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Constraining Convection in Evolved Stars with the VLTI

Claudia Paladini [1]
Fabien Baron [2]
Alain Jorissen [3]
Jean-Baptiste Le Bouquin [4]
Bernd Freytag [5]
Sophie Van Eck [3]
Markus Wittkowski [1]
Josef Hron [6]
Andrea Chiavassa [7]
Jean-Philippe Berger [4]
Christos Siopis [3]
Andreas Mayer [6]
Gilles Sadowski [3]
Kateryna Kravchenko [3]
Shreeya Shetye [3]
Franz Kerschbaum [6]
Jacques Kluska [8]
Sofia Ramstedt [5]

[1] ESO
[2] Department of Physics and Astronomy, Georgia State University, USA
[3] Institut d'Astronomie et d'Astrophysique, Université libre de Bruxelles, Belgium
[4] Université Grenoble Alpes, CNRS, IPAG, France
[5] Department of Physics and Astronomy, Uppsala University, Sweden
[6] Department of Astrophysics, University of Vienna, Austria
[7] Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, Lagrange, Nice, France
[8] Institute of Astronomy, KU Leuven, Belgium

We used the Precision Integrated-Optics Near-infrared Imaging ExpeRiment (PIONIER) at the Very Large Telescope Interferometer (VLTI) to image the stellar surface of the S-type Asymptotic Giant Branch (AGB) star π^1 Gruis. The angular resolution of two milliarcseconds allowed us to observe the surface of this giant star in unprecedented detail. At the observed wavelength the stellar disc appears circular and dust-free. Moreover, the disc is characterised by a few bubbles of a convective nature. We determine the contrast, and the characteristic horizontal length-scale of the convective granules. The latter is determined, for the first time, directly from the image, without involving the usual geometric modelling that has been used in the literature. The measurements fall along empirical scaling relations between stellar parameters and convective sizes, which are determined on the basis of three-dimensional stellar convection models. Our results open up a new era for the characterisation of stellar convection in stars other than the Sun.

The surface of the Sun is populated by about two million convective cells that are roughly 2000 km in size. According to the theory outlined by Schwarzschild (1975), when the Sun evolves towards the red giant branch, its atmosphere will inflate and, because of the lower surface gravity, only a few convective cells will survive at the surface. On the other hand, it is known that stars evolving along the giant branch lose mass via stellar winds. Mass loss from evolved stars is one of the crucial processes for galactic chemistry. Stellar convection is one of the dynamical processes that plays a crucial role in shaping the inner atmospheres of evolved stars. In particular, through its interplay with dust formation, it contributes to the mass-loss process.

The angular resolution of optical interferometry allows the stellar discs of evolved stars to be resolved, as well as smaller structures such as convective granulation. However, for several years we have been limited by the number of available apertures. Several papers have reported asymmetric structures in evolved giants. The departure from spherical symmetry was measured either by comparing visibilities observed at different position angles, or via measurements of closure phase different from zero or ±180 degrees. The observations were then interpreted by superimposing bright spots with varying contrasts on limb-darkened discs (Young et al., 2000; Ragland et al., 2006; Montarges et al., 2016, 2017). In other cases, the interpretation was done using physical models including radiative transfer (for example Cruzalebes et al., 2013, Arroyo-Torres et al., 2015). However, because of the scarce uv coverage, the interpretation of the data was highly non-unique, and asymmetric structures could also be interpreted as indications of the presence of a binary companion (Mayer et al., 2014), or even an increase of the density scale-height in the equatorial plane due to rotation (van Belle et al., 2013). At this stage the need for high angular resolution images became clear.

Stellar surfaces with PIONIER

The PIONIER instrument (Le Bouquin et al., 2009) combines the light of four telescopes (the four Auxiliary Telescopes, or the four Unit Telescopes) in the *H*-band. PIONIER is very stable and efficient, and is best suited to imaging bright targets (see for example, Wittkowski et al., 2017).

