

The Impact of UV Radiation on Circumstellar Chemistry

Maryam Saberi¹, Wouter Vlemmings¹, Tom Millar²
and Elvire De Beck¹

¹Dep. of Space, Earth and Environment, Chalmers University of Technology &
Onsala Space Observatory, 43992 Onsala, Sweden
email: maryam.saberi@chalmers.se

²School of Maths and Physics, Queen's University Belfast, University Road,
Belfast BT7 1NN, Northern Ireland

Abstract. UV radiation plays a critical role in the chemistry of circumstellar envelopes (CSEs) around evolved stars on the asymptotic giant branch (AGB). However, the effects of all potential sources of UV radiation have not been included in models. We present preliminary results of adding an internal source of UV to the CSE chemistry and predict large enhancements of atomic and ionic species arising from photo-destruction of parent species. Observations of atomic carbon towards the UV-bright AGB star *o* Cet are consistent with the modelling. In addition, we calculate the precise depth dependence of the CO photodissociation rate in an expanding CSE. We incorporate this within a chemical network active in the outflows of AGB stars, which includes 933 species and 15182 reactions. Our results show that the CO envelope size is about 30% smaller at half abundance than the most commonly used radius reported by Mamon *et al.* (1988).

Keywords. astrochemistry, stars: abundances, stars: AGB and post-AGB, stars: carbon, stars: chromospheres, stars: circumstellar matter, ultraviolet: stars, binaries: general, radiative transfer

1. Introduction

In the standard paradigm of a CSE, photodissociation by external UV radiation from the interstellar radiation field has been considered to be the agent that controls molecular photodestruction. However, there is now ample evidence for the presence of extra UV radiation which permeates the inner part of a CSE. Recent GALEX observations revealed 180 asymptotic giant branch (AGB) stars (57% of the observed sample) have detectable far- and/or near-UV emission (Montez *et al.* 2017), indicating the presence of extra UV radiation inside the CSE. The internal UV radiation can originate from stellar chromospheric activity, a hot binary companion, and/or the accretion of material between two stars in a binary system. To constrain the effects of both internal and external UV radiation in the chemical modelling of CSEs, observations of main photodissociation/photoionization products are required. Moreover, comparison of isotopologue ratios of molecular species such as $^{12}\text{CO}/^{13}\text{CO}$ and $\text{H}^{12}\text{CN}/\text{H}^{13}\text{CN}$, which dissociate through different mechanisms, can be used to trace the UV-chemistry (Saberi *et al.* 2017).

2. The isotopic chemistry

To model the chemistry active in the CSE of an AGB star we use an extended version of the rate13-cse code (McElroy *et al.* 2013). In the extended version, we apply the updated version of the UMIST06 chemistry file which includes the ^{13}C and ^{18}O isotopes, all

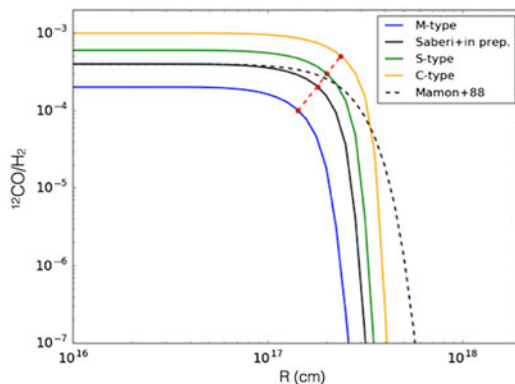


Figure 1. Fractional abundance distributions of CO for models with different initial abundances of f_{CO} which are usually adopted for M-, S-, and C-type AGB stars and the value of the Mamon *et al.* (1988) standard model. The black dashed line shows the Mamon standard model. Comparison of the black solid and black dashed lines shows the difference between our model and that of Mamon *et al.* (1988).

corresponding isotopologues, their chemical reactions, and the properly scaled reaction rate coefficients from Röllig & Ossenkopf (2013). The chemical network includes 933 species and 15182 gas-phase reactions (Saberi *et al.*, in prep.).

