

A catalogue of high angular resolution and contrast polarimetric maps of 45 nearby AGB stars with SPHERE/ZIMPOL

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ABSTRACT

Aims. We present the largest catalogue of asymptotic giant branch (AGB) stars, 45 targets in total, observed in polarized light at high angular resolution (~ 20 milliarcsec). The main goal of the study is to detect and characterize dust shells in the close environment of nearby AGB stars. This work also aims to systematically classify the AGB star circumstellar morphologies obtained with the SPHERE instrument installed at the Very Large Telescope (VLT), thanks to its Zurich Imaging Polarimeter (ZIMPOL).

Methods. We extracted and analyzed polarized intensity maps for 45 AGB stars, constructed from polarimetric observation data obtained with the SPHERE/ZIMPOL instrument. An ellipse fitting method was applied to characterize the circumstellar envelopes. Stellar parameters (luminosity, effective temperature, surface gravity, extinction, metallicity) were compiled and recalculated when necessary from spectral energy distribution (SED) fitting using the Python SED fitting tool (PySSED) software. These data were then used to train a random forest machine learning model to determine the most discriminating variables for a resolved envelope around a given star.

Results. We constructed polarization maps for all stars in the sample, revealing a wide diversity of circumstellar morphologies. We detected 16 dusty circumstellar envelopes, including three never observed before. They display a wide range of morphologies, all of them showing a clear departure from spherical symmetry, indicating interaction with a companion or asymmetric mass ejections. The random forest model identified optimal thresholds for several physical parameters, thus providing robust criteria to anticipate SPHERE's ability to resolve dust envelopes around AGB stars. These results facilitate the selection of targets for future observations and contribute to a better understanding of the evolution mechanisms of circumstellar envelopes.

Key words. Stars: AGB and post-AGB, (Stars:) circumstellar matter, Techniques: high angular resolution

1. Introduction

During the late stages of their evolution, low- and intermediate-mass stars (stars with an initial mass ranging between 0.8 and 8 $M_{\odot}$) evolve through the asymptotic giant branch (AGB) (Bresan et al. 2012). This phase of stellar evolution is characterized by an intense mass loss, with rates up to $10^{-4} M_{\odot} \text{yr}^{-1}$ (De Beck et al. 2010). This mass loss is an important contributor to the chemical enrichment of galaxies, since $\sim 95\%$ of all stars will pass through this phase, bringing newly formed elements to the interstellar medium (ISM) (McDonald & Trabucchi 2019). The mechanisms at play to trigger this mass loss are not fully understood, yet a combination of pulsation and convection is proposed to extend the atmosphere and trigger dust formation via shocks. Radiation pressure on newly formed dust grains triggers mass loss and gas is carried along via friction (Höfner & Olofsson 2018). After the AGB phase, the star shrinks and warms. The envelope formed during the mass-loss phase becomes detached and then ionized by the central star. A planetary nebula (PNe) is formed. For more than three decades, observations of PNe have shown that departures from spherical symmetry are common (Balick 1987). It is now widely accepted that the bipolar and multipolar morphologies of PNe are due to the presence of binary companions (Miszalski et al. 2009). The excess of lin-

ear momentum observed after the AGB phase (Bujarrabal et al. 2001) cannot be explained by a single star (Soker 2006; Nordhaus & Blackman 2006).

Recent observations at high angular resolution of the gas in the millimetre range with the ALMA array have revealed a wealth of morphologies for the inner circumstellar environments of a sample of 17 AGB stars (Decin et al. 2020). The leading interpretation is that this is due to the influence of (sub)stellar companions that are shaping the inner winds of these giant stars. Observations of the dust distribution in the inner part of the envelopes of AGB stars should thus give us clues about its distribution around AGB stars and the envelopes' alteration by binary companions. To better understand this mass loss process, high angular and high-contrast observations of such mass-losing stars are thus crucial.

The Zurich Imaging Polarimeter (ZIMPOL) camera (Schmid et al. 2018) onboard the SPHERE extreme adaptive optics instrument (Beuzit et al. 2019) on the Very Large Telescope (VLT) is one of the instruments best suited for this. The combination of an extreme adaptive optics system with an 8.2m-diameter telescope offers images with an angular resolution of ~ 20 mas in the optical range. The polarimetric capabilities of the instrument enable us to study faint dusty structures around bright stars: the

light from the central star is not polarized, while light scattered by dust becomes polarized.

In this work, we present the largest catalogue to date of AGB stars observed in polarized light at high angular resolution with SPHERE/ZIMPOL, with 45 targets. This catalogue provides a unique resource for the study of circumstellar envelopes and mass loss mechanisms in these evolved stars. We propose a systematic classification of circumstellar morphologies according to their resolved or unresolved character. We then use these results to train a machine learning model based on the random forest approach (Ho 1995; Breiman 2001). This aims to identify the most discriminating physical parameters to predict the resolved character of AGB circumstellar envelopes observed with SPHERE. Based on stellar properties, this work allows us to define simple and robust criteria to anticipate SPHERE’s ability to resolve dust envelopes around AGB stars. In the long term, this work will help us optimize the selection of targets for future observation campaigns dedicated to studying the evolution of circumstellar envelopes.

The paper is structured as follows. Section 2 presents the observations and data reduction of the 45 stars observed with SPHERE/ZIMPOL. In Section 3, we detail our methodology to produce the polarized intensity maps of our targets. We then assess the resolved nature of their circumstellar envelopes to enable a classification of their morphology. We finally present a first random forest model to predict the resolved nature of our targets. The results of this analysis are discussed in Section 4. We present our conclusions and prospects for future campaigns of AGB stars in Section 5.