The semi-regular variable π^1 Gruis, an evolved star with a period of 195 days and a parallax of 6.13 ± 0.76 milliarcseconds, was observed with PIONIER in September 2014 (Figure 1). Given the complexity of the target, we collected as many uv points as possible, which resulted in a total of two nights of observations. The data were obtained using the compact and the medium arrays of the VLTI, which are best suited to imaging targets with a diameter of about 20 milliarcseconds, as in the case of π^1 Gruis. The switch between the array configurations was done within one week to minimise the effect of variability of the star. The *H*-band (like the *K*-band) gives access to the photospheres of evolved stars. AGB stars with oxygen-rich chemistry, such as π^1 Gruis, are ideal candidates for studies of the stellar surface convection, as oxygen-rich dust is transparent at those wavelengths.

We collected 303 spectrally dispersed visibilities (three spectral channels at 1.625, 1.678, and 1.730 micrometers) and 201 closure phases. Model-independent images have been reconstructed for each spectral channel using the software packages SQUEEZE (Baron et al., 2010), and the Multi-aperture image Reconstruction Algorithm (MiRA, Thiebaut, 2008). Figure 2 shows the result of the reconstruction algorithms, which use different principles but give two very robust and similar results in this case. The stellar disc is nearly round, populated by several patterns of a convective nature.

Characterising stellar convection

The three quantities characterising convective granules are the contrast, the size

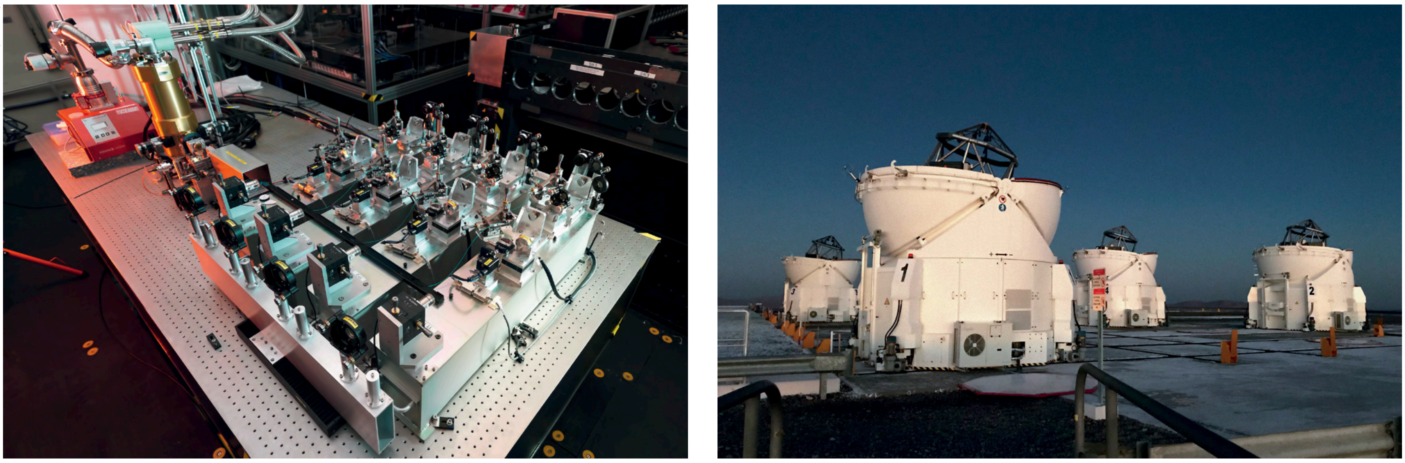

Figure 1. (Above) Left: the PIONIER instrument in the VLTI Lab. Right: the four Auxiliary Telescopes in the compact configuration.