3. The CO envelope size

Photodissociation is the dominant process which determines the abundances and distributions of CO and its photodissociation products such as C and C^+ throughout the CSE. The depth dependence of the CO photodissociation mechanism in an expanding spherical CSE was presented by Morris & Jura (1983) through a “1-band approximation”. After new laboratory measurement of far-UV absorption and fluorescence cross sections by Letzelter *et al.* (1987), the rate was updated by Mamon *et al.* (1988) considering 34 dissociating bands. In two recent works by Li *et al.* (2014) and Groenewegen (2017), updated CO photodissociation rates in a CSE were presented. However, in both cases they used shielding functions calculated for the ISM by Visser *et al.* (2009). Here, we derive the depth dependence of the photodissociation rate for all dissociating CO lines taking into account the physical properties of a CSE (Saberi *et al.* in prep.). Our derived CO envelope size at half the abundance ($r_{1/2}$) is about 30% smaller compared to that calculated by Mamon *et al.* (1988). Moreover, we find that the CO envelope size depends not only on the mass loss rate and the expansion velocity of the envelope but also on the CO initial fractional abundance f_{CO} . Figure 1 shows how the CO distribution profiles varies for models with different values of f_{CO} . We used the commonly used f_{CO} for M-type, S-type, and C-type AGB stars, and that being used in the standard model of Mamon *et al.* (1988).

4. The internal UV field

The internal UV radiation can arise from a hot binary companion, stellar chromospheric activity, or accretion of matter between two stars in a binary system. This UV field is expected to cause significant photodissociation of CO isotopologues in the inner part of the CSE. This, in turn, has important effects on the chemistry of the gas. The preliminary results of adding an internal source of UV radiation (a blackbody with $T = 18000$ K) is shown in Fig. 2. As can be seen, there is an enhancement of C and C^+ in the inner CSE. There is also a variation in the fractional abundance distributions of the CO isotopologues, meaning that the circumstellar $^{12}\text{CO}/^{13}\text{CO}$ ratio can not be a reliable tracer of

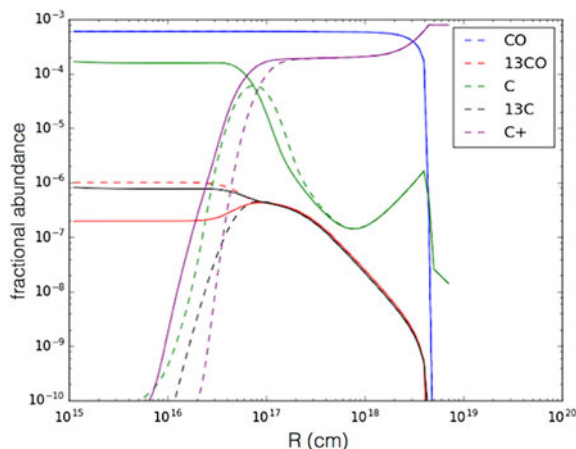


Figure 2. The fractional abundance distributions of CO, C, and C⁺ before (dashed lines) and after (solid lines) adding an internal source of UV radiation.

the photospheric ¹²C/¹³C ratio in the UV-dominated parts of a CSE. A further detailed analysis of the consequences of the presence of the internal UV radiation on the CSE chemistry is in progress (Saber *et al.* in prep.).

5. An observational tracer of the internal UV radiation

5.1. The photo-destruction products

To empirically constrain the effects of internal and external UV radiation sources, observations of the main photo-destruction products, e.g., C and C⁺, are required. To date, C has been detected in four post-AGB stars (Knapp *et al.* 2000, and references therein) and three carbon-type AGB stars IRC+10216 (Keene *et al.* 1993; van der Veen *et al.* 1998), R Scl (Olofsson *et al.* 2015), and (tentatively) V Hya (Knapp *et al.* 2000, Saber *et al.* 2018). Moreover, Saber *et al.* (2018) reported the detection of C emission from the oxygen-rich AGB star *o* Cet (Fig. 3), and argued that it arises from a compact region near its UV-bright binary companion. To extend our analysis, we have applied for C and C⁺ observations with ALMA and SOFIA towards a larger sample of UV-bright AGB stars.

