Constraining Stellar Parameters and Atmospheric Dynamics of the Carbon AGB star V Oph

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Abstract

Molecules and dust produced by the atmospheres of cool evolved stars contribute to a significant amount of the total material found in the interstellar medium. To understand the mechanism behind the mass loss of these stars, it is of pivotal importance to investigate the structure and dynamics of their atmospheres. Our goal is to verify if the extended molecular and dust layers of the carbon-rich asymptotic giant branch (AGB) star V Oph, and their time variations, can be explained by dust-driven winds triggered by stellar pulsation alone, or if other mechanisms are in play. We model V Oph mid-infrared interferometric VLTI-MIDI data (8–13 μm), at phases 0.18, 0.49, and 0.65, together with literature photometric data, using the latest-generation self-consistent dynamic atmosphere models for carbon-rich stars: DARWIN. We determine the fundamental stellar parameters: \( T_{\text{eff}} = 2600 \, \text{K} \), \( M_{\text{bol}} = 3585 \, L_\odot \), \( M = 1.5 \, M_\odot \), \( C/O = 1.35 \), \( M = 2.50 \times 10^{-6} \, M_\odot \, \text{yr}^{-1} \). We calculate the stellar photospheric radii at the three phases: 479, 494, 448 \( R_\odot \); and the dust radii: 780, 853, 787 \( R_\odot \). The dynamic models can fairly explain the observed N-band visibility and spectra, although there is some discrepancy between the data and the models, which is discussed in the text. We discuss the possible causes of the temporal variations of the outer atmosphere, deriving an estimate of the magnetic field strength, and computing upper limits for the Alfvén waves velocity. In addition, using period-luminosity sequences, and interferometric modeling, we suggest V Oph as a candidate to be reclassified as a semi-regular star.

Key words: circumstellar matter – stars: AGB and post-AGB – stars: carbon – stars: mass-loss – stars: winds, outflows – techniques: interferometric

1. Introduction

After moving off the main sequence (MS), stars that are born with an initial mass in the range between 0.8 and \( \sim 8 \, M_\odot \) evolve to become red giant (RG) and horizontal branch (HB) stars, and then move forward ascending the asymptotic giant branch (AGB).

After experiencing several third dredge-ups, the mechanism responsible for transforming AGB stars from O-rich to C-rich (Iben & Renzini 1983), AGB stars can change their spectral appearance and become carbon stars. Being surrounded by dust and gas, AGB stars are one of the most important contributors to the enrichment of the interstellar medium. In particular, the contribution from carbon-rich AGB stars is essential for producing carbon-bearing molecules and dust, in particular C2, C3, C2H2, CN, and HCN molecules (see, e.g., Olofsson et al. 1993; Cernicharo et al. 2000; Gong et al. 2015); and amorphous carbon (amC) and silicon carbide (SiC) dust (see, e.g., Yamamura & de Jong 2000; Loidl et al. 2001; Bladh et al. 2019a).

As the star evolves, and becomes bigger in dimension, brighter, and cooler, it will eventually begin to pulsate. The pulsation will generate shock waves, and together with convection, lead to strongly extended molecular atmospheres. There, if the conditions are favorable (i.e., temperature and density sufficiently low and high, respectively), dust could eventually form. Up to now, the commonly accepted scenario for the mass loss of carbon stars is the following: if the opacity of the amC dust is high enough, the radiation pressure acting upon the dust grains will eventually provide enough momentum to the grains to accelerate them, and drag along by collision of the gas, driving an outflow (stellar wind) from the star. (see e.g., Fleischer et al. 1992; Höfner & Dortii 1997).

Höfner et al. (2003) modeled this scenario, solving the coupled equations of hydrodynamics, with frequency-dependent radiative transfer and time-dependent formation, growth, and evaporation of dust grains. The DARWIN models are the results of these dynamic atmospheres calculations. These models have successfully reproduced observations of carbon-rich stars, e.g., line profile variations (Nowotny et al. 2010) and time-dependent spectroscopic data (Gautschy-Loidl et al. 2004; Nowotny et al. 2013). However, several discrepancies remain when comparing those with interferometric observations (e.g., Sacuto et al. 2011; Cruzelèbes et al. 2013; Klotz et al. 2013; van Belle et al. 2013; Rau et al. 2015, 2017; Rau 2016; Wittkowski et al. 2018).

If this means that pulsation and radiation pressure alone are not able to explain the amount of mass lost by these stars, other mechanisms could play a role in helping drive the winds of cool giant stars. The possibility of (magnetic) Alfvén waves driving stellar winds and producing clumpy mass loss is discussed in, e.g., Woitke (2006), Vidotto & Jatenco-Pereira (2006), Höfner (2007), Höfner & Olofsson (2018), Rau et al. (2019), and very recently by Yasuda et al. (2019).
V Oph is currently classified as a carbon-rich, Mira star (e.g., Pojmanski 2002) with a period of 297 days. Its distance estimation from Luri et al. (2018) is $731 \pm 22$ pc, and the variability amplitude is 4.3 mag. Table 1 shows this and other parameters of the star.

Ohnaka et al. (2007; hereafter OH07) modeled the temporal variation of the physical properties of the outer atmosphere and circumstellar dust shell of V Oph, based on the mid-infrared interferometric data taken at 8–13 $\mu$m with the MID-infrared Interferometric instrument (MIDI, Leinert et al. 2003) observations at the Very Large Telescope Interferometer (VLTI). They derived the physical properties of the molecular outer atmosphere of C$_2$H$_2$ and HCN and the inner dust envelope based on semi-empirical models. However, as the same author suggests, to better understand the physical processes responsible for molecule and dust formation close to the star, a comparison of the observations with self-consistent dynamical models is necessary. Such a comparison has not yet been attempted, and is not presented in OH07.

Our intent is thus to analyze the previously existing data on the carbon-rich AGB star V Oph (reported in Ohnaka et al. 2007), modeling them with the state-of-the-art grid of dynamic atmosphere models for C-rich stars from Mattsson et al. (2010) and Eriksson et al. (2014). We aim also to explore and untangle the possible explanations (see also Section 5 in OH07) on whether the prominent role in causing C$_2$H$_2$ molecular extended layers is due to the dust-driven winds triggered by large-amplitude stellar pulsation alone, or if other physical mechanisms have a stake in V Oph, such as e.g., winds driven by Alfvén waves (e.g., Airapetian et al. 2000, 2010, 2015). We calculate the Alfvén wave speed to investigate this possible mechanism, which has not yet been tried before.

