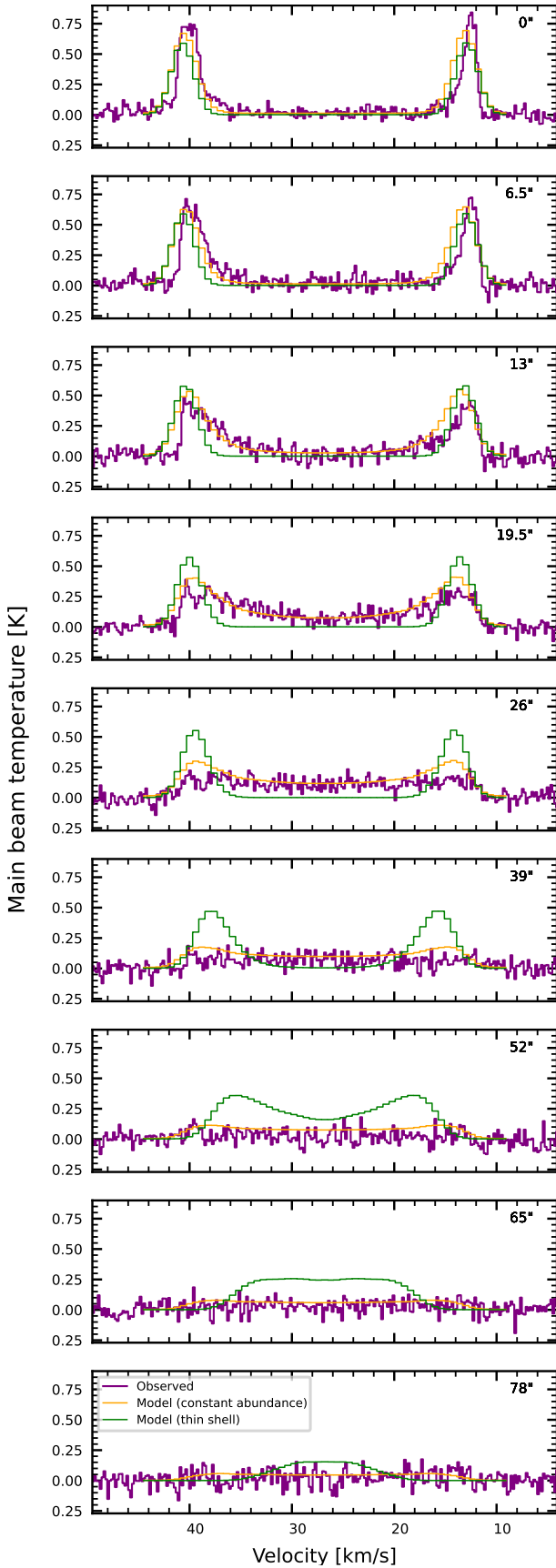


Fig. 2. As Fig. 1, except that the [C I] spectra are overlaid with those from the constant-abundance, thick-shell model (in orange), and a thin-shell model (in green). The latter clearly fails on all sightlines except for the two innermost ones.

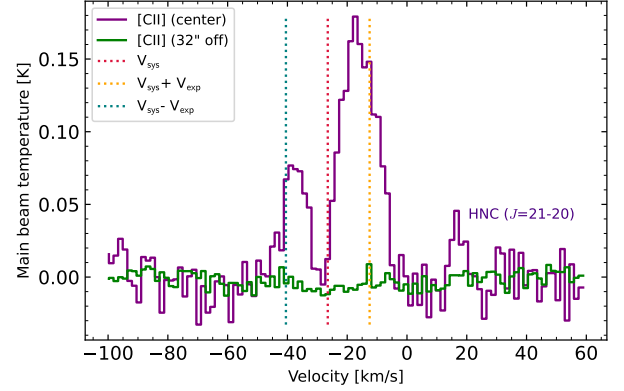


Fig. 3. [C II] $^2P_{3/2} \rightarrow ^2P_{1/2}$ spectrum (2015–2021 average) towards the central line of sight. The average off-centre spectrum (at 32'' from the centre) is overlaid in green. The systemic velocity (V_{sys}) is marked with a red dotted line, and $V_{\text{sys}} + V_{\text{exp}}$ and $V_{\text{sys}} - V_{\text{exp}}$ values are marked with an orange and blue dotted line, respectively, where V_{exp} is the gas terminal expansion velocity. The emission feature at 15 km s $^{-1}$ could be from the HNC $J = 21-20$ transition, and is marked as such.