5.2. The isotopologue ratio

ALMA observations of R Scl show a discrepancy between the ¹²CO/¹³CO ratio in the present mass loss (> 60) and the detached shell (~19) (Vlemmings *et al.* 2013). The ratio in the inner wind is surprisingly much higher than in the outer region. This may indicate more effective photodissociation by the interstellar radiation field, penetrating deeper into the CSE. More likely, an active binary companion or an active chromosphere of the AGB star would provide an additional source of UV radiation in the inner CSE. The presence of atomic carbon in the inner CSE of R Scl, as reported by Olofsson *et al.* (2015), strengthens the likelihood of the presence of an internal source of UV radiation. Chemical models which consider an internal UV field can explain the variation of the ¹²CO/¹³CO throughout the CSE. On the other hand, from a detailed excitation analysis of H¹²CN and H¹³CN, Saber *et al.* (2017) found a ratio of H¹²CN/H¹³CN ~ 26 ± 12 close to the star, in agreement with the photospheric estimate of ¹²C/¹³C ~ 19 ± 6 reported by Lambert *et al.* (1986). Since CO isotopologues are photodissociated by the UV radiation in well-defined bands and HCN is dissociated in the continuum, we suggested that isotope-selective photodissociation of ¹²CO and ¹³CO causes this discrepancy (Saber *et al.* 2017).

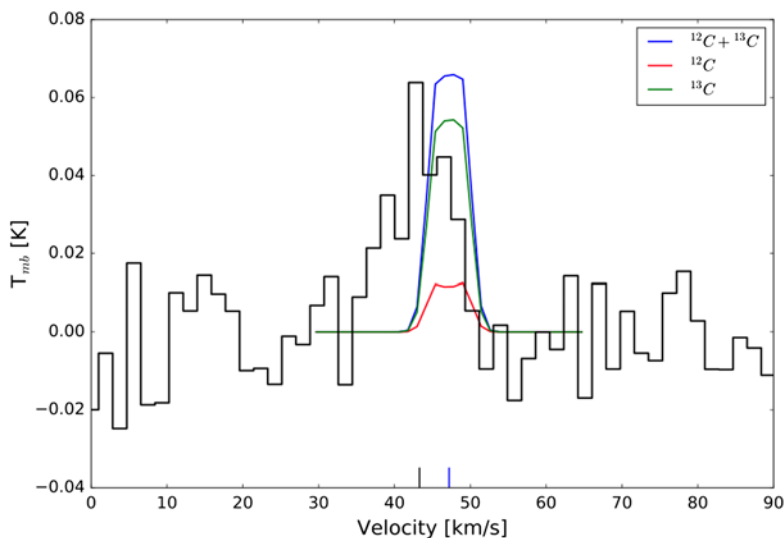


Figure 3. The CI emission towards *o* Cet, 1.8 km/s velocity resolution, in LSR scale (histogram). The stellar, 47.2 km/s, and spectrum peak, 43.4 km/s, velocities are indicated as blue and black vertical markers on the x-axis, respectively. The results of the radiative transfer modelling of the C isotopes are shown in red and green, respectively. The blue profile indicates the total amount of C (from Saberi *et al.* 2018).

This implies that the circumstellar $\text{H}^{12}\text{CN}/\text{H}^{13}\text{CN}$ ratio might be a better tracer of the photospheric $^{12}\text{C}/^{13}\text{C}$ ratio in UV-irradiated CSEs. To confirm this, a more extended analysis towards more UV-bright AGB stars is required.