We summarize and describe the archive observations of the C-rich AGB stars V Oph in Section 2, together with its basic parameters. Section 3 illustrates the comparison of the observables with the self-consistent dynamic atmosphere models used. Section 4 presents our results, which will be discussed in Section 5, including a comparison with the evolutionary tracks, a speculative alternative scenario for the mass loss, and a possible recategorization of V Oph as a semi-regular star. We conclude in Section 6 with perspectives for future works.

### 2. Observational Data

V Oph has been classified up to now as a Mira variable star. This target has been observed by OH07 with the VLTI of ESO Paranal Observatory with the mid-infrared interferometric recombining (MIDI, Leinert et al. 2003) using the 8.2 m Unit Telescopes. MIDI, now decommissioned, provided wavelength-dependent visibilities, photometry, and differential phases in the N-band, i.e., from 8 to 13 $\mu$m.

OH07 presented the wavelength-dependent visibilities, differential phases, and spectra taken from 8 to 13 $\mu$m. For the journal of observations we refer to OH07, their Table 1. The star, observed over 6 nights at different periods, shows evidence of interferometric variability, as reported by the same authors. For the modeling described in Section 3 we adopted the data set binning as in OH07, i.e., a binning into three epochs: $\phi = 0.18, \phi = 0.49$, and $\phi = 0.65$.

The main parameters of the star, namely variability class, period, amplitude of variability, distance, and mass-loss rate, are shown in Table 1.

V Oph visual light curves were collected from archive data of Henden et al. (2016), Pojmanski (2002), Gunther (2006), Alfonso-Garzón et al. (2012), and shown in Figure 1, where the time of the MIDI observation is marked in purple, and some light-curve irregularities are noticeable. The nature of these irregularities is discussed in Section 5.1. A blow-up around the MIDI observations is shown in Figure 2.

#### 2.1. Photometry

We collected photometry from the literature in the V, R, L, and M photometric bands (Ohlson et al. 1986; Pojmanski 2002; Cutri et al. 2003b; Smith et al. 2004; DENIS Consortium 2005; Whitelock et al. 2006). A mean value was calculated for each filter, with amplitudes derived from the variability. For the other bands where no light curves were available ($B, I, J, H, K$), we collected values from the literature and averaged them. The standard deviations have been adopted as the errors on those values. In the case of bands with only one value and no associated error from the literature, we assumed a conservative 20% of the value as error.

#### 3. Modeling with Dynamic Atmosphere Models

##### 3.1. Models Description

We compared the observations with self-consistent dynamic atmosphere models for carbon-rich evolved stars. Using a grid of models representing a range of stellar parameters (Mattsson et al. 2010; Eriksson et al. 2014), we calculated synthetic photometry and synthetic interferometric profiles. Those were then compared with the observed (literature) photometric and interferometric data. The dynamic atmosphere models give

| Name | Variability Type | $P^*$ (days) | $\Delta V^a$ (mag) | $d^b$ (pc) | $L_{bol}^c$ ($L_\odot$) | $M^2$ ($10^{-7} M_\odot$ yr$^{-1}$) | $M^4$ ($10^{-7} M_\odot$ yr$^{-1}$) | $M^4$ ($10^{-7} M_\odot$ yr$^{-1}$) | $v^5$ (km s$^{-1}$) |
|------|-----------------|------------|----------------|--------|----------------|-----------------|-----------------|-----------------|-------------|
| V Oph | M               | 297        | 4.3            | 731 ± 22 | 3585           | 1.2 ± −        | 1.4 ± −        | 0.5 ± −        | ~7.5        |

Notes. The "−" indicate that no literature value is given.

a Samus et al. (2009).

b GAIA DR2: Gaia Collaboration et al. (2016, 2018), Luri et al. (2018).

c $L_{bol}$ is the bolometric luminosity derived from the SED fitting.

d Whitelock et al. (2006).

e Bergeat & Chevallier (2005).

f Groenewegen et al. (1999).

$g$ Observed terminal gas expansion velocity from CO lines (Groenewegen et al. 1999).
varying results from cycle to cycle; therefore we compared the data with each time step. The details on the fitting procedure are given in Section 3.2.

Those models result from solving the system of equations for hydrodynamics and spherically symmetric frequency-dependent radiative transfer, plus equations describing the time-dependent dust formation, growth, and evaporation. The models start with an initial hydrostatic structure; then a “piston” simulates the pulsation of the star, varying the inner boundary below the stellar photosphere. In C-rich stars amorphous carbon (amC) and silicon carbide (SiC) are the most abundant dust species found (see later). We underline that in those models only the dust formation of amorphous carbon is calculated in a self-consistent way, through the “method of moments” (Gail & Sedlmayr 1988; Gauger et al. 1990). We refer to Höfner & Dori (1997), Höfner (1999), Höfner et al. (2003, 2016), and Bladh et al. (2019b) for a detailed description of the modeling approach; the applications to observations are described in Loidl et al. (1999), Gautschy-Loidl et al. (2004), Nowotny et al. (2010), Nowotny et al. (2011), Sacuto et al. (2011), Rau et al. (2015, 2017), and Rau (2016).

These models are characterized by a series of parameters, such as effective temperature $T_{\text{eff}}$, luminosity $L$, mass $M$, carbon-to-oxygen ratio $C/O$, piston velocity amplitude $\Delta u$, and the parameter $f_L$ used in the calculations to adjust the luminosity amplitude of the model. From the hydrodynamic calculations the mean degree of condensation, wind velocity, and the mass-loss rate are calculated. Each model is described by a set of “time steps,” i.e., snapshots, each at different phases of the stellar pulsation.

The COMA code (Aringer 2000; Aringer et al. 2009), and the subsequent radiative transfer, were used to calculate the synthetic spectra, intensity profiles, and visibilities, from the temperature and pressure stratification of the dynamical models at each time step. To derive the synthetic photometry we integrated the synthetic spectra over the selected filters mentioned in Section 2.1. The abundances of the atomic, molecular, and dust species were calculated, from the temperature-density structure versus radius, considering the equilibrium for ionization and molecule formation. Assuming local thermal equilibrium (LTE), the atomic and molecular spectral line strengths were computed, together with the continuous gas opacity. The molecular opacities data are listed in Cristallo et al. (2007), while Aringer et al. (2009) show the
molecular spectral line strengths, and are consistent with the data used for constructing the models.

From the output of the dynamic atmosphere models, which are subsequently used in the COMA modeling, we took the amount of dust condensed into amorphous carbon (amC), in g cm$^{-3}$. We treated the amC dust opacity consistently (Rouleau & Martin 1991 in small particle limit—see also Eriksson et al. (2014) for further details on the dust treatment), as amC, as opposed to SiC, is considered in the models, so there has been no need to add it a posteriori with COMA. On the other hand, SiC is added artificially a posteriori, with COMA.

