New windows on massive stars: asteroseismology, interferometry, and spectropolarimetry
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On the atmospheric structure and fundamental parameters of red supergiants

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Abstract. We present near-infrared spectro-interferometric studies of red supergiant (RSG) stars using the VLTI/AMBER instrument, which are compared to previously obtained similar observations of AGB stars. Our observations indicate spatially extended atmospheric molecular layers of water vapor and CO, similar as previously observed for Mira stars. Data of VY CMa indicate that the molecular layers are asymmetric, possibly clumpy. Thanks to the spectro-interferometric capabilities of the VLTI/AMBER instrument, we can isolate continuum bandpasses, estimate fundamental parameters of our sources, locate them in the HR diagram, and compare their positions to recent evolutionary tracks. For the example of VY CMa, this puts it close to evolutionary tracks of initial mass $25-32\,M_{\odot}$. Comparisons of our data to hydrostatic model atmospheres, 3d simulations of convection, and 1d dynamic model atmospheres based on self-excited pulsation models indicate that none of these models can presently explain the observed atmospheric extensions for RSGs. The mechanism that levitates the atmospheres of red supergiant is thus a currently unsolved problem.

Keywords. convection, techniques: interferometric, stars: atmospheres, stars: evolution, stars: fundamental parameters, stars: individual (VY CMa, KW Sgr, UY Sct, AH Sco, V602 Car, HD 95687), stars: mass loss, supergiants

1. Introduction

Asymptotic giant branch (AGB) and red supergiant (RSG) stars are located in the Hertzsprung-Russell-Diagram (HRD) at cool effective temperatures between about 2500 K and 4500 K and cover a large range of luminosities depending on their initial mass. Levesque *et al.* (2005) showed that observed HRD positions of RSGs are not as cool as previously thought and that they are consistent with the red edge of stellar evolutionary tracks.

Due to the low temperatures of AGB and RSG stars, molecules and dust can form, and are subsequently expelled into the insterstellar medium via a stellar wind with widely overlapping mass-loss rates of $(4\cdot10^{-8}-8\cdot10^{-5})\,M_{\odot}/\mathrm{yr}$ (AGB stars) and $(2\cdot10^{-7}-3\cdot10^{-4})\,M_{\odot}/\mathrm{yr}$ (RSGs) (De Beck *et al.* 2010). The mechanism for this mass-loss process has been established for carbon-rich AGB stars (e.g.; Wachter *et al.* 2002; Mattsson *et al.*

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2010), but are less well understood for oxygen-rich AGB stars (Woitke 2006; Höfner 2008; Bladh *et al.* 2013) and even less for RSGs (Josselin & Plez 2007). Both AGB stars and RSGs are affected by pulsation and convection. Variable RSGs have pulsation amplitudes of about 3 times less than AGB stars (Wood *et al.* 1983).

Interferometry is well suited to provide direct measurements of angular diameters of AGB and RSG stars, to directly estimate their effective temperatures based on measured angular diameters and measured bolometric fluxes, to constrain the stratification of their atmospheres and of molecular layers, and to probe surface inhomogeneities. Most powerful is the technique of spectro-interferometry, which allows us to separate continuum and molecular bands. For instance, Perrin *et al.* (2004, 2005) used narrow-band interferometry at the IOTA interferometer to confirm the ”molecular layer scenario” for AGB and RSG stars, respectively.

2. AGB stars

Spectro-interferometry using the VLTI/AMBER instrument has proven to be a very powerful tool to study the atmospheres and close molecular layers of AGB stars, starting with the observations of the Mira S Ori by Wittkowski *et al.* (2008). The spectro-interferometric capabilities of AMBER allow us to observe the source at near-continuum and molecular bands simultaneously, resulting in a diagnostic curve of visibility versus wavelength. This curve shows a “bumpy” shape, which is a signature of the presence of molecular layers lying above the atmosphere: At near-continuum wavelengths, the molecular opacity is low, the target appears relatively small, and the observed visibilities are relatively high. At other wavelengths, the molecular opacity –in the near-IR range most importantly of water vapor and CO– is larger, the target appears larger, and the visibilities are smaller. For comparison, cool giants on the first giant branch that do not exhibit extensions of molecular layers, have a smooth curve of visibility versus wavelength.

