Interferometric imaging of the photosphere of Betelgeuse

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The mass loss mechanism of massive evolved stars is poorly understood. The proximity of Betelgeuse makes it an appealing target to study its close environment, and map the structure of its envelope. The new generation of optical interferometers opens new possibilities to image the surface of nearby stars. Thanks to its very large apparent angular diameter (~44 milliarcseconds), Betelgeuse is particularly well suited for interferometric imaging. Its surface is expected to host very large convective cells, and therefore present irregularities. We present observations of Betelgeuse using the IOTA/IONIC and VLTI/PIONIER instruments, in the near-infrared H band, obtained in 2005.8 and 2012.1, respectively. We present reconstructed images for epoch 2005.8 and a preliminary reconstruction for epoch 2012.1. They show the presence of spots at the surface, that are expected from 3D convection models. We also briefly discuss our projects for further interferometric observations of this fiducial supergiant.

Observations and data analysis

We obtained interferometric observations of Betelgeuse with two instruments: IOTA/IONIC (Epoch Oct. 2005, Haubois et al. 2009) and VLTI/PIONIER (Epoch Jan. 2012, Kervella et al. 2012). These two instruments rely on integrated optics components for the recombination of the light collected by the telescopes. IONIC is a 3-telescope combiner coupled to the 40cm aperture siderostats of the IOTA array, and PIONIER is a 4-telescope combiner coupled to the four auxiliary telescopes of the VLTI (1.8m aperture). These instruments are particularly well suited to produce interferometric images, thanks to their ability to measure closure phases in addition to the classical visibility amplitudes. The coverage of the two series of observations in baseline length and orientation is represented in **Fig. 1**.

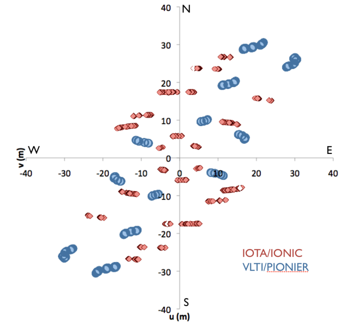

Figure 1: *(u,v)* coverage of the IONIC (epoch 2005, red diamonds) and PIONIER (epoch 2012, blue circles) observations of Betelgeuse.

Model fitting and overall properties of the star

From our 2005 IOTA/IONIC observations, we measure an average limb-darkened diameter of $\theta_{LD}(2005)= 44.28 \pm 0.15$ mas with linear and quadratic models. These measurements correspond to an effective temperature of 3600 ± 66 K. We detect a fully-resolved flux contribution from the environment of Betelgeuse (4% relative contribution in the *H* band), possibly linked to the envelopes imaged by Kervella et al. (2009, 2011) in the near (1.0-2.5 µm) bands) and thermal (8-20 µm) infrared domains.

To derive the general properties of the star, we initially consider only the visibility values in the first and second lobe of the visibility function. They are directly linked to the intensity of the resolved envelope of the star γ (resolved flux / photospheric flux), the photospheric angular size θ_{LD}, and the power law limb darkening coefficient α. Using these data, our PIONIER observations (epoch 2012) give γ=0.18, $\theta_{LD}(2012)= 44.57 \pm 0.10$ mas, α = 0.29.

The angular diameters measured in 2005 and 2012 are therefore in reasonably good agreement (within 2σ), and show that the overall size of the star in the near-infrared did not change significantly over 6.5 years. This value is also comparable to the size obtained by Ohnaka et al. (2009), who found $\theta_{LD}(2002)= 43.56 \pm 0.06$ mas, α = 0.12 from AMBER+VINCI data (see also Ohnaka et al. 2011). Ravi et al. (2012) also showed that the size of the star did not change significantly in the thermal infrared over a decade.

Image reconstruction

The visibility and closure phase signals measured on Betelgeuse differ significantly from a simple limb darkened disk starting, starting from the 3rd lobe of the visibility function (**Fig. 2**). This behavior is due to the inhomogeneous structures at the surface of the star. Due to the complexity of the light distribution, the classical model fitting approach alone is not well suited to interpret these observations. Our limited *a priori* knowledge of the overall properties of the spots (number of photospheric features, spatial extension, contrast,...) results in a poor fidelity of the model to the star, and inaccurate physical parameters of the modeled spots. In this case, the image reconstruction approach is more efficient to retrieve the properties of the photospheric features of the star.