model to the observed ones. A reasonable fit can be obtained with $n(\text{C}^0)/n(\text{H}) = 4 \times 10^{-5}$ and $r_{\text{in}} = 4 \times 10^{16}$ cm, but otherwise the model has the same parameters. This abundance falls an order of magnitude below that of elemental carbon (e.g. $[\text{C}/\text{H}] = 2.1 \times 10^{-4}$ from young B-type stars, Nieva & Przybilla 2012), because it attributes elemental carbon to C^0 at distances from the star where it should still be taken up by mainly CO.

Figure 1 shows both models overlaid on the observations, reproducing a weakly self-absorbed blue-shifted peak towards the centre and the overall distribution of the [C I] emission. On the innermost sightlines, both models reproduce the observed spectral profiles reasonably well. At 19.5'' from the star, the variable-abundance model somewhat underestimates the emission arising closer to the systemic velocity, by 1–2 σ_{rms} , whereas the constant abundance model works well. Beyond this offset, both models agree with each other fairly well. We infer that the model of Reach et al. (2022) can be used to describe the inner boundary of the C^0 shell; whereas, in the constant-abundance model, a C^0 abundance that is a factor two higher could be compensated for by displacing the inner boundary from 2.3×10^{16} cm outwards to 4×10^{16} cm. Such a degeneracy reflects the scaling expected from the adopted density and temperature profiles and the spherical symmetry. Shifting the inner boundary even more towards the photo-destruction radius of CO indeed brings the abundance of C^0 required for a good fit closer to the cosmic, elemental carbon abundance. However, an authoritative chemical model cannot be deduced from these observations alone. We, therefore, continue with a closer look at the [C II] emission from the central sightline.

3.4. [C II] emission

The average [C II] $^2P_{3/2} \rightarrow ^2P_{1/2}$ spectra from the central sightline and at 32'' from the star are shown in Fig. 3. Unlike the [C I] $^3P_1 \rightarrow ^3P_0$ emission, the [C II] emission is only detected towards the central pixel of the upGREAT array. The outer ring of the array's hexagonal layout displays no detectable [C II] emission. This finding, and the broader components of the strongly asymmetric double-peak profile (FWHM 8.1 and 13.4 km s $^{-1}$ in the blue- and red-shifted peak, respectively), which are less pronounced than that of [C I], indicate that the emission cannot solely originate from the outer boundary of the circumstellar envelope, exposed to the interstellar radiation field. Additionally,

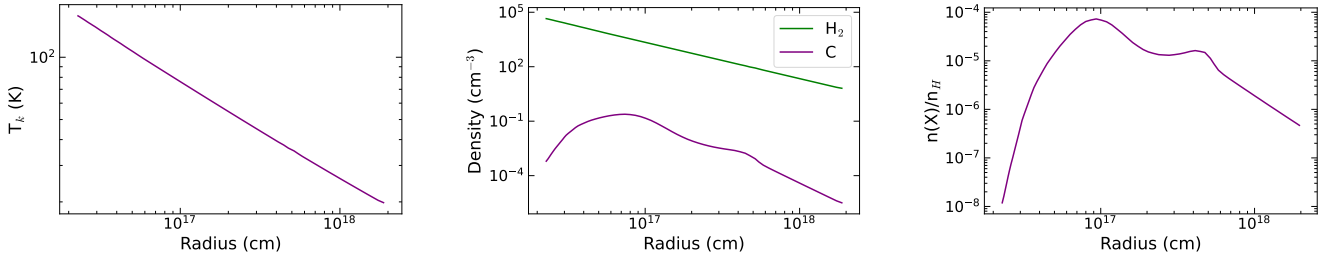


Fig. 4. Model profiles of (left) kinetic temperature, (centre) densities of C^0 and H_2 (the latter taken from Reach et al. 2022), and (right) C^0 abundance (from Reach et al. 2022), used as input for the RATRAN model.