Follow-up observations of a number of Miras using the medium spectral resolution mode of AMBER by Wittkowski *et al.* (2011) as well as studies by Woodruff *et al.* (2009) and Hillen *et al.* (2012) showed that observed visibilities are well consistent with predictions by the latest 1d dynamic model atmosphere series based on self-excited pulsation models of oxygen-rich Mira (`CODEX` models, Ireland *et al.* 2008, 2011). Closure phase data show deviations from point symmetry in molecular bands, possibly caused by clumpy extended molecular layers, but which affect the visibility moduli by less than a few percent. Best-fit parameters based on the `CODEX` models are consistent with independent estimates. In the dynamic model atmospheres, shock fronts reach the atmospheric layers, which leads to a geometric extension of the atmosphere of a few stellar radii.

3. The red supergiant VY CMa

The parameters of the red supergiant VY CMa have been controversially discussed during the last decade with effective temperatures between 2700 K and 3650 K, radii between 600 $R_\odot$ and 3000 $R_\odot$, and initial masses between 12 $M_\odot$ and 40 $M_\odot$. A previous interferometric angular diameter was obtained with a broad filter in the K-band (Monnier *et al.* 2004), which may be contaminated by molecular and dusty circumstellar emission.

Wittkowski *et al.* (2012) observed VY CMa with the VLTI/AMBER instrument using the low and medium spectral resolution modes. The visibility data at low spectral resolution indicate again a ”bumpy” curve, resembling those of Miras as discussed above in Sect. 2, which is indicative of atmospheric layers of CO and H_2O. The closure phases,

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which are indicative of deviations from point symmetry, show small deviations from symmetry near the near-continuum bandpass at 2.25 μm and strong asymmetries in the CO and H_2O bands. Medium resolution data show in addition the presence of strong CO bandheads in the flux and visibility spectra. A comparison with hydrostatic `PHOENIX` model atmospheres shows that molecular features of water vapor and CO are consistent with the `PHOENIX` models in the integrated *flux* spectra, but these models do not reproduce the strong observed features in the *visibility* spectra. This means that, though molecular opacities are included in these model atmospheres, they are clearly too compact compared to our observations.

However, although molecular layers are observed at certain bandpasses, we could also separate two near-continuum bandpasses around 1.7 μm (in the H-band) and 2.25 μm (in the K-band) that are little contaminated by molecular emission. The visibility curves versus spatial frequency reach up to the first minimum of the visibility function and beyond, and are consistent with a UD or a `PHOENIX` atmosphere model. They give consistently a Rosseland angular diameter of 11.3±0.3 mas. Together with the recently improved distance estimate to VY CMa and the well probed bolometric flux, this interferometric measurement corresponds to a Rosseland radius of $1420 \pm 120\, R_\odot$, an effective temperature of 3490 ± 90 K and a luminosity of $(2.7 \pm 0.4) \cdot 10^5\, L_\odot$.

Compared to the ranges discussed above, this places VY CMa near the larger effective temperature of 3650 K by Massey *et al.* (2006), but with a radius twice as large as that of Massey *et al.* and at the same time less than half as large as the largest radii discussed so far. The luminosity estimate is improved by the improved distance. With these values, VY CMa is confirmed to be located close to the red limit of evolutionary tracks of initial masses $25 \pm 10\, M_\odot$.

4. More red supergiants

Arroyo-Torres *et al.* (2013) and Arroyo-Torres *et al.* (in prep.) used the VLTI/AMBER instrument in a similar way to observe a larger sample of red supergiants covering cool spectral types between M3 and M4–5, including AH Sco (M4–5), UY Sct (M4), KW Sgr(M4), V602 Car (M3), and HD 95687 (M3). These sources show CO features in their flux spectra that are consistent with synthetic spectra based on `PHOENIX` models. However, as in the case of VY CMa, all of these sources also show much stronger drops of the visibility in the CO bandheads than predicted by the `PHOENIX` models. This confirms for a larger sample of RSGs that, though the opacities of CO are included in the `PHOENIX` models, the CO layers are observed to be much more geometrically extended than predicted. Some of these sources also show indications of geometrically extended layers of water vapor. Uniform disk diameters in the water band are increased by up to 25% and in the CO band-heads by up to 50%.

