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Precision Monitoring of Cool Evolved Stars: Constraining Effects of Convection and Pulsation

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Mass loss from cool evolved stars is an important ingredient of the cosmic matter cycle, enriching the Universe with newly formed elements and dust. However, physical processes that are not considered in current models represent uncertainties in our general understanding of mass loss. Time-series of interferometric data provide the strongest tests of dynamical processes in the atmospheres of these stars. Here, we present a pilot study of such measurements obtained with the GRAVITY instrument on the Very Large Telescope Interferometer.

Cool evolved stars

Asymptotic giant branch (AGB) and red supergiant (RSG) stars are located in the Hertzsprung–Russell diagram at low effective temperatures (about 2500–4500 K). They are major contributors to the integral luminosity of stellar systems, and they are major sources of the chemical enrichment of galaxies. Owing to the low temperatures, molecules and dust can form in their atmospheres, and are subsequently expelled into the interstellar medium via stellar winds.

Both AGB stars and RSGs are affected by pulsation and convection, but RSGs show lower variability amplitudes than AGB stars. For AGB stars, it has been shown that pulsation and convection lead to strongly extended molecular atmospheres, where the temperature is low enough for dust condensation. Radiation pressure on dust then gives rise to a general mass outflow as the surrounding gas is dragged along through friction (for example, Höfner & Olofsson, 2018).

For RSGs, it has been speculated that the same processes may explain their mass loss. However, Arroyo-Torres et al. (2015) showed that current dynamic model atmospheres of RSGs, based on pulsation and convection alone, cannot explain the observed extensions of RSG atmospheres, or how they can reach distances where dust can form. This points to missing physical processes in current RSG dynamic models. It translates into uncertainties in our general understanding of mass loss, as such processes may to some degree also affect the atmospheric structures of AGB stars and other cool giants.

1D and 3D model atmospheres

Significant advances are being made in the development of dynamic atmosphere models of cool evolved stars. Latest developments include 1D DARWIN (Bladh et al., 2019), and 3D CO5BOLD radiative hydrodynamics (RHD) simulations (Freytag et al., 2017; Höfner & Freytag, 2019). In contrast to existing CO5BOLD and CODEX models, DARWIN models include the wind acceleration region, which affects atmospheric structure and molecular features (Bladh et al., 2013, 2015; Höfner et al., 2016), and may account for some of the previously found discrepancies between AGB star models and interferometric observations. Additional processes that may contribute to larger atmospheric extension in RSG dynamic models include radiation pressure on molecular lines (Josselin & Plez, 2007) or the effects of magnetic fields and Alfvén waves (for example, Airapetian et al., 2010; Cranmer & Saar, 2011; Yasuda & Kozasa, 2019; Rau et al., 2019). Radiative pressure is currently being implemented in global CO5BOLD models. Magneto-hydrodynamical effects can, in principle, be described by CO5BOLD models (Freytag et al., 2012; Steiner et al., 2014), but an application to AGB and RSG stars requires further work.

Pilot study with GRAVITY

Time-series of interferometric observations provide the strongest tests of dynamical processes in the atmospheres of evolved stars, as they spatially resolve the star and provide constraints on different atmospheric layers, following the variability cycle of the star. However, such time-series are still very rare.

Wittkowski et al. (2018) recently conducted a pilot study measuring the variability of the continuum radius and of extended molecular layers for the oxygen-rich Mira star R Peg during science verification and early (P98) science operations, using the newly available near-infrared *K*-band beam combiner GRAVITY (GRAVITY Collaboration, 2017) at the VLTI. This became possible because of the improved performance of the GRAVITY instrument compared to, for example, the Astronomical Multi-BEam combineR (AMBER), with an increased precision in visibilities, data for six baselines in one snapshot, and a spectral resolution of about 4000 across the full *K*-band.