there is an emission feature present at 15 km s^{-1} velocity, which could be from the HNC $J = 21-20$ transition. This line's small width ($\sim 5 \text{ km s}^{-1}$), which is much smaller than the IRC+10216 CSE's terminal velocity, suggests an origin close to the stellar photosphere, following the conclusions Patel et al. (2009, 2011) drew for similarly narrow vibrationally excited lines from various molecules. Consistent with Reach et al. (2022), we do not detect any emission from the $[^{13}\text{C II}]$ ion. Furthermore, the $[C II]$ emission was found to be variable on a timescale corresponding to that of the stellar pulsation (paper II). This and the signature of self-absorption in the blue-shifted line component corroborate the presence of a contribution from within the envelope. Although with time the $[C II]$ line profile shown in Fig. 3 varies both in strength and shape, its overall appearance (broad, strongly asymmetric peaks) is persistent.

4. Discussion

The $[C I] \ ^3P_1 \rightarrow \ ^3P_0$ lines display profiles that are characteristic for optically thin emission from a geometrically extended, expanding envelope. The profiles towards the star, and towards the envelope's limb, could be readily explained by a spatially resolved optically thin shell, whose atomic carbon is produced from the dissociation of CO by the interstellar radiation field: towards the central position, the double-peaked "horn profile" is attributed to the front and rear part of the expanding envelope (the slight asymmetry between the blue- and red-shifted peaks is commented on below), while the single-peaked, flat-topped spectra beyond $26''$ from the star are dominated by sightline elements of which the expansion velocity vector is mostly parallel to the sky plane. The interstitial positions, however, show that the shell cannot be geometrically thin, thanks to the emission close to the systemic velocity filling the double-horn profile. Indeed, a model consisting of a thin, constant-abundance shell extending from 10^{17} to 1.6×10^{17} cm fits only the central spectrum and that at a $6.5''$ distance; however, from a $13''$ to $39''$ distance, it cannot provide the emission observed close to systemic velocity (Fig. 2). At $52''$ and beyond, where the shell starts to emit at a zero sightline-projected velocity, that is -26.5 km s^{-1} in local standard of rest (LSR) velocity, the double-peak profile is still too pronounced and strong, while the observed emission starts to fall below the detection limit. Likewise, a thin shell extending from 1.2×10^{16} to 1.6×10^{16} cm, as advocated by Reach et al. (2022) to explain the $[C II]$ observation of *Herschel*/HIFI, fails to reproduce our observations as well (see paper II).

Curiously, the $[C II] \ ^2P_{3/2} \rightarrow \ ^2P_{1/2}$ line towards the star (Fig. 3) does not show a narrow double-peak profile either (components $\sim 10 \text{ km s}^{-1}$ wide at a corresponding half-maximum); although in a picture where C^+ is produced by the exposure to an external radiation field, the line should originate outwards from the $[C I]$ emitting layers. On the other hand,

producing the $[C II]$ emission in a layer adjacent to the stellar photosphere is not easily understandable either, because the beam dilution there would require an unusually high emissivity.

