Ionized Carbon around IRC+10216

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Abstract

Asymptotic giant branch stars create a rich inventory of molecules in their envelopes as they lose mass during later stages of their evolution. These molecules cannot survive the conditions in interstellar space, where they are exposed to ultraviolet photons of the interstellar radiation field. As a result, daughter molecules are the ones injected into space, and a halo of those molecules is predicted to exist around cool evolved stars. The most abundant molecule in the envelopes other than H2 is CO, which dissociates into C that is rapidly ionized into C+. In a halo around the star that is optically thin to the interstellar radiation field. We develop the specific predictions of the ionized carbon halo size and column density for the well-studied, nearby star IRC+10216. We compare those models to observations of the [C II] 157.7 μm far-infrared fine structure line using the Stratospheric Observatory for Infrared Astronomy and Herschel. The combination of bright emission toward the star and upper limits to extended [C II] is inconsistent with any standard model. The presence of [C II] toward the star requires some dissociation and ionization in the inner part of the outflow, possibly due to a hot companion star. The lack of extended [C II] emission requires that daughter products from CO photodissociation in the outer envelope remain cold. The [C II] profile toward the star is asymmetric, with the blueshifted absorption due to the cold outer envelope.

Unified Astronomy Thesaurus concepts: Evolved stars (481); Stellar mass loss (1613); Far infrared astronomy (529); Interstellar molecules (849); Asymptotic giant branch stars (2100); Circumstellar envelopes (237)

1. Introduction

After their main-sequence lifetimes, low-mass stars lose considerable mass, primarily near the end of their lifetime as giants (Willson 2000; Smith et al. 2014). The mass loss affects the stars’ evolution and the composition of the regions around them, with star-forming regions capable of significant enrichment on timescales less than 100 Myr (McWilliam 1997). The material shed by these evolved stars enriches the interstellar medium with nucleosynthetic products that depend on the temperature and composition of the portion of the star’s atmosphere that is ejected.

IRC+10216 (CW Leonis) is a well-studied asymptotic giant branch (AGB) star that is exceptionally bright (Becklin et al. 1969) owing to its high luminosity (1600 L⊙; Menten et al. 2012) and nearby distance (123 pc; Groenewegen et al. 2012). The star is shedding mass at 2 × 10−7 M⊙ yr−1 (Fonfría et al. 2022), leading to a rich circumstellar chemistry close to the star (Agúndez et al. 2008, 2012), followed by an expanding envelope prominent in CO and far-infrared continuum including shells (Fong et al. 2006; Decin et al. 2012; Cernicharo et al. 2015). Farther from the star, a bow shock has formed where the expanding envelope collides with the surrounding interstellar medium (ISM; Sahai & Chronopoulos 2010).

AGB stars are a significant source of carbon and oxygen, from nucleosynthesis in the stellar interior by the CNO cycle, then dredged up during stellar evolution, leading to enrichment of the ISM (Busso et al. 1999). The carbon is launched into the wind by drag on solid particles formed just outside the photosphere (Fonfría et al. 2021). Stars with C/O > 1 require dredge-ups that occur only if the initial mass was >1.5 M⊙ (Höfner & Olofsson 2018). For stars with initial mass 1.5–2 M⊙, the carbon abundance in the wind is 1 × 10−5 < [C/H] < 5 × 10−3 (Karakas 2010). In contrast, the carbon abundance in the ISM, as inferred from abundances in B-star photospheres, is [C/H] = 2.1 × 10−4 (Nieva & Przybilla 2012). Thus, 1.5–2 M⊙ carbon stars eject material that is enriched in carbon by 5–25 times compared to the present-day ISM. The abundance of carbon-bearing molecules (primarily CO) is only [C/H] = [C/H2] = 4 × 10−4 (Saberi et al. 2019), so the bulk of the carbon, between 60% and 92% for the 1.3–2 M⊙ initial mass models, is not in molecules and is presumably in solid form.

In this paper we calculate the size, column density, and brightness of far-infrared fine structure line emission from the circumstellar envelope (CSE) extending all the way to where the CO gas is dissociated. The size of the CO envelope is a basic observable property of evolved star mass loss and is an accessible tracer of the mass-loss rate with high-resolution millimeter-wave imaging (Ramstedt et al. 2020). Our model predicts the properties of the halo of carbon that should occur outside the CO envelope. We compare the model to far-infrared observations of [C II] with Herschel and the Stratospheric Observatory for Infrared Astronomy (SOFIA).
2. Model for Halo of Ionized Carbon

The standard model for steady mass loss from a star at rate $M$, expanding with constant velocity $v$, produces a cloud of material with density $n$ that decreases as the inverse square of distance $r$ to the star:

$$n = \frac{M}{4\pi \mu \rho v r^2},$$

(1)

where $\mu = 2.21$ is the mean mass for neutral, molecular gas (predominantly $H_2$ and He). For a mass-loss rate of $2 \times 10^{-5} M_{\odot} \text{yr}^{-1}$ (Cernicharo et al. 2015), at a projected separation of 100″ (1.8 × 10^{17} \text{cm}) from the star, the standard model $H_2$ density is 550 cm$^{-3}$. Due to chemical reactions between gas species and on solid particle surfaces, and due to interaction with photons from the star and photons and cosmic rays from the interstellar medium, each gas species has a distinct variation from the bulk profile of Equation (1). The most abundant parent molecule, $H_2$, and the solid particles, are formed in the dense environment close to the star where the gas is close to the condensation temperatures ($> 500$ K, Wood et al. 2019). The $H_2$ remains largely chemically inert through the portion of the envelope we are concerned with in this paper, spanning the resolvable envelope of the star out to where it merges with the ISM ($10^{15}$–$10^{18}$ cm).