2. Observations and data reduction

2.1. Target selection

This catalogue is mostly based on observations of nearby AGB stars from the SPHERE ‘Other Science’ guaranteed time observations program (GTO). Some of the observations were taken as fillers for the program. Other available ZIMPOL observations of nearby AGB stars were also retrieved from the archive. The goal was to produce the most homogeneous sample possible, despite the multiple observing constraints (e.g. stars’ observability, the weather and so on).

The sample of stars is mostly selected from the ‘fundamental parameters and infrared (IR) excesses catalogue of Tycho-Gaia stars’ (McDonald et al. 2012, 2017). It contains fundamental parameters for 1475 921 Tycho-2 and 107 145 Hipparcos stars, based on distances from Gaia Data Release 1. It contains a sub-sample of 558 stars classified as giants, all located within a radius of 300 pc around the Sun (hereinafter McDonald’s catalogue).

For our Other Science program, we observed 19 stars from McDonald’s catalogue. We selected bright stars ($V < 8$ mag, when possible) with a large IR excess ($E_{\text{IR}} \geq 1.2$, as we expect them to have observable circumstellar envelopes) to ensure optimal correction by adaptive optics. The targets were chosen according to their observability during the given observing nights. To this set, we added 18 targets observed by ZIMPOL for other programs, and present in McDonald’s catalogue. The Other Science program included three nearby AGB stars not present in McDonald’s catalogue (L_2 Puppis, V Hya, and Y Pav). Finally, to increase our sample of resolved envelopes around AGB stars by ZIMPOL, we added previously published data from five AGB stars (U Del, W Aql, V Psa, R Aql, and GY Aql). This selection is therefore not random, but intentionally biased towards bright

AGB stars with significant IR excess, and is representative of the subset of objects in the McDonald’s catalogue that are accessible to visible polarimetric imaging (see Appendix A for complementary details). Table B.1 presents the properties of the 45 targets we observed.

2.2. Observations

All observations presented in this study were acquired between September 2015 and January 2021 using the SPHERE / ZIMPOL instrument installed on the VLT (Schmid et al. 2018). The log of the observations is presented in Table B.2. The data were obtained with the following filters: I_PRIM, CntHa, N_R, R_PRIM, VBB, Cnt820, V, Cnt748, N_Ha, and B_Ha, the characteristics of which are given in Table 1.

We observed 26 stars as part of the GTO, to which we added 19 previously published datasets, which we reduced in a uniform way. Part of the observations were carried out within the framework of the ALMA Tracing the Origins of Molecules In dUst-forming oxygen-rich M-type stars (ATOMIUM) project. ATOMIUM focused on 17 evolved stars observed with ALMA for molecular mapping (Gottlieb et al. 2022), and also combines high-spatial-resolution observations with SPHERE/ZIMPOL for polarized dust imaging on 14 of the 17 sources (Montargès et al. 2023).

This diversity of origin of the observations made it possible to cover a wide range of instrumental configurations and seeing conditions, reinforcing the representativeness of the analyzed sample. Depending on the case, some stars were observed with alongside observations of a dedicated point-spread function (PSF) calibrator, while others were observed without.

Table 1: Characteristics of the ZIMPOL filters (Schmid et al. 2018) used for our observations.

Filter name	λ_c (nm)	$\Delta\lambda$ (nm)
VBB	735	290
R_PRIM	626	149
I_PRIM	790	153
V	554	81
N_R	646	57
Cnt748	747.4	20.6
Cnt820	817.3	19.8
CntHa	644.9	4.1
B_Ha	655.6	5.5
N_Ha	656.9	1.0

2.3. Data reduction

The raw observational data of all our catalogue were reduced using the SPHERE Data Centre (SPHERE-DC), a data processing service developed by the French scientific community for users of the SPHERE instrument (Delorme et al. 2017). This centre uses a reduction pipeline enriched with specific routines to optimize the reduction of SPHERE data. The raw data were calibrated using bias and flat-field frames. We then produced aligned images at different polarization modulator positions, recombination of polarized beams (I^+ , I^-), and differential subtraction to extract the Stokes polarization maps (Q , U) necessary for the construction of intensity maps (Schmid et al. 2018; de Boer et al. 2020).

In addition to data reduction, the SPHERE-DC pipeline also provides polarimetric observables such as the Stokes intensity (I), the polarized intensity (PIL), the degree of linear polarization (DoLP), and the angle of linear polarization (AoLP). These observables are used to shape the dust distribution around the structures. We described the polarized intensity and the degree of polarization using the following relations

$$\begin{aligned} \text{PIL} &= \sqrt{U^2 + Q^2} \\ \text{DoLP} &= \frac{\text{PIL}}{I} \\ \text{AoLP} &= \frac{1}{2} \arctan(U/Q). \end{aligned} \quad (1)$$

3. Results

3.1. Classification criteria for our 45 stars sample

We classified our sources envelopes into two main groups: resolved objects (clearly resolved and marginally resolved) and unresolved objects. For the classification, we used a resolution criterion based on both a study of the 2D Gaussian profile of the envelopes and the calculation of their mean radial profile of the data in polarized light.

To optimize the envelope characterization and improve the stellar classification, we applied automatic thresholding of the star intensity in polarized light to all 45 stars studied. Unlike the conventional method based on the estimation of the full width at half maximum (FWHM), we determine the width w_h at a normalized intensity height h which is much lower than 50% of the intensity peak for each star. The selection of h is automatically adapted to the observed morphology of the considered star.

