Spatially Resolved Dusty Torus Toward the LMC Red Supergiant WOH G64 "Behemoth Has a Thick Belt"


WOH G64, Artist Impression (ESO Press Release)

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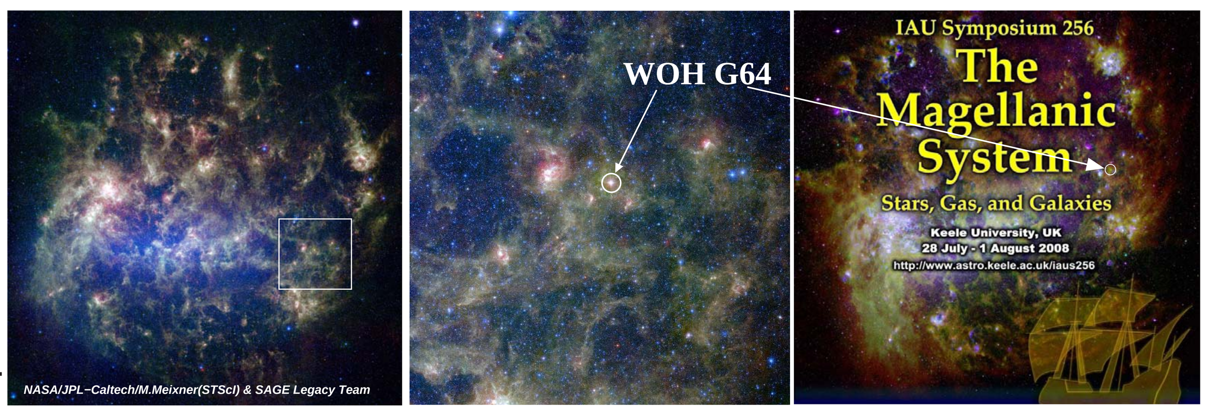
Abstract

We present mid-IR long-baseline interferometric observations of the LMC red supergiant WOH G64 with MIDI at the ESO's Very Large Telescope Interferometer (VLTI). Our MIDI observations of WOH G64 are the first VLTI observations to spatially resolve an individual stellar source in an extragalactic system. Our 2-D radiative transfer modeling reveals the presence of a geometrically and optically thick torus seen nearly pole-on. This model brings WOH G64 in much better agreement with the current evolutionary tracks for a 25 $M_\odot$ star (about a half of the previous estimate of 40 $M_\odot$) and solves the serious discrepancy between theory and observation which existed for this object.

Mystery behind the LMC Red Supergiant WOH G64

Red supergiants in the LMC and SMC provide an excellent opportunity to observationally test the current stellar evolution theory for massive ($\gtrsim 8\ M_\odot$) stars. Another advantage of studying RSGs in the LMC and SMC is that we can probe metallicity effects on the mass loss.



WOH G64 is a luminous red supergiant in the LMC (right figure), surrounded by an optically thick dust envelope with the 10 μm silicate feature seen in self-absorption.

The strength of the TiO bands suggests spectral types of M5–M7 (Elias 1986, ApJ, 302, 675; van Loon et al. 2005, A&A, 438, 273), which translate into $T_{\rm eff}$ = 3200–3400 K. The luminosities of 5–6$\times10^5\ L_\odot$ estimated by these authors assuming spherical shells correspond to an initial mass of $\sim$40 $M_\odot$. However, $T_{\rm eff}$ is too low for the current evolutionary tracks for a 40 $M_\odot$ star ($\Delta T \approx$ 3000 K!, Fig. 1, box). The above authors note that the low obscuration in the near-IR/visible, despite the huge mid-/far-IR excess (Fig. 4a), may indicate the possible presence of a disk or torus. Such deviation from spherical symmetry affects the luminosity estimate. To examine this possibility, we carried out mid-IR high-spatial resolution observations with VLTI/MIDI.