Many molecular species are dissociated when exposed to the interstellar radiation field (ISRF), where they are exposed to a significant and sustained intensity of ultraviolet light. The situation is very similar to that experienced by comet mass loss, where material is released from the comet surface then survives until it is dissociated by sunlight or has a chemical reaction. We will borrow the standard terminology from comet studies and call the molecules emerging from the hot inner envelope the parent molecules and their dissociation products the daughter molecules (Festou et al. 2004). The abundant, readily observable, and chemically important parent molecule CO forms early in the outflow from the star and determines the subsequent chemistry. If the stellar mass loss has more C than O, then nearly all the O is locked into CO and carbon chemistry determines the gas (e.g., hydrocarbons) and solid (e.g., polycyclic aromatic hydrocarbons, PAHs) composition. If the stellar mass loss has more O than C, then nearly all the C is locked in CO and the gas and oxygen chemistry determines the gas (e.g., PAH H$_2$O) and solid (e.g., silicates) composition. CO survives in the portion of the outflow where it is protected from UV photons in the ISRF by dust extinction and by self-shielding of overlapping absorption lines of the CO and $H_2$ molecules (Mamon et al. 1988; Saberi et al. 2019). The hydrogen remains molecular in the region where CO is photodissociated because $H_2$ continues to be self-shield from dissociating photons in that region.

2.1. Basic Models for Carbon in Envelope

The CO abundance relative to $H_2$ is characterized by the radius where it drops by half, $r_{\text{ph}}$, which is in the range $3 \times 10^{15}$–$10^{18}$ cm for a wide range of mass-loss rates and ISRF intensities (Saberi et al. 2019). For a mass-loss rate of $2 \times 10^{-5} M_{\odot} \text{yr}^{-1}$, which applies for expansion velocity $15 \text{km s}^{-1}$ and [CO/$H_2$] = $8 \times 10^{-4}$, the photodissociation radius $r_{\text{ph}} = 3.6 \times 10^{17}$ cm (Mamon et al. 1988), corresponding to 200″ projected separation from the star. The more recent calculation gives $r_{\text{ph}} = 3.0 \times 10^{17}$ cm (Saberi et al. 2019). As a simple illustration, the CO/$H_2$ abundance is constant for $r < r_{\text{ph}}$, beyond which CO is photodissociated but H remains molecular. For a more accurate representation we use this exponential decrease that closely matches the theoretical models for photodissociation:

$$\frac{n_{CO}}{n_{H_2}} = 2[C/H] e^{-\ln2 r/r_{\text{ph}}}^2$$

(2)

(Mamon et al. 1988), where [C/H] is the elemental abundance of carbon relative to hydrogen and the factor of 2 is because there are two hydrogen atoms in each $H_2$ molecule. For the abundance of carbon we consider two values: [CO/$H_2$] = $8 \times 10^{-4}$ (so [C/H] = $4 \times 10^{-5}$), which has been used in prior theoretical models for evolved star mass loss (Saberi et al. 2019), and [C/H] = $2.1 \times 10^{-4}$ is based on analysis of photospheres of young, B-type stars (Nieva & Przybilla 2012).

Upon dissociation of CO, the daughter products C and O are formed. The O remains largely in neutral form in the diffuse ISM because its ionization potential is slightly higher than that of H, and the photons that would ionized O are absorbed by the more abundant H instead. The C is rapidly ionized by ISRF photons above 11.26 eV, and the primary carbon daughter product of CO is C$^+$. For the density of atomic and ionized C, we assume it derives entirely from CO, so

$$\frac{n_C}{n_{H_2}} = \left(1 - \frac{n_{CO}}{n_{H_2}}\right)[CO/H_2],$$

(3)

where the abundance of CO in the dense inner envelope is [CO/H] $\sim 8 \times 10^{-4}$ from previous models (Saberi et al. 2019). Based only on cosmic abundances, the abundance [CO/$H_2$] = 2 [C/H] = $4.2 \times 10^{-4}$ (Nieva & Przybilla 2012). A higher [CO/$H_2$] than cosmic abundance means the stellar mass loss enriches the ISM, while a lower means it dilutes the C abundance. The fraction of carbon that is ionized, at each distance from the star, was calculated by balancing the recombinant rate against the ionization rate from the ISRF extincted by the column density from that distance outward assuming an extinction per column density as in the ISM. To get a simple estimate of the C$^+$ column density, assuming a sharp CO/C$^+$ boundary at $r_{\text{ph}}$, the column density of C$^+$ along the line of sight through the star is

$$N(C^+) = 2n(r_{\text{ph}})r_{\text{ph}}[CO/H_2],$$

(4)

where the initial factor of 2 is for the line of sight to the star and behind the star. For the standard model and a sharp dissociation of CO at $r_{\text{ph}}$, the column density of C$^+$ on the line of sight through the star is $4.3 \times 10^{16}$ cm$^{-2}$. For the various models considered in this paper, the column density of C$^+$ remains within a factor of 2 of that value.

The gas kinetic temperature is a balance between heating from the central star and from the external ISRF: there are heat waves propagating from both directions. Cooling is via adiabatic expansion, plus molecular lines in the inner envelope and atomic fine structure lines in the outer envelope (Goldreich & Scoville 1976; Tielens & Hollenbach 1985). Models of the inner envelope have used an approximation $T = 14.6(v_p/r)^3$ with $v_p = 9 \times 10^{16}$ cm, $\beta = 0.72$ for $r < r_o$, and $\beta = 0.54$ for $r > r_o$ (Kwan & Linke 1982; Mamon et al. 1988). Measurements of gas temperature from CO lines in IRC+10216 yield...
temperatures of 20 K at $7 \times 10^{16}$ cm and 15 K at $1 \times 10^{17}$ cm (Guélin et al. 2018). The CO molecules are therefore very cold when approaching the ISM, but exposure to the full ISRF both dissociates the molecules and eventually heats the gas. In diffuse interstellar gas, observations of UV rotational lines of H$_2$ show temperatures of 78 K (Savage et al. 1977). Cooling rates are shorter than the expansion time in the outer envelope. The material flowing out from IRC+10216 would reach comparable temperatures if it had an abundance of small carbon grains (which dominate photoelectric heating of the gas) comparable to that of the diffuse ISM. However, the abundance and charge of small carbon grains is not known. To bound temperature predictions in the shell beyond where the CO is dissociated, we use two illustrative models. In one model, we
set a minimum temperature $T_{\text{min}}$ for the gas. In the other model, we spliced the molecular gas temperature in the envelope with a power law that begins at $r_1 = 9 \times 10^{16}$ cm and ends with $T = 78$ K at $r_2 = 10^{18}$ cm to merge with the diffuse ISM. The values of $r_1$ and $r_2$ were chosen based upon a static PDR model where we set the density as per the standard model for IRC +10216, then illuminated with the ISRF from the outside, balancing photoelectric heating with cooling from fine structure and molecular line emission and where cooling by adiabatic expansion was neglected.

