Mem. S.A.It. Vol. 88, 393

Memorie della

Estimating dust production rate of carbon-rich stars in the Small Magellanic Cloud

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Abstract. We compute a grid of spectra describing dusty Circumstellar Envelopes of Thermally Pulsing Asymptotic Giant Branch carbon-rich stars by employing a physically grounded description for dust growth. The optical constants for carbon dust have been selected in order to reproduce simultaneously the most important color-color diagrams in the Near and Mid Infrared bands. We fit the Spectral Energy Distribution of ≈2000 carbon-rich in the Small Magellanic Cloud and we compute their total dust production rate. We compare our results with the ones in the literature. Different choices of the dust-to-gas ratio and outflow expansion velocity adopted in different works, yield, in some cases, a total dust budget about three times lower than the one derived from our scheme, with the same optical data set for carbon dust.

Key words. infrared: stars - stars: AGB and post-AGB - stars: carbon - stars: mass loss - stars: winds, outflows - stars: circumstellar matter

1. Introduction

The Small Magellanic Cloud (SMC) is an ideal galaxy for the study of carbon-rich (C-rich) Thermally pulsing Asymptotic Giant Branch (TP-AGB) stars. Photometric observations of TP-AGB stars in the SMC are available in a wide range of wavelengths. We use the TP-AGB candidate list from Srinivasan et al. (2016), based on Boyer et al. (2011, 2015).

C-rich TP-AGBs are the most relevant stars for the interpretation of the Near and Mid Infrared colors (NIR and MIR) of the resolved population in the SMC, since the most dust obscured sources, classified as extreme-stars (x-stars), are likely to be C-rich (van Loon et al., 1997, 2006, 2008; Matsuura et al., 2009). Among the dust species produced within the Circumstellar Envelope (CSE) of C-rich TP-AGBs, carbon dust has a strong influence on the shape of the emerging Spectral Energy Distribution (SED) of the star.

In order to model the SED of a C-rich star one needs to choose the optical data set and grain size of carbon dust. However, several optical data sets for carbon dust, very different from each other, are available in the literature (Hanner, 1988; Rouleau & Martin, 1991; Zubko et al., 1996; Jager et al., 1998). Moreover, the typical grain size of carbon dust is uncertain. It is therefore necessary to determine which optical constants best reproduce the observations in the NIR and MIR bands.

In the recent work by Nanni et al. (2016) we systematically analyzed which combinations of optical data sets and grain sizes best reproduce most of the NIR and MIR colors simultaneously, without limiting the investigation to individual color-color or color-magnitude diagrams (CCDs, CMDs). The analysis was performed by employing some selected TP-AGB evolutionary tracks, modelled through the PARSEC and COLIBRI codes (Bressan et al., 2012; Marigo et al., 2013; Rosenfield et al., 2014, 2016) together with a consistent description of dust growth coupled with a stationary outflow (Nanni et al., 2013, 2014). Other constraints on the optical constants and grain size of carbon dust have been set by hydrodynamical calculations by Andersen et al. (1999); Mattsson et al. (2010).

We compute a grid of dusty models based on our physically grounded dust growth scheme and employing the optical constants constrained in Nanni et al. (2016). By using such a grid of models, we fit the SEDs of the C-rich stars in the SMC and we compute their total dust production rate (DPR). Differently from the standard approach used so far in the literature, our dust model consistently computes the dust-to-gas ratio, dust chemistry and expansion velocity, without the need of relying on assumptions or scaling relations for these quantities (van Loon, 2006; Groenewegen et al., 2007, 2009; Srinivasan et al., 2011; Gullieuszik et al., 2012; Boyer et al., 2012; Matsuura et al., 2013; Srinivasan et al., 2016; Goldman et al., 2017).

2. Method

The scheme we adopted for the description of the dust growth process coupled with a stationary outflow was first introduced by Gail & Sedlmayr (1999); Ferrarotti & Gail (2006) and used in several works (Zhukovska et al., 2008; Ventura et al., 2012; Di Criscienzo et al., 2013).

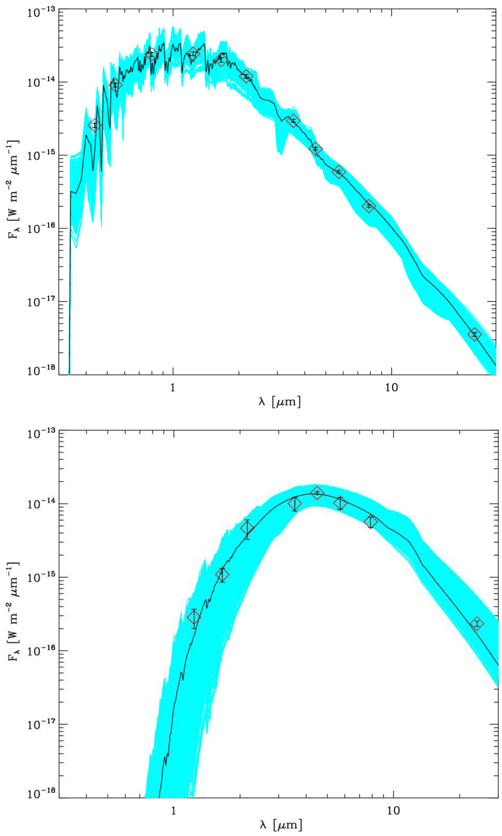

Fig. 1. Two examples of sources well fitted by our dusty models. Observed data points are plotted with red diamonds. The solid black line is the best-fit modelled spectrum, while the light blue curves are the spectra providing 68% of confidence level. An almost dust-free star (J−K_s ≈ 1.4) and an heavily dust-enshrouded source (J−K_s ≈ 5.2) are shown in the upper and lower panels, respectively.