For each image, we explore a range of h that is linearly distributed between 0.5% and 10% of the maximum intensity. At each threshold h , a set A is defined as

$$A(x, y) = \begin{cases} 1 & \text{if } \text{PIL}(x, y) > h \times \text{PIL}_{\max} \\ 0 & \text{otherwise,} \end{cases} \quad (2)$$

where $\text{PIL}_{\max}$ is the maximum linear polarized intensity of the image and (x, y) denote the coordinates of a given pixel. This region therefore defines the set of pixels above a given threshold h . To determine how close A is to an ellipse region, we set a function ellipse with semi-major axis a , semi-minor axis b , its centre coordinates (x_0, y_0) , and rotation angle θ from the positive horizontal axis to the ellipse's major axis with

$$\text{Ellipse}(X, Y) = \frac{X^2}{a^2} + \frac{Y^2}{b^2} - 1, \quad (3)$$

with the coordinates (X, Y) given by

$$\begin{cases} X &= (x - x_0) \cos \theta + (y - y_0) \sin \theta \\ Y &= -(x - x_0) \sin \theta + (y - y_0) \cos \theta. \end{cases} \quad (4)$$

We define a set B with all pixels of coordinates (x, y) located inside the area determined by the ellipse function. It is written as

$$B(x, y) = \begin{cases} 1 & \text{if } \text{Ellipse}(x, y) < 0 \\ 0 & \text{otherwise.} \end{cases} \quad (5)$$

For each image, we define the Dice coefficient (Dice 1945), which is a standard estimate of similarity between binary sets defined as

$$\text{Dice}_h(A, B) = \frac{2|A \cap B|}{|A| + |B|}. \quad (6)$$

Based on this Dice coefficient, we then minimize a function cost such as

$$\text{Cost} = 1 - \text{Dice}_h(A, B). \quad (7)$$

For a given h , the ellipse parameters are optimized to minimize the cost function, ensuring the best overlap between A and B .

For each h , we obtain a corresponding Dice_h . The optimal height $\hat{h}$ is defined as the value of h that maximizes Dice_h . With $\hat{h}$, we keep the associated ellipse parameters a and b for the remainder of the paper for a given star.

The choice of h and the ellipse parameters corresponds to a trade-off between maximizing the spatial extent and S/N ratio of the polarized signal in the detected region A . The ellipse is used here as a simple geometrical proxy, and therefore the optimal value $\hat{h}$ can be interpreted as a characteristic intensity level that captures a significant fraction of the circumstellar polarized emission.

We then calculated the mean radial PIL profile from the brightest pixel of total intensity, which we take as the origin, and computed the width $\hat{w}_h$ at a given normalized intensity level $\hat{h}$. Here, $\hat{w}_h$ is defined as the characteristic radial extent, derived from the azimuthally averaged radial profile, at which the polarized intensity exceeds the threshold $\hat{h}$. The same operation is performed for the star and its PSF. The ratio η is then calculated as the fraction w_h^*/w_h^{PSF} , where w_h^* and w_h^{PSF} are the widths computed for the star and the PSF, respectively.

For targets with multiple ZIMPOL observations obtained in different filters, we verified that the global envelope morphology and resolved or unresolved nature remain consistent across filters within the observational uncertainties, although moderate variations in polarized intensity and apparent extent are expected from the wavelength dependence of dust scattering and polarization (Khouri et al. 2020; Montargès et al. 2023). However, a detailed, systematic analysis of the wavelength dependence is beyond the scope of this work, as the available observations were not designed to provide homogeneous multi-filter coverage for each source.

Therefore, we retained a single observation per star to ensure a homogeneous and conservative classification. Specifically, we selected the filter that maximizes the measured stellar width w_h^* (and thus η), so that the envelope extent is not underestimated when several observations are available for the same star.

If the star has no dedicated PSF observation (this was the case for 21 of the 45 stars in our sample), the average value of w_h measured from the PSFs of other stars observed in the same filter is assigned as w_h^{PSF} , allowing the computation of η for this object. This average PSF width is systematically accompanied by its standard deviation, which quantifies the intrinsic dispersion of the PSF for a given filter and is propagated as an uncertainty when a mean PSF is used instead of a dedicated reference. The corresponding statistics (mean, median, standard deviation, and minimum–maximum range of w_h for each filter) are reported in Table 2.

The dispersion of the PSF widths as a function of the filter is further illustrated in Figure 1, where notched boxplots (with red

lines marking the medians and symbols indicating the mean values) provide a visual assessment of the PSF variability available in each band. This representation allows us to directly evaluate the level of uncertainty introduced when adopting an average PSF width in the absence of a dedicated PSF observation.

After this, we set ourselves a resolution ratio threshold η of 1.35, and proceeded to rank stars on the basis of this threshold. This value was chosen because it corresponds to the point at which clear morphological features start to become visible in the images. Stars for which η is larger than 1.35 are considered to be resolved; those for which η ranges between 1 and 1.35 are considered to be marginally resolved; and those for which η is smaller than 1 are considered to be unresolved (we include $\eta = 1$ in this category to take into account any errors in calculation, reading, and assessment).