The most powerful spectral line from diffuse interstellar gas heated by the ISRF is the 157.7 $\mu$m [C II] line. With an excited state 91 K above ground, this transition can be excited in the diffuse ISM, though it becomes exponentially more difficult to excite at low temperatures. We estimate the line brightness as a function of the temperature of the gas, density of H$_2$, and density of C$^+$, following Goldsmith et al. (2012) to derive the emissivity then integrating through the envelope along lines of sight separated from the star by $0''$--$800''$.

Figure 1 shows the radial variation of the density, temperature, and emissivity in the CSE, for Models 0 and 0t. The C$^0$ abundance never builds higher than 6% of gas-phase carbon, while CO is 100% in the inner envelope and C$^+$ is 100% in the outer envelope. Model 0t has a cold outer envelope, and the [C II] emissivity peaks at around $3 \times 10^{16}$ cm from the star. Model 0, with the warmer outer envelope, has an additional [C II] emissivity peaks in the outer envelope near $R_{\text{phot}} = 3.65 \times 10^{17}$ cm. For the other models, the relative amplitudes of the two peaks change. In Model 0t, the temperature of the outer envelope is allowed to decrease as a power law down to 10 K (dashed lines in Figure 1), and the outer peak is eliminated, so the [C II] emission is significantly fainter and closer to the star. If the temperature in the outer envelope is 20 K, the outer peak is also eliminated. If the temperature in the outer envelope is 30 K, then the outer envelope dominates over the inner envelope.

Figure 2 shows the predicted brightness of [C II] for observations through the envelope at a range of projected separations from the star. Predictions are shown for a set of models with parameters summarized in Table 1. Model 0 is the baseline model because it uses the photodissociation radius, CO density profile, and CO abundance from Mamon et al. (1988), albeit with the temperature modification described above, rising to that of the diffuse ISM. Model 0t is the baseline model, but with the temperature decreasing to 10 K and remaining constant thereafter. Models 1 and 2 have mass-loss rates that are higher and lower, respectively, than the baseline model; both models 1 and 2 use the rising temperature law, and the photodissociation radius was scaled by $M^{-0.5}$ based upon the results of Saberi et al. (2019).

Table 1 shows the model parameters and the resulting C$^+$ column density, brightness of the [C II] line toward the star, and maximum [C II] brightness from the resolved envelope. The predicted brightness is highest at a separation from the star approximately 150$''$--200$''$ with a central depression due C$^+$ being absent from an inner, fully molecular region centered on the star. The prediction is a thick shell, with central depression...
The Astrophysical Journal, 926:69 (10pp), 2022 February 10

Reach et al.

Table 1
Models for IRC+10216 [C II]

| Model | $R_{\text{phot}}$ (cm) | $M$ ($M_\odot$ yr$^{-1}$) | Heating (note$^a$) | N(C$^+$) (cm) | central $\tilde{f}T_{dv}$ (K km s$^{-1}$) | max $\tilde{f}T_{dv}$ (K km s$^{-1}$) |
|-------|------------------------|--------------------------|------------------|-------------|-----------------------------------|----------------------------------|
| 0     | $3.65 \times 10^{17}$  | $2 \times 10^{-5}$       | rise 78          | $3.3 \times 10^{16}$ | 1.4                               | 1.7                              |
| 0t    | $3.65 \times 10^{17}$  | $2 \times 10^{-5}$       | $T > 10$         | $3.3 \times 10^{16}$ | 0.012                             | 0.014                            |
| 1     | $4.47 \times 10^{17}$  | $3 \times 10^{-5}$       | rise 78          | $4.1 \times 10^{16}$ | 2.2                               | 2.7                              |
| 2     | $2.58 \times 10^{17}$  | $1 \times 10^{-5}$       | rise 78          | $2.4 \times 10^{16}$ | 0.57                              | 0.69                             |
| 3     | CSE (Section 2.2)      | $2 \times 10^{-5}$       | $T > 10$         | $6.8 \times 10^{16}$ | 0.064                             | 0.096                            |
| 4     | CSE (Section 2.2)      | $2 \times 10^{-5}$       | $T > 20$         | $6.8 \times 10^{16}$ | 1.6                               | 2.0                              |
| 5     | CSE (Section 2.2)      | $2 \times 10^{-5}$       | $T > 30$         | $6.8 \times 10^{16}$ | 7.7                               | 9.8                              |
| 6     | note$^b$               | $2 \times 10^{-5}$       | $T > 10$         | $3.3 \times 10^{16}$ | 4.8                               | 8.8                              |

Notes.

$^a$ Temperature distribution. All models begin at small $r$ with a power-law decrease of $T(r)$. Models $T > T_{\text{min}}$ decrease to a minimum temperature $T_{\text{min}}$. Models with “rise 78” have the temperature decrease until $r = 9 \times 10^{16}$ cm then increase to 78 K at $10^{19}$ cm.