The absence of detectable $[C II]$ emission at a projected distance of $\gtrsim 20''-30''$ from the star and its presence towards it (Fig. 3) suggest that the environment of the inner shell harbours an additional source of ionisation. As a matter of fact, at a 700 AU distance, the star cannot drive any photo-chemistry (10^{16} cm, Fig. 5). This led Reach et al. (2022) to suggest that mass transfer from the star to a nearby companion locally enhances the UV radiation field, thanks to the shock forming in response to the accretion flow. The presence of such a companion, on a highly eccentric orbit, was indeed advocated by Cernicharo et al. (2015), searching for an explanation for the multiple, partial shells discovered in the optical by light scattering (Mauron & Huggins 1999) and, subsequently, in thermal dust emission (beyond $1'$ from the star, Decin et al. 2011) and CO emission (Cernicharo et al. 2015; Decin et al. 2015; Guélin et al. 2018). The depth and extent of the CO studies demonstrate that a solar-like companion star would provide an explanation for the multiple shells, which form neither in response to thermal pulses, nor to the stellar pulsation, which would result in larger or shorter spacings, respectively. The binary hypothesis was also adopted by Siebert et al. (2022, further references therein), in support of a photo-chemical model of cyanoacetylene (HC_3N) emission from the inner envelope, which would explain the presence of other molecules closer to the star than expected (CH_3CN , C_4H_2) or typical of O-rich stars (H_2O). With the data at hand, and the restriction of our models to spherical symmetry, we cannot provide an argument favouring a binary system. We note that Matthews et al. (2018) confirm the proper motion determined for IRC +10216's by Menten et al. (2012) with longer time span data and find no evidence of statistically significant astrometric perturbations as would be expected from a binary companion, despite claims to the contrary. As discussed above, some asymmetry seen in the $[C I]$ profiles is suggestive of a fingerprint of the multiple-shell structure. Given that it is evident in CO (2–1) emission observed at $11''$ resolution (FWHM, Cernicharo et al. 2015), it should also be discernible in our $13''$ resolution $[C I]$ data. The Fourier transforms analysis of Guélin et al. (2018) reveals a $16''$ shell spacing in all quadrants except in the south-eastern one, where our direct line-profile fits display larger residuals. Whether this observation is coincidental or not can only be settled by a full, critically sampled $[C I]$ map.

5. Conclusion

Following the pioneering observations of atomic carbon in IRC +10216 by Keene et al. (1993), we present more sensitive and more extensive observations of the $^3P_1 \rightarrow \ ^3P_0$ emission from the $[C I]$ fine structure triplet. Accounting for differences in the

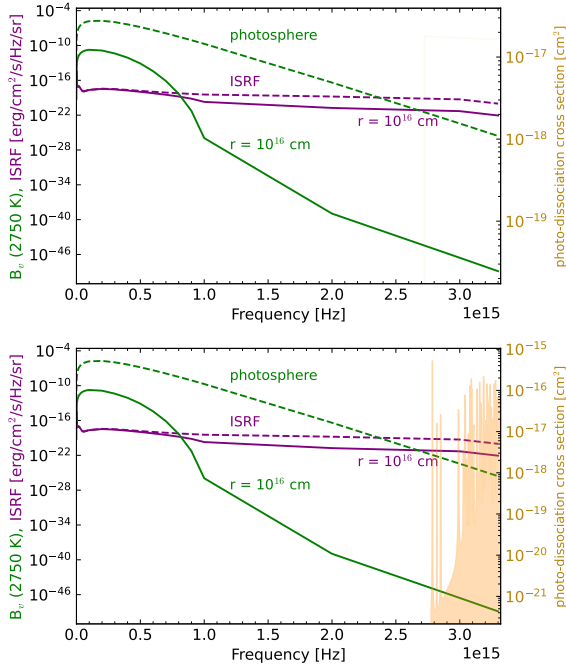


Fig. 5. Comparison of cross-sections from the Leiden Observatory database for photochemistry (Heays et al. 2017) for the photo-ionisation of C I and the photo-dissociation of CO (gold curves *top* and *bottom*, respectively, with right-hand ordinates) with SEDs of the attenuated stellar photosphere (green) and the interstellar radiation field (purple) at 10^{16} cm from the star (with left-hand ordinate). The corresponding dotted curves refer to the unattenuated and undiluted radiations fields. Dust extinction coefficients were calculated from Rouleau & Martin (1991). The frequency scale is linear, so as to enhance its high-frequency end.

data quality, and allowing for an underlying variability which might show after the 30 yr time lapse between the observations, we notice an overall good agreement. We present a model employing an abundance gradient that best reproduces the lines profiles at increasing distance from the star; however, even a model employing a constant C^0 abundance would work. We infer that the inner boundary of the [C I]-emitting shell is at $\sim 10^{16}$ cm from the star, but cannot yet locate it more precisely. The fact that the [C II] line is seen only towards the inner sightlines through the circumstellar envelope (≤ 4000 AU), while the outer envelope, ranging to up to ~ 10000 AU, is void of [C II] emission, remains an enigma. Both findings call for a full map of the [C I] emission and deeper observations of the [C II] line. The line profiles obtained so far from both tracers exclude a picture in which atomic carbon is only produced in a thin low-density shell fully exposed to the interstellar radiation field.

