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Modelling a set of C-rich AGB stars: the cases of RU Vir and R Lep

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Abstract. We study the atmospheres of a set of carbon-rich asymptotic giant branch AGB stars to improve our understanding of the dynamic processes happening there. We compare in a systematic way spectrometric, photometric and mid-infrared (VLTI/MIDI) interferometric measurements with different types of model atmospheres: (1) hydrostatic models + MOD-dusty models added a posteriori; (2) self-consistent dynamic model atmospheres. These allow us to interpret in a coherent way the dynamic behavior of gas and dust. The results underline that the joint use of different kinds of observations, as photometry, spectroscopy and interferometry, is essential for understanding the atmospheres of pulsating C-rich AGB stars. For our first target, the carbon-rich Mira star RU Vir, the dynamic model atmospheres fit well the ISO/SWS spectrum in the wavelength range λ = [2.9, 13.0] μm. However, the object turned out to be somehow "peculiar". The other target we present is R Lep. Here the agreement between models and observations is much better although the MIDI data at 11.4 μm cannot be properly modelled.

Key words. instrumentation: high angular resolution – techniques: interferometric – stars: AGB and post-AGB – stars: atmospheres – stars: circumstellar matter – stars: fundamental parameters

1. Introduction

Stars with initial masses from about 0.8 to 8.0 $M_{\odot}$ undergo the asymptotic giant branch (AGB) phase in their evolution (Habing & Olofsson 2003). In those objects the third dredge-up can change the chemistry from oxygen-rich to carbon-rich (Iben & Renzini 1983). Carbon stars contribute significantly to the total flux emitted by galaxies containing populations of young/intermediate ages. This underlines the importance of taking into account C-rich AGB stars in models of galaxies. Therefore the study of C-rich AGB stars atmospheres is essential in the broader context of galaxy evolution.

Several important processes are taking place in the atmospheres of C-rich AGB stars like the formation of dust and molecules, mass loss via strong stellar winds, or the strong interplay between pulsation and atmospheric structure.

While at the early stages of C-rich AGB stars, when the pulsation is not pronounced, static models agree with the observations (Aringer et al. 2009), time-dependent processes become more important as the star evolves. The atmosphere expands and shock waves propagate through it. Those dynamic processes need to be taken into consideration via proper modelling, therefore dynamic model atmospheres (DMA) are required (e.g. Bowen 1988; Fleischer et al. 1992; Höefner & Dorfi 1997; Höfner et al. 2003).

This work demonstrates that the combined use of different kind of observations, as photometry, spectroscopy and interferometry, is crucial to determine the stratification of the atmospheres of those stars.

2. Observations

We combine three different types of observations: photometry, spectroscopy and interferometry.

We used published photometric data in the *B*, *V*, *R*, *I*, *J*, *H*, *K* bands. Additionally, *L*, *M*, *N*1, *N*2, *N*3 and IRAS photometry at 12 μm were used for R Lep.

Also, for both stars presented in this work, ISO/SWS spectra ($\lambda = [2.4, 25.0]$ μm, de Graauw et al. 1996) are available, and R Lep has also an IRTF spectrum (Rayner et al. 2009) that covers the wavelength range $\lambda = [0.8, 5.0]\,\mu$m.

Interferometric observations obtained with the MIDI instrument at the ESO Very Large Telescope Interferometer (Leinert et al. 2003) were used for both stars. MIDI provides spectrally resolved visibilities, photometry and differential phases in the *N* band (λ = [813]μm).

3. Modelling

For the aim of comparing the data to the models, we used DMAs from Mattsson et al. (2010) and model spectra from Eriksson et al. (2014). Those models are the result of solving the system of equations for hydrodynamics, frequency-dependent and spherically symmetric radiative transfer, plus a set of equations for the time-dependent dust grain formation, growth, and evaporation.

The DMAs start from initial hydrostatic structures. Then, the stellar pulsation is described by a "piston", i.e. a variable inner boundary below the stellar photosphere, and the dust formation (only amorphous carbon) is treated with the "method of moments" (Gauger et al. 1990; Gail & Sedlmayr 1988).

With the COMA code (Aringer 2000; Aringer et al. 2009) SiC dust is added a posteriori by dividing the condensed material from the model into 90% amorphous carbon using data from Rouleau & Martin (1991) and 10% silicon carbide based on Pegourie (1988).