As a simple characterization of the observed extensions of the CO layers, Arroyo-Torres *et al.* (in prep.) computed the ratio of the observed visibilities in the near-continuum band just before the first CO bandhead (average between 2.27 μm and 2.28 μm) and in the first (2-0) CO line at 2.29 μm. Figure 1 shows the obtained values for red supergiants compared to those of Miras (Wittkowski *et al.* 2011) and red giants (Arroyo-Torres *et al.* 2014). For the red giants, the ratio is close to unity and consistent with the PHOENIX model atmospheres. The RSGs and Miras show similar ratios that lie significantly above unity. This illustrates that these sources show similarly large extensions of the CO layer, which are not predicted by the hydrostatic `PHOENIX` models. Furthermore, Fig. 1 suggests a correlation between the visibility ratio of our RSGs and the luminosity, contrary to the Miras. This may suggest that, unlike for Miras, RSGs develop large atmospheric

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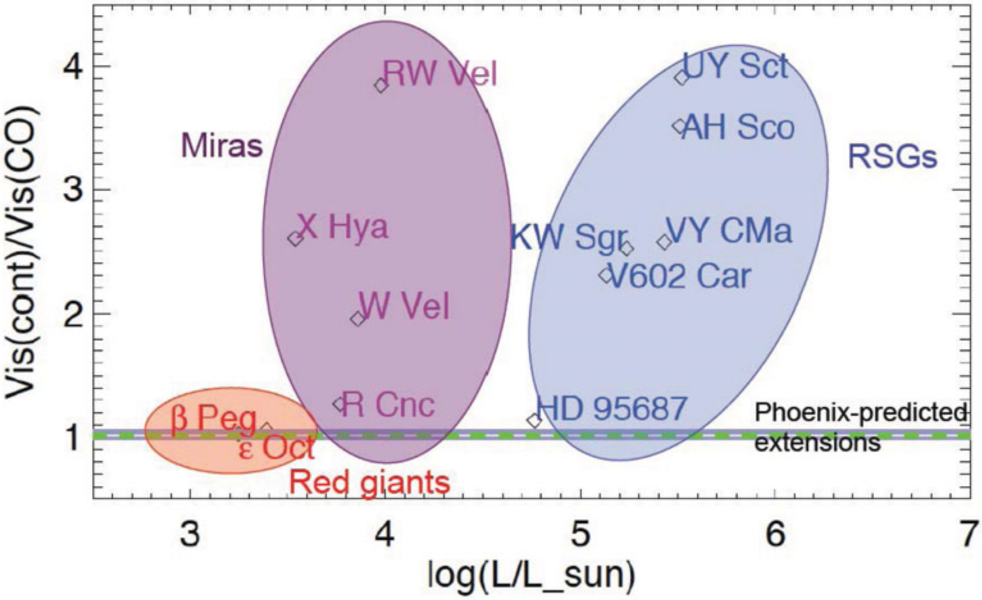

Figure 1. Atmospheric extensions in the CO 2-0 line at 2.29 μm, measures as the ratio of the visibilities in the nearby continuum and in the line, versus luminosity. Shown are red giants, Miras, and red supergiants of our sample.

extensions only for high luminosities of above about $10^5\ L_\odot$ and that a radiatively driven process might (partly) explain their atmospheric extensions.