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Appendix A: Individual results for directly fitted and modelled [C I] line profiles

Table A.1. Parameters deduced from direct fits to the observed spectra.

Offset	V_1 (km s ⁻¹)	$\int T_{\text{MB}} dV_1$ (K km s ⁻¹)	ΔV_1 (km s ⁻¹)	$T_{\text{peak}1}$ (K)	V_2 (km s ⁻¹)	$\int T_{\text{MB}} dV_2$ (K km s ⁻¹)	ΔV_2 (km s ⁻¹)	$T_{\text{peak}2}$ (K)
0''	-40 (0.03)	1.8 (0.04)	2.5 (0.07)	0.67	-12.2 (0.08)	1.3 (0.1)	1.7 (0.2)	0.69
R. A. (negative)								
-6.4''	-39.9 (0.1)	1.5 (0.15)	2.17 (0.2)	0.64	-12.9 (0.05)	1.3 (0.01)	1.9 (0.1)	0.66
-12.9''	-38.8 (0.4)	2.3 (0.3)	5.9 (0.9)	0.36	-13.8 (0.2)	1.4 (0.1)	3.2 (0.4)	0.43
-19.4''	-36.3 (0.3)	2.9 (0.2)	11.2 (0.7)	0.25	-16.2 (0.3)	2.07 (0.1)	8.4 (1)	0.23
-25.9''	-34.5 (1)	2.9 (0.3)	15.6 (2.1)	0.17	-20.3 (1.1)	1.9 (0.3)	12.4 (2.3)	0.15
R. A. (positive)								
6.6''	-39.6 (0.1)	1.67 (0.1)	2.7 (0.2)	0.57	-12.5 (0.1)	1.06 (0.1)	1.35 (0.2)	0.74
13.1''	-38.95 (0.2)	1.15 (0.1)	3.4 (0.3)	0.315	-12.92 (0.2)	0.85 (0.1)	2.19 (0.4)	0.36
19.6''	-36.9 (0.5)	1.97 (0.2)	9.02 (1.2)	0.21	-14.25 (0.5)	1.6 (0.3)	6.6 (1.5)	0.23
26.1''	-34.1 (0.9)	1.8 (0.2)	14.1 (2.1)	0.11	-18.5 (1.4)	1.43 (0.3)	13.2 (2.9)	1.01
Dec (negative)								
-6.5''	-39.6 (0.01)	1.74 (0.1)	2.7 (0.2)	0.6	-12.8 (0.01)	1.39 (0.1)	1.7 (0.2)	0.72
-13''	-38.8 (0.2)	1.95 (0.1)	5.5 (0.6)	0.35	-13.2 (0.1)	1.13 (0.1)	2.3 (0.2)	0.47
-19.5''	-36.6 (0.3)	2.95 (0.2)	10.1 (0.8)	0.27	-17.8 (0.5)	3.05 (0.2)	12.9 (1.1)	0.22
-26''	-32.5 (1.3)	3.02 (0.4)	17.2 (2.8)	0.17	-20.7 (1.4)	2.7 (0.4)	16.9 (2.7)	0.15
Dec (positive)								
6.5''	-39 (0.1)	1.6 (0.1)	2.3 (0.2)	0.6	-12.7 (0.1)	1.2 (0.01)	1.7 (0.1)	0.66
13''	-39.3 (0.3)	1.4 (0.2)	3.3 (0.6)	0.38	-13 (0.1)	1.3 (0.1)	3.0 (0.4)	0.39
19.5''	-37.53 (0.4)	1.83 (0.2)	8.3 (1)	0.21	-14.5 (0.3)	1.14 (0.1)	4.10 (0.7)	0.26
26''	-34.8 (0.8)	1.7 (0.2)	11.0 (1.6)	0.15	-17.4 (0.8)	1.9 (0.2)	11.9 (1.7)	0.15

Notes. The table summarises the physical parameters constrained at different offsets from the star. Subset 1 refers to the blue-shifted peak and subset 2 refers to the red-shifted peak. The parameters obtained for offsets away from the central position were calculated by fitting the Gauss method. We note that V is the LSR velocity, $\int T_{\text{MB}} dV$ is the calculated integrated intensity, ΔV refers to the line width calculated from the Gauss method, and finally T_{peak} is the peak temperature of the fitted line.

