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Spatially resolving the inhomogeneous structure of the dynamical atmosphere of Betelgeuse with VLTI/AMBER

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Abstract. We present spatially resolved high-spectral resolution K-band observations of the red supergiant Betelgeuse (α Ori) using AMBER at the Very Large Telescope Interferometer (VLTI). IR long-baseline interferometry combined with spectral resolutions of 4800–12000 enables us to probe the inhomogeneous structures in the dynamical atmosphere of Betelgeuse using the CO first overtone lines near 2.3 μm. Our AMBER observations mark the highest spatial resolution (9 mas) achieved for Betelgeuse with five resolution elements over its stellar disk. The AMBER data in the CO lines reveal salient inhomogeneous structures. Particularly, the visibilities and differential/closure phases within the CO lines show that the blue and red wings of the lines originate in spatially distinct regions over the stellar disk, clearly demonstrating an inhomogeneous velocity field in the atmosphere of Betelgeuse. The AMBER observations in the CO lines can be roughly explained by a simple model, in which a patch of CO gas is moving outward or inward with velocities of 10–15 km s^{-1}, while the CO gas in the remaining region in the atmosphere is moving in the opposite direction at the same velocities. This model also suggests the presence of dense molecular layers extending to ~1.4–1.5 $R_\star$ with a CO column density of ~ 1×10^{20} cm^{-2}. Our AMBER observations of Betelgeuse in the CO first overtone lines are the first spatially resolved study of the gas motion in a stellar atmosphere (photosphere and extended, warm molecular layers) other than the Sun and have opened a door to a better understanding of macroturbulence.

1. Introduction

Red supergiants (RSGs) experience slow, intensive mass loss up to $10^{-4}\ M_\odot$ yr^{-1}. Despite its importance not only in stellar evolution but also in the chemical enrichment of the interstellar matter, the mass loss mechanism in RSGs is not well understood.

The atmosphere of RSGs exhibits complicated structures. In the lower photosphere, vigorous convective motion is expected with the convective cell size possibly comparable to the stellar radius (Schwarzschild 1975). Extended chromospheres exist in the outer region. For example, the UV observations of the M supergiant Betelgeuse (α Ori) with the Hubble Space Telescope revealed that the hot (~6000–8000 K) chromospheric plasma is more than twice as extended as the photosphere measured in the near-IR with a bright feature (Gilliland & Dupree 1996;

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Uitenbroek et al. 1998). However, radio continuum observations of Betelgeuse with the Very Large Array (VLA) suggest that much cooler (~1000–3000 K) gas extends to several stellar radii, showing an irregular structure (Lim et al. 1998). The presence of such cool gas in the outer atmosphere of RSGs is consistent with dense molecular layers existing close to the star, the so-called "MOLsphere", which was proposed by Tsuji (2000a,b) to explain the IR spectra of the early M supergiants α Ori and μ Cep. Furthermore, the narrow-slit spectroscopy of Betelgeuse in the 10 μm region by Verhoelst et al. (2006) reveals that silicate dust forms only at large distances from the star ($\gtrsim$20 $R_\star$) and that Al_2O_3 may form as close as $\sim$2 $R_\star$. This means that the hot chromospheric plasma, cooler gas, and Al_2O_3 dust may coexist within several stellar radii from the star, but the cooler component is much more abundant compared to the chromospheric gas, because it dominates the radio emission.

A better understanding of the inhomogeneous structure of the outer atmosphere of RSGs is a key to unraveling the mass-loss mechanism in these stars. To glean clues to the origin of the inhomogeneities and the mass-loss mechanism in RSGs, high spatial resolution observations in IR molecular lines are very effective. In this paper, we present high-spectral and high-spatial resolution *K*-band AMBER observations of the prototypical RSG Betelgeuse (M1-2Ia–Ibe) in the CO first overtone lines.

2. VLTI/AMBER observations

AMBER (Petrov et al. 2007) operates in the *J*, *H*, and *K* bands with spectral resolutions of 35, 1500, and 12000, combining three 8.2 m Unit Telescopes (UTs) or 1.8 m Auxiliary Telescopes (ATs). Betelgeuse was observed on 2008 January 08 with AMBER using three ATs in the E0-G0-H0 array configuration with 16–32–48 m baselines. We used a spectral resolution of 12000 covering wavelengths from 2.28 to 2.31 μm. This wavelength range was chosen to observe the strong CO first overtone lines near the (2,0) band head. Sirius was observed for the calibration of the interferometric data of Betelgeuse and also as a spectroscopic standard star.