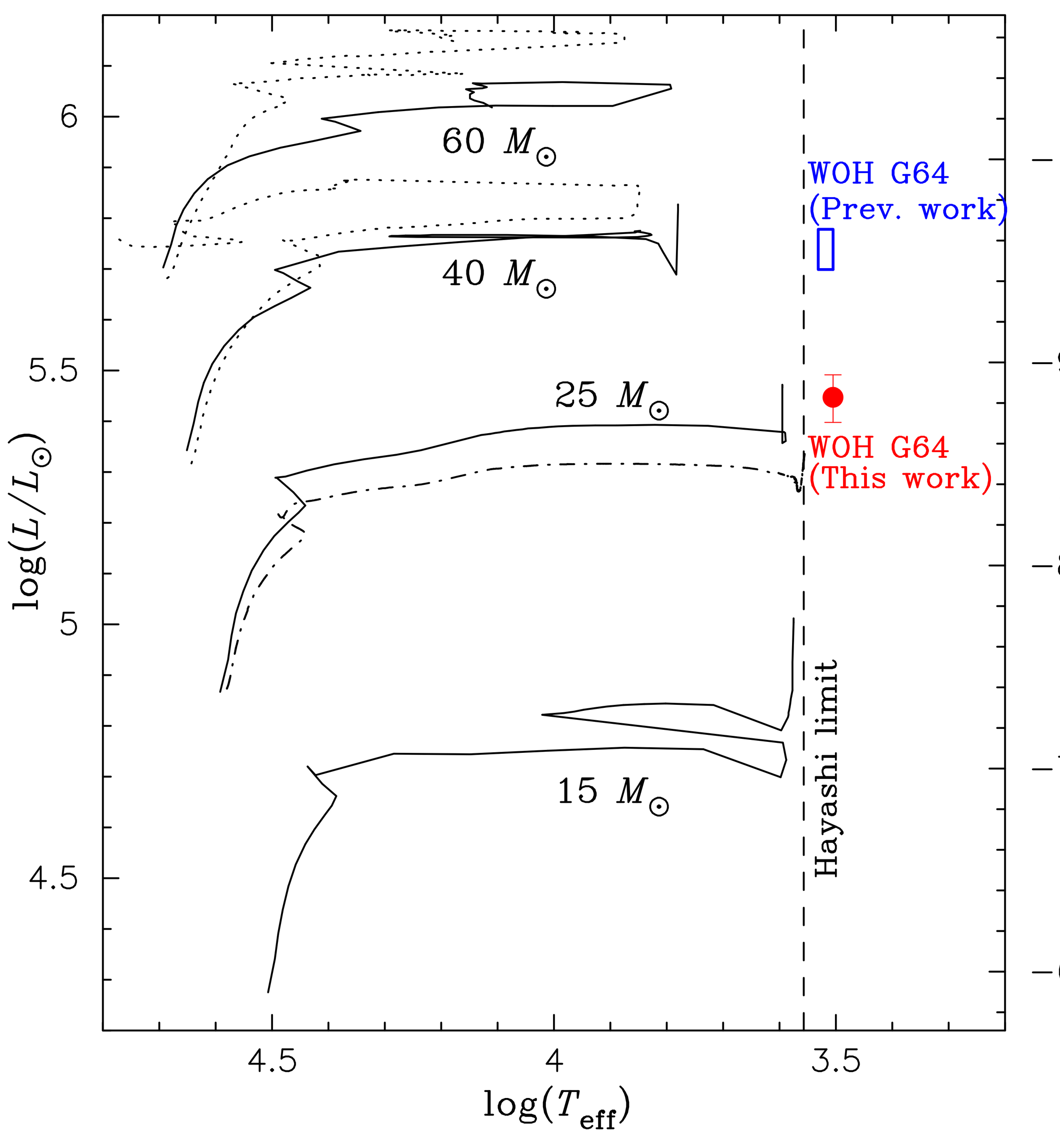


Figure 1: H-R diagram with theoretical evolutionary tracks with $Z = 0.008$ (solid lines: Schaerer et al. 1993, A&AS, 98, 523; dotted lines: Meynet & Maeder 2005, A&A, 429, 581) and that newly calculated with $Z = 0.01$ by T. Driebe (dashed-dotted line). The box and circle represent the observationally derived locations of WOH G64.

Spatially Resolved VLTI/MIDI Observations of WOH G64

MIDI is a 10 μm interferometric instrument which combines two beams from 8.2 m Unit Telescopes (UTs, Fig. 2) or movable 1.8 m Auxiliary Telescopes (ATs). With the maximum baseline length of 200 m, it can achieve a spatial resolution of $\sim$5 mas. It measures the "visibility amplitude" (= Fourier amplitude of the object's intensity distribution), which contains information on the object's size and shape. MIDI records spectrally dispersed fringes between 8 and 13 μm with $\lambda/\Delta\lambda \approx 30$ (or 230) (Fig. 3).

We observed WOH G64 in 2005 and 2007 with the UT3-UT4-62m baseline. We found no significant temporal variation in the N-band spectra between the two epochs (also in agreement with the Spitzer/IRS data taken in 2005). We measured visibilities at 4 position angles differing by $\sim$60° but at almost the same baseline length (57–62 m).