5. Comparisons to 1d pulsation and 3d convection models

In the case of Miras, `CODEX` dynamic model atmospheres based on self-excited pulsation models have been successful to describe interferometric observations, in particular their extended atmospheric molecular layers (cf. Sect. 2). As the observed visibility spectra and atmospheric extensions of our sample of RSGs are similar to those of Miras (Sect. 4), one may speculate whether similar models could also explain the atmospheric extensions of RSGs despite the different fundamental parameters. Doubts have been expressed because of the lower variability of RSGs compared to Miras (Josselin & Plez 2007), but a detailed study of pulsation models for RSGs has not yet been available. Indeed, variability amplitudes of variable RSGs are typically lower by a factor of 2-3 compared to Miras (Wood *et al.* 1983). Arroyo-Torres *et al.* (in prep) calculated a pulsation model based on stellar parameters that are typical for an RSG star and in particular similar to those of V602 Car of our sample. The amplitude of the photospheric radius variation was 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 1, leading to a geometric extension of the stellar atmosphere of the order a few Rosseland radii, it turned out that no shock fronts reach at any phase the atmospheric layers in case of the RSG model. As a result, the model produces a compact atmosphere with extensions similar to those of the hydrostatic `PHOENIX` models.

Photospheric convection has been discussed as a possible explanation of high velocities on short time scales that were observed in atmospheres of RSGs (Gray 2000), and possibly as a mechanism to levitate the atmospheres to radii where dust can form. Arroyo-Torres

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(in prep) thus compared the visibility data of RSGs to 3d radiative hydro-dynamical (RHD) simulations of stellar convection. We used two simulations (st35gm03n07, st35gm03n13) from Chiavassa *et al.* (2011) and references therein. These models take into account the Doppler shifts occurring due to convective motions. Using the method explained in detail in Chiavassa *et al.* (2009) we computed azimuthally averaged intensity profiles and averaged the monochromatic intensity profiles to match the spectral channels of the individual observations. The resulting intensity profiles show that the intensity in the CO bandhead is lower by a factor of about 2 compared to the intensity in the continuum, which is consistent with observed flux spectra. The detailed surface structure in the CO line intensity map appears less corrugated and the details such as intergranular lanes almost disappear. The CO line surface is slightly more extended, but only by few percent (7%, estimated at the 0% intensity radius). The model-predicted visibility curves of the 3d RHD simulation are very similar to those of the hydrostatic `PHOENIX` models at the AMBER resolution. This means that also these can not explain the large observed atmospheric extensions of RSG stars.

In summary, comparisons of our RSG data to hydrostatic model atmospheres, 1d dynamic model atmospheres based on self-excited pulsation models, and 3d simulations of convection can all not explain the observed large atmospheric extensions of red supergiants. The mechanism that levitates the atmospheres of red supergiant is thus a currently unsolved problem. The observed correlation of atmospheric extension with luminosity may hint toward a radiatively driven levitation process as suggested by Josselin & Plez (2007).

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Discussion

Arnett: Are the pulsation simulations 1d and the radiative-hydrodynamics simulations 3d? Are the 3d simulations sufficiently resolved?

Wittkowski: The pulsation model that I showed is 1d. The 3d RHD simulations in principle include pulsations if these are excited. They are small for RSG stars and larger for AGB stars. It would be interesting to inject the velocities from the 1d pulsation model into the 3d RHD model as an initial condition. The resolution of the 3d models is still limited. We clearly should try to go for a better resolution of the RSG models. However, we presently do not expect the atmospheric velocity fields (due to convection and pulsation alone) to grow enough to remotely reach the amplitude necessary to give a molsphere extension of a few stellar radii as observed.

Puls: You argued that the extension might be related to a wind. Have you checked whether with typical mass-loss rates the wind can reach a typical optical depth of unity around the sonic point?

Wittkowski: We have not yet checked this, but it would be interesting to calculate.

Meynet: Just a comment. Actually, the position in the HRD of red giants and supergiants depends, among other things, on the value of the mixing length. For a given physics, changing ℓ/H_P will move to redder (lower value) or hotter values (higher values) allowing to fit observed positions. So a good fit can actually be obtained by a given choice of this free parameter.

Wittkowski: Thank you for the comment. The Lagarde *et al.* grid fits our positions of red giants in the HRD better than the Ekström *et al.* grid. There might be more differences between these grids than the treatment of thermohaline mixing.

Markus Wittkowski

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