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VLTI/AMBER studies of the atmospheric structure and fundamental parameters of red giant and supergiant stars

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Abstract. We present recent near-IR interferometric studies of red giant and supergiant stars, which are aimed at obtaining information on the structure of the atmospheric layers and at constraining the fundamental parameters of these objects.

The observed visibilities of the red supergiants (RSGs) and also of one red giant indicate large extensions of the molecular layers, as those previously observed for Mira stars. These extensions are not predicted by hydrostatic PHOENIX model atmospheres, hydrodynamical (RHD) simulations of stellar convection, or self-excited pulsation models. All these models based on parameters of RSGs lead to atmospheric structures that are too compact compared to our observations. We discuss how alternative processes might explain the atmospheric extensions for these objects.

As the continuum appears to be largely free of contamination by molecular layers, we can estimate reliable angular Rosseland radii of our stars. Together with distances and bolometric fluxes, we estimate the effective temperatures and luminosities of our targets, locate them in the HR diagram, and compare their positions to recent evolutionary tracks.

1. Introduction

The motivations for this study are principally two: first, to improve our understanding of the circumstellar environment of asymptotic giant branch stars (AGBs) and of red supergiants stars (RSGs) close to the photosphere, to obtain their fundamental parameters, and to locate them in the Herzsprung-Russel (HR) diagram; and second, to understand the mechanisms that levitate the extended atmospheres of RSGs.

Recent studies with VLTI/AMBER have shown the structure of the molecular distribution in AGB stars (Wittkowski et al. 2008, 2011; Martí-Vidal et al. 2011). In particular, Martí-Vidal et al. (2011) found that the apparent size of RS Cap increased around 12% in the CO band (2.29-2.47 μm). They also showed that the MARCS models (Gustafsson et al. 2008) did not fit the visibilities in CO band. However, when they added an *ad hoc* spherical water envelope around the star (Perrin et al. 2004), the synthetic visibilities fitted well the observations in the CO bands.

For RSGs, interferometric observations showed that the continuum photosphere can be well described by a limb-darkened disk (Perrin et al. 2004; Ohnaka et al. 2011). These and other studies also suggest the presence of extended CO and water layers, which cannot be explained by hydrostatic models (Perrin et al. 2005; Ohnaka et al. 2011; Wittkowski et al. 2012). Additionally, Cruzalèbes et al. (2013) observed sixteen red giants and supergiants with VLTI/AMBER. They used MARCS models to fit their data and to estimate the angular diameters. Also, spectrophotometric observations compared to MARCS models caused a dramatic revision of the location of RSGs in the HR diagram (Levesque et al. 2005; Massey et al. 2006).

Interferometric observations of Mira variable stars show evidence of molecular layers lying above the photosphere (Perrin et al. 2004; Wittkowski et al. 2008, 2011), which can be explained by dynamic models (Ireland et al. 2004a,b, 2008, 2011). Interestingly, Chiavassa et al. (2010) showed that the red supergiant VX Sgr can be fit well with 1-d dynamical models of Miras atmospheres (M18 series, Ireland et al. 2004a), although its expected fundamental parameters are different than those of Mira stars.

2. Our observations and results

In our project, we have observed five red giants (Arroyo-Torres et al. 2014) and six supergiants (Arroyo-Torres et al. 2013, in prep.) stars with the ESO Very Large Telescope Interferometer (VLTI), using three of the Auxiliary Telescopes (AT) of 1.8 m diameter. We used the Astronomical Multi-BEam combineR (AMBER) in medium resolution mode (R $\sim$ 1500) in K band (1.9 μm - 2.5 μm) with the external fringe tracker FINITO (Petrov et al. 2007). Visibility and closure phase values were obtained from AMBER data using the latest version of the amdlib data reduction package (Tatulli et al. 2007; Chelli et al. 2009). After that, using our scripts in IDL (Interactive Data Language), we performed the absolute wavelength, relative flux, and visibility calibration.

The normalized flux spectra are typical for red giant and supergiant stars. We observe a decreasing flux longwards of 2.25 μm and strong absorption lines of CO. The

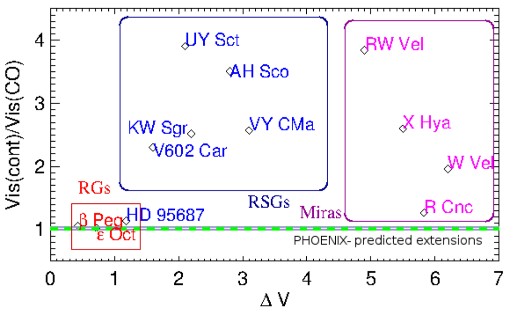

Figure 1. Atmospheric extensions in the CO (2-0) line at 2.29 μm, measured as the ratio of the visibilities in the nearby continuum and in the line, versus the variability amplitude. Notice the different loci of RG, RSG, and Mira stars.

synthetic spectra of PHOENIX models agree well with our spectra at all wavelengths. This indicates that the opacities of CO lines are well reproduced by the PHOENIX models.