Following Sacuto et al. (2011) and Rau et al. (2015, 2017), the percentage of condensed material is as follows: 90% amorphous carbon, using data from Rouleau & Martin (1991), and 10% silicon carbide, based on Pegourie (1988).

### 3.2. The Fitting Procedure

We follow the fitting procedure approach described extensively in Rau et al. (2017). First, we compared the photometric observations taken from the literature to the whole grid of 540 dynamic atmosphere models. The parameter space of the grid can be found in Eriksson et al. (2014, i.e., their Figure 2).

We have calculated the model best fitting the photometric literature data among the whole grid, with the method of least-squares ($\chi^2$) as follows:

$$
\chi^2 = \sum_{(k,j)}^N \frac{(m_{MOD}(k,j) - m_{OBS}(j))^2}{\sigma_{OBS}^2(j)},
$$

where $m_{MOD}$ is the model magnitude and $m_{OBS}$ is the observed magnitude. The magnitudes have been normalized to the $K$-band magnitude, where the variability is the smallest, i.e., $m = m_{K_{\text{band}}} - m_{\text{band}}$, and this is the quantity plotted in the ordinate in Figure 3. $\sigma_{OBS}$ is the error on the photometry. The parameters of this model, together with its corresponding best-fit photometric time step, are listed in Table 2.

Second, from the computed intensity distribution, we produced the synthetic visibilities, following the approach of Davis et al. (2000) and Tango & Davis (2002), for all the time steps belonging to the best-fitting model for photometry. We calculated the Hankel transformation of the intensity distribution $I$, and then compared them to V Oph interferometric MIDI data, determining the best-fitting model using a chi-square analysis as from Equation (1), where visibilities (and their errors) replace the magnitudes (and their errors). The error on the interferometric visibilities is that of order of 10%–15% (see also Figure 4). For time-computational reasons, we only produced the synthetic visibilities for all the time steps belonging to the best-fit photometric model.

We note that the present work does not attempt to find the best pulsational single-cycle model fit to the set of three observational epochs (see the three different phases mentioned previously), to derive a model of the full cycle; in fact we do not know if there is any model that would fit a full cycle of V Oph in this model. We have, instead, used the model structures from the entire set of time steps in the one model best fitting the photometric data to find the one atmospheric structure that best fits the observations at each specific epoch—thusly making a semi-empirical determination of the parameters of the star’s atmosphere at that epoch. But we do not intend, nor claim, to have found a model that corresponds to the star throughout its cycle. We have simply used this semi-empirical fitting to assess the differences in atmospheric structure from one phase to another in this cycle.

The interferometric $\chi^2$ values of the best-fit time steps (Table 2) are provided for each of the three observed phases, to guide the discussion. For readability of the figures involving model visibilities, only the best time step is shown; we show in Figure 8 an example of figures of all the time steps of this model.

In the following paragraphs, we present the results of the comparison of the dynamic atmosphere models with the photometric and interferometric archive data of V Oph.

### 4. Results

#### 4.1. Photometry

The best-fit models for photometry of V Oph resulted, at first, in a model without mass loss. Since this star displays loss of mass in the literature (see Table 1), we perform a selection a priori. We choose, among the grid of 540 models, only the ones allowing for wind formation, that is, having a condensation factor $f_c > 0.2$. This results in a sub-grid of 168 models, among which we performed our analysis. The best-fit models for photometry (“Photom”) and interferometry (“Interf” at the three phases) are listed in Table 2, together with the initial best-fit windless model (“NO M”).

We would like to remark that this fit was done only with the aim of pre-selecting a model for the subsequent interferometric comparison. With this in mind, we noticed that, concerning photometry, the archival literature data longward of 2 $\mu$m contain only one observing date (single epoch). Data at shorter wavelengths often consist only of a small number of measurements, obtained during different light cycles. The only light curves available are the three ones in the $V$-band: Pojmanski (2002), Henden et al. (2016), and Alfonso-Garzón et al. (2012) (see also Section 2 and Figure 1). However, keeping our aim in mind, we noticed that the interferometric observations are not covered by the AAVSO and AFOEV light curves. Only in the case of the AAVSO light curve are photometric data available at the three different phases of the interferometric observations (see also Figure 1). The visual variability between the three epochs is $V = 9.1$ mag at $\phi = 0.18$, $V = 10.4$ mag at $\phi = 0.49$, and $V = 9.3$ mag at $\phi = 0.65$, and we can consider it negligible with respect to the visual amplitude ($\Delta V = 4.3$, see Table 1). We thus fit all the time steps of the best-fit model to the average observed $V$-magnitude photometry. Section 5 contains an extensive discussion on the interferometric variability with the dynamic model atmosphere, and derivation of stellar parameters.

The photometric data of V Oph agree well with the model predictions (see Figure 3) at all wavelengths, within the error bars. The small differences at wavelengths shorter than 1 $\mu$m, seen in Rau et al. (2017) for the two Mira stars of their sample (R Lep and R Vol), are not found in our fits of V Oph. However, a literature spectrum covering this whole wavelength range is missing. In Section 5.1 we discuss the similarities and differences in terms of model and observed parameters. As previously noticed by Rau et al. (2015, 2017) in their spectral analysis of other sources, the photometric synthetic models tend to show a higher flux in emission at $\sim 14 \mu$m, which is not seen in the observed data. The origin of this feature, predicted by the model, is the C$_2$H$_2$ $\nu_5$ band, as well as HCN $\nu_2$ (OH07),
as mentioned also by Loidl (2001). The good fit is confirmed by a $\chi^2$ of 1.72; see Table 2.

4.2. Interferometry

As mentioned several times in this work, V Oph shows interferometric variability. We thus fit its visibility profiles to the model independently, at each of the three phases. V Oph interferometric data are shown, for each of the three phases, as visibility versus wavelength in Figure 4, and as visibilities versus baselines in the lower panels of Figures 5–7. The typical shape of carbon-rich AGB stars in the mid-infrared is noticeable in the visibility spectra; indeed the visibility versus wavelength goes up from $\sim 8$ to $\sim 10.5 \mu m$. The emission from the C$_2$H$_2$ $\nu_4$ and $\nu_5$ bands makes the object appear larger than the star itself. Since the strength of the C$_2$H$_2$ bands becomes weaker from 8 to $\sim 10 \mu m$, the object’s apparent size decreases from 8 to $\sim 10 \mu m$, resulting in an increase of the visibility. At longer wavelengths, the object’s apparent size increases because of the presence of SiC dust around 11.3 $\mu m$ (see Figure 4), resulting in the decrease in the visibility.

