Why Galaxies Care About AGB Stars: A Continuing Challenge through Cosmic Time
Proceedings IAU Symposium No. 343, 2019
F. Kerschbaum, M. Groenewegen & H. Olofsson, eds.

doi:10.1017/S1743921318007378

Constraining convection across the AGB with high-angular-resolution observations

Claudia Paladini[1], Fabien Baron[2], A. Jorissen[3], J.-B. Le Bouquin[4,5], B. Freytag[6], S. Van Eck[3], M. Wittkowski[7], J. Hron[8], A. Chiavassa[9], J.-P. Berger[10], C. Siopis[3], A. Mayer[8], G. Sadowski[3], K. Kravchenko[3], S. Shetye[3,11], F. Kerschbaum[8], J. Kluska[11] and S. Ramstedt[6]

[1]European Southern Observatory, Alonso de Cordova 3107, Vitacura, Santiago, Chile
email: cpaladin@eso.org

[2]Department of Physics and Astronomy, Georgia State University, PO Box 5060 Atlanta, Georgia 30302-5060, USA

[3]Institut dAstronomie et dAstrophysique, Université libre de Bruxelles, CP 226, 1050 Bruxelles, Belgium

[4]Institut de Planétologie et d'Astrophysique de Grenoble, CNRS, Univ. Grenoble Alpes, France

[5]University of Michigan, 1085 S. University Ave. 303B West Hall Ann Arbor, USA

[6]Department of Physics and Astronomy, Uppsala University, Box 516, 75120 Uppsala, Sweden

[7]European Southern Observatory, Karl-Schwarzschild-Strasse 2, 85748 Garching bei München, Germany

[8]Department of Astrophysics, University of Vienna, Türkenschanzstrasse 17, 1180 Vienna, Austria

[9]Laboratoire Lagrange, UMR 7293, Université de Nice Sophia-Antipolis, CNRS, Observatoire de la Côte dAzur, BP 4229, 06304 Nice Cedex 4, France

[10]Univ. Grenoble Alpes, CNRS, IPAG, 38000 Grenoble, France

[11]Institute for Astronomy, KU Leuven, Celestijnenlaan 200D B2401, B-3001 Leuven, Belgium

Abstract. We present very detailed images of the photosphere of an AGB star obtained with the PIONIER instrument, installed at the Very Large Telescope Interferometer (VLTI). The images show a well defined stellar disc populated by a few convective patterns. Thanks to the high precision of the observations we are able to derive the contrast and granulation horizontal scale of the convective pattern for the first time in a direct way. Such quantities are then compared with scaling relations between granule size, effective temperature, and surface gravity that are predicted by simulations of stellar surface convection.

Keywords. convection, stars: AGB and post-AGB, stars: imaging, stars: mass loss, techniques: high angular resolution, techniques: interferometric

1. Introduction

Convection plays a major role in many astrophysical processes, including energy transport, pulsation, dynamos and winds on evolved stars. Most of our knowledge about stellar convection comes from studying the Sun. Two millions of convective cells are observed on the surface of our star, each one with a size of about 2000 km. Following predictions dating back to the '70, the surface of evolved stars (e.g. the Asymptotic Giant Branch stars, AGB) is expected to be populated by a few large convective cells several tens of thousand times the size of the solar ones. Direct evidence of the presence of such structures has been observed for the red supergiant (RSG) star Betelgeuse with the

Hubble telescope by Gilliland & Dupree (1996), and later with the VLTI by Haubois *et al.* (2009). Asymmetric structures on the surface and in the very inner region of AGB stars have been detected by several authors (Ragland *et al.* 2006, Cruzalèbes *et al.* 2015). The properties of granulation (i.e., size of the cells and contrast) were usually derived via geometric modelling. This method however is degenerate and does not provide information about the physical origin of the convective cells. To observe directly convection on the surface of AGBs one had to wait till 2014, when Monnier *et al.* (2014) imaged for the first time the oxygen-rich mira R Car within the frame of the *Image Beauty Contest 2014*. Few years later, Wittkowski *et al.* (2017) reported the observations of the surface of the carbon semiregular variable R Scl. Observing directly and characterizing convection on the surface of AGB stars is challenging for several reasons. AGB stars are variable, and the observations need to be collected almost simultaneously. This is often not possible because of the limited amount of apertures of the interferometers, and scheduling requirements. AGB stars are smaller than RSGs, and the details of the surfaces can be retrieved only for stars within 600 pc. Most importantly the surface of AGB stars is obscured by dust and molecular opacity, which partially masks the photosphere of the star.