The visibility curves of the RSGs and β Peg show a decrease at the water bands (not in all RSGs) and at the CO bandheads, which are not reproduced by the PHOENIX models. This shows that in the models the extension of these molecular layers are too compact compared to our observations. However, the visibility curves of red giants and of HD 183589 (initially classified as RSG) do not show this drop in the CO lines; therefore these sources have a compact atmospheric structure and the CO layers are located close to the continuum-forming layers. In all cases (RSGs and RGs), the continuum visibility values are consistent with a limb-darkened disk, and thus, we can estimate the angular diameters from fits with PHOENIX models to this region. The angular diameter, obtained in this way, corresponds to the outermost layer (zero intensity) of the model. To estimate the Rosseland angular diameter, we multiplied this value by the ratio between the Rosseland layer and the outermost model layer.

For RSGs, the uniform disk diameter calculated from our data as a function of wavelength is constant in the continuum, and increases in the H_2O and CO bands. In the CO bands the increase is between 25% and 65% with respect to the continuum, while the PHOENIX models predict UD size increases below 5%. These results indicate that these stars have a larger contribution from extended atmospheric layers than predicted by the PHOENIX models. The data of β Peg show a layer (possibly of water) that is not reproduced by the PHOENIX model, but the CO bands have a size increase ($\sim$ 5%) similar to those modeled with PHOENIX. In the cases of red giants and HD 183589, we observe that the uniform disk diameter is constant across the band, i.e. these sources do not show extended atmospheric layers.

As a simple characterization of the observed extensions of the CO layers, we use the ratio of the observed visibilities in the continuum band (average between 2.27 μm and 2.28 μm) and the first CO line at 2.29 μm (Arroyo-Torres et al. in prep.). Since this ratio depends on the height of the continuum visibility, we limited the study to continuum squared visibilities between 0.2 and 0.5, a range where the visibility function is nearly linear. In the left of figure 1, we show the obtained values for our sample of red supergiants (Wittkowski et al. 2012; Arroyo-Torres et al. 2013, in prep.), red giants (Arroyo-Torres et al. 2014) and a sample of Mira stars (Wittkowski et al. 2011) versus the variability amplitude. We observe that the giant stars (red) do not show extended CO layers; they are consistent with the PHOENIX models. In contrast, the RSGs (blue) and Mira stars (pink) show a more extended CO layer. The RSG and Mira stars show similar atmospheric extensions. On the other hand, if we consider only the RSGs, we observe an increasing atmospheric extension with increasing luminosity and with decreasing surface gravity (Arroyo-Torres et al. in prep.). We do not observe this correlation in the Mira stars, which could indicate that the extended atmospheric layers are produced by different processes in both types of stars.

With the effective temperature and the luminosity calculated from the Rosseland angular diameter, the bolometric flux, and the distance, we locate our targets in the HR diagram with the evolutionary tracks from Ekström et al. (2012). The RSGs are consistent with the red limits of the Ekström evolutionary tracks, but the red giants are located to the right of these evolutionary tracks. On the other hand, the location of these stars in the HR diagram is consistent with the STAREVOL evolutionary models (Lagarde et al. 2012). The main differences between both models are the assumed mixing length and thermohaline mixing.

3. Comparisons to convection and pulsation models

In the following, we discuss physical mechanisms that could explain the observed large extensions of RSGs.

First, we discuss the photospheric convection as possible mechanism to levitate the atmospheres to radii where dust can form (Arroyo-Torres et al. in prep.). In order to do this, we compare our visibility data of RSGs to 3-d radiative hydro-dynamical (RHD) simulations of stellar convection computed with CO^5BOLD (Freytag et al. 2012) and presented in Chiavassa et al. (2011). We use the pure-LTE radiative transfer *Optim3D* (Chiavassa et al. 2009) to compute intensity maps from these simulations at the same wavelength of related observations. We observe that the intensity in the CO line is lower by a factor 2 compared to the intensity in the continuum, which is consistent with our flux spectra. On the other hand, the CO line surface is about 7% more extended than the continuum surface. However, when we compare our visibility data, the best-fit PHOENIX model, and the RHD simulation, we see that the synthetic visibilities of the 3-d RHD simulation are very similar to the hydrostatic PHOENIX model at the AMBER resolution and can thus not explain our observations.

Another possible mechanism is self-excited pulsation. The CODEX dynamic models based on this mechanism have been successful in describing the interferometric observations of Miras (Ireland et al. 2008, 2011). The observed visibility spectra of our RSGs show similar features in the CO bands as those of Mira stars. We note that such a model can provide a good fit to our data, even though the stellar parameters and the variability amplitudes of RSGs are different to those of Mira stars. We have therefore calculated a pulsation model with typical parameters of RSGs (Arroyo-Torres et al. in prep.). In this model, the amplitude of the photospheric radius variation is about 10% with radial velocities of up to about 5 km/s, which reproduces the amplitude of the visual lightcurve of V602 Car and typical observed long-term velocities. Whilst shock fronts enter the stellar atmosphere in a typical CODEX model of a Mira variable at or below optical depth one, leading to a geometric extension of the stellar atmosphere of the order a few Rosseland radii, it turns out that no shock fronts reach at any phase the atmospheric layers in case of the RSG model. Consequently, this model leads to compact atmospheres with extension similar to those of the PHOENIX and RHD models, and can thus not explain either the observed extensions of the molecular layers.

On the other hand, we speculate that other processes, that are not yet included in the theoretical models, could contribute to the mass-loss. These processes could be radiation pressure on Doppler-shifted molecular lines, magnetic fields, and/or dust grains forming at a few stellar radii.

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