$^b$ Model 6 is Model 0 with enhanced ionized carbon in an inner shell from 1.5–2 $\times 10^{16}$ cm from the star, as discussed in Section 5.

less than 50%, and a tail extending out to large distances from the star. An inner peak is predicted for some models, due to the innermost C$^+$ warmed by the star. The presence or lack of an inner C$^+$ shell depends critically on the assumed temperature and the initial fall-off of the CO density. The most critical factor determining the brightness of the [C II] line is the mass-loss rate. This can be readily understood from Equation (4); with the dependence of $n$ and $R_{\text{phot}}$ on $M$, the column density of C$^+$ scales as $M^{1.5}$. The second most important factor for determining the C$^+$ brightness is the abundance of CO in the envelope.

2.2. CSE Model for Carbon in the Envelope

In order to predict the [C II] envelope brightness in more detail, we established a CSE model similar to Glassgold (1996) and Millar et al. (2000), with the mass density set per Equation (1), with inner radius $3 \times 10^{14}$ cm. The temperature profile was as per Mamon et al. (1988), but with a threshold such that the temperature is never lower than a minimum $T_{\text{min}}$. This minimum temperature threshold allows us to explore the effects of additional sources of heating in the outer envelope that are important for predicting the brightness of the [C II] line. The outer envelope temperature accounts for heating in the outer envelope that originates from sources other than the CW Leonis; for example, photoelectric heating from UV-excited grains excited by the ISRF that can raise the temperature as discussed above. The chemistry is solved as a function of distance to the star (e.g., Glassgold 1996). The chemical network is based on the kida.uva.2014 network (Wakelam et al. 2015), which includes $\sim 500$ chemical species and $\sim 5000$ reactions. For gas-phase photoprocesses, we follow an approach similar to Gorti & Hollenbach (2004) to split the far-UV (FUV) portion of the ISRF into nine energy bins from 0.7–13.6 eV where the nine intervals were chosen to correspond to dominant gas photoabsorption thresholds. When available, destruction rates are computed by integrating photoabsorption, photodissociation, and photoionization cross sections over each energy bin to get the weighted cross sections for each species in each bin. The effect of self-shielding on the photodissociation rates is taken into account for H$_2$, CO, and N$_2$. H$_2$ self-shielding is treated following Tielens & Hollenbach (1985). For CO and N$_2$, we use tabulated shielding functions that include the effects of self-shielding and the shielding provided by H and H$_2$ (Visser et al. 2009; Li et al. 2013). For absorption by dust, we simply assume that the dust extinction scales with the total hydrogen column density and use $A_V = 5.3 \times 10^{-22} N_H$. We use initial abundances from Agúndez et al. (2012), for which the total carbon and oxygen abundance are $[C/H] = 4 \times 10^{-4}$ and $[O/H] = 3 \times 10^{-4}$, leading to a $[C/O]$ ratio of 1.3.

Figure 3 shows the computed abundance profile of C$^+$, C$^0$, and CO as a function of the distance from the star. While CO is by far the dominant carrier of gas-phase carbon through most of the envelope, the daughter products begin appearing as close to the star as a significant abundance of C$^0$ at $8 \times 10^{16}$ cm then C$^+$ dominates outside $4 \times 10^{17}$ cm, in accord with the Mamon et al. (1988) and Saberi et al. (2019) calculations.

Table 1 and Figure 2 (Models 3–5) shows the predicted line brightness for [C II] emission for $T_{\text{min}} = 10, 20, \text{and} 30$ K, respectively. The predicted brightness depends strongly upon the temperature profile, because the excited state is 91 K above ground: the predicted brightness changes by two orders of magnitude for the modeled range of $T_{\text{min}}$. The CSE models do not have a peak of emission from the outer envelope (like Model 0 does), due to its assumed higher temperature in the envelope. The CSE models have the [C II] emission more closely concentrated to the star, with a peak brightness for lines
of sight about 60" offset from the star due to gas at 10^{17} cm from the star. The contrast between the central and peak brightness is about 25%, so sensitive observations with a resolution <30" could in principle resolve the extended envelope and detect limb brightening.

### 3. Observations of IRC+10216

Expecting that evolved stars are surrounded by halos of these daughter products, forming a thick shell centered on the star, we designed an experiment to test the model on a well-known star.

#### 3.1. SOFIA

SOFIA (Young et al. 2012; Temi et al. 2018) enables measurement of the [C II] 157.7 \( \mu \)m line at an angular resolution of 14".1. The line was observed with the upgraded German Receiver at Terahertz Frequencies (upGREAT; Risacher et al. 2016, 2018), which has a horn arranged in a center-filled-hexagonal pattern and a backend capable of spectral resolution better than 1 km s\(^{-1}\). The low-frequency array was tuned to the [C II] \( ^3P_1-^3P_0 \) line at 1900.536 GHz, and the high-frequency array was tuned to the [O I] \( ^3P_1-^3P_2 \) line at 4744.777 GHz.

The observing strategy was to take deep spectra, using the secondary mirror to chop N and S of the envelope to cancel atmospheric emission. Each pointing of the array yielded seven measurements of the [C II] line at orthogonal linear polarizations, for 14 independent spectra. The array was offset from the star along a line straight east, with an offset of 96" between pointings, yielding a straight line of beams along the eastward direction together with rows just N and S of that straight line offset N and S by 28". The first pointing was offset so that the closest spectrum to the star was 23.5 E and the central row of the raster map was sampled approximately every 32" from there to 278" E of the star. This set of pointings covers the region where extended C\(^+\) is predicted to exist. An additional pointing toward the Galaxy Evolution Explorer (GALEX)-detected bow shock (Sahai & Chronopoulos 2010) was made along the same eastward line as the other observations but offset 470" E.