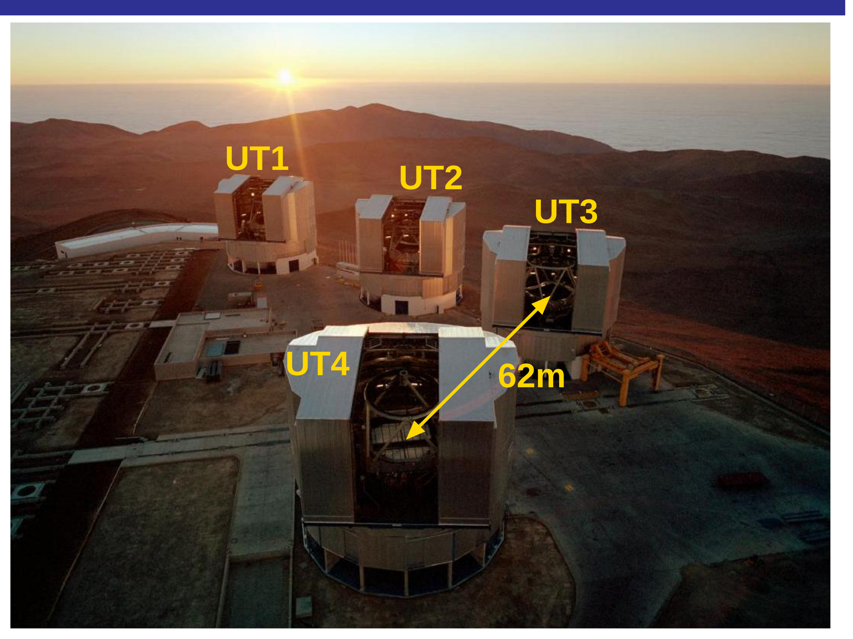


Figure 2: ESO's VLTI. The UT3-UT4-62m baseline was used for our MIDI observations.

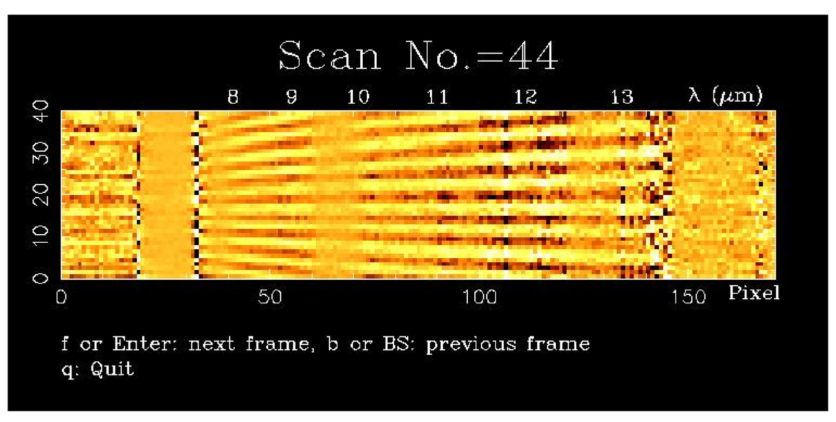


Figure 3: MIDI spectrally dispersed fringes on WOH G64 visualized by stacking 40 frames in one scan. Each row corresponds to one frame.

Observational Results: Interferometry and Spectroscopy

Figure 4 shows the observed SED and 10 μm visibilities of WOH G64. Our major observational findings are:

- WOH G64 was spatially resolved (i.e., visibilities < 1, Fig. 4c). This is the first VLTI observations to spatially resolve an individual star in an extragalactic system. The angular diameter (Fig. 4d, uniform-disk fitting) increases from $\sim$15 to 23 mas between 8 and 10 μm and is roughly constant above 10 μm.
- Visibilities (and angular sizes) measured at 4 position angles do not show a noticeable difference (Figs. 4c,d), suggesting that the object appears nearly centrosymmetric.
- H_2O absorption is identified at 2.7 and 6 μm (Fig. 4b). The 2.7 μm feature mostly originates in the photosphere and/or MOLsphere. The 6 μm feature is of circumstellar origin.