Table 2 shows the fit at the three different phases. The quality of the fit, indicated by the values of $\chi^2$, is fair. However, comparison of the visibility as a function of wavelength, also as a function of baseline, shows that the models do not reproduce the observations at all the baselines/phases: we notice some differences between observations and models in terms of visibility shape (e.g., at baselines 85.6, 71.8, 41.9 m; see the upper and middle left panels of Figure 4) and absolute visibility level (e.g., at baseline $B_p = 124.2$ m, $\phi = 0.49$; see the middle right panel of Figure 4); these differences are discussed in detail in Section 5.

5. Discussion

5.1. The SED and the Interferometric Visibilities

The dynamic atmosphere models reproduce the literature photometric data well, and reproduce the the archive MIDI interferometric data quite well, even though the latter show discrepancies at the longest baseline. The best-fit model for V Oph is characterized by a relatively compact atmosphere, with gas and dust shells that are less pronounced than the previous models for carbon-rich Miras (e.g., Rau et al. 2015, 2017; Rau 2016). The best-fit model for V Oph shows episodic mass loss, and its mass-loss rate is $\sim 20$ times higher than the observed values reported in the literature (see Table 1). It should be noted that the model mass-loss rates are computed as averages over pulsation periods as described in Section 2.3 of Eriksson et al. (2014). Similar higher values for the mass-loss rates were found in Rau et al. (2017) with the best-fit model mass-loss rate being $\sim 10$ times higher than the literature value for the semi-regular star Y Pav, and $\sim 5$ times for the irregular star X TrA.

In Rau et al. (2017) we noticed that the models that best fit the Mira stars R Lep and R Vol have a more pronounced shell-like structure (i.e., the discontinuous, step-like structure of the intensity versus radius plot) than the non-Mira stars, and their visibility versus baselines profiles decline, leveling off at longer baselines (see Figure 6 in Rau et al. 2017). The best-fit models for V Oph are characterized by compact intensity profiles, as Figures 5–7 show. These differences could be related to the atmosphere of V Oph, which is probably less extended, and which shows signs of weak shell-like stratification. This suggests that the atmosphere of V Oph, albeit its
classification as a Mira star, might be similar to those of non-Mira stars (this is discussed in Section 5.6).

The best-fit model of V Oph interferometric data shows, as in the case of all the non-Mira stars in Rau et al. (2017; see their Figure 4), high visibility levels but no slope, i.e., the model visibilities do not increase with wavelength. We could explain this different behavior by examining the density structure (in terms of density versus radius, discussed in the Appendix, Figure 10) of the best-fit time steps at each phase. We notice that the the density profile in V Oph is smoother (i.e., the density falls off slowly with radius; see Figure 10) compared to the case of the Mira stars previously studied (i.e., RU Vir, R Lep, R Vol). As hypothesized by Rau et al. (2017), such smoother density distribution does not produce the slope difference seen in the Mira models of R Lep and R Vol. From this result we could portray the atmosphere of V Oph to be characterized by less pronounced shocks, which might result from a different cooling function or different dust formation parameters.

One possible way of interpreting these results is that the shock waves producing dust change at different cycles. A different interpretation could be related to the choice of selecting a priori only those models producing mass loss (see Section 4.1). To verify our choice, we check whether or not the model without mass loss (which was originally best fitting the photometric models, see Section 4.1) reproduces the visibilities well (this was the case for, e.g., R Scl in Wittkowski et al. 2017). We show the results of this experiment in the Appendix, which shows that the windless model cannot reproduce the data as well (see Figure 11).

However, an alternative explanation could be that such smooth, and not extended, intensity profiles could be caused by, instead of large-amplitude stellar pulsation alone, some other mechanism operating in the lower part of the atmosphere, such as Alfvén waves propagating at different speeds (Vidotto & Jatenco-Pereira 2006; Suzuki 2007). This possibility is discussed in Section 5.5. Another possible scenario for the behavior of the V Oph atmosphere is that the star could be more similar to semi-regular/irregular stars than to Mira stars. This hypothesis is discussed in Section 5.6.

We discuss below, separately, the shape and the level of the visibility profiles:

1. Level of visibility profiles: overall, the visibilities fit show that at phase 0.18 (Figure 4, upper panel) the model can reproduce the observations from 8 until 11.2 μm for baseline 71.8 m, and until 9.4 μm for baseline 85.6 m, within the error bars (which are not shown in the corresponding panel for clarity reasons). At phase 0.49 (Figure 4, middle panel) the models at baseline 41.9 m (left) are within the observation’s error bar until ~11.1 μm, while for baseline 124.2 m (right) the models do not reproduce the observations in the entire wavelength range. Phase 0.65 (Figure 4, lower panel) shows a good fit of visibilities versus wavelength from 9.3 until 12.5 μm for baseline 87.6 m (left) and from 10 until 13.0 μm for baseline 120.0 m (right).

2. Shape of visibility profiles: this shape of the visibility profiles (i.e., the visibility at a given wavelength as a function of spatial frequency or baseline), is not always reproduced by the models: we observe that the synthetic visibility profile remains that after 10.5 μm for φ = 0.18 and φ = 0.49 Bp = 41.9 (upper and middle left panels in Figure 4). In the latter, we note that at the long baseline (Bp = 124.2 m) the shape of the visibilities is reproduced well by the models, but not the level (as encountered in Rau et al. 2017), and this can also be seen in the visibilities versus baselines at the same phase (Figure 6 right panel). We note that at the long baseline of φ = 0.65 (Bp = 120.0 m, lower right panel in Figure 4), the visibility profile fits better than that at the long baseline of φ = 0.49, both in terms of visibility versus wavelength, and especially of visibility versus baselines (Figure 7, right panel).

Concerning the visibilities versus baselines, we note the same trend as in Rau et al. (2017): in general the fit is better at 8.5 μm than at 11.4 μm, with an exception made for φ = 0.65 (Figure 7). The latter could be due to the fact that, for such compact (less extended) intensity profiles, the effect of the SiC inclusion in the models could be more pronounced than that for the extended profiles (see Rau et al. 2017, their Figures 6 versus Figure 7, and discussion therein).

