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

B. Arroyo-Torres, M. Wittkowski and J. M. Marcaide


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Introduction

Aims:

We present recent near-IR interferometric studies of red giants 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.

Previous works:

- Cruzalèbes et al. 2013 observed sixteen red giants and supergiants with VLTI/AMBER. They estimate the angular diameters of these sources using MARCS model.
- Interferometric observations of RSGs suggest the presence of extended molecular layers, which cannot be explained for by hydrostatic model atmospheres (Perrin et al. 2004, 2005; Ohnaka et al. 2011, 2013; Wittkowski et al. 2012).
- VX Sgr (Chiavassa et al. 2010) showed a good agreement with the Mira models, although they have very different stellar parameters than expected for this source.
Theoretical models

- **PHOENIX model:**
  - Hauschildt & Baron (1999) – version 16.03
  - This model is based on a hydrostatic atmosphere, local thermodynamic equilibrium and spherical geometry.

- **Optim3D convection model:**
  - The pure-LTE radiative transfer Optim3D (Chiavassa et al. 2009) compute intensity maps from radiative hydrodynamical (RHD) simulations of stellar convection computed with CO$^5$BOLD (Freytag et al. 2012).

- **Pulsation code:**
  - Keller & Wood (2006)
  - We also use the CODEX dynamical model atmosphere based on this code.
Our observations

<table>
<thead>
<tr>
<th>Target (Sp. type)</th>
<th>Date</th>
<th>Baseline</th>
<th>Projected baseline m</th>
<th>PA deg</th>
<th>Calibrator</th>
</tr>
</thead>
<tbody>
<tr>
<td>β Peg (M2.5 II-III)</td>
<td>2012 Jun. 25</td>
<td>D0-A1-C1</td>
<td>30.4/15.6/16.4</td>
<td>-122/76.6/140</td>
<td>HIP 114144 – HIP 1168</td>
</tr>
<tr>
<td>NU Pav (M6 III)</td>
<td>2012 Aug. 02</td>
<td>B2-A1-C1</td>
<td>10.9/15.8/9.8</td>
<td>-70.6/71.6/28.8</td>
<td>HIP 82363</td>
</tr>
<tr>
<td>ψ Peg (M3 III)</td>
<td>2012 Jun. 16</td>
<td>D0-I1-G1</td>
<td>82.1/32.8/66.1</td>
<td>102/–128/124.5</td>
<td>HIP 114144 – HIP 1168</td>
</tr>
<tr>
<td>γ Hya (G8 III)</td>
<td>2013 Mar. 16</td>
<td>A1-G1-J3</td>
<td>74.9/132.2/135.7</td>
<td>118/15.3/47.7</td>
<td>K Hya</td>
</tr>
</tbody>
</table>

Arroyo-Torres et al. (2014)

Arroyo-Torres et al., in prep.

Arroyo-Torres et al. (2013)
Results – V602 Car (RSG)

Arroyo-Torres et al., in prep.
Results – beta Peg (RG)

Arroyo-Torres et al. (2014).
Results – epsilon Oct (RG)

Arroyo-Torres et al. (2014).
RSG and Mira stars have similar atmospheric extensions.

RG stars do not show an extended CO band. They are consistent with the PHOENIX model.

Arroyo-Torres et al., in prep.
The atmospheric extension of RSGs (based on the first CO band) increases with increasing luminosity and decreasing surface gravity.

This correlation is not observed for Miras, pointing to a different physical mechanism.

Considerable extensions are only observed for luminosities above about $10^5 \, L_{\odot}$ and below $\log(g) \sim 0.0$.
Comparison to convection models

The fundamental parameters of the RHD simulation are: $T_{\text{eff}} = 3487 \text{K}$, $\log(g) = -0.335$, $R = 830 R_{\text{sun}}$ and $M = 12M_{\text{sun}}$.

- The intensity in the CO line is lower by a factor $\sim 2$ compared to the intensity in the continuum.
- The CO line surface is slightly more extended than the continuum surface ($\sim 7\%$ at the limb).
- The predicted visibility curves of the RHD simulation are very similar to the PHOENIX model at the AMBER resolution and can thus not explain the large observed atmospheric extension of our sources.

Arroyo-Torres et al., in prep.
Comparison to pulsation model

- The Mira pulsation models (CODEX) describe interferometric observations of our RSG stars, although the stellar parameters are very different and variability amplitudes of RSGs are typically lower by a factor 2-3 compared to Mira.

- The RSG pulsation model leads to an atmosphere as compact as the hydrostatic PHOENIX model, and can not explain the observed atmospheric extensions.

Arroyo-Torres et al., in prep.
Alternative mechanisms

- Velocities higher than those predicted by pulsation models on time scales much shorter than the variability period were shown by Josselin & Plez (2007) and Gray et al. (2008).

- Observed correlation between the atmospheric extension and the luminosity

Hypothesis

Convection motions plus waves generate quite some levitation of the atmosphere by generating shock speeds with Mach numbers of 5 to 8. That give rise to a significant Doppler shift, so that radiation pressure on Doppler-shifted lines could accelerate the material

Reminiscent of what happens in the winds of hot stars
HR diagram

Ekström evolutionary tracks

STAREVOL evolution model

Arroyo-Torres et al., in prep.

Arroyo-Torres et al. (2014)
Conclusions

★ **AMBER spectro-interferometry** is an excellent tool to separate continuum and molecular layers, and to study the atmospheric structure and the fundamental parameters of stars.

★ **The PHOENIX atmosphere models** predict the spectra, but cannot reproduce the large extensions of the molecular layers in the RSGs. However, the RGs (except beta Peg) are consistent with the synthetic visibility, concluding that their atmospheres can be modeled with a limb-darkened disk.

★ **Pulsation models and Optim3D convection model** can not explain the observed molecular extensions. Currently, there is no model simulation that can reproduce the observations.

★ **The observed extended atmospheres** of our RSGs are comparable to those of Mira stars.

★ There is an **observed correlation** of increasing atmospheric extensions with increasing luminosity for RSGs.

★ We speculate that **the radiative pressure on molecules** may be the dominant processes that cause the extended atmospheres.
Thanks