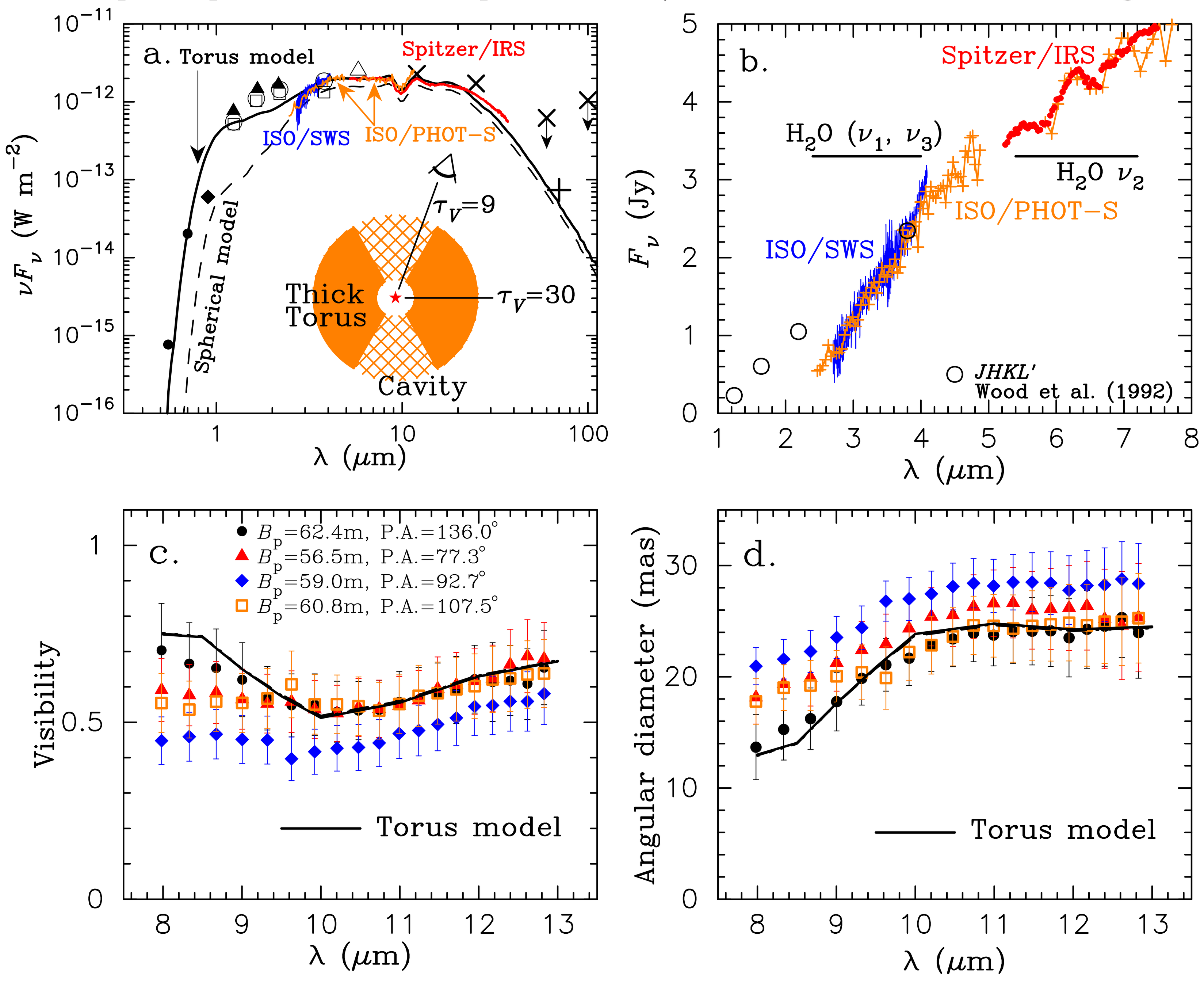


Figure 4: **a:** SED. ●: MACHO, ♦: ASAS, ▲: 2MASS, ○: Wood et al. (1992, ApJ, 397, 552), □: Whitelock et al. (2003, MNRAS, 342, 86), △: SAGE (Spitzer/IRAC), ×: IRAS, +: Spitzer/MIPS. **b:** H_2O absorption between 2 and 8 μm. **c:** N-band visibilities observed with VLTI/MIDI and the torus model. **d:** N-band angular sizes observed at 4 different position angles and the torus model.

Dusty Torus Model Solves the Mystery

We performed 2-D radiative transfer modeling to characterize the dust envelope around WOH G64, using our Monte Carlo code (see Ohnaka et al. 2008, A&A, 484, 371 for details).