An explanation of the discrepancies found in fitting the longest baseline Bp = 124.2 m at phase 0.49 could be related to, e.g., regular or irregular dust obscuration events (see, e.g., Clayton 2012 for R Crb stars), or by deviation from spherical symmetry due to a possible binary star that creates an elongated dust envelope or disk. However, the Bp and PA of phase 0.49 (Bp = 124.2 m, PA = 65.6) and phase 0.65 (Bp = 120.0 m, PA = 66.0) are very similar. Hence, while the non-spherical nature of the object cannot be excluded, it is unlikely to explain the bad fit of phase 0.49, Bp = 124.2 m. We also checked if there is significant cycle-to-cycle variation at phase 0.49 in the model visibility, which might explain the poor fit, and for this

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**Table 2**

Summary of the Best-fit Model for Each Type of Observation: Photometry and Interferometry

|                | T_eff (K) | log(L/Lo) | M (M_☉) | P (days) | log r (cm² s⁻¹) | C/O | Δu_v (km s⁻¹) | f_L (10⁻⁶ M_☉ yr⁻¹) | v_x² (km s⁻¹) | λ_ran (μm) | χ² red | φ_observ | φ_model |
|----------------|-----------|-----------|---------|----------|----------------|-----|---------------|---------------------|---------------|-------------|--------|-----------|----------|
| **V Oph**      |           |           |         |          |                |     |               |                     |               |             |        |           |          |
| Photom         | 2600      | 4.00      | 1.5     | 525      | −0.79          | 1.35| 6             | 1                   | 2.51          | ~8          | [0.4–25] | 1.72     | ...      |
| NO M           | 2600      | 4.00      | 2.00    | 525      | −0.66          | 1.35| 6             | 1                   | ...           | ...         | [0.4–25] | 1.53     | ...      |
| Interfl₁       | 2600      | 4.00      | 1.5     | 525      | −0.79          | 1.35| 6             | 1                   | 2.51          | ~8          | [8–13]  | 1.36     | 0.18     | 0.85     |
| Interfl₂       | 2600      | 4.00      | 1.5     | 525      | −0.79          | 1.35| 6             | 1                   | 2.51          | ~8          | [8–13]  | 5.03     | 0.49     | 0.10     |
| Interfl₃       | 2600      | 4.00      | 1.5     | 525      | −0.79          | 1.35| 6             | 1                   | 2.51          | ~8          | [8–13]  | 1.18     | 0.65     | 0.75     |

**Notes.** Listed are the corresponding values of the χ² red, and the parameters of the models.

* Model gas velocity from online material at Eriksson et al. (2014).
we refer to Section 5.2, where we report a substantial cycle-to-cycle variability among all the time steps of V Oph at the baseline $B_p = 124.2$ m.

### 5.2. The Cycle-to-cycle Variations at Phase 0.49

A significant cycle-to-cycle variation at phase 0.49 could impact the fit of the visibility spectra. We verify such a scenario by showing the visibility versus wavelength at phase 0.49 for all the time steps of the V Oph best-fit model with wind (projected baselines: $B_p = 41.9$ m and $B_p = 124.2$ m; see the upper left and upper right panels of Figure 8, respectively). We report a substantial cycle-to-cycle variability among all the time steps of V Oph at the baseline $B_p = 124.2$ m.

We would like to underline that we compare the model prediction to both baseline data at the same time (but not averaging them). The resulting best-fit time step, reported in Figure 8 (see also Table 2), is marked with a green line for...
\( B_p = 41.9 \text{ m} \) and a purple line for \( B_p = 124.2 \text{ m} \). The cyan line represents the best-fit time step obtained from fitting only \( B_p = 124.2 \text{ m} \) to the grid of time steps (versus fitting both baselines at the same time), and it corresponds to a \( \chi^2 \) of 9.95. Fitting only \( B_p = 41.9 \text{ m} \) alone to the grid of time steps of the best-fit photometric model would give a \( \chi^2 \) of 1.51.

For comparison and for completeness, we also show all the time steps of the windless model at the two baselines (see Figure 8, lower panels). When at \( B_p = 124 \text{ m} \) the visibility level increases by \( \sim 0.2 \) at the shorter wavelength, but the shape is not well reproduced, indicating that comparing the data to the windless model does not improve the quality of the fit.

5.3. Fundamental Stellar Parameters Compared to the Literature, and Evolutionary Tracks

From the best-fit models at the three phases we derive a number of parameters, as listed in Table 2. These values refer to the hydrostatic initial structure of the model (see also Nowotny et al. 2005). We then calculate the Rosseland diameter (\( \theta_{\text{Ross}} \)), to be able to compare the fundamental parameters of V Oph to the ones found in the literature; this is the diameter corresponding to the distance from the center of the star to the layer at which the Rosseland optical depth equals \( 2/3 \). We also calculated the corresponding effective temperature \( T_{\text{Ross}} \), i.e., the temperature of the time step at this Rosseland radius. Following the Stefan–Boltzmann law we can compute the Rosseland luminosity \( L_{\text{Ross}} \). Furthermore, from the literature photometric data, we derive the bolometric luminosity \( L_{\text{bol}} \), a diameter \( \theta_{(V-K)} \), using the diameter versus \( (V-K) \) relation of van Belle et al. (2013), and its corresponding effective temperature \( T(\theta_{(V-K)}) \). The error on the luminosity is assumed to be approximately 40%, on the basis of the distance uncertainty. (The uncertainties are known to be underestimated by up to \( \sim 30\% \) for bright stars Luri et al. 2018.) The errors of the temperature are estimated through the standard propagation of error. We list all these parameters in Table 3, for the three different phases. No \( K \)-band diameter is available for this target. We note that the observed and model gas velocities (see, respectively, Tables 1 and 2) agree quite well.

We compare the evolutionary stage of V Oph with ones for previously studied Mira and non-Mira stars (see Figure 9). We place temperatures and luminosities in thermally pulsing \( (\text{TP}) \) AGB evolutionary tracks from Marigo et al. (2013), illustrating the thermal pulse (TP) AGB tracks for three choices of the initial mass on the TP-AGB: 1.0, 2.0, and 3.0 \( M_{\odot} \). The first TP is extracted from the PARSEC database of stellar tracks (Bressan et al. 2012), and starting from this, the TP-AGB phase is computed, until the whole envelope is removed by stellar winds. The TP-AGB sequences are selected with an initial scaled-solar chemical composition: the mass fraction of helium \( Y \) is 0.273, and the one of metals \( Z \) is 0.014. To guarantee the full consistency of the envelope structure with the surface chemical
abundances, which may significantly vary due to the third dredge-up episodes and hot-bottom burning, the TP-AGB tracks are based on numerical integrations of complete envelope models in which, for the first time, molecular chemistry and gas opacities are computed on-the-fly with the ÆSOPUS code (Marigo & Aringer 2009). For further details on the calculations of the evolutionary tracks, we refer to Bressan et al. (2012), Marigo et al. (2013), and Marigo & Aringer (2009).

We note that the TP-AGB model for M=1.0 Mₗ does not experience the third dredge-up, hence it remains with C/O < 1 until the end of its evolution. Conversely, the model with M=2 and M=3 Mₗ experiences a few third dredge-up episodes that lead to reach C/O > 1, thus causing the transition to the C-star domain. The location of the observed C-stars in the H-R diagram, as well as their C/O ratios, appear to be nicely consistent with the part of the TP-AGB track that corresponds to the C-rich evolution. It is worth noting that the current mass along the TP-AGB track is reduced during the last thermal pulses, which supports (within the uncertainties) the relatively low values of the mass (~0.75–1.0 Mₗ) assigned to some of the stars studied by Rau et al. (2017) and reported for comparison in Figure 9 through the best-fitting search on the DARWIN models data set.