Observations took place during SOFIA's deployment to Cologne, Germany, in 2021 March under program number 08_0007. Table 2 summarizes the observations. On flight 709, two legs (one rising, one setting) at different altitudes were observed. To minimize baseline structure (due to instabilities in the receiver and atmosphere) a chop throw smaller than the total size of the extended [C II] cloud has to be utilized, so care must be taken in comparing the models to the observations, as is done in Section 4. For the raster map of three positions E of the star, a symmetric chop N and S was used. For the bow shock position the secondary was chopped 300" E only, to avoid chopping back onto the extended envelope. In the end, each pointing in the raster map received 30 minutes of integration.

The calibration was done using the KOSMA atmospheric calibration software for SOFIA/GREAT (Guan et al. 2012). For the atmospheric opacity corrections, the precipitable water vapor column was obtained from a free fit to the atmospheric total power emission. The dry constituents were fixed to the standard model values. All receiver and system temperatures are on the single-sideband scale. The antenna temperature (\( T_A \)) was converted to \( T_{mb} \) using beam efficiencies that were computed for each pixel and polarization (\( \eta_{mb} = 0.63-0.69 \)). The main beam size is 14"1 and the error in the calibration is better than 20%.

The data were reduced using the CLASS package from the GILDAS software.\(^7\) A first-order baseline was removed from all spectra. One polarization from one of the horns (horn 5, vertical polarization) was excluded because its data were corrupted by interference. Figure 4 shows the [C II] spectra, averaging the data in four distance ranges from the star. No lines were detected in the spectra with an rms brightness temperature of 0.03 K in spectra smoothed to 0.39 km s\(^{-1}\) resolution. Because of the potential for self-chopping on the extended envelope, the data with ±150" and ±200" were reduced separately and found to be identical with no line detection. The [C II] line is predicted to be wider, but there is still no line detected when smoothed to 3 km s\(^{-1}\) resolution, despite a low rms brightness temperature of 0.015 K. For an upper limit to the [C II] brightness, we use the rms from the spectra smoothed to 3 km s\(^{-1}\) times a 10 km s\(^{-1}\) line-width based on other far-infrared lines (see Herschel observations below), yielding \( \Delta T dB < 0.15 \) K km s\(^{-1}\). The [O I] observations similarly showed no detection, with rms brightness temperature 0.1 K at 0.16 km s\(^{-1}\) resolution.

#### 3.2. Herschel

The 1900.5369 GHz [C II] frequency from IRC +10216 was observed by Herschel (Pilbratt et al. 2010) with the Heterodyne Instrument for the Far Infrared (HIFI; de Graauw et al. 2010) as part of an early calibration observation (2011 October 26), and it was observed with the Photodetector Array Camera and Spectrometer (PACS; Poglitsch et al. 2010) as part of a line survey (2011 May 29). The HIFI observation, at high spectral resolution, shows a bright line near—but not consistent with—the frequency of [C II], making it impossible to separate detect the low spectral resolution of PACS. Therefore, we first investigate the HIFI observation in detail. That short (875 s duration) observation was taken using double beam switching, symmetrically offsetting the changer 3' centered on the star.

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\(^7\)https://www.iram.fr/IRAMFR/GILDAS/
Figure 4. SOFIA/GREAT observations of IRC+10216 at four separations from the star, vertically offset for clarity.

with observation ID 1342231460. The data were retrieved from the archive in $T_{\text{A}}^\star$ units appropriate for a compact source (Shipman et al. 2017). We interpolated the two orthogonal polarization spectra to a common frequency grid and averaged them to create the final spectrum, shown in Figure 5. The Herschel telescope angular resolution is $11''$ at 157.7 $\mu$m. The reference spectrum (3' from the star) was obtained from the Herschel archive (Teyssier & Rengel 2016), to evaluate possible contamination from extended emission as is often present due to the ISM in [C II]. The reference spectrum shows no such sign of emission lines, indicating the lines in the spectrum centered on the star are all from IRC+10216. HIFI spectra are double sideband, so a spectral line can appear from either lower or upper sidebands. The bright line near the center of the spectrum in Figure 5 is at 1901.309 GHz (LSR frame). The line is likely CS(39–38) in the upper sideband with a $-26.5$ km s$^{-1}$ LSR velocity that matches ground-based CO line observations (Cernicharo et al. 2015; Guélin et al. 2018), based on the rest frequency in the Cologne Database for Molecular Spectroscopy (CDMS; Müller et al. 2005) of 1901.151 GHz. Archival Herschel observation also show the other CS rotational lines as among the brightest in this frequency range; we verified 38–37, 37–36, 36–35, and 35–34. (The frequency of CS(39–38) in the JPL molecular spectroscopy database is significantly different from CDMS, at 1900.732 GHz, but it is based on much older literature references. Based on the more modern references and the matching of all four other lines with CDMS, the line identification is of high confidence.) A Gaussian fit to this line has amplitude 1.12 K, FWHM 14.8 km s$^{-1}$, and line integral 19 K km s$^{-1}$. Fainter emission is at the correct frequency for [C II] if it is also in the upper sideband and has two components, at radial velocities $-39.1$ and $-15.1$ km s$^{-1}$. We interpret these components as the approaching and receding portions of the expanding outflow. The average of the central velocities of each of the two components is $-27$ km s$^{-1}$, which is consistent with the $-26.5$ km s$^{-1}$ of the CS and CO lines. The separation between the velocities of the two components is 24 km s$^{-1}$, also consistent with the components the approaching and receding portions of a shell expanding with velocity 15 km s$^{-1}$ that has been determined from prior studies of the star (see, Cernicharo et al. 2015). The flux of the [C II] line is $5.1$ K km s$^{-1}$ ($1.0 \times 10^{-16}$ W m$^{-2}$).