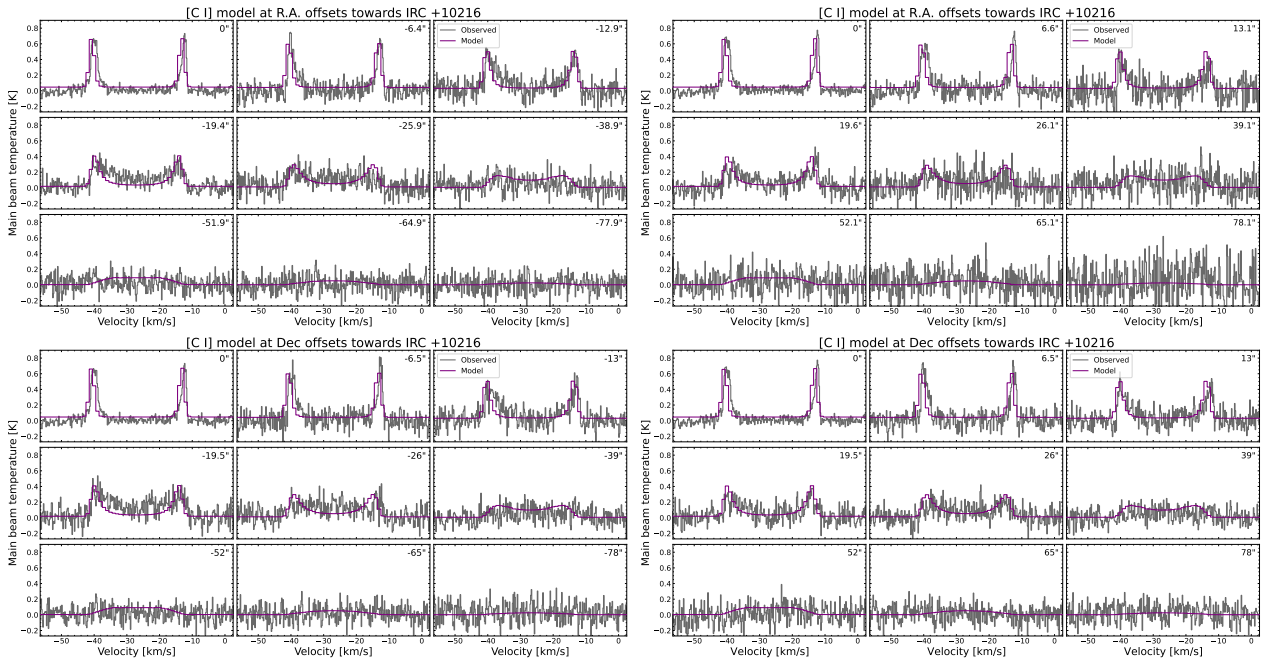


Fig. A.1. Observed [C I] spectra (in black) and line profiles modelled with RATRAN (in purple) at the sampled positions.

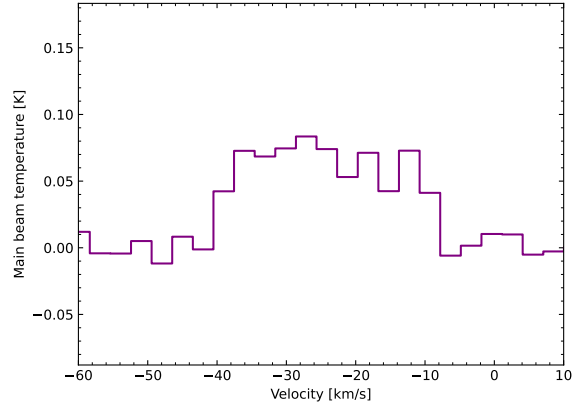


Fig. A.2. [C I] emission smoothed to 3 km s⁻¹ at 39'' from the star.