2. The target and the observations

π^1 Gruis is a semiregular variable (SRb) with a Period of 195 days and a parallax of 6.13±0.76 milliarcseconds. The star was observed with several ground and space facilities. It has an effective temperature ($T_{\rm eff}$) of $\sim$3100 K, a mass of 1.5–2 $M_\odot$, a luminosity (L) of $\log(L/L_\odot)\sim 3.86$, and it is close to the tip of the AGB with a mass-loss rate of $2.7\times10^{-6} M_\odot$ yr^{-1} (Mayer *et al.* 2014, and references therein).

We observed π^1 Gruis with the PIONIER instrument (Le Bouquin *et al.* 2011) in September 2014. PIONIER combines the light of 4 telescopes in a coherent way providing visibility and closure phase interferometric measurements. The observations were made in the H-band in low spectral resolution ($R\sim 35$). π^1 Gruis was observed for a total of 1.5 nights using the compact and medium array configuration of the VLTI. The baselines span between 8 and 90 m achieving and angular resolution ($\lambda/2B$) of $\sim$2 mas.

3. Method

We reconstructed 3 independent images, one per each spectral channel (1.625, 1.678, and 1.73 μm), using both the SQUEEZE (Baron *et al.* 2010) and MiRa (Thiebaut 2008). image reconstruction tools. The dusty envelope is transparent in the wavelength range covered by PIONIER. The molecular contribution is mainly due to CO and CN, and the opacity reaches a minimum in the third spectral channel. Both imaging algorithms give a consistent result showing a nearly spherical disc with structures of convective nature on the surface (Fig. 1).

Contrast and typical granulation size were derived from the images after correcting for the limb darkening effect. Such correction was executed using three different masks: (i) a square mask, (ii) a gaussian mask, (iii) an intensity profile from the MARCS model atmosphere (Van Eck *et al.* 2017) that best fits the spectral energy distribution of the star. The results presented here correspond to the ones obtained using the square mask. The other two methods produce similar results, and we refer the reader to Paladini *et al.* (2018) for a detailed discussion. The intensity contrast is estimated as $\Delta I_{\rm rms}/I_{\rm mean}$ following the definition from Wedemeyer *et al.* (2009). To derive the typical granulation size we estimated the spatial power-spectrum density (PSD) from the three images (Fig. 2).

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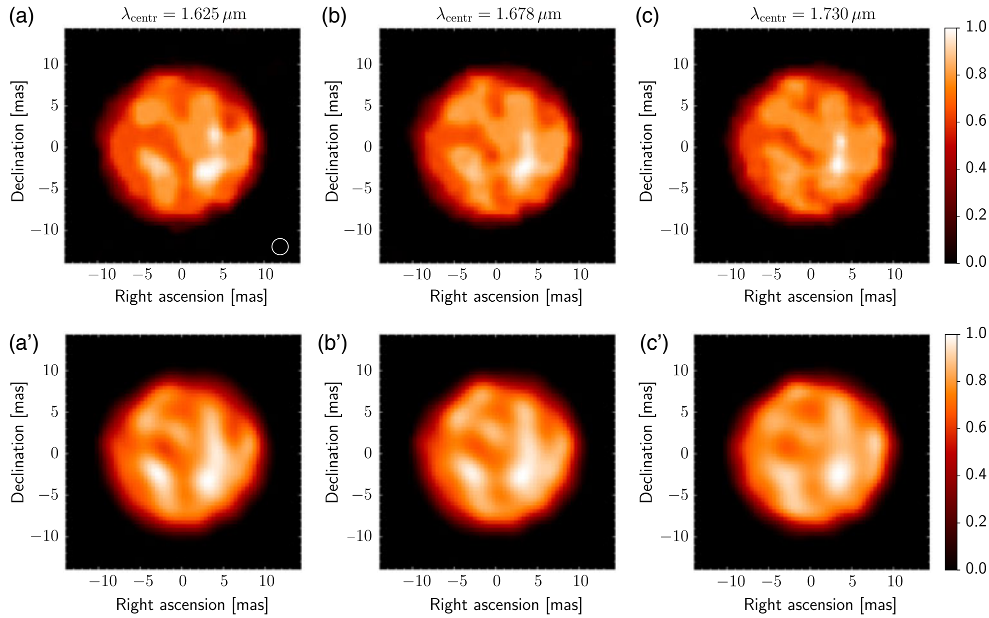