Figure 5. Herschel/HIFI observation of IRC+10216, with the lower horizontal axis being velocity relative to that of the rest-frame [C II] line, and the upper axis being the rest frequency in the upper sideband. The bright line observed at USB frequency 1901.31 GHz (velocity $-121$ km s$^{-1}$) is CS(39–38), which has a rest frequency of 1901.1510 GHz (Müller et al. 2005); a Gaussian profile fit is shown. We identify the fainter two components at $-15$ and $-39$ km s$^{-1}$ as [C II], which has a rest frequency of 1900.5369 GHz, and a model profile with the blueshifted component absorbing the continuum is shown, as appropriate for an expanding shell with the star in the center (see text for details). The magnitude curve shows the reference position spectrum (180' from the star). Note the difference in baseline brightness between source and reference, which is due to dust emission from IRC+10216. Straight blue lines indicate the frequencies of the [12C II] components, and straight green lines indicate the frequencies of the corresponding [13C II] hyperfine transitions, which are not detected.

The [C II] line profile is noticeably asymmetric, with the blueshifted component fainter than the redshifted component. This “P Cygni” like profile can arise if the approaching (blueshifted) part of the outflow is in front of the star and absorbs the bright continuum from the dust envelope. From AKARI observations, the total flux density of the star at 160 $\mu$m is 475 Jy (Ueta et al. 2019), which with Herschel HIFI the antenna temperature would convert to 0.87 K (Shipman et al. 2017). But at Herschel resolution, the shell is well resolved, so a lower brightness is observed, around 0.57 K if we look at frequencies away from the emission lines. If the blueshifted component has a peak optical depth $0.25 \pm 0.05$, then an excellent fit to the line profile is obtained (Figure 5). The integrated optical depth $\int dv = 3.0 \pm 0.4$ km s$^{-1}$, which requires a C$^+$ column density $(4 \pm 0.6) \times 10^{17}$ cm$^{-2}$ (Goldsmith et al. 2012). This is the column density integrated from the star to the observer through the expanding shell.

There is no evidence of extended [C II] emission. The extent of the [C II] emission can be partly assessed from inspecting the HIFI reference spectrum at 180' from the star, which shows no significant line emission, and for the SOFIA spectra showing no emission 23' from the star, for which there is an even more strict upper limit. Therefore, the [C II] is primarily compact. We inspected the PACS line observations to determine whether there is any evidence of extended emission near IRC+10216. The PACS spectral imager has a $5 \times 5$ array of spaxels of size 9.4' covering the 47'' centered on the star. The spectral resolution of 240 km s$^{-1}$ cannot separate the CS and [C II] lines seen in the HIFI spectrum in Figure 5. The CS(39–38) line arises from a much higher energy level (1800 K above ground) than that of the [C II] line (91 K above ground), so the former should arise only from a relatively hot region close to the star.
We used the PACS data to compare the spatial distribution of those blended emission lines (at 157.69 μm) to that of a bright, nearby molecular line at 158.11 μm that is evident in the PACS spectrum and presumably also arising in the inner hot envelope. The emission from both features declines similarly with distance from the star, indicating no significant extended emission from \([\text{C} \, \text{II}]\) within 23″ of the star.

The isotopic \([^{13}\text{C} \, \text{II}]\) fine structure comprises three hyperfine components with frequency offsets, converted to velocity offsets from rest (i.e., where the \([^{13}\text{C} \, \text{II}]\) line would appear) of −65.2 \((F=1\rightarrow0)\), +11.2 \((F=2\rightarrow1)\), and +63.2 \((F=1\rightarrow0)\) km s\(^{-1}\) (Cooksy et al. 1986). The relative intensities of the hyperfine components are 0.4, 1, and 0.2, respectively (Ossenkopf et al. 2013). Figure 5 shows where the \([^{13}\text{C} \, \text{II}]\) components would appear. The \(F=2\rightarrow1\) component would be blended with the \([^{12}\text{C} \, \text{II}]\) line, and could conceivably contribute to the apparent asymmetry of that line. There is a faint potential line at the location of the \(F=1\rightarrow1\) component, at \(\lesssim0.1\) K and there is no evidence of an \(F=1\rightarrow0\) component (<0.08 K).

With the predicted branching ratios of the components, it is not possible for \([^{13}\text{C} \, \text{II}]\) to be a significant contribution to the observed spectrum. Using the upper limit to \(F=1\rightarrow0\), the potential wiggle in the spectrum near the \(F=1\rightarrow1\) frequency would be too bright by a factor of 2.5. And even neglecting the lack of \(F=1\rightarrow0\), if the \(F=1\rightarrow1\) line were detected at 0.1 K, the central \(F=2\rightarrow1\) component should be 0.5 K which is brighter even than the \([^{12}\text{C} \, \text{II}]\) line. Therefore, the observations indicate no \([^{13}\text{C} \, \text{II}]\) emission, with a weak lower limit on the abundance ratio of \(^{12}\text{C}/^{13}\text{C} > 2.3\), based on the ratio of observed \([^{13}\text{C} \, \text{II}]\) to the summed upper limits of the \([^{12}\text{C} \, \text{II}]\) components. The lower limit is not surprising, given \(^{13}\text{C}/^{12}\text{C} = 89\) in the solar photosphere (Clayton & Nittler 2004) and 68 in the ISM (Milmam et al. 2005). In IRC+10216, the isotopic ratio \(^{12}\text{CO}/^{13}\text{CO} = 40\) (Guélín et al. 2018), so that \(^{13}\text{CO}\) dissociation may be expected to yield \(^{12}\text{C}/^{13}\text{C}\) closer to 40 for the daughter products. The lower limit from the present data does not approach these expected values.

4. Confronting Predictions with Observations

The measured and upper-limit brightness of the \([\text{C} \, \text{II}]\) line are shown in Figure 6 as a function of distance from the star. Due to the large predicted size of the \(\text{C}^+\) cloud around the star, and the differential, chopped nature of the observations with chop throws of comparable size to the cloud, we generated virtual chopped models to allow a direct comparison between the model and the observations. We assumed the cloud is azimuthally symmetric, and for each modeled distance to the star, we subtracted the brightness predicted to occur in the chop beam. The virtual chopped radial brightness profiles are shown in Figure 6 with the same coloring scheme as the actual models from Figure 2. The predicted central brightness is suppressed in the chopped models of extended envelopes because the radial profile of the surface brightness is relatively flat out to the projected photodissociation radius.

