Mid-infrared circumstellar emission of the long-period Cepheid ℓ Carinae resolved with VLTI/MATISSE

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Objectives

- The nature of circumstellar envelopes (CSEs) around Cepheids is a matter of ongoing debate. The physical origin of their infrared (IR) excess could be shown to either be made up of **a shell of ionized gas, a dust envelope, or a combination of both**.
- This IR excess is poorly understood despite observational evidence and **could induce systematics on the period-luminosity relation used in the calibration of the extragalactic distance scale**.
- **CSEs around Cepheids have been spatially resolved by long-baseline interferometry** in the *K* band (2.2 µm), with the Very Large Telescope Interferometer (VLTI) and the Center for High Angular Resolution Astronomy (CHARA; Kervella et al. 2006; Mérand et al. 2006).
- **Our aim is to give constraints on the physical nature of the CSE** by inferring the size of the CSE of ℓ Car and its flux contribution thanks to the unique capabilities provided by the Multi AperTure mid-Infrared SpectroScopic Experiment (VLTI/MATISSE; Lopez et al. 2021 (submitted) in the *L* (2.8–4.0 µm), *M* (4.5–5 µm), and *N* bands (8–13 µm).

Method : VLTI/MATISSE observations

- MATISSE is the four-telescope beam combiner in the *L*, *M*, and *N* bands of the VLTI. The VLTI array consists of four 1.8-m auxiliary telescopes (ATs) and four 8-m unit telescopes (UTs), and provides baseline lengths from 11 m to 150 m. **Thus MATISSE is suitable for image reconstruction with a resolution of few milliarcseconds in the IR.**
- The observations were carried out during the nights of 27 and 28 February 2020 with the so-called large configuration of the ATs quadruplet (baseline lengths from 58 to 132 m) in low spectral resolution ($R = \lambda/\Delta\lambda \approx 30$).
- The steps of the data reduction process are described in Millour et al. (2016). The MATISSE absolute visibilities are estimated by dividing the measured correlated flux by the photometric flux.

- Thermal background effects affect the measurement in the *M* and *N* bands significantly more than in the *L* band. Thus, we use only the *L* band visibilities in our modeling of the CSE.
- In the *N* band, the total flux of ℓ Car is at the lower limit of the ATs sensitivity with MATISSE for accurate visibility measurements. Hence, we rather use the correlated flux measurements (not normalized by the photometric flux) as an estimate of the *N* band photometry.
- We discarded spectral regions where the atmosphere is not transmissive, and noisy edges of the atmospheric spectral bands.

As a result, we analyze the following spectral region :

- ***L* (3.1–3.75 µm) for absolute visibility and flux,**
- ***M* (4.75–4.9 µm) for flux,**
- ***N* (8.2–12 µm) for correlated flux**
- ***L*, *M* and *N* for the closure phase measurements which contain the information about the spatial centro-symmetry of the brightness distribution of the source.**

Modeling of visibilities : Gaussian envelope

- For all the closure phase measurements, we find an average closure phase of about 0° in the *L*, *M*, and the *N* band. That justifies our use of centro-symmetric model such as a Gaussian for the CSE.
- We fit a geometrical model on the measured *L* band visibilities, with ℓ Car and its CSE modeled with an uniform disk (UD) and a surimposed Gaussian distribution, as in previous studies (Kervella et al. 2006, 2009).
- **This CSE Gaussian model has two parameters** :
  - **CSE diameter** taken as the Full Width at Half Maximum.
  - **CSE flux** contribution normalized to the total flux. The derived visibility model is shown in black in Figure 1.