The model mass resulting from the dynamic atmosphere model is 1.5 Mₗ (see Table 2, second column). Such low current mass has been reduced during the last thermal pulses along the TP-AGB tracks; hence, within the uncertainties, this value agrees with the one derived from the observations (open circles), which place the star on a 2.0 Mₗ track before a TP phase, while the Rosseland calculations place V Oph in the vicinity of a 3.0 Mₗ Sun track. We also note a good agreement with the mass derived using the Wood (2015) WJK index and period (see Section 5.6).

We note that the temperature derived from the (V–K) relation and the bolometric luminosity of V Oph better resemble the temperatures of semi-regular stars than those of the other Mira stars.

The differences between the luminosity and estimations, Lₚ and Lₚₒ, are not within the error bars. This may be related to the abovementioned episodic mass loss of the best-fit model. Literature values of luminosity can be found in McDonald et al. (2017), and they agree within the uncertainties, with our estimate, considering the differences in the data sets and methods (Gaia DR2 is not refined yet for the most luminous stars⁶). We underline the very good agreement between Tₚ and the purely empirically determined T(θᵥ–K), as in the case of Rau et al. (2017).

We observe that the diameters θₚ and θᵥ in Table 3 agree extremely well, despite the episodic mass loss of the best-fit model.

⁶ Exempli gratia, https://gea.esac.esa.int/archive/documentation/GDR2/Data_processing/chap_cutspe/sec_cutspe_qa/sec_cutspe_val.html, Katz et al. (2019), and Bailer-Jones et al. (2018).
5.4. A Comparison with Ohnaka et al. (2007)

In this section we compare the results obtained by OH07 with their modeling, with the ones in the present work derived from the modeling with self-consistent dynamic atmosphere models. OH07 modeling consisted of a so-called “MOLSPHERE” model, with two separate molecular layers, and one layer of dust. The details of these models can be found in Ohnaka et al. (2007).

OH07, with their simple layer modeling, estimate the dust layer to be at \( \sim 2.5 R_\ast \), and calculate the stellar photospheric angular sizes (see Table 3 in OH07) at the three different phases. We converted these values in stellar radii. Those are reported in Table 4, together with the model photospheric radius (model size), and the dust radii, i.e., the radii in the models at which the dust starts to condense, derived at each phase from our modeling.

The modeling in this paper improves the estimation of the photospheric and dust radii of V Oph. This motivates future snapshot and imaging observations of this star in the mid- and near-IR, to observe if molecule and dust may coexist in the atmosphere of this star. Studying the variation in temperature/radius of molecules and dust will help put constraints on their distribution in the circumstellar environment of C-rich AGB stars (see also Section 6).

From Table 4 we note that the values of the photospheric radii estimated in this work are, at each phase, \( \sim 25\% \) higher with respect to the results in OH07. The difference with respect to OH07 could be due to the way in which the DARWIN models consider, in a self-consistent way, the production of dust, i.e., including radiation pressure on gas, which is not present in the simple layer model of OH07. The larger difference w.r.t. OH07 in the stellar radii may result from the fact that stellar radius was not directly measured in the MIDI data.

5.5. Discussion on the Possible Causes of the Temporal Variations of the Outer Atmosphere

In this section we discuss three possible causes of the interferometric variability detected by OH07. As stated above, variability was observed by OH07 between the interferometric data at phase \( \phi = 0.49 \) and \( \phi = 0.65 \) (see Section 2 and Table 1 in OH07). This variability means that OH07 observations of visibility versus wavelength, taken approximately at the same projected baseline length and position angles but 60 days apart, indicate a temporal variation at certain wavelengths (see their Table 1, data sets #3 and #6). These observations clearly indicate a temporal variation at 8.3, 10, and 12.5 \( \mu \text{m} \).

5.5.1. Alfvén Waves

We investigate below if the prominent role in causing C\(_2\)H\(_2\) molecular extended layers is due to the dust-driven winds triggered by large-amplitude stellar pulsation alone, or if other physical mechanisms could be called into question. The acceleration of this shell indeed can be driven by the stellar
radiation pressure on molecules and dust, and/or pulsation and convection, and/or thermal or magnetic pressure. Höfner & Freytag (2019) showed, through modeling an M-type star with 3D CO5BOLD radiation-hydrodynamics simulations, that pulsation and convection are likely mechanisms for producing the observed clumpy dust clouds. Here we provide a hypothetical, alternative scenario.

Using the results from OH07, the velocity of motion of a molecular shell of C$_2$H$_2$ from \( \sim 1.4 R_*$ \) to \( \sim 1.7 R_* \) at the timescale of 60 days represented by the time difference between phases 0.49 and 0.65, is \( \sim 20 \text{ km s}^{-1} \). From the model of wind acceleration via radiative pressure on dust best fitting our observations, the gas velocity is \( v_g \sim 8 \text{ km s}^{-1} \) (see Table 2), i.e., 2.5 times less than that observed in C$_2$H$_2$ shells. Gas motions with velocities of this order have been seen in the atmospheres of many AGB stars (e.g., Hinkle 1978; Vlemmings et al. 2017; Vlemmings et al. 2018), and these are interpreted as an effect of stellar pulsation. This is certainly a plausible interpretation. However, there are not sufficient observations in terms of time coverage of the whole stellar cycle, to confirm that the 20 km s$^{-1}$ flow is solely due to pulsation. In addition, e.g., Vlemmings (2018), referring to Falceta-Gonçalves & Jatenco-Pereira (2002), as well as several other authors (see also Section 1 and the end of this subsection), mentions that magnetic field could help levitate material off the stellar surface via Alfvén waves.

The gas in the shell is a weakly ionized gas that can support the propagation of Alfvén waves via ion-neutral collisions. The propagation of such waves in weakly ionized star-forming environments and molecular clouds is invoked to explain gas and dust acceleration, as they are less subject to damping compared to acoustic and compressible magnetohydrodynamic (MHD) waves (e.g., McKee & Zweibel 1995; Jatenco-Pereira 2014; Ballester et al. 2018). This suggests that the additional momentum could be exerted by some mechanical flux. The surface magnetic field has been measured on a number of giant and supergiant stars and post-AGB stars at the strength of a few Gauss (e.g., Vlemmings 2014; Sabin et al. 2015; Duthu et al. 2017; Vlemmings 2018); this suggests that rigorous convection could excite Alfvén waves, as seen on the Sun.