In contrast to the models, the observations show (1) a detection toward the star, brighter than predicted by any of the models, and (2) upper limits on extended emission, fainter than predicted models in which the outer envelope is warmer than 10 K. Further, comparing to the \(\text{C}^+\) column density predictions in Table 1 to the column density derived toward the star from the Herschel/HIFI spectrum, none of the models have high enough column density of \(\text{C}^+\).

![Figure 6](image-url)

**Figure 6.** Comparison between the \([\text{C} \, \text{II}]\) line observations and models. Model parameters are listed in Table 1. The model curves are the same as those in Figure 2, but virtually chopped using a 200″ throw as in most of the SOFIA observations. Open circles are the models at the location of, and with simulated chop appropriate for, the specific SOFIA and Herschel observations. A negative chopped brightness means that the reference chop would have been brighter than the targeted position, so a spectral line of negative apparent brightness would appear with standard processing; such a feature would be as readily evident in the data as a positive brightness. Black circles and bars denote the 95% confidence upper limits from the SOFIA/GREAT observations. The black circle at zero distance is the Herschel/HIFI detection toward the star, and the upper limit at 180″ distance is from the Herschel/HIFI reference position spectrum. All of the models are ruled out with high confidence except the post hoc Model 3, which places a shell of \(\text{C}^+\) in close to the star.

Thus, while the extended envelope is not detected, the inner envelope requires more \(\text{C}^+\) than predicted. It is possible to explain the lack of \([\text{C} \, \text{II}]\) emission from the outer envelope as being due to low temperatures there, such as in Model 0t. While this did not agree with our expectation that the ISRF would heat the envelope, the balance of heating and cooling depends upon the nature of the macromolecules and solids that contain most of the heavy elements in the envelope. If the photoelectric heating is suppressed in the envelope, as compared to the diffuse ISM, then the temperature could be low in the envelope, even for densities comparable to the diffuse ISM. Also, if the mass loss is nonsteady such that the envelope is not smoothly filled, then the local volume density could be higher than large-scale averages, which would enhance the cooling due to collisionally excited lines from the gas. Furthermore, the gas is not necessarily in thermal equilibrium, and the adiabatic cooling during its expansion could lower the temperature enough that the \(^3\text{P}_1\) level of \(\text{C}^+\) is not excited. Any of these effects (decreased heating, enhanced cooling, and adiabatic expansion) could keep the gas cold and suppress the \([\text{C} \, \text{II}]\) emission from the envelope. But the emission and absorption on the line of sight to the star remain unexplained by the a priori models.

5. How to Explain the Gas-phase Carbon Distribution

In order to explain the \([\text{C} \, \text{II}]\) emission and absorption toward the star, we introduce a shell of \(\text{C}^+\) at a distance from the star \(r\), with a thickness \(r/2\), and we use observational results to constrain \(r\). The atomic gas in the shell contains a fraction \(f_C\) of the gas-phase carbon available at \(r\). Then the column density is

\[
N(\text{C}^+) = n(r)rf_C,
\]

(5)
where \( n(r) \) is from Equation (1). The material must not extend far enough that it would be resolved and detected in the SOFIA spectra, which limits \( r < 3 \times 10^{16} \) cm. Using the observed column density from the blueshifted absorption in the Herschel spectrum, the shell could occur at \( r = 1.2 \times 10^{16} \) cm, if it contains \( f = 60\% \) of the gas-phase carbon there. This close to the star, external ISRF heating is negligible, and the gas temperature inferred from the astrochemistry models and observations (Saberi et al. 2019; Cernicharo et al. 2015) is 62 K. The upper level of the [C II] line is readily excited in this inner envelope. The density must fall off very quickly in order to remain consistent with the SOFIA and Herschel upper limits in the outer envelope. Figure 7 shows a model of the density versus distance to the star in the same format as Figure 1, with a thin, inner shell added.

The [C II] observational result is qualitatively similar to that obtained for [C I] by Keene et al. (1993), who detected optically thin emission in the 492 GHz line from the \( ^3P_1 \rightarrow ^3P_0 \) transition. They fit the spatial and spectral distribution of the emission with shells at 2.7 \( \times 10^{16} \) and 8.2 \( \times 10^{16} \) cm radius, with a column density in the upper level inferred to be \( N(C^0) = 7 \times 10^{15} \) and \( 4 \times 10^{15} \) cm\(^{-2} \), respectively. The inferred locations of the C\(^0\) shells are outside those we inferred for the C\(^+\). For a concordance, the C\(^+\) would need to be a bit further out, and \( f_C \) lower, which is only marginally allowed given the upper limit to the [C II] emitting region size. Using the same temperature law as described above (heating only from the star), the inferred inner and outer C\(^0\) shells are at 35 and 16 K, respectively. The upper level of the 492 GHz fine structure line is readily excited at such temperatures, and the total (not just upper level) C\(^0\) column densities of the shells are 1.2 \( \times 10^{16} \) and 1.0 \( \times 10^{16} \) cm\(^{-2} \). The column density of C\(^+\) is much higher than that of C\(^0\), suggesting that the ionized carbon in the inner envelope rapidly recombines and is incorporated into molecules.