Figure 1. Images of the stellar surface of π^1 Gruis. The upper row shows the three spectral channels reconstructed using SQUEEZE and the smoothness regularizer function. The lower row shows the reconstruction obtained with MiRa and the total variation regularizer. (See also Paladini *et al.* 2018)

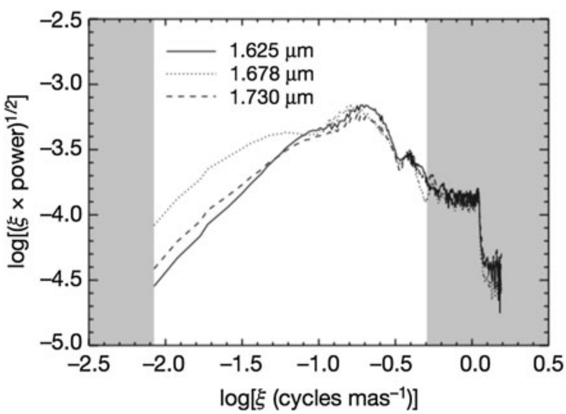

Figure 2. Spatial power spectrum density derived from the three PIONIER SQUEEZE images. The grey-shaded area to the left represents the size of the box of the image. The grey-shaded area to the right marks the angular resolution of the observations, e.g., the observations are not sensitive to surface structure at $\log \xi > -0.3$. The peak of the PSD gives information on the typical granulation size.

4. Results and discussion

The photosphere of π^1 Gruis has an intensity contrast of the order of 12%, which increases slightly towards shorter wavelengths. The systematic errors are very difficult to assess, and there are also no models to compare our results with. However the constrast so determined is in qualitative agreement with the contrast derived from bolometric intensity maps of RSGs (Freytag *et al.* 2017). The characteristic granulation size

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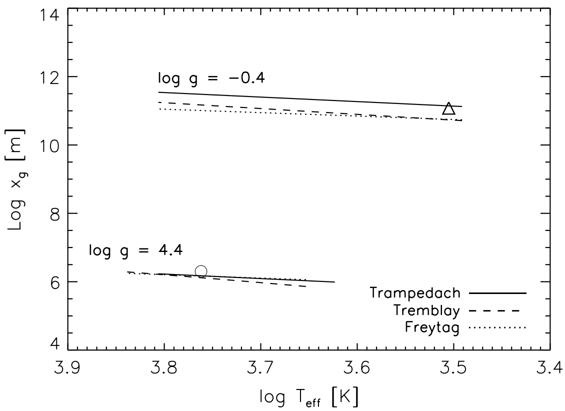

Figure 3. The characteristic granulation size of convection measured on the Sun (circle), and the one derived in this work for π^1 Gruis (triangle). The different lines represent the parametric formulas derived from theoretical model predictions of convection.

obtained is 5.3 ± 0.2 mas, corresponding to 1.2×10^{11} m. Such measurement was compared with parametric formulas relating the granulation size to the stellar parameters, and obtained from theoretical model predictions of stellar convection (Freytag *et al.* 1997, Trampedach *et al.* 2013, Tremblay *et al.* 2013). Figure 3 shows how our results are in agreement with the model predictions, which is remarkable considering the models do not cover the parameter space of π^1 Gruis. As a next step we have an ongoing monitoring program to derive the time-scale of convective granules on the surface of AGB stars. We also plan to image more AGB stars and repeat the same kind of analysis to help constraining the theory of convection on the AGB.

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