We reduced the AMBER data with amdlib ver.2.2, which is based on the P2VM algorithm (Tatulli et al. 2007). AMBER observations with three telescopes allow us to measure three visibilities and three differential phases (DPs), as well as one closure phase (CP). While the visibilities and DPs on the shortest baseline reduced from the data taken with a spectral resolution of 12000 are of sufficient quality, the visibilities and DPs on the longer baselines and CPs turned out to be noisy. To improve the S/N for these observables, we binned the data in the spectral direction with three pixels for the visibilities and DPs on the 32 m baseline and with five pixels for the observables on the longest baseline and CPs. This binning resulted in spectral resolutions of 8000 (three-pixel binning) and 4800 (five-pixel binning). Details of the AMBER observations and the data reduction are described in Ohnaka et al. (2009).

3. Observational results and modeling

Figure 1a shows the observed visibilities. Particularly surprising is that the visibility observed within a given CO line on the shortest baseline (~16 m) is anti-symmetric with respect to the line core (i.e., "~"-shaped). While the visibility on the middle baseline (~32 m) is roughly symmetric, the visibility on the longest baseline (~48 m) is asymmetric with the peak slightly redshifted with respect to the line core in most cases. These results mean that Betelgeuse appears different in the blue and red wings of the CO lines and that the blue and red wings originate in spatially distinct regions differing in size and/or shape. The observed DPs and CPs show remarkable non-zero and non-π values. These non-zero and non-π DPs and CPs confirm that the blue and red wings of the CO lines originate in spatially distinct regions.

As explained in Ohnaka et al. (2009), the observed asymmetry in visibility and differential/closure phase is difficult to explain by rotation or spherically expanding/infalling flows. Instead, the observed blue-red asymmetry is

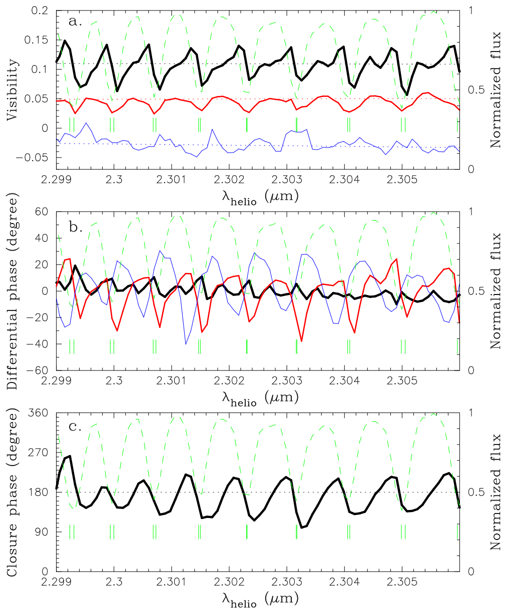

Fig. 1. Visibilities (a), DPs (b), and CP (c) observed in the CO lines toward Betelgeuse. In a) and b), the thick, normal, and thin solid lines represent the visibilities or DPs observed on the 16m, 32m, and 48m baselines, respectively. The visibility on the longest baseline is scaled by a factor of six and shifted downward by 0.1 for the sake of visual clarity. The dotted lines represent the continuum visibilities of a uniform disk with 43.19 mas for the corresponding baselines. In c), the observed CP is shown by the solid line. The dotted line represents CP = π, which is observed in the continuum. The normalized flux is overplotted in each panel (dashed lines). The positions of the CO lines are marked with the vertical ticks.

likely to be explained by an inhomogeneous velocity field in the atmosphere, in which upwelling and downdrafting CO gas exist in spatially distinct regions.

To characterize the inhomogeneous velocity field and the properties of the CO gas in the atmosphere of Betelgeuse, we constructed a patchy two-layer model. In this model, the star is surrounded by the inner and outer CO layers, which represent the photosphere and the MOLsphere, respectively. While the densities and temperatures of these layers were assumed to be homogeneous over the stellar surface, we introduced the following inhomogeneous velocity field: CO gas is moving radially outward (or inward) within one patch, while it is moving in the opposite direction at the same velocity in the remaining region. We assumed the same velocity field for two layers. We do not know a priori the actual number and shape of patches (if any) on the stellar surface, and the present data are insufficient to derive the inhomogeneous surface pattern uniquely. We only assumed one patch in our modeling to keep the number of free parameters as small as possible. Details of the modeling are described in Ohnaka et al. (2009).