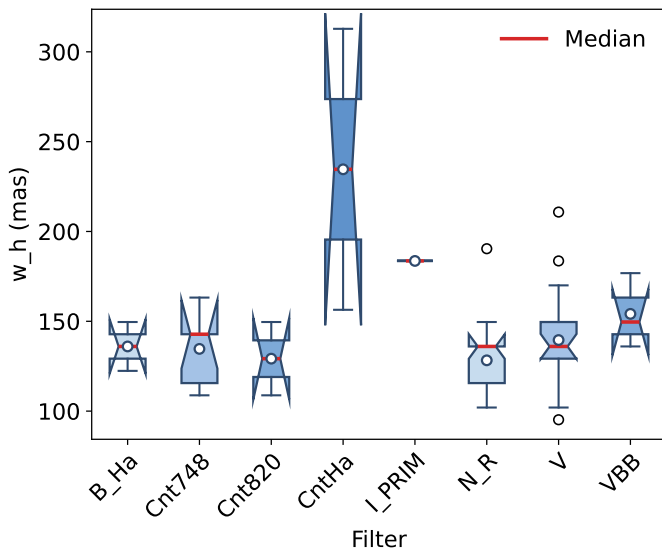


Fig. 1: Distribution of the PSF width w_h measured in polarized intensity for each SPHERE/ZIMPOL filter. The boxplots show the median (horizontal red line), the interquartile range (boxes), and the overall spread of the measurements, while the notches indicate the confidence interval on the median and the symbols mark the mean values. This figure illustrates the intrinsic variability of the PSF width as a function of the filter and provides a visual estimate of the uncertainty associated with the use of an average PSF width when no dedicated PSF observation is available.

The classification criterion relies on the normalized width ratio $\eta = w_h^*/w_h^{\text{PSF}}$, such that variations in atmospheric conditions (as illustrated by the range of seeing values reported in Table B.2) affect both the target and the PSF in a similar way and therefore are largely cancelled out. Although variations in seeing can influence the quality of the adaptive optics (AO) correction, they do not set the final angular resolution delivered by SPHERE, as the AO system corrects a large fraction of the atmospheric turbulence. In addition, our analysis is performed in polarized light, for which the impact of residual seeing-related effects is further reduced. In addition, although the absolute degree of linear polarization may vary with wavelength and filter width, the large-scale morphology and spatial extent of the polarized emission are expected to be robust across the visible range probed by ZIMPOL. For stars observed in several filters, we therefore retained a single dataset per target by selecting the filter that yields the largest measured w_h^* , corresponding to the most

extended polarized signal at the adopted threshold. This choice provides a conservative estimate of the envelope extent and prevents filter-dependent underestimation. As our analysis relies primarily on relative and morphological criteria through the ratio η , neither seeing variations nor filter-dependent effects significantly impact the resolved/unresolved classification results.

3.2. Previously published resolved targets

In this section, we briefly present the properties of the objects in our catalogue observed with SPHERE/ZIMPOL that have already been published. We also discuss, based on DoLP maps, the morphologies of envelopes already mapped with SPHERE. The DoLP maps, on which the morphological analysis of the individual stars presented in this section and the following one is based, are grouped in Figure 2.

3.2.1. S Pav

S Pav is an oxygen-rich AGB star of type M7Ie, classified as a semi-regular variable (SRa). Its distance was estimated at 470 pc by (Heras & Hony 2005), who also observed a relatively low mass loss rate of $1.0 \times 10^{-7} \text{ M}_{\odot} \cdot \text{yr}^{-1}$. Several studies suggest that S Pav could be a binary system, a hypothesis supported by the asymmetry of its circumstellar envelope revealed by high resolution imaging with ALMA (Decin et al. 2020). The polarimetric study of Montargès et al. (2023) highlighted a maximum DoLP of 6% in N_R filter for S Pav, revealing a relatively spherical material distribution extending up to a radius of $20 R_{\star}$. Our observations show a maximum DoLP of $\sim 5\%$. Around S Pav, an asymmetry is observed with a well-organized structure, extending up to $12 R_{\star}$ (184.7 mas), with material continuing beyond this radius in the form of small clusters.

3.2.2. V PsA

V PsA is an M-type semi-regular variable (SRb) AGB star with a pulsation period of 148 days (Aringer et al. 1999). The available observations of the star do not reveal the presence of a stellar companion. Wallström et al. (2024) estimated its distance at 278 pc, its effective temperature at 2400 K, and its mass loss rate at $4.8 \times 10^{-7} \text{ M}_{\odot} \cdot \text{yr}^{-1}$. For V PsA, polarization revealed an elongated structure extending beyond $20 R_{\star}$ around the star, with a maximum DoLP of 6% in N_R (Montargès et al. 2023) indicating an extended and significant dust distribution. Our observations reveal a slightly higher maximum DoLP of $\sim 7\%$ and confirm a strongly asymmetric morphology, with a dominant structure oriented at a position angle of $\sim 45^{\circ}$. Polarized emission is detected from $\sim 2 R_{\star}$ (~ 20 mas) and extends outward up to $\sim 34 R_{\star}$ (~ 305 mas), indicating that dust is distributed over a wide range of spatial scales around the star.

3.2.3. R Hya

R Hya is an oxygen-rich AGB star of spectral type M6–9 and one of the best studied Mira variables (Wenger et al. 2000). Its pulsation period is 385 days, with a high amplitude in the visible, and its distance is estimated at 165 pc based on the parallax and the light curve (Zijlstra et al. 2002). Its stellar diameter is about 34 mas at $\sim 0.90 \mu\text{m}$ (Haniff et al. 1995), while near-IR measurements yield smaller values of ~ 24 mas (Richichi et al. 2005), giving a radius of about 2.6 AU. Its effective temperature is 2830 K (Feast 1996), and its mass loss rate is of the or-

Table 2: Summary statistics of the PSF width w_h (in polarized intensity) for each SPHERE/ZIMPOL filter.