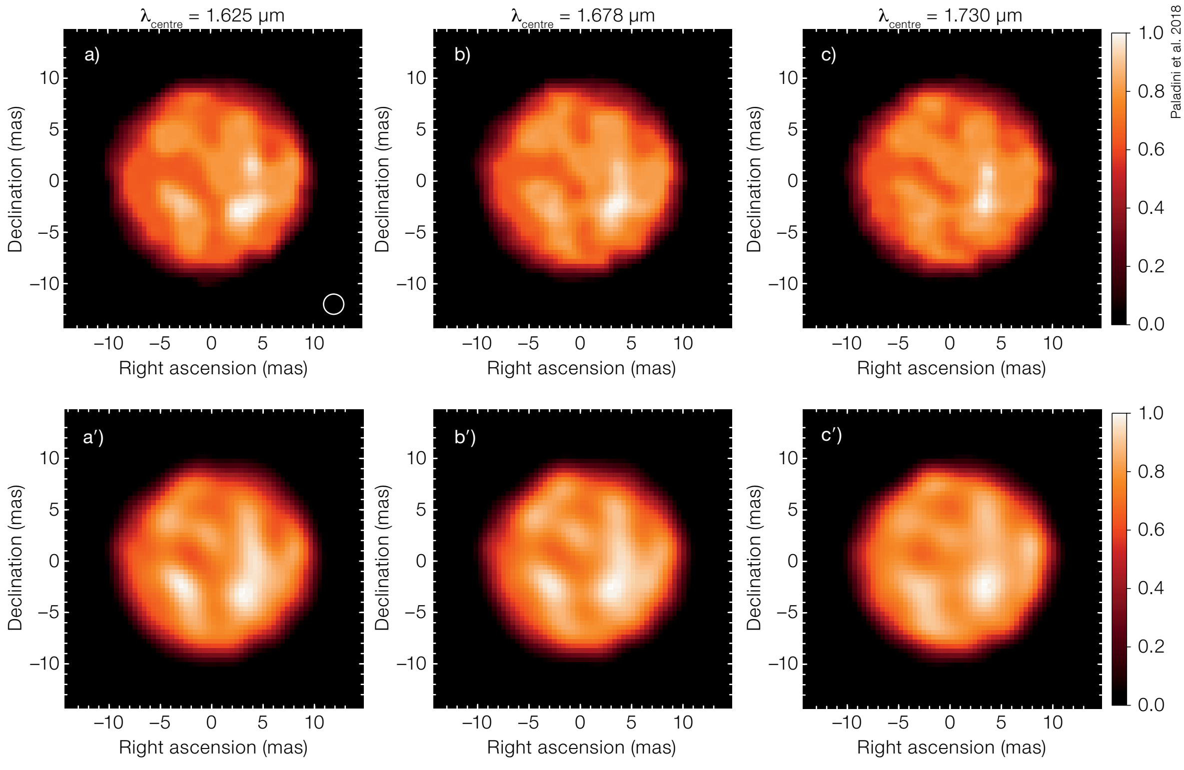

Figure 2. (Right) Upper panels: the three images in different spectral channels of the surface of π^1 Gruis reconstructed with SQUEEZE. The white circle in the upper left panel represents the angular resolution of the observations. Lower panels: same as above, using the image reconstruction algorithm MiRa.

of the granules, and their characteristic lifetime. The last of these cannot be determined as we currently only have observations obtained at one epoch. The contrast was obtained for every individual spectral channel after correcting the image for limb darkening. We obtained a contrast between 12% and 13%, with a slight increase towards short wavelengths where the contamination from molecular opacities becomes more significant. To derive the characteristic scales of the granules in the images, we did not use any geometric model, but derived the power spectrum density of the image; this method is commonly used in several fields of astronomy, especially when modelling stellar convection. However, a mere power spectrum of our image would simply provide the diameter of the star. As we are interested in the characteristic size of granulation, we subtracted the stellar disc from the image using dedicated masks. Three masks were designed: 1) a limb darkening profile obtained from the Model Atmospheres in Radiative and Convective Scheme (MARCS) model (Van Eck et al., 2017) that best fits the spectral energy distribution; 2) a Gaussian profile; and 3) a square mask that excludes the steep decrease in brightness of the limb darkening in the image.

After subtracting the limb darkening, we scaled the background of the image using the average over the image, and then added space around the image to better isolate the maximum power scale. The resulting power spectrum density is shown in Figure 3. The maximum power corresponds to a typical granulation size of the order of 5.3 (±0.5) milliarcseconds (mas), which corresponds to a linear size of 1.2 (± 0.2) × 10^{11} m at the distance of π^1 Gruis.

