Resolving the Mass Loss in Red Supergiants with the Very Large Telescope Interferometer and *SPICA*

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ABSTRACT

The mass-loss mechanism in red supergiants (RSGs) is one of the long-standing problems in stellar astrophysics. For solving this problem, it is crucial to probe the dynamics of the outer atmosphere. The milliarcsecond angular resolution achieved by IR long-baseline interferometry provides us with the only way to spatially resolve this key region. We present high spatial and high spectral resolution observations of the best-studied RSGs Betelgeuse and Antares in the 2.3 μm CO lines using ESO's Very Large Telescope Interferometer (VLTI). We have succeeded in "velocity-resolved" aperture-synthesis imaging of the atmosphere of stars for the first time. This allows us to probe not only inhomogeneous structures over the surface of stars but also their kinematics, as routinely done in solar physics. We have detected vigorous upwelling and downdrafting motions of large CO gas clumps (as large as the radius of the stars) at up to 20–30 km s^{-1} within 1.5 stellar radii. *SPICA* will provide a unique opportunity to probe the region farther away from the star, helping us to link the inhomogeneous, vigorous atmospheric motions to the physical properties of the circumstellar envelope.

1. INTRODUCTION

The mass loss in the red supergiant (RSG) phase significantly affects not only the evolution of massive stars but also the chemical enrichment of galaxies. Nevertheless, the mass-loss mechanism in RSGs is a long-standing problem in stellar astrophysics. While dust, pulsation, convection, and magnetohydrodynamical (MHD) waves are often considered to be candidates, there is currently no working theory for the mass loss in RSGs (e.g., Harper 2010).

For understanding the mass-loss mechanism in RSGs, it is crucial to study the dynamical structure of the outer atmosphere, where the energy and momentum for the wind acceleration are expected to be deposited. The outer atmosphere of RSGs has complicated, inhomogeneous structures, with the hot chromospheric plasma and the cool neutral/molecular gas coexisting within several stellar radii (e.g., Harper et al. 2001, and references therein). Inhomogeneous structures on the surface of RSGs are also spatially resolved by IR interferometry (e.g., Tuthill et al. 1997; Haubois et al. 2009). Kervella et al. (2009, 2011) and Marsh et al. (2001) reveal clumpy structures in the circumstellar envelope of the RSGs Betelgeuse and Antares. This inhomogeneous, multicomponent nature of the outer atmosphere and the circumstellar envelope is considered to be a key to understanding the driving mechanism of the mass loss.

However, milliarcsecond spatial resolution and high spectral resolution ($\gtrsim$6000) are required to spatially resolve the dynamical structure of the inhomogeneous atmosphere. The near-IR (1.3–2.4 μm) interferometric instrument AMBER at the ESO's Very Large Telescope Interferometer (VLTI) is a unique instrument to achieve this (Petrov et al. 2007). With the

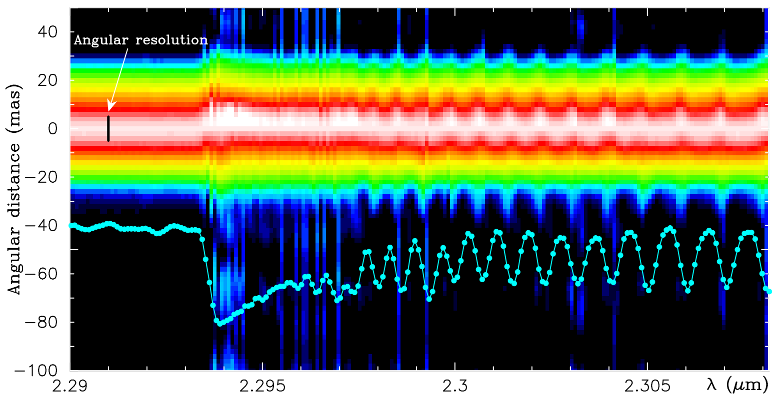

Figure 1. Spatially resolved 2-D spectrum of the RSG Betelgeuse in the CO first overtone lines obtained with VLTI/AMBER. The star is well resolved by our angular resolution (9.8 mas), which is shown by the vertical tick. The observed spatially unresolved (= normal) CO line spectrum of Betelgeuse is shown by the solid line. The extended outer atmosphere is seen as “spikes” in the CO lines. The atmosphere is more extended to the negative direction (PA = −107°) than to the positive direction.