- N-band visibilities and SED can be reproduced by an optically and geometrically thick silicate torus model viewed close to pole-on (inset of Fig. 4a). This pole-on model can explain the low obscuration in the near-IR/visible and the absence of position angle dependence of the visibilities (solid lines in Fig. 4 and images in Fig. 5).
- Dust torus parameters: $\tau_V = 30 \pm 5$ (equatorial plane), $\tau_V = 9 \pm 2$ (polar direction), inner boundary = $15 \pm 5\ R_\star$ ($R_\star$ = 1730 $R_\odot$, $\rho \propto r^{-2}$), torus half-opening angle = $60 \pm 10°$.

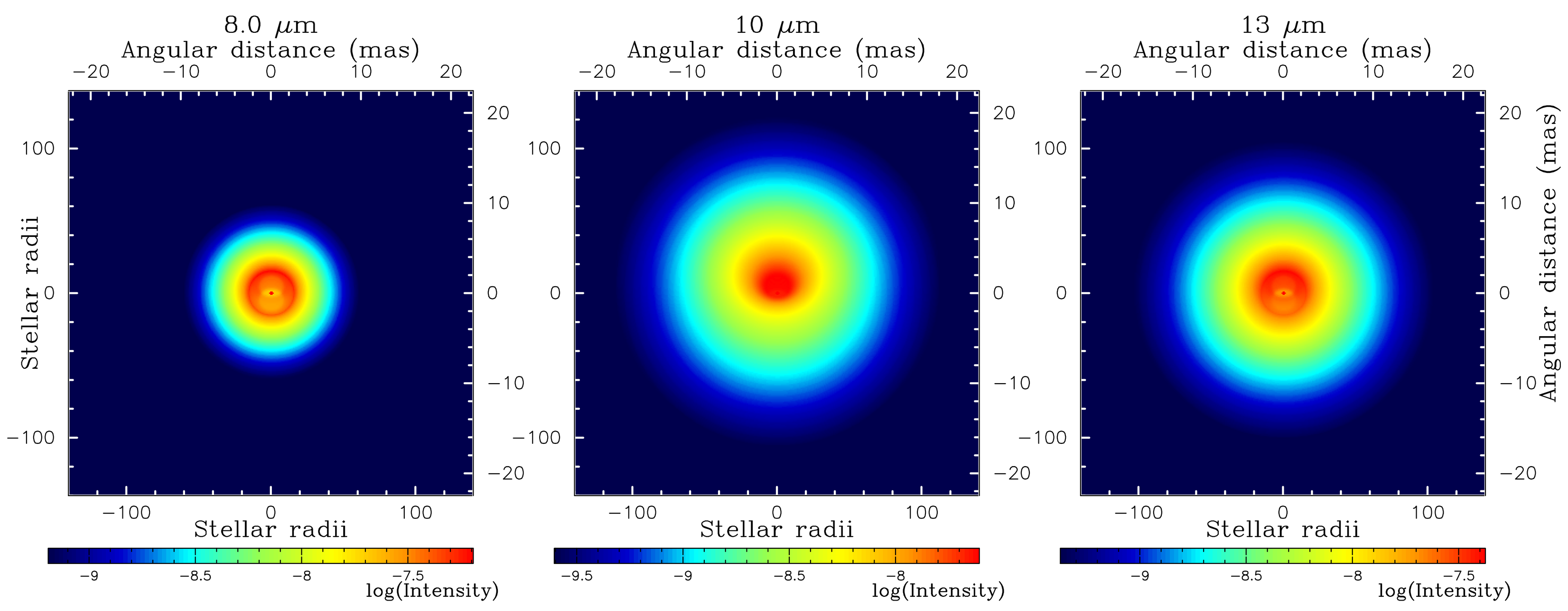


Figure 5: N-band model images for WOH G64.

- The derived luminosity, $\sim 2.8 \times 10^5\ L_\odot$, is about a half of the previous estimates based on spherical models. This is because we look into the torus from nearly pole-on. Radiation escapes preferentially toward the cavity (i.e., toward us), and the luminosity is overestimated when derived assuming spherical symmetry.
- New, lower luminosity brings the location of WOH G64 on the H-R diagram in much better agreement with theoretical evolutionary tracks for a 25 $M_\odot$ star (filled circle in Fig. 1).
- WOH G64 lies very close to or even beyond the Hayashi limit (dashed line in Fig. 1), which implies that this object may be experiencing unstable, violent mass loss. Actually, the derived total envelope mass, 3–9 $M_\odot$, represents a considerable fraction of its initial mass.

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