Figures : Visibilities (Fig. 1) and Flux (Fig. 2)

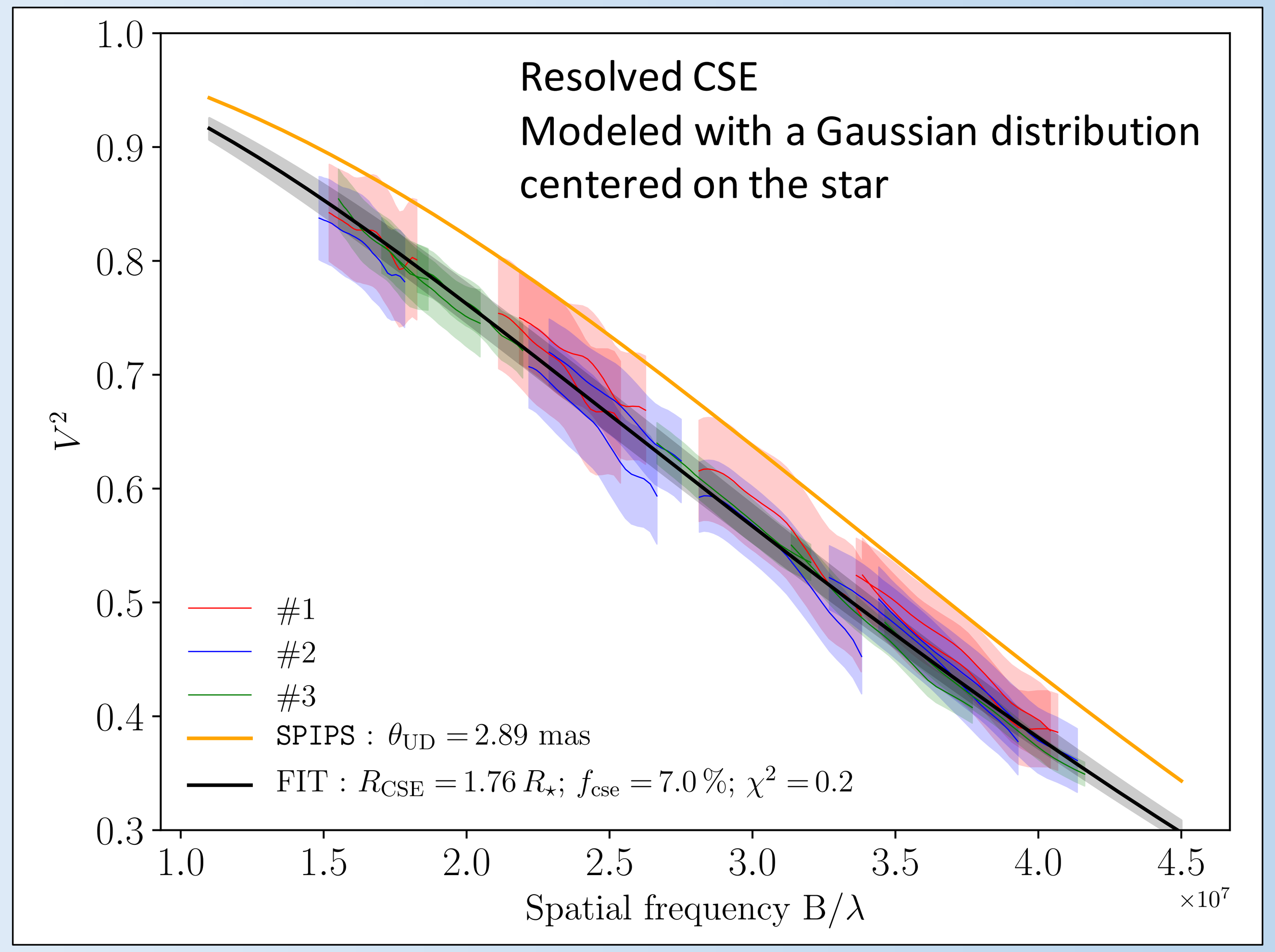

Figure 1 : Calibrated squared visibilities of ℓ Car as a function of the spatial frequencies in the *L* band for observations 1, 2, and 3. The theoretical visibility curve corresponding to an uniform disk of ≈2.89 in the *L* band (as derived from the SPIPS analysis) is indicated for comparison (orange curve). The fitted Gaussian CSE around ℓ Car for the combined observations in the L band is shown in black.