The amount of free gas-phase carbon (i.e., not in molecules or dust) required to explain the observed [C II] absorption is about \( 2 \times 10^{-6} M_\odot \) (for a column density \( 4 \times 10^{17} \) cm\(^{-2} \) in a region of radius 1.2 \( \times 10^{16} \) cm), which is a small fraction (< 0.1\%) of the total yield of C from a solar metallicity AGB star with main-sequence mass 1.5–4.5 \( M_\odot \) (Karakas 2010). The column density we derive for C\(^+\) is 9 times higher than predicted by the detailed chemical model of Millar et al. (2000). Similarly, the column density derived of C\(^0\) is 2.2 times higher than the model. In the warm, dense environment near the star, gas-phase carbon is rapidly consumed into molecules like CO and C\(_2\)H\(_2\), with timescales of order 1 yr for gas within 10\(^{15} \) cm of the star. However, if any carbon were liberated to the gas phase in the outer envelope, then it can survive much longer, due to the rapid \( r^{-2} \) decrease in gas density and \( n^2 \) nature of chemical reactions. For example, at 10\(^{16} \) cm from the star, chemical timescales are \( > 10^3 \) yr. For comparison, the dynamical timescale of gas expansion is \( r/v = 210 \) yr at that same distance from the star. Therefore, carbon formed from photodissociation at \( \sim 10^{16} \) cm will flow together with the molecules outward to the rarefied outer parts of the envelope.

There was no sign of [C II] or [O I] emission from the bow shock that is 8.6 \( \times 10^{17} \) cm (470") from the star due to its motion through the surrounding ISM (Ladjal et al. 2010; Sahai & Chronopoulos 2010). The actual velocity is not well known, having been inferred from the location of the termination shock and assumption about the ISM density (which is unknown). For example, if the motion is 90 km s\(^{-1} \), the ISM will experience a 44 km s\(^{-1} \) J-type shock and the outer envelope will experience a 7 km s\(^{-1} \) wind termination shock. The upper limit from SOFIA of 0.15 K km s\(^{-1} \) corresponds to a surface brightness 10\(^{-6} \) erg s cm\(^{-2} \) sr\(^{-1} \). For a radiative shock, the total energy loss rate is \( \rho v^2/8\pi \sim 10^{-5} n_0 v_3^2 \) erg cm\(^{-2} \) s\(^{-1} \), where \( n_0 \) is the surrounding ISM density (per cubic centimeter), and \( v_3 \) is the star’s velocity divided by 45 km s\(^{-1} \). The [C II] upper limit constrains the pre-shock ISM density to \( n_0 < 1 \) cm\(^{-3} \) if 10\% of the radiative losses are in the [C II] line. Limiting the power of the shock also limits its UV production. The GALEX FUV intensity is interpreted as fluorescent H\(_2\) rather than shocks or dust scattering (Sahai & Chronopoulos 2010), so there is only weak UV radiation from the bow shock, which is unlikely to significantly affect the CSE except in the immediate vicinity of the bow shock itself. Estimating the envelope density at 8.6 \( \times 10^{17} \) cm from the star as 20 cm\(^{-3} \) and the reverse (termination) shock velocity as 7 km s\(^{-1} \), the power in the reverse shock is about 10 times lower than the bow shock, with negligible UV production.

6. Conclusions

For the standard model of mass loss considered in this paper, CO is a parent molecule, with C being a daughter product and C\(^+\) a quickly formed granddaughter. We do not detect emission from the C\(^+\) that should exist at the outer edge of the CO envelope. The strict upper limits require that the carbon gas is injected into the ISM is very cold (\( \lesssim 20 \) K), either due to its rapid adiabatic expansion or due to a lack of the heating mechanisms that apply to average ISM gas (where photoelectrons from small PAH dominate heating). If there is another C-bearing parent molecule, with a very short lifetime to dissociation by interstellar radiation field photons in the outflow, then it could in principle explain an inner shell of carbon. Hypothetically, such a parent would be rich in C and susceptible to dissociation by longer wavelength photons that penetrate deeper into the envelope. The photons from the star could also contribute, forming a two-sided PDR with the star and its thick dust shell on the inside and the ISRF on the
outside. The presence of a remarkable wealth of complex molecules in the IRC+10216 including CH₂CHCN, CH₃CN, CH₂CCH, and H₂CS (Agúndez et al. 2008), with prominent C-bearing species in the inner envelope within 2 × 10⁻¹⁵ cm of the star including C₂H₂ and HCN at abundances within an order of magnitude of CO (Agúndez et al. 2012), encourages such speculation. The atomic carbon in the inner envelope has been suggested to be dissociation products of C₂H₂ and CO, though the locations of those shells is much closer to the star than expected for ISRF photodissociation of those molecules (Keene et al. 1993).

Carbon formed in the inner envelope is rapidly incorporated back into hydrocarbons, so maintaining a large column density of atomic and ionized carbon requires an additional source of dissociating photons. The average photospheric emission of the central star of IRC+10216, CW Leo, has insufficient blue to ultraviolet light. The source of the additional dissociation could be a companion star, the existence of which has already been inferred from the geometry of shells of mass loss (Cernicharo et al. 2015), or shocks in the inner envelope. The bow shock would primarily affect the outer envelope, which appears unperturbed, being primarily molecular and having roughly spherical geometry, throughout the CO emission region. The SOFIA and Herschel observations can only be explained with ionization well inside the CO emitting region. Visible and ultraviolet light from accretion shocks of material onto a companion star are a potential source of dissociating photons. A white dwarf companion would produce enough dissociating and ionizing photons to significantly alter the circumstellar chemistry and lead to C⁺ deep in the envelope (Millar 2020). Atomic carbon near evolved stars has also been detected for α Ori (Huggins et al. 1994) and α Cet (Saberi et al. 2018) and interpreted as potentially due to presence of UV radiation from a chromosphere or accretion shocks. In R ScI, atomic carbon was detected from a detached shell, due to dissociation of molecules other than CO (Olofsson et al. 2015). The column density of atomic and ionized carbon in the inner envelope of IRC+10216 is estimated to be 4 × 10¹⁹ cm⁻². For comparison, for theoretical models of outflows, the total column density of carbon-bearing gas species (primarily CO, C₂H₂, and HCN) is 2 × 10¹⁸ cm⁻² (Millar et al. 2000), so the additional carbon implied by the new observations is a significant but not dominant constituent of the total envelope.

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Facilities: SOFIA, Herschel.

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