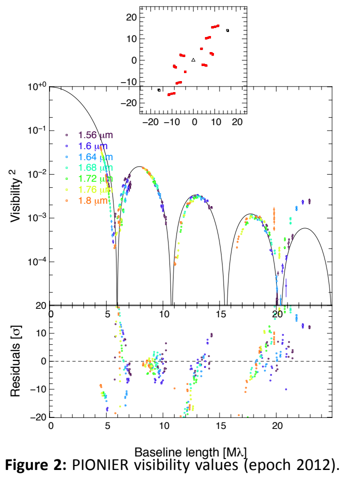

Figure 2: PIONIER visibility values (epoch 2012). The dispersion visible in the 4th and 5th lobes is caused by the presence of surface structures.

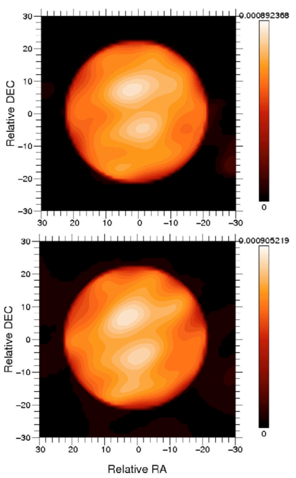

Figure 3: Epoch 2005. *Top:* contour image reconstruction from the MIRA software. *Bottom:* contour image reconstruction from WISARD of Betelgeuse in a 60 mas field. Both images were reconstructed with the same *a priori* and the same type of regularization (Haubois et al. 2009). The brightest spot in the image contributes approximately 8.5% of the total flux.

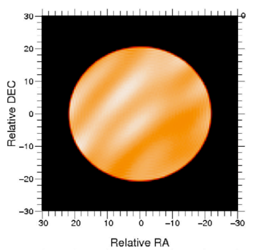

Figure 4: Epoch 2012. Preliminary image reconstruction obtained with the MIRA software. The visibility of the first and second lobes have been forced to match a limb darkened disk with an angular size of 44.57 mas and α = 0.29 (Kervella et al. 2013).

2005.8 epoch: We applied two image reconstruction algorithms: MIRA and WISARD (Haubois et al. 2009). The resulting images show clearly two bright spots on the surface (**Fig. 3**). One spot has a diameter of ~ 11 mas and accounts for 8.5% of the total flux. The second one is unresolved (<9 mas) with 4.5% of the total flux of the star in the H band.

2012 epoch: We applied the MIRA algorithm to our new PIONIER data. We observed the presence of a relatively large dispersion of the data points in the first and second lobes of the visibility function. This dispersion is most probably caused by instrumental biases in the measured visibilities, due the extreme brightness of Betelgeuse. The cause for the presence of these biases is currently investigated, and we chose for this preliminary analysis to force the visibility in the 1st and 2nd lobes to those of a limb darkened disk + envelope with the parameters determined previously (γ=0.18, $\theta_{LD}(2012)= 44.57 \pm 0.10$ mas, α = 0.29). This is justified by the fact that the expected surface structures have an angular size smaller than the star diameter, and their signatures in the visibility function are thus present essentially in the 3rd lobe and above. The result of the reconstruction is presented in **Fig. 4**. Bright structures are present at both epochs, and may correspond to convective cells. The elongation of the structures in the 2012 image is caused by the asymmetric coverage of the (u,v) plane of our PIONIER observations (**Fig. 1**). Our angular resolution is significantly lower in the NW-SE direction than along the NE-SW axis.

Further interferometric observations are foreseen in late 2012, with an enhanced coverage of the (u,v) plane. They will allow us to reconstruct a better image of the surface with a more homogeneous spatial resolution. We also plan to derive directly the spatial power spectrum of the light distribution of the photosphere, which is expected to be a very efficient statistical constraint for the 3D hydro convection models. This new type of observable will enhance our knowledge of the conplex convective motions present in Betelgeuse.

References:

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