Filter	N_{obs}	Mean (mas)	Median (mas)	Std (mas)	Min (mas)	Q1 (mas)	Q3 (mas)	Max (mas)	CV (%)
B_Ha	2	136.00	136.00	13.60	122.40	129.20	142.80	149.60	10.00
Cnt748	5	134.64	142.80	19.90	108.80	115.60	142.80	163.20	14.78
Cnt820	2	129.20	129.20	20.40	108.80	119.00	139.40	149.60	15.79
CntHa	2	234.60	234.60	78.20	156.40	195.50	273.70	312.80	33.33
I_PRIM	1	183.60	183.60	0.00	183.60	183.60	183.60	183.60	0.00
N_R	22	128.27	136.00	19.16	102.00	115.60	136.00	190.40	14.93
V	21	139.56	136.00	27.01	95.20	129.20	149.60	210.80	19.35
VBB	3	154.13	149.60	16.96	136.00	142.80	163.20	176.80	11.00

Notes. N_{obs} denotes the number of available PSF observations per filter. The coefficient of variation (CV) is defined as the ratio between the standard deviation (Std) and the mean (Mean) value of w_h , and provides a normalized measure of the PSF dispersion within each filter.

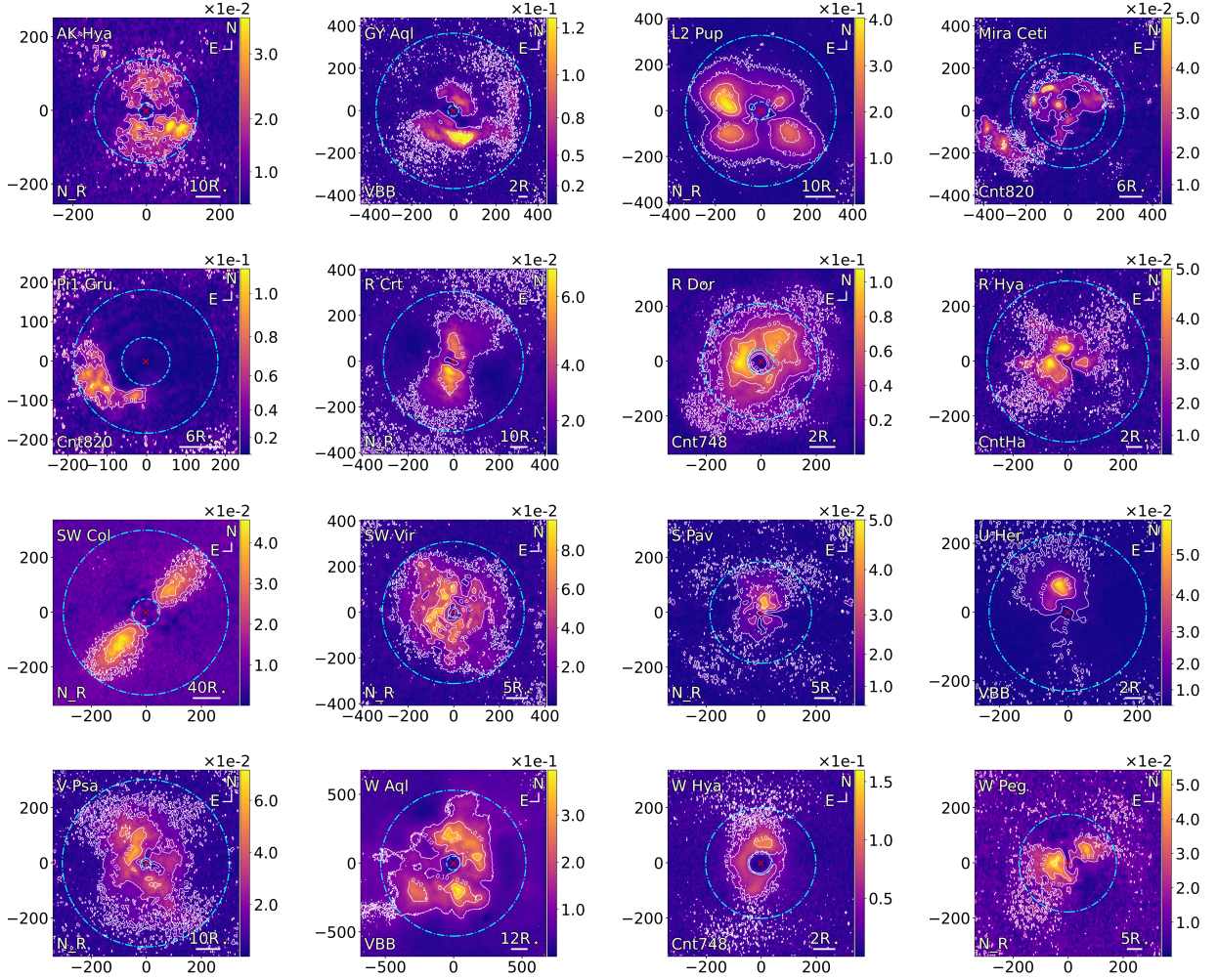


Fig. 2: Linear polarization degree maps of the 16 clearly resolved objects in our sample. White contours, customized for each star, highlight the morphological structure of the circumstellar envelope. Cyan circles, also customized for each star, delineate regions containing strong polarized signals, indicating the presence of dust. The horizontal axis corresponds to relative right ascension (RA) mas, while the vertical axis corresponds to relative declination (Dec) in mas. The scale bar at the bottom right is expressed in units of stellar radius ($R_{\star}$).