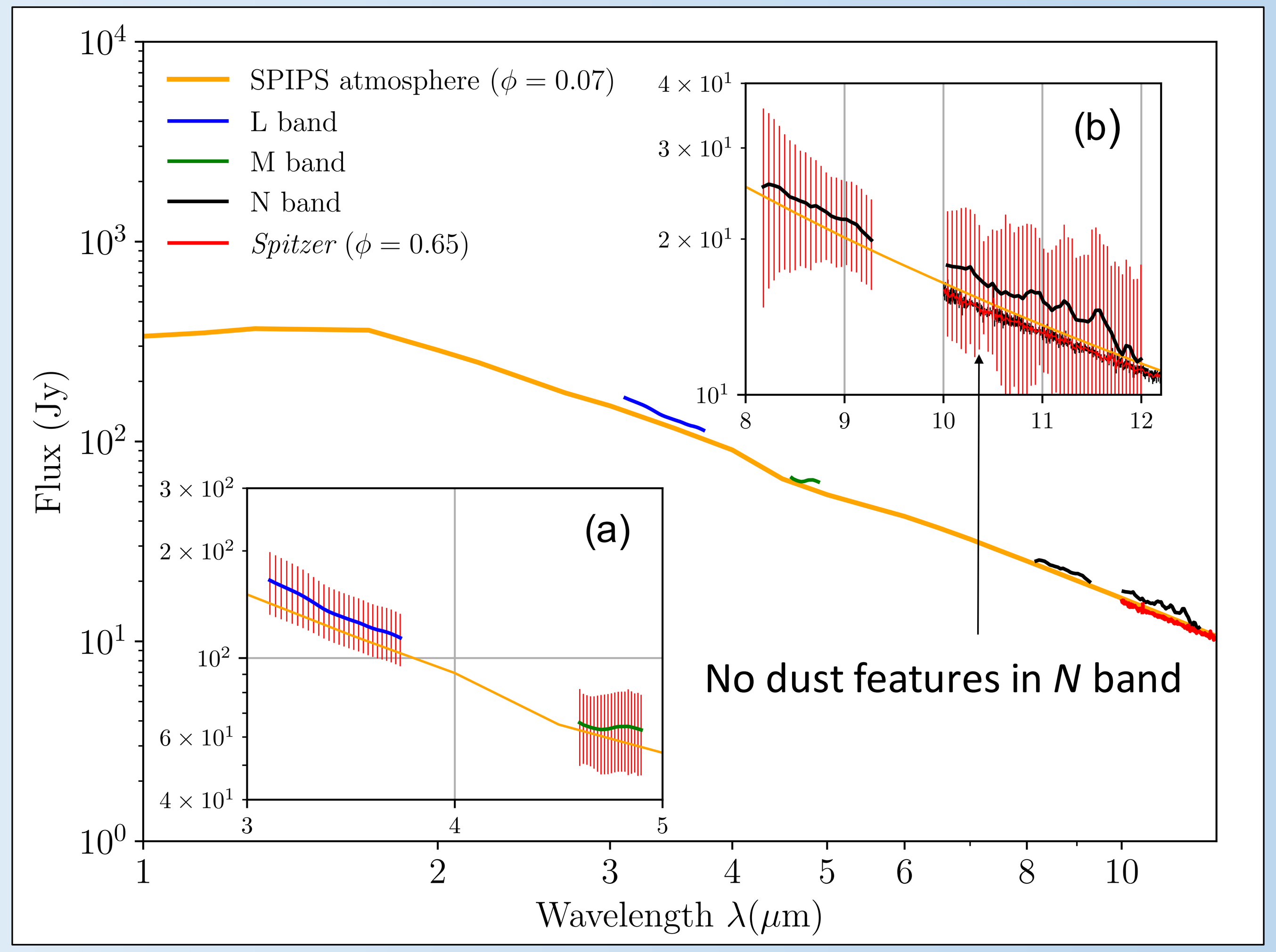

Figure 2 : Averaged calibrated total flux for observations 1, 2, and 3 in LM bands plus the correlated flux in N band for observation 3. Panels (a) and (b) refer to *LM* and *N* bands respectively. SPIPS photosphere model is interpolated at the phase corresponding to the MATISSE. The Spitzer spectrum (red) used is plotted for comparison.