Figure 2 shows a model characterized by a large, upwelling spot covering nearly a half of the apparent stellar disk. Given the simple nature of the model, the overall agreement is reasonable, although there are still discrepancies between the model and the observed data. The velocity field makes the star appear different in the blue and red wings. This can cause the visibility to be anti-symmetric with respect to the line core as observed on the shortest baseline and also explains the observed asymmetric DPs and CPs.

Our AMBER data and modeling suggest an inhomogeneous velocity field with amplitudes of ~10–15 km s^{-1}. These values compare favorably with the macroturbulent velocities of 10–20 km s^{-1} derived in the previous spectroscopic analyses (Lobel & Dupree 2000; Gray 2000; Jennings et al. 1986; Jennings & Sada 1998; Ryde et al. 2006; Tsuji 2006).

4. Conclusions

We have spatially resolved the CO gas motion in the atmosphere of Betelgeuse with high-spectral resolution using VLTI/AMBER—the first study to spatially resolve the so-called macroturbulence in a stellar photosphere (and possibly MOLsphere as well) other than the Sun. The spatially resolved CO gas motion is likely to correspond to the convective motion or intermittent, failed clumpy mass ejections. In fact, the recent high-resolution images of Betelgeuse obtained by Kervella et al. (2009) reveal a prominent plume extending to six stellar radii, showing that the mass loss is highly inhomogeneous.

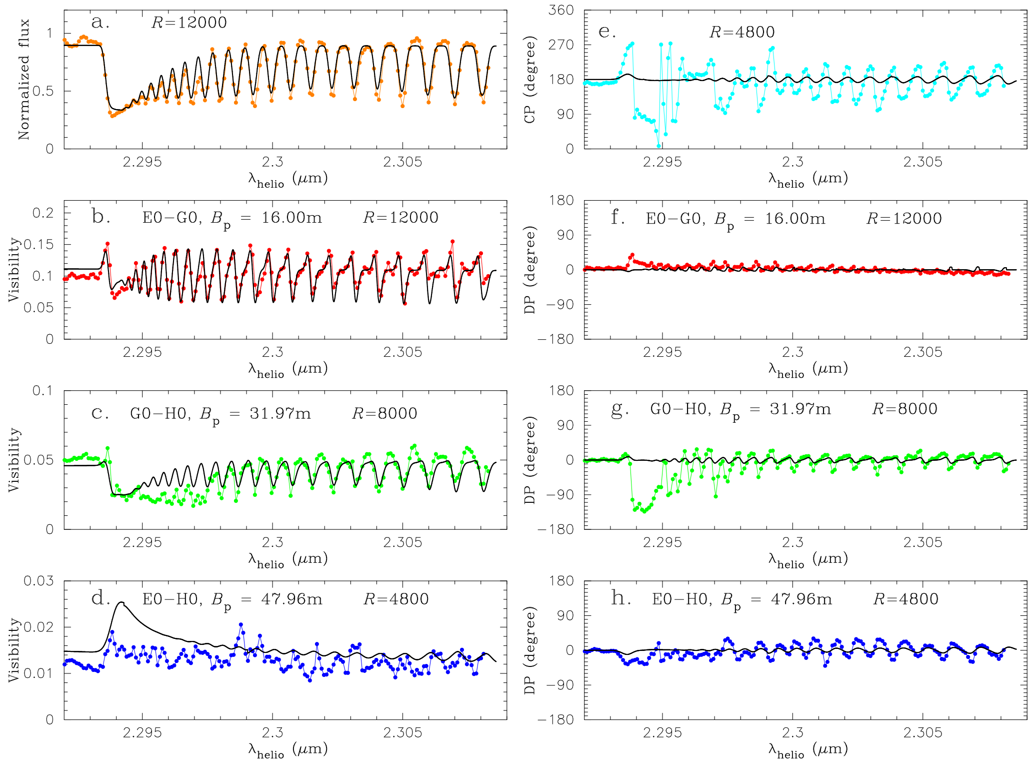

Fig. 2. Comparison between our patchy model and the AMBER data for Betelgeuse. In all panels, the solid lines represent the model, while the dots represent the observational data. a) Normalized flux. b)–d) Visibilities on the 16m, 32m, and 48m baselines. e) Closures phase. f)–h) Differential phases on the 16m, 32m, and 48m baselines. See Ohnaka et al. (2009) for details of the model.

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