der $3 \times 10^{-7} M_{\odot} \text{yr}^{-1}$, with significant historical variations (Zijlstra et al. 2002). Infrared observations from the MIPS InfraRed Imaging of AGB Dust shells (MIRIAD) program with Spitzer have revealed a nebulous extent of about $400''$ around R Hya,

interpreted as a bow shock at the interface between the stellar wind and the interstellar medium (Ueta et al. 2006). No companion has been detected (Haniff et al. 1995; Richichi et al. 2005), but the circumstellar envelope shows asymmetries and complex

structures, with the presence of amorphous silicate dust (olivine, pyroxene) and oxides typical of oxygen-rich AGB stars (Bege-mann et al. 1997). The polarimetric study of Montargès et al. (2023) revealed structures in the form of isolated clumps in the environment of R Hya, extending up to $10 R_\star$, with a maximum DoLP of $\sim 5\%$. Our observations confirmed this structure with a global radius of $10 R_\star$ (~ 293 mas).

3.2.4. W Aql

W Aquilae (W Aql) is an evolved intermediate-mass S star on the AGB branch, with a C/O ratio of 0.98 (Brunner et al. 2018) and Mira variability (period of 490 days). Its mass loss rate is $3.0 \times 10^{-6} M_\odot \text{yr}^{-1}$, its expansion velocity is 16.5 km s^{-1} , and its distance is 395 pc (Ramstedt et al. 2018; Danilovich et al. 2014). W Aql has a F8–G0 companion at $0.46''$ (180 AU), inducing spiral structures and arcs in the circumstellar envelope (Ramstedt et al. 2017), with an overall smooth envelope that exhibits local asymmetries and a southwest-polarized extension. The W Aql object exhibited the strongest and most extensive DoLP, with a maximum of 39%, and material localized in places around the star, mainly beyond $20 R_\star$ (Montargès et al. 2023). This pronounced polarized DoLP indicates a particularly efficient dust production and the presence of dust grains with sizes and compositions that efficiently scatter stellar light and produce a high degree of linear polarization in the visible. For this object, our DoLP map shows an extremely large asymmetrical morphology around the star with an inner radius of $5 R_\star$ (51.1 mas), reaching $53 R_\star$ (530.7 mas). Inside the large envelope, we can see mainly asymmetrical clumps of dust with a DoLP of $\sim 39\%$. This study confirms the results of (Montargès et al. 2023) and suggests an important mass loss activity in the star. They are also in agreement with previously reported structures observed with ALMA (Ramstedt et al. 2017).

3.2.5. GY Aql

Gamma Aquilae (GY Aql) is an evolved M6–M10 star identified as a Mira-type AGB star that stands out as one of the most powerful SiO emitters among AGB stars (Pardo et al. 2004). Initially considered semi-regular, studies such as Alcolea et al. (1999) revealed a remarkable regularity in SiO variability and a contrast of 4–5, typical of Mira stars. The optical period of GY Aql, set at 461.5 ± 76 days, agrees perfectly with the period of the SiO maser determined by time series analysis (Pardo et al. 2004). The SiO maser emission has a main peak at $34 \pm 0.5 \text{ km s}^{-1}$, reflecting the velocity of the circumstellar gas, with a typical width of 1 to 6 km s^{-1} (Alcolea et al. 1999). To date, no interpretation in favour of the presence of a binary companion has been proposed for GY Aql, and the line profiles do not show signatures of binary interactions or complex circumstellar structures. The linear polarization of GY Aql, as observed by Montargès et al. (2023), appears as two lobes: the smaller lobe is located within $2 R_\star$, while the larger one is situated outside $2 R_\star$, with a maximum DoLP of $\sim 18\%$. This analysis coincides with the onset of spiral arms in ALMA gas maps, suggesting that dust forms or grows in these structures. For GY Aql, our DoLP map shows a maximum DoLP of $\sim 13\%$ and two asymmetrical clumps at $1.2 R_\star$ (25.9 mas) in the north and ~ 20 AU in the south of the star. The matter extends clearly as clumpy structures and reaches a radius of $\sim 17 R_\star$ (~ 337 mas) around the star.