Conclusions and perspectives

- We resolved a centro-symmetric and compact structure in the *L* band with VLTI/MATISSE that has a radius of about 1.76 $R_\star$. The flux contribution is about 7%. (see Figure 1 and 3)
- We find no clear evidence for dust emission features in *N* band in MATISSE and Spitzer spectra, which suggests an absence of circumstellar dust (see Figure 2 panel b).
- While the compact CSE of ℓ Car is likely gaseous, the exact physical origin of the IR excess remains uncertain. Hocdé et al. (2020a) used an analytical model of free-free and bound-free emission from a thin shell of ionized gas to explain the IR excess of Cepheids. They found a typical radius for this shell of about Rshell = 1.15 $R_\star$
- A shell of ionized gas (see Hocdé et al. 2021 for details) implies a size for the CSE that is lower than the one derived from VLTI/MATISSE observations (1.13 vs 1.76 $R_\star$) as well as a lower flux in the L band (1% vs 7%).
- We suggest that improving the model with the inclusion of free-free emission from negative hydrogen ion is likely to help reproducing the observation of a larger envelope.
- Further Galactic Cepheid observations with VLTI/MATISSE are necessary for determining the properties of CSEs, which may also depend on both the pulsation period and the evolutionary state of the stars.

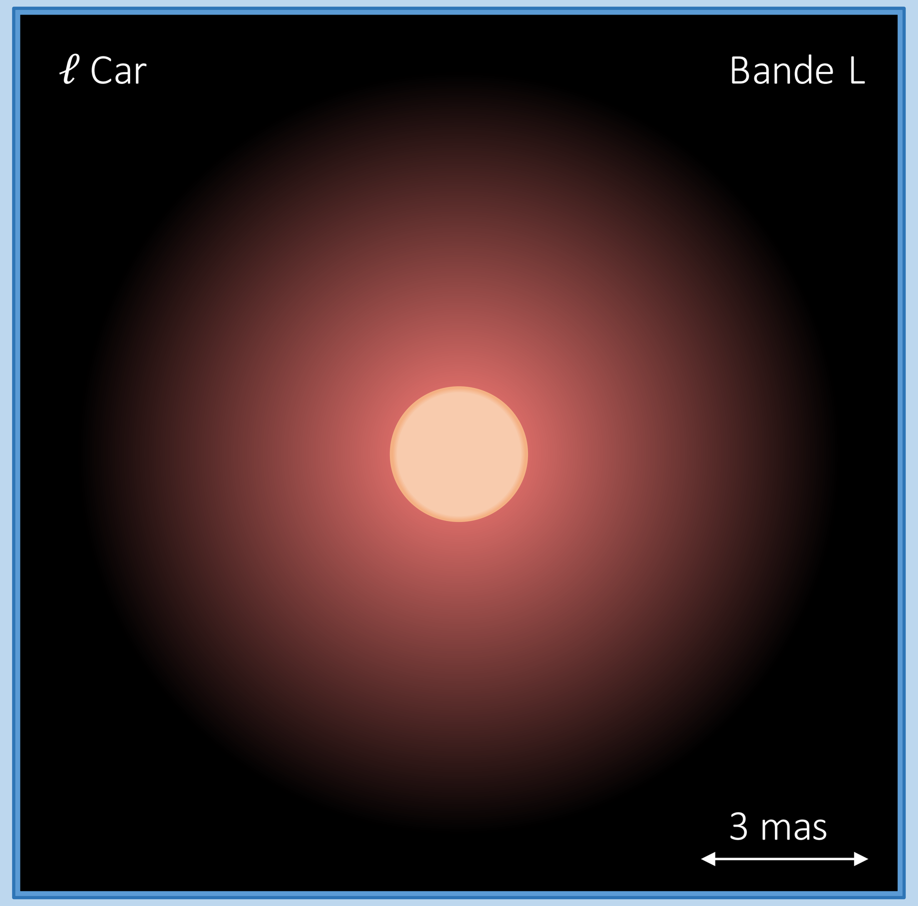

Figure 3 : Illustration of the main result : centro-symetric CSE resolved around ℓ Car in *L* band.