3.1. RU Vir

RU Vir is a C-rich AGB variable of Mira type, with a period of 433.2 days in the *V* band (Samus et al. 2009). Whitelock et al. (2006) estimates a distance of 910 pc. The amplitude in the visual band is 5.2 mag and the average magnitude is 11.6 mag.

Interferometric observations were conducted in 2010 and 2014 with the 1.8-m Auxiliary Telescopes (ATs). The target RU Vir was observed 12 times, with three different baseline configurations: D0-G1, H0-I1 and H0-E0.

For RU Vir we find a discrepancy between the photometric and spectroscopic data and the models. Those differences are especially noticeable in the visible part of the spectral energy distribution (SED) shortward of 2 μm, and beyond 14 μm (see Fig. 1). Also the visibilites vs. baselines show a slight discrepancy for long wavelengths. Please refer to Rau et al. (2015) for a detailed description of the data used, the modelling and results found for RU Vir.

3.2. R Lep

Other targets were analyzed to check whether the differences in the SED and visibilities between DMAs and observations are found only in RU Vir or is a general characteristic.

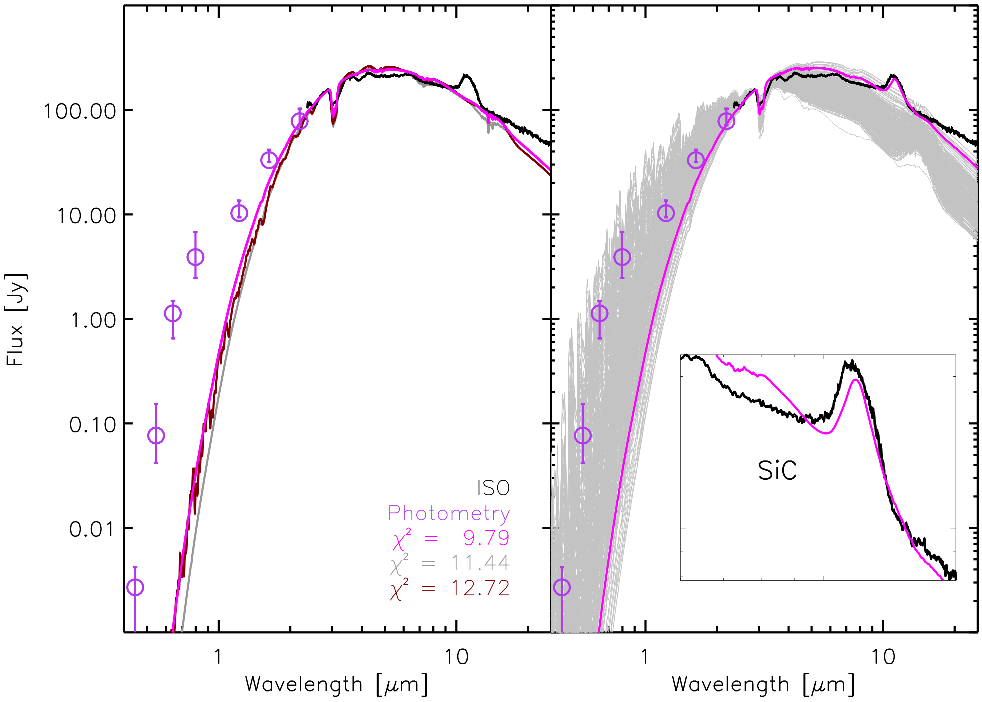

Fig. 1. Left: Observational data (ISO spectrum in black line and photometry in violet circles), compared with synthetic spectra of the three best fitting time-steps (belonging to different DMA). Right: Best fitting time-step (pink) compared with ISO (black). The gray lines are the various other phases (time-steps) of the same model.

We report here on the C-rich Mira star R Lep. It has a period of 427 days in the *V* band. An estimate of the distance of 470 pc is given by Whitelock et al. (2006). The amplitude in the visual band is 6.2 mag and the average magnitude is 8.6 mag. R Lep was observed 10 times with MIDI, with four different baseline configurations: D0-A1, D0-B2, H0-I1 and A1-G1.