3.2.6. π^1 Gruis

π^1 Gruis (π^1 Gru) is an AGB star of type S5.7, located at about 163 pc, at the transition between oxygen-rich and carbon-rich stars (Mayer et al. 2014). Its initial mass is about $2 M_\odot$, for a current mass close to $1.5 M_\odot$ (Mayer et al. 2014). The star exhibits semi-regular variability and a mass-loss rate estimated between $7.7 \times 10^{-7} M_\odot \text{yr}^{-1}$ (Doan et al. 2017) and $2.7 \times 10^{-6} M_\odot \text{yr}^{-1}$ (Winters et al. 2003). It has an effective temperature of 3100 K (Eck et al. 1998), a luminosity of $7240 L_\odot$ (Mayer et al. 2014), a gas-to-dust mass ratio of 380 (Groenewegen & de Jong 1998), and a wind expansion velocity of 14.5 km s^{-1} (Guandalini & Busso 2008). ALMA observations have revealed a complex circumstellar envelope around π^1 Gru, dominated by an extended and inclined equatorial disk, whose expansion varies with latitude (Nhing et al. 2016; Doan et al. 2017). This disk is associated with a rapid bipolar outflow, exceeding 100 km s^{-1} , well above typical AGB values (Doan et al. 2017, 2020), probably due to an episode of enhanced mass loss a century ago. The gas morphology also reveals a spiral structure, detected in CO, HCN, and SiO emissions (Doan et al. 2020; Homan et al. 2020). The observed dynamics cannot be explained by the distant G0V-type companion located at a separation ~ 460 AU (Mayer et al. 2014), but rather by a hidden stellar companion, recently revealed by ALMA and SPHERE at 6.05 ± 0.55 AU (Montargès et al. 2025), responsible for the formation of the equatorial disk and the spiral structure (Homan et al. 2020). Recent studies further constrained the nature of this close companion. Using multi-epoch ALMA observations, Esseldeurs et al. (2026) showed that it follows a Keplerian circular orbit and is likely a main-sequence star slightly more massive than π^1 Gru itself. In addition, VLT/MATISSE imaging by Drevon et al. (2026) revealed ongoing mass transfer through a WRLOF scenario, together with a circumcompanion disk-like structure and plume features linked to the onset of large-scale spiral morphology. The study of the π^1 Gru DoLP by Montargès et al. (2023) presents a polarized signal localized on one side of the star, between 10 and $20 R_\star$, with a maximum DoLP of 20%. This is probably related to the interaction between the stellar wind and a nearby companion, forming a polarized dust trail. For π^1 Gru, our observations reveal a DoLP maximum of $\sim 11\%$ and show clumpy polarized structures organized in an arc-like morphology, evocative of a spiral pattern, extending up to a radius of $18 R_\star$ (313.3 mas). This interpretation is supported by ALMA observations, which reveal spiral patterns and an equatorial disk in the gas component, suggesting a close coupling between the gas dynamics and the dust distribution.

3.2.7. U Herculis

U Herculis (U Her) is a Mira oxygen-rich AGB star, exhibiting intense maser activity in the H_2O , SiO, and OH lines (van Langevelde et al. 2000). Interferometric observations using very long baseline interferometry (VLBI) have allowed the precise localization of the maser regions. The brightest H_2O maser spot is identified as the amplified stellar image (Vlemmings et al. 2002), and for the OH maser at 1667 MHz, the amplified stellar image model is confirmed: VLBI measurements show that the most blueshifted maser spot traces the stellar position, $\mu_\delta = -10.9 \pm 1.4 \text{ mas yr}^{-1}$ (van Langevelde et al. 2000). The SiO masers, studied by (Cotton et al. 2010), form rings about twice as large as the stellar disk in the near-IR, comparable to the size of the molecular envelope, without marked asymmetry but with radial velocity gradients.

U Her was observed with a coronagraph, and its polarization map reveals a relatively extensive structure around the central star. The overall DoLP reaches relatively high values in the circumstellar environment of the star, with a maximum of $\sim 18\%$. The morphology of the scattering material reveals a highly asymmetric structure, preferentially extended towards the north-east, reaching up to $9 R_\star$ (~ 200 mas). This complex structure is consistent with the rings and the stellar disk reported by Cotton et al. (2010), and suggests the presence of a binary interaction.

3.2.8. SW Vir

SW Virginis (SW Vir) is an M7III AGB star located at 143 ± 20 pc according to van Leeuwen (2007). It exhibits semi-regular variability (SRb) with a period of 154 days and a visual amplitude of approximately 1.5 mag (Jura & Kleinmann 1992). The presence of technetium indicates that it is a thermally pulsating AGB (Lebzelter & Hron 2003). Its uniform angular diameter is 16.8 mas and 16.7 mas in H- and K-band (Ridgway et al. 1982; Schmidtke et al. 1986), giving a physical radius of approximately 1.2 AU. SW Vir has a luminosity of $4500 \pm 1100 L_\odot$ and an effective temperature of 2990 ± 50 K according to (Ohnaka et al. 2019), for an estimated mass between 1 and $1.25 M_\odot$. The Astronomical Multi-BEam combineR installed on Very Large Telescope Interferometer (VLTI/AMBER) observations revealed an extended outer atmosphere, with a diameter increasing from 16.2 mas in the continuum to 22–24 mas in the CO lines, indicating a MOLsphere up to $\sim 2 R_\star$ and a H_2O column of 10^{19} – 10^{20} cm^{-2} (Ohnaka et al. 2019). According to Olofsson et al. (2002) and Khouri et al. (2020) the SW Vir mass loss rate is estimated between 1.7×10^{-7} and $9.8 \times 10^{-7} M_\odot \text{ yr}^{-1}$ with an expansion velocity of 7.5 – 8.5 km s^{-1} . Khouri et al. (2020) estimated a less resolved polarized envelope in the visible, but with polarization detected at distances shorter than $2 R_\star$ ($R_\star \sim 0.9$ – 1.1 AU). The maximum DoLP is about 9.5 %, and the polarized region remains close to the star, mainly in the eastern hemisphere. With our observations, the DoLP map shows an inner radius of $1.2 R_\star$ (22.6 mas) and an outer radius of $16.5 R_\star$ (310.7 mas). This morphology is consistent with previous studies that report the presence of an extended MOLsphere and dust formation that occurs already in the close vicinity of the star (Ohnaka et al. 2019; Khouri et al. 2020).