We showed that the continuum size and the size in a bandpass that is dominated by water vapour were anti-correlated with the visual light-curve. The size in the CO (2–0) line instead follows the visual light-curve more closely, indicating a different — possibly more stable — behaviour of CO compared to water vapour (Figure 1). The wavelength-dependent visibility variations could be reproduced by a set of CODEX (Ireland et al., 2008, 2011) dynamic model atmospheres at phases between 0.3 and 0.6. However, we noticed the following issues: (1) best-fit model phases did not correspond well

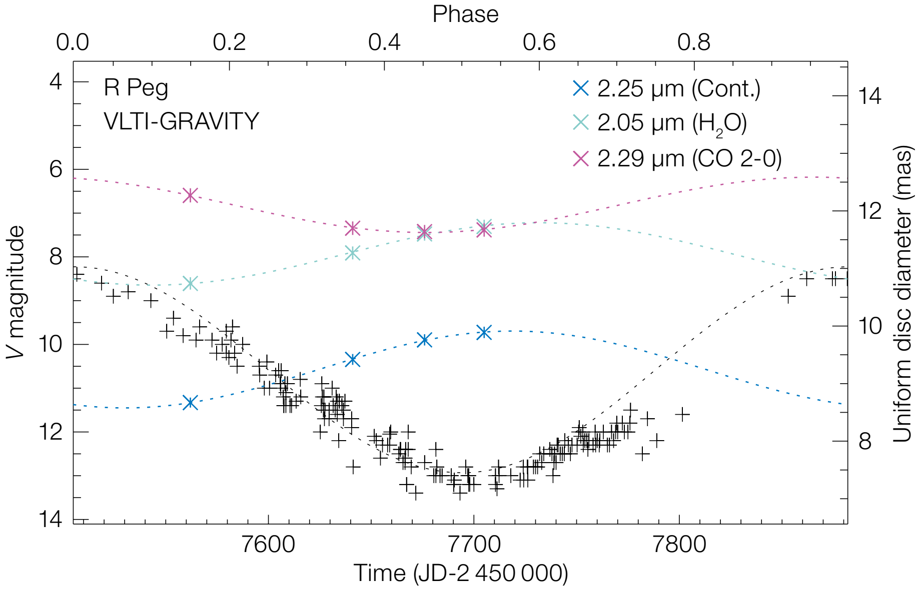

Figure 1. Variability of R Peg in the *V*-band (grey crosses) and of the uniform disc angular diameter in a near-continuum band (blue × symbols), and in bands dominated by H_2O and CO (light blue and pink × symbols, respectively). Also shown are sinusoidal fits in the corresponding colours. The minimum continuum size tracks the maximum light, which can be understood by the increase in effective temperature while the star gets smaller in radius. The minimum contribution of H_2O also tracks the maximum light, which relates to the destruction of water vapour at maximum, and formation at minimum, light. The contribution by CO is, however, largest at maximum light, indicating different, possibly more stable, behaviour compared to H_2O. From Wittkowski et al. (2018).

with observed phases, and (2) the observed amplitude of the continuum radius is 14% — this is smaller than predicted by CODEX model atmospheres (45%–67%), and closer to those predicted by 3D RHD simulations (Freytag et al., 2017). The data covered only four epochs, and more are needed to be meaningfully compared to 3D models, which show strong intra-cycle and cycle-to-cycle irregularities.

Outlook

We plan to extend the GRAVITY pilot study described above to a larger sample of cool evolved stars, and in particular to include a comparison of AGB stars, for which current models successfully predict observed extensions, and RSG stars, for which models and observations show strong discrepancies in this respect. We need a denser and wider phase sampling compared to our plot study, including intra-cycle and cycle-to-cycle variations, to be able to make meaningful comparisons to the latest dynamic models.

We will be able to use more, and better-defined, atmospheric layers compared to our pilot study by applying a tomographic method that relies on spectral masks selecting lines that form in given ranges of optical depths in the stellar atmosphere (Kravchenko et al., 2018, 2019). Combined with spectro-interferometric GRAVITY observations on the VLTI, the tomographic method will permit a simultaneous spectral and spatial characterisation of AGB and RSG star atmospheres. By extracting interferometric visibilities at wavelengths contributing to different masks, we can measure the corresponding geometrical extents of the atmosphere and recover the link between optical and geometrical depth scales.

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Links

[1] GRAVITY Science Verification: https://www.eso.org/sci/activities/vltsv/gravitysv.html

[2] GRAVITY consortium: http://www.mpe.mpg.de/ir/gravity