In R Lep the discrepancy between observed photometry and DMAs is significantly less prominent than in RU Vir. As to the interferometric observations (see Fig. 2), there is a rather good agreement at 8.5 μm, while at 11.4 μm the models are not able to reproduce the shape of the data well. In fact, the shape of the data at the two wavelengths is very similar. The main difference in the models between the two wavelengths is in the flux ratio between the shells seen in the intensity profiles. In general, we note that the overall structure of the dust beyond 10 μm is not correct in the models. This leads to the conclusion that the distribution of the dust opacities could be wrong.

A detailed description of the results can be found in Rau et al. (in prep), together with an extensive comparison between DMA and observations for a larger sample of C-rich Miras.

4. Conclusions

The joint use of different observational methods and a comparison with models is essential to achieve a full understanding of the atmospheres of AGB stars.

The shape of the SED in most of the ISO range can be well reproduced in both stars discussed here, some discrepancies re-

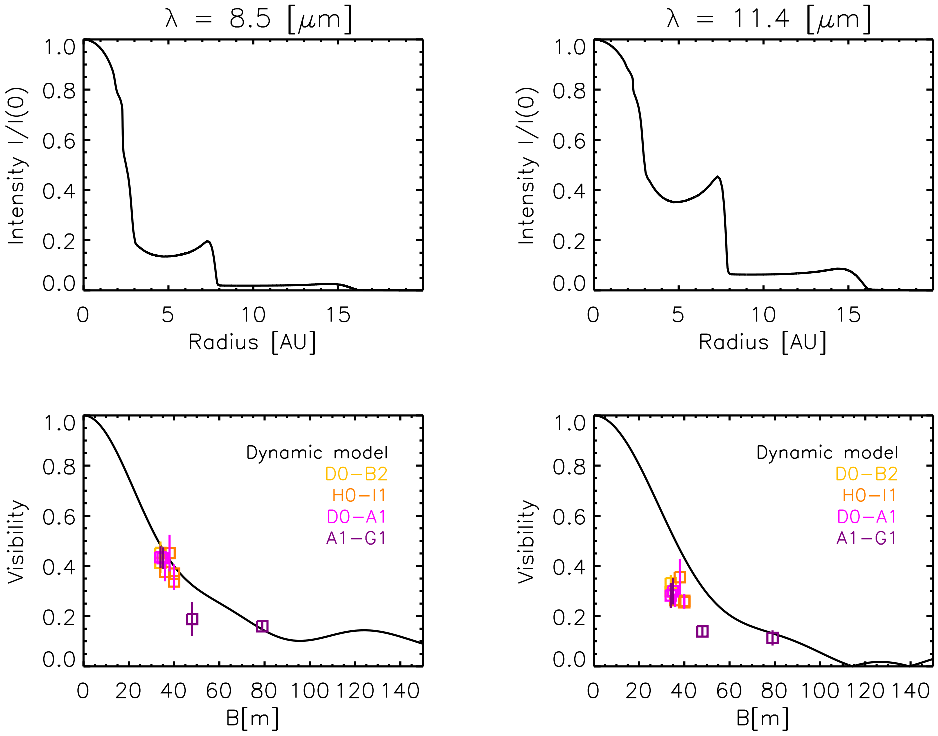

Fig. 2. Comparison of interferometric observational data for R Lep with the results from dynamic model atmospheres. **Upper panel**: intensity profiles at two different wavelengths: 8.5 μm and 11.4 μm. **Lower panel**: visibilities vs. baseline. The black line shows the dynamic model. Colored symbols stand for the MIDI measurements at different baselines configurations.

main shortward of 2 μm and longward of 14 μm. Concerning the interferometric data, a discrepancy was also observed, both in the shape and level of the visibilities versus baseline. Some of the differences might be explained by a combination of intra- and inter-cycle differences as the observations have been taken over many pulsation cycles and both the star and the best fitting DMA show inter-cycle variations. For RU Vir another possible explanation could be a decrease in mass loss over the last few hundred years or a sub-stellar companion associated with a dusty disk. However, those last scenarios are not considered to be very likely given the available observational evidences.

We will extend the comparison between models and observations to a larger sample of C-rich Mira variables (Rau et al., in prep.), in order to provide the general characteristics of the atmospheres of these stars and to provide further constraints for the DMAs.

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