3.2.9. R Crt

R Crateris (R Crt) is a semi-regular variable AGB star of type SRb, with a period of about 160 days and optical brightness varying between 9.8 and 11.2 mag, i.e. an amplitude of ~ 1.4 mag (Kholopov et al. 1987; Szymczak et al. 1999). Its spectral classification varies from M4 to M7/M8III depending on the studies (Szymczak et al. 1999). The O-rich star R Crt exhibits OH (1612, 1665, 1667 MHz), H_2O , and SiO maser emissions (Jewell et al. 1991; Le Squeren et al. 1979). The OH maser emission, imaged using polarimetric data with MERLIN, reveals a compact structure (< 0.2 arcsec) and an envelope modelled as a thin shell of radius 0.14 ± 0.04 arcsec (42–66 AU at 300 pc) (Szymczak et al. 1999). The OH envelope expansion velocity is 7.9 km s^{-1} , smaller than that of the H_2O masers (12.8 km s^{-1}) and CO (11 km s^{-1}), suggesting an axisymmetric structure or regional velocity variations. The estimated mass loss rate of the star via OH is 0.7 – $1 \times 10^{-7} M_\odot \text{ yr}^{-1}$, while estimates via CO are ten times higher (Kahane & Jura 1994). The study of Khouri

et al. (2020) on R Crt showed an envelope with a well-marked bipolar morphology in visible polarization, with a polarized cone extending up to ~ 6 – 12 AU from the centre (i.e. $5 R_\star$, with $R_\star \sim 1.25$ – 2.5 AU in the visible). The maximum DoLP reaches about $\sim 6.5\%$, with the south-eastern cone being the brightest in polarization. Our DoLP map (the same data as (Khouri et al. 2020)) confirms the large bipolar morphology around the star which reaches $40 R_\star$ (306.5 mas). In this large envelope, two asymmetrical clumps, consistent with the observations of Kahane & Jura (1994), suggest high mass loss activity in the inner regions of the envelope.

3.2.10. L₂ Pup

L₂ Puppis is an AGB star located at 64 pc, with a mass $\sim 2 M_\odot$ (Kervella et al. 2014), a prototype for the study of the latest evolutionary phases (Kervella et al. 2014). Observations with the NAOS-CONICA adaptive optics infrared camera at the VLT (NACO) in 2013 and 2015 revealed an opaque dust lane in the J band, interpreted as a disk inclined at 84° (Kervella et al. 2014; Lykou et al. 2015). In 2015, SPHERE/ZIMPOL confirmed the disk and discovered a companion at 2 AU (Kervella et al. 2015a). Modelling with RADMC-3D allowed Kervella et al. (2015b) to locate the inner edge of the disk at 6 AU and the dense outer edge at 13 AU from the centre of the star. The DoLP reaches a maximum of 42% in the V filter and 58% in the NR filter, indicating efficient scattering by dust grains on the disk. Their analysis suggested an early stage of bipolar planetary nebula formation. A recent ALMA study (Van de Sande et al. 2024) modelled the disk, estimated its age at $\lesssim 10^5$ years, and showed carbon-rich chemistry despite an oxygenated disk, paving the way for chemical exploration of disks around AGBs. For L₂ Pup, our DoLP map shows an elongated structure with a P.A. of ~ 50 and a size of $25 R_\star$ (308.8 mas). Inside this envelope are located mainly four asymmetrical clumps with different levels of polarization, as observed by (Kervella et al. 2015b), and explained as the polarimetric signature of an edge-on disk.

3.2.11. R Doradus

R Doradus is an oxygen-rich AGB star with low mass loss and a complex circumstellar envelope. The abundance profiles of SiO and HCN in the stellar wind show high initial abundances and specific radial declines, illustrating the chemical dynamics of the circumstellar medium (Van de Sande et al. 2018). ALMA observations have modelled gas density, temperature, and velocity, revealing complex motions and local overdensities in the extended atmosphere (Khouri et al. 2024). Interaction with the ISM is manifested by a bubble detected in UV, interpreted as the result of the stellar wind on the galactic environment (Ortiz & Guerrero 2023). The VLTI/AMBER infrared interferometry on this object revealed an expanding outer atmosphere, linked to dust formation (Ohnaka et al. 2019). Visible studies carried out with SPHERE/ZIMPOL by Khouri et al. (2016) revealed a resolved stellar disk around R Doradus, with a FWHM ranging from 58 to 71 mas depending on the filter and the epoch. The most representative size of the visible continuum is about 59 mas (i.e. ~ 3.4 AU at 59 pc), reflecting the influence of the variable molecular opacity in the star's atmosphere. Finally, ALMA revealed rotation, fast flows, and cold layers of SiO, revealing the morpho-kinematic complexity of the envelope (Nhung et al. 2021). For R Doradus, our observations (ESO program 098.D-0731(A), PI: Theo Khouri), which had not yet been published at

the time of this study and are therefore distinct from previous observations reported in the literature, in particular those of [Khouri et al. \(2016\)](#); [Schirmer et al. \(2025\)](#), show a high polarization with a maximum of $\sim 10\%$. Matter is detected at a distance less than $2 R_\star$ (<105 mas) with the highest DoLP close to the star. The envelope of this matter is clearly structured in a radius of $4.5 R_\star$ (~ 210 mas) and extends beyond the envelope as clumpy structures. Our observations are consistent with previous SPHERE/ZIMPOL studies of R Doradus ([Khouri et al. 2016](#); [Schirmer et al. 2025](#)), confirming an asymmetric dusty environment close to the star. The prominent polarized