References

- Groenewegen, M. A. T. 2017, *A & A*, 606, 67
 Keene, J., Young, K., Phillips, T. G., *et al.* 1993, *ApJ*, 415, 131
 Knapp, G. R., Crosas, M., Young, K., Ivezić, Ž 2000, *ApJ*, 534, 324
 Lambert, D. L., Gustafsson, B., Eriksson, K., Hinkle, K. H. 1986, *ApJ*, 62, 373
 Letzelter, C., Eidelsberg, M., Rostas, F., *et al.* 1987, *Chem. Phys.*, 114, 273
 Li, X., Millar, T. J., Walsh, C., *et al.* 2014, *A & A*, 568, 111
 McElroy, D., Walsh, C., Markwick, A. J., *et al.* 2013, *A & A*, 550A, 36
 Montez, R. Jr., Ramstedt, S., Kastner, J. H., *et al.* 2017, *ApJ*, 841, 33
 Morris, M., & Jura, M. 1983, *ApJ*, 267, 179
 Olofsson, H., Bergman, P., Lindqvist, M 2015, *A & A*, 582, 102
 Röllig, M., Ossenkopf, V. 2013, *A & A*, 550A, 56
 Saberi, M., Maercker, M., De Beck, E., *et al.* 2017, *A & A*, 599A, 63
 Saberi, M., Vlemmings, W. H. T., De Beck, E., *et al.* 2018, *A & A*, 612, L11
 van der Veen, W. E. C. J.; Huggins, P. J.; Matthews, H. E. 1998, *ApJ*, 505, 749
 Visser, R., van Dishoeck, E. F., Black, J. H. 2009, *A & A*, 503, 323
 Vlemmings, W. H. T., Maercker, M., Lindqvist, M., *et al.* 2018, *A & A*, 556, 1

Discussion

DECIN: How exactly have you calculated the CO photodissociation radius? You presented your new chemical network, but I do not understand your link with the photodissociation radius.

SABERI: I calculate the depth dependence of the CO photodissociation rate for all CO dissociating lines in a spherical envelope which expands with a constant velocity v_{exp} . These calculations have been done for the ISM by Visser *et al.* (2009). This is the first time that

we calculate this for CSEs. Mamon *et al.* (1988) calculated the CO photodissociation rate using a “band-approximation” considering 34 dissociating bands. Groenewegen (2017) updated the CO photodissociation rate, however, he used the shielding functions that were calculated for the ISM. In our work, we calculate the CO photodissociation rate considering the physical properties of the CSE and explained the environment dependency of the CO photodissociation rate.

DECIN: I do not understand the picture you presented in R Scl where a binary or chromospheric activity can explain the variation in the $^{12}\text{CO}/^{13}\text{CO}$ fraction in the wind of R Scl. Once ^{13}CO is photo-dissociated (and hence $^{12}\text{CO}/^{13}\text{CO}$ is 60), it will not recombine further out in the wind due to the low gas density. Hence no explanation is offered for the $^{12}\text{CO}/^{13}\text{CO} \sim 19$ of the detached shell.

SABERI: Considering penetration of the standard UV field from the ISM, we expect a constant $^{12}\text{CO}/^{13}\text{CO}$ throughout the CSE which is constant with the photospheric $^{12}\text{C}/^{13}\text{C} \sim 19$. In case of R Scl, we got a ratio $^{12}\text{CO}/^{13}\text{CO} \sim 19$ in a detached shell which is consistent with the photospheric $^{12}\text{C}/^{13}\text{C}$, however the ratio increases $^{12}\text{CO}/^{13}\text{CO} > 60$ in the inner CSE (present mass loss). To explain the lack of ^{13}CO in the inner part, we speculate that the UV radiation from the binary companion, or stellar activity of R Scl itself, destroys most of the ^{13}CO while the most abundant ^{12}CO gets self-shielded (isotope-selective photodissociation).