Granulation size across the Hertzprung–Russell diagram

The predictions from a three-dimensional model including convection for AGB stars are still at an exploratory stage. The model grids available in the literature can reproduce solar observations. However, they cover a different stellar parameter space from that of our star (Freytag et al., 1997; Tremblay et al., 2013; Trampedach et al., 2013). Under the assumption that stellar convection works in the same way across the Hertzsprung–Russell diagram, we extrapolated our results and compared the granulation size determined so far with model prescriptions relating the characteristic scale to stellar parameters. Figure 4 shows that our result, represented by the triangle, is well reproduced by the model prescriptions.

Outlook

The next step of this work will be to add the vertical scale information by using the high spectral resolution mode of the VLTI/GRAVITY instrument (Eisenhauer et al., 2011). The characteristic lifetime of convection should involve a monitoring programme that acquires at least an image per month.

A deeper understanding of convection, and how this process depends on stellar parameters, will require extending such studies to several other targets. An imaging survey of AGB stars will be rather straightforward as the VLTI reaches the right angular resolution to resolve the convective granules on the surface of such stars. Given the interplay of convection with pulsation and dust formation, the optimum strategy for future follow up observations would be to use all of the various wavelength bands available at the VLTI — from *H*- to *N*-bands, using PIONIER, GRAVITY, and the Multi AperTure mid-Infrared SpectroScopic Experiment (MATISSE) — as simultaneously as possible so all the spatial scales could be captured at the same time.

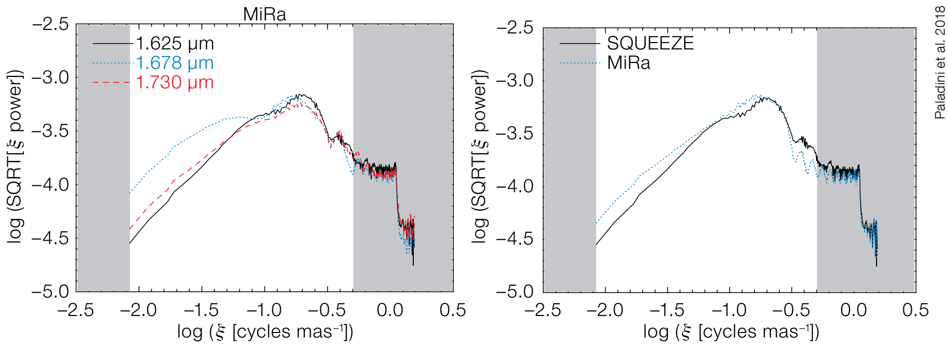

Figure 3. (Left) The power spectrum density of the three spectral channels of the SQUEEZE images. The peaks of the three curves have been averaged after smoothing to derive the power carrying length. The grey shaded area on the left represents the size of the box, while the area on the right is the angular resolution of the observations. (Right) The power spectrum density obtained for the first spectral channel and the two different image reconstruction algorithms.

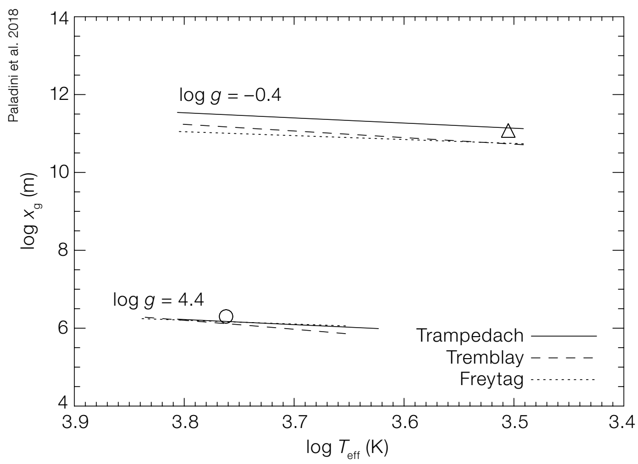

Figure 4. The characteristic granulation size of convection derived from the π^1 Gruis PIONIER images (triangle), compared with theoretical predictions extrapolated from the Sun.

Observations of convective granules for stars less evolved than π^1 Gruis would require higher angular resolution than the one currently available. The latter could be achieved either with longer baselines, or moving to shorter wavelengths.

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