In Nanni et al. (2013, 2014) we revised the original model in order to successfully reproduce some important observed trends in solar-like environments, i.e. outflow expansion velocities vs the mass-loss rate, for both M- and C- TP-AGBs. The model requires as input some stellar parameters, i.e. effective temperature ($T_{\rm eff}$), luminosity (L), actual stellar mass (M), mass-loss rate ($\dot{M}$) and the initial elemen-

Table 1. Our DPR for C-rich stars in the SMC computed as explained in the text, compared with other DPRs from the literature. The DPRs are espressed in $M_{\odot}yr^{-1}$.

Rouleau & Martin (1991) $a \approx 0.06\ \mu$m	C-stars	x-stars	Total (C-rich)
	$\approx 6\times10^{-7}$	$\approx 3.4\times10^{-6}$	$\approx 4\times10^{-6}$
Zubko et al. (1996) (ACAR sample) $a \approx 0.06\ \mu$m	C-stars	x-stars	Total (C-rich)
	3×10^{-7}	2.0×10^{-6}	$\approx 2.3\times10^{-6}$
Srinivasan et al. (2016)	C-stars	x-stars	Total (C-rich)
	$\approx 1.2\times10^{-7}$	$\approx 6.8\times10^{-7}$	$\approx 7.1\times10^{-7}$
Boyer et al. (2012)			Total (C-rich)
			≈ 7.5 - 8.4×10^{-7}
Matsuura et al. (2013)			Total (C-rich)
			$\approx 4\times10^{-6}$

tal abundances in the atmosphere. The integration of each CSE provides the dust chemistry, grain size, dust condensation temperature, dust-to-gas ratio and the expansion velocity profile. In addition to carbon dust we include in the calculation silicon carbide (SiC) and metallic iron. The quantities obtained from our dusty scheme are used as input to calculate the radiative transfer throughout the dusty CSE by means of the code More of DUSTY (Ivezic & Elitzur, 1997; Groenewegen, 2012, MoD). The photospheric input spectra are taken from the COMARCS grid of models (Aringer et al., 2016).

We build a grid of models for a set of values of $T_{\rm eff}$, L, M, $\dot{M}$ and carbon excess for Z=0.004 and for different optical data sets (Nanni et al., 2016). We then find the best fitting spectrum for each of the C-rich sources in the SMC, by selecting the model with the lowest χ^2 evaluated between the modelled photometric data points and the observed ones.

3. Results

Two examples of well fitting sources are shown in Fig. 1 for an almost dust-free star, with J−Ks∼ 1.4, and for an heavily dust enshrouded x-star, with J−Ks∼ 5.2 (upper and lower panel, respectively). The sources shown are fitted with models computed with the optical data by Rouleau & Martin (1991) and grain sizes $a_{\rm amC} \approx 0.06\ \mu$m.

We list in Table 1 the DPRs of the C-rich sources obtained by adopting two different optical data sets by Rouleau & Martin (1991); Zubko et al. (1996) with grain size $\approx$ 0.06 μm. From the comparison between the results of two data sets, we notice that the total DPR computed with Rouleau & Martin (1991) is twice the DPR obtained with Zubko et al. (1996).

By comparing the results of our investigations with other in the literature, we find that the DPR computed by Boyer et al. (2012); Srinivasan et al. (2016), with the optical data set by Zubko et al. (1996), is about three times lower than the one obtained by our approach. On the other hand, the DPR estimated by Matsuura et al. (2013) is in good agreement with our findings for the same choice of the optical data set (Rouleau & Martin, 1991). The differences between our DPR and the one by Boyer et al. (2012); Srinivasan et al. (2016) can be due to their underlying assumptions related to the dust-to-gas ratio and expansion velocity, which scales with the stellar luminosity and with the dust-to-gas ratio. This difference was already pointed out by Srinivasan et al. (2016) when comparing their results with the ones by Matsuura et al. (2013). The difference between our DPR and the ones by Boyer et al. (2012); Srinivasan et al. (2016) can be also partly due to different assumptions related to the grain size distribution.

4. Summary and conclusions

We build the first grid of dusty models which employs a physical grounded description of the dust growth process, coupled with a stationary outflow, as a function of the stellar parameters (Nanni et al., 2013, 2014, 2016). Using such a grid, we find the best fit of ≈2000 carbon-rich stars in the SMC and their total DPR. The total DPR is dependent on the carbon dust optical data set selected and it varies by factor of ≈ 2 for the two optical data sets here presented (Rouleau & Martin, 1991; Zubko et al., 1996).

By comparing our DPR with the works by Boyer et al. (2012); Srinivasan et al. (2016), we find that their assumptions related to the dust-to-gas ratio, outflow expansion velocity and grain size distribution, yield a DPR three times lower than the one obtained from our analysis, for the same optical data sets of carbon dust (Zubko et al., 1996). On the other hand, the DPR by Matsuura et al. (2013) is in good agreement with ours for the same optical data set of carbon dust (Rouleau & Martin, 1991).

Acknowledgements. This work was supported by the ERC Consolidator Grant funding scheme (*project STARKEY*, G.A. n. 615604).

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