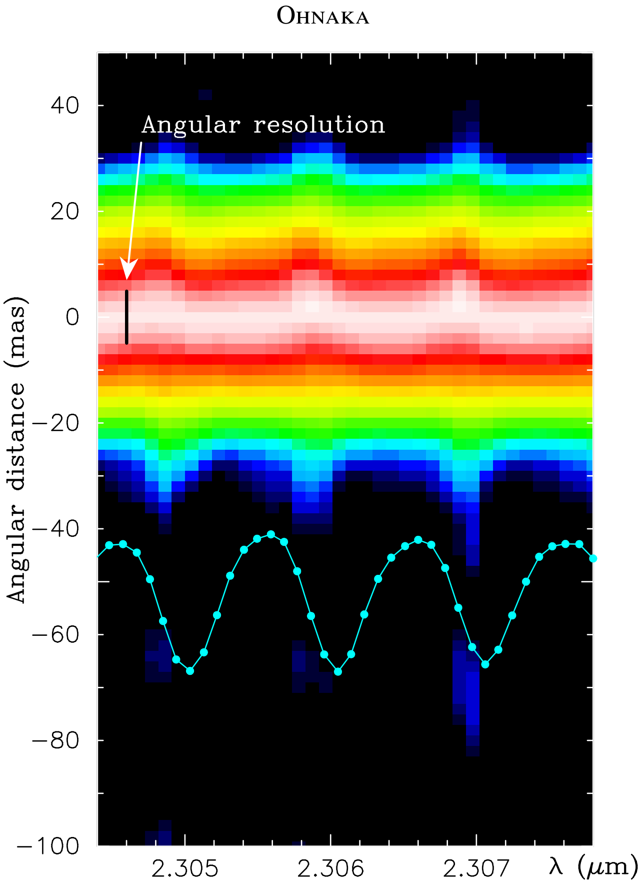

Figure 2. Enlarged view of the spatially resolved 2-D spectrum of Betelgeuse for three CO lines. The star appears extended only in the blue wing and line center, not in the red wing of the CO lines. The observed spatially unresolved CO line spectrum of Betelgeuse is shown by the solid line.

currently available maximum baseline at VLTI, it is possible to have a spatial resolution of down to 1 mas and a spectral resolution of up to 12000.

2. VLTI/AMBER OBSERVATIONS OF THE RSGS BETELGEUSE AND ANTARES

Our VLTI/AMBER observations of Betelgeuse were the first study to spatially resolve this well-studied RSG in the individual CO first overtone lines near 2.3 μm (Ohnaka et al. 2009). The AMBER data revealed that the star is more extended in the CO lines than in the continuum and appears differently in the blue wing, line center, and red wing of the CO lines. Our modeling of the AMBER data showed that an inhomogeneous velocity field can make the star appear differently within the CO lines. However, with only six *uv* points, we could not determine how inhomogeneous the star appears.

Therefore, we observed Betelgeuse again one year later with better *uv* coverage. The almost linear *uv* coverage allowed us to reconstruct "1-D projection images" from 2.28 to 2.31 μm, which represent a 1-D intensity distribution of the star obtained by squashing the actual 2-D intensity distribution onto the projected baseline vector on the sky (see Ohnaka et al. 2011, for details). Figure 1 shows the observed spatially resolved 2-D spectrum of Betelgeuse. If one carried out long-slit spectroscopy placing the slit on the star using a 48 m telescope with an angular resolution of 9.8 mas, such a spatially resolved spectrum would be obtained. The figure reveals that the star is more extended in the CO lines, seen as "spikes" in the 2-D spectrum, suggesting an outer atmosphere extending to ~1.3 stellar radii. The figure also shows that the outer atmosphere is more extended to the negative direction (corresponding to a position angle of −107°) than to the positive direction. This is the first imaging of the extended outer atmosphere of an RSG in individual CO first overtone lines. The horizontal "wiggling" near the stellar disk center means that the photocenter of the star changes in the CO lines. Moreover, Figure 2 shows that the appearance of the outer atmosphere in each CO line is asymmetric with respect to the line center: it appears only in the blue wing and line center of the line but there is no trace of it in the red wing. Therefore, our high spatial and high spectral resolution AMBER observations enabled us to image how differently the star appears across the CO line profiles. Our modeling shows that the AMBER data can be explained by a model with an inhomogeneous velocity field, in which the CO gas within a region as large as the stellar radius is upwelling at 0–5 km s^{-1}, while the gas in the remaining region is downdrafting much faster at 20–30 km s^{-1} (see Ohnaka et al. 2011, for details of the modeling).

We also observed another well-studied RSG Antares with VLTI/AMBER with the same instrumental set-up. We succeeded in reconstructing 2-D images within the individual CO first overtone lines, although with a strongly elongated beam (Ohnaka et al. 2013). Furthermore, our AMBER imaging at two epochs reveals that the appearance of the star in the blue and red wing of the CO lines swapped completely within one year. Our modeling of the AMBER data of Antares suggests the vigorous, inhomogeneous gas motions in the outer atmosphere similar to Betelgeuse.

3. PROSPECTS WITH *SPICA*

Our "velocity-resolved" aperture-synthesis imaging of Betelgeuse and Antares with AMBER suggests that the material within 1.5 stellar radii is undergoing chaotic, vigorous motions without systematic outflows. To obtain a comprehensive picture of how the stellar winds are accelerated, it is important to link the dynamics of the inhomogeneous outer atmosphere to the physical properties of the region farther away from the star. *SPICA*'s coronagraphic instrument SCI will provide a unique opportunity to probe inhomogeneous or clumpy structures in the region at $\gtrsim$10 stellar radii. High spectral resolution observations of molecular and atomic lines with MCS will also be useful for spatially resolving the dynamics of the circumstellar envelope. This will help us to unveil the nature of the mass loss from RSGs.

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