The V Oph molecular shell contains gas consisting of mainly hydrogen and C$_2$H$_2$. From Cherchneff (2012)—see their Table 2—the total gas density for a carbon star at 1.5 \( R_* \) is \( n_{\text{gas}} = 8.24 \times 10^{15} \text{ cm}^{-3} \). The mass density of this gas is about \( \rho = n_{\text{gas}} \cdot M_{\text{gas}} \approx 6 \times 10^{-11} \text{ g cm}^{-3} \). However, this gas is partially ionized, and we can consider the ionization fraction for a carbon star of the order of 7.8 \times 10^{-5} (Groenewegen 1997). With the gas-mass density \( \rho \) as mentioned above,
and this ionization fraction, we obtain a mass density of the ionized gas: \( \rho_{\text{ionized}} = 4.68 \times 10^{-15} \). Ionization fraction limits are also given by Spelverg et al. (1983): \(<4 \times 10^{-5}\); and Drake et al. (1991): \(<10^{-4}\). These correspond to, respectively, \( \rho_{\text{ionized}} < 2.4 \times 10^{-15} \), and \( \rho_{\text{ionized}} < 6 \times 10^{-15} \).

Maser polarization observations in AGB stars provide constraints on the magnetic field (see Vlemmings 2018, Figure 1). Assuming that the wind from V Oph is formed from an open radially diverging magnetic field (see, e.g., Airapetian et al. 2000, 2010), then from the conservation of the magnetic flux, \( B \propto r^{-2} \) (also consistent with Figure 1 of Vlemmings 2018). Then, the magnetic field strength at the distance of the molecular layer should be \( \sim 10 \text{G} \). This is consistent with the estimation of the magnetic field strength at the molecular C2H2 as an upper limit from the magnetic pressure and the thermal pressure forces:

\[
\frac{B^2}{8 \pi} \leq n_{\text{gas}} \cdot k_B \cdot T, \tag{2}
\]

from which we obtain the estimate of \( B \approx 7.6 \text{G} \), where \( k_B \) is the Boltzmann constant. However, considering the conservative estimation of the magnetic field (\( \sim 10 \text{G} \)), the corresponding Alfvén speed can be then estimated as

\[
v_A = \frac{B}{\sqrt{4\pi \rho_{\text{ionized}}}}, \tag{3}
\]

where \( \rho_{\text{ionized}} \) is the gas-mass density of the ionized material, and \( B \) is the magnetic field. With the gas-mass density of the ionized material given above, we obtain the following estimations of the Alfvén velocities: \( v_A \approx 410 \text{km s}^{-1}, <570 \text{km s}^{-1}, \) and \( <360 \text{km s}^{-1} \), using, respectively, the ionization fractions from Groenewegen (1997), Spelverg et al. (1983), and Drake et al. (1991).

While these calculations do not prove the presence of Alfvén waves in V Oph, or that the variation in the C2H2 shell is related to this mechanism, they offer upper limits for the Alfvén wave velocity, showing that it could be a reasonable possibility in the presence of a material with a higher degree of ionization, or higher gas mass. Indeed, if the mass density of the ionized material were even a factor of \( \sim 100 \) higher, the velocity would be lower, matching the observed \( \sim 20 \text{km s}^{-1} \) inferred for the C2H2 shell variability. In the same direction, if the ionization factor were higher, the Alfvén wave velocity value would decrease to match the observations. Future detailed MHD calculations, which are beyond the purpose of this paper, can provide further constraints on the Alfvén wave velocity.

Alfvén waves occur in the weakly ionized environment of the solar photosphere (Vranjes et al. 2008). Alfvén waves have been found to be efficient in driving winds, and produce clumpy mass loss from giant and supergiant stars (e.g., Vlemmings 2014; see also Hartmann & MacGregor 1982; Airapetian et al. 2000; Suzuki 2007; Airapetian et al. 2010, 2015; Carpenter et al. 2018; Yasuda et al. 2019, and Figure 7 in Rau et al. 2018). In a weakly ionized but collisional shell, a propagating Alfvén wave would also involve the motion of the neutral species that are present in the shell. This is due to the friction between charged particles and neutrals (e.g., Jephcott & Stocker 1962; Tanenbaum & Mintzer 1962; Woods 1962, and many subsequent works, e.g., Kulsrud & Pierce 1969; Pudritz 1990; Haerendel 1992; de Pontieu & Haerendel 1998; Watts & Hanna 2004). This is valid for any weakly ionized plasma, including the lower solar atmosphere and extended atmospheric environments of cool stars. The shell ionization could be caused by the heating from shocks and galactic cosmic rays (Harper et al. 2012; Wedemeyer et al. 2017; Höfler & Olofsson 2018).

### 5.5.2. Pattern Motion

A further hypothesis could be related to the matter of molecules appearing at a certain distance from the stars because of favorable conditions at that epoch. This would generate a pattern speed, rather than material moving at a high velocity. In this case the observed time variations would not be related to the motion of material but to a change in the region of molecule/dust formation. This could cause the molecules to form at one epoch, then get destroyed, and at the second epoch to form at another distance, then get destroyed again, and so on. Therefore, molecules would not physically move, but just be formed and destroyed at different radii, at different epochs.

### 5.6. A Hypothesis for Reclassifying V Oph as a Semi-regular Star

The period of V Oph is 297 days (Samus et al. 2009), which is relatively short for Mira stars, and similar to the period of, e.g., the semi-regular star Y Pav (see Table 1 in Rau et al. 2017). Not surprisingly, the observed visibilities versus wavelength at the shortest baseline 41.9 m (see the middle left panel of Figure 4) show a profile that is similar to that of a semi-regular rather than a Mira star. We observed the same behavior in the visibility versus baselines (see Figures 5–7), in terms of radial extension of the models.

To verify this hypothesis, following Wittkowski et al. (2017) we placed V Oph in the period–luminosity (P–L) diagram by Wood (2015; see Figure 10), where pulsation sequences are designated. Even though the diagram is based on the Large Magellanic Cloud (LMC), Whitelock et al. (2008) did not find significant differences

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**Table 3**

| Target | \( \phi \) | \( \theta_{V-K}^* \) (mas) | \( T_{V-K} \) (K) | \( \theta_{Ross}^* \) (mas) | \( R_{Ross} \) (R\(_{\odot}\)) | \( L_{Ross} \) (L\(_{\odot}\)) | \( T_{Ross} \) (K) |
|--------|-------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| V Oph  | 0.18        | 3.45            | 2710 ± 332      | 3.23            | 253             | 11669           | 2664            |
| V Oph  | 0.49        | 3.54            | 2677 ± 328      | 3.39            | 266             | 12442           | 2640            |
| V Oph  | 0.65        | 3.46            | 2704 ± 331      | 3.01            | 236             | 10204           | 2669            |

**Notes.**

* Relation from van Belle et al. (2013).
* \( \theta_{Ross} \) is the Rosseland diameter of the best-fit time step of the corresponding best-fit model.
in the $P$–$L$ relations at different metallicities. Correcting the
2MASS catalog $J$ and $K$ magnitudes (Cutri et al. 2003a) for LMC
distance, we calculated the $W_{JK}$ index value of V Oph: $W_{JK} = 9.37 \pm 0.3$, ($W_{JK} = K-0.686(J-K)$) is a reddening-free measure of
the luminosity—see Figure 1 in Wood (2015). Considering its
pulsation period, V Oph is located on the sequence that
corresponds to the radial first overtone mode pulsation, which is
more similar to semi-regular stars than Mira stars. In addition, from
the $W_{JK}$ relation, V Oph’s mass is estimated to be between 1.6 and
2.4 $M_\odot$ (see Figure 8 in Wood 2015).

We could interpret these results as V Oph displaying traits
that are closer to a semi-regular star rather than a Mira star.
While Feast & Whitelock (1987) suggested that semi-regulars
will become Miras as the stars evolve, and Habing (1996)
instead claimed the opposite, other authors e.g., Kerschbaum
& Hron 1992; Speck et al. 2000, and references therein)
advocate that the evolution of Mira and semi-regular stars is
likely to be non-monotonic, with the stars alternating between
being Mira and semi-regular.

### 6. Conclusions

We have compared archive VLTI/MIDI observations of the
carbon-rich star V Oph with the DARWIN grid of self-
consistent dynamic atmosphere models for carbon stars.
The photometric modeling agrees extremely well with the
literature data, but we emphasize that the spectrum of V Oph
covering the wavelength from the visual to the mid-infrared is not
available in the literature. Spectral observations with the NASA
Infrared Telescope Facility (IRTF) SpeX and BASS instruments
covering a wide wavelength range would be of extreme
importance for future modeling efforts.

Our results from the interferometric modeling exhibit a fair
agreement with the observations, with some discrepancies. The
parameters of the molecular outer atmosphere and the dust shell
derived using the self-consistent dynamical models agree with
those derived based on the semi-empirical modeling by OH07,
given the different modeling approaches, showing that the star
radius is bigger at minimum light, i.e., at $\phi = 0.49$, than at
phases 0.18 and 0.65. We calculate the photospheric size
through our modeling: respectively 479, 494, 448 $R_\odot$ at
the fundamental mode.

The interferometric modeling of V Oph shows that this star
may be more similar to a semi-regular star, rather than a
Mira (e.g., the compact atmosphere, and the comparison with
previous works); we further confirm this hypothesis using the
pulsation sequences and relation in Wood (2015), which shows
that V Oph might pulsate in the first overtone mode rather than
the fundamental mode.

To explain the interferometric variability at the different
phases, we calculate the characteristic speed of perturbation.
This time variation could be interpreted as a change in the

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**Figure 9.** Hertzsprung–Russel diagram zooming in on the Asymptotic Giant Branch part. The lines show solar metallicity evolutionary tracks from Marigo et al. (2013). The different line colors display the regions of: oxygen-rich stars in gray ($C/O < 1.0$); C-rich stars in yellow ($1.0 < C/O \leq 1.5$); and stars with $C/O > 1.5$ in black. The numbers indicate the mass values at the beginning of the thermal pulsing (TP)-AGB. The track with $2 M_\odot$ is plotted with a dotted line, and the one with $3 M_\odot$ is plotted in a dotted–dashed line. The different symbols and colors refer to the luminosity and effective temperature, estimated through the comparison in this work of the models with photometric and interferometric observations. A typical error–size bar for the observation estimates is shown in the lower side of the figure. We note that the circles representing V Oph’s location on the tracks are open, unlike the ones for the other stars that are full, to make them better distinguishable; otherwise they would overlap.

### Table 4

| $\phi$   | $R_{\text{OH07}}^{\text{Oph}}$ ($R_\odot$) | $R_\text{Lep}$ ($R_\odot$) | $R_{\text{OH07}}^{\text{Dust}}$ ($R_\odot$) | $R_{\text{Lep}}^{\text{Dust}}$ ($R_\odot$) |
|----------|------------------------------------------|----------------------------|--------------------------------------------|------------------------------------------|
| 0.18     | 352                                      | 479                        | 880                                        | 780                                      |
| 0.49     | 402                                      | 494                        | 1005                                       | 853                                      |
| 0.65     | 360                                      | 448                        | 901                                        | 787                                      |

*Note.* For comparison, values from OH07 are also reported.
velocity. The strength of the magnetic plasma, and we provide upper limits for the Alfvén waves. Such waves could propagate in a magnetized density and temperature at different regions, or if the Alfvén waves. Detailed MHD modeling is needed to provide further constrains on the Alfvén wave calculations.

Simultaneous near- and mid-infrared interferometric (snapshot) monitoring observations of V Oph with the latest second-generation VLTI instrument MATISSE (Lopez et al. 2014) will be essential in order to better understand the phase and cycle dependence of the physical properties of the outer atmosphere and the dust shell. Finally, MATISSE will also be able to image this star, which will substantially help with studying the distribution and formation of the molecular and dust environments of the C-rich star V Oph. Consequently, these observations would help constrain the temperatures at different regions, and help to verify if the time variation is due to changes in the density and temperature at different regions, or if the Alfvén-wave-driven winds could play a role in explaining the extended molecular and dust layers.

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Software: COMA code (Aringer 2000; Aringer et al. 2009), ESOPUS code (Marigo & Aringer 2009).

Appendix
Windless Model

Table 2 shows the parameters of the windless model (“NO M”), which initially was reproducing the grid of models (before our a priori selection of only models losing mass). We show in Figure 11 the visibility fits for this model.

Note that there is no significant difference between the wind and the windless visibility profiles in terms of visibility level, despite the great difference in the mass-loss rate. This could be related to the similarity in parameter space of the two models: the model with winds and the windless one have the same T, C/O, L, piston velocity amplitude, and the only different parameters among the two models are surface gravity log(g) (and hence the ability to produce mass loss) and the mass M. This similarity produces very comparable visibility levels, but not shapes, as the windless model does not produce mass loss.

The major difference between the wind and the windless models fits (Figure 4, and Figure 11 respectively) is the shape of the visibility spectra, and this is related to the fact that the windless model does not reproduce the dust formation and wind zone.

Also, comparing the two density profiles (see Figure 10), the density structure does not differ much within ∼5 R. This region within ∼5 R may be where C2H2+HCN emission and dust emission originate, which primarily affects the MIDI data.
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Figure 11. Same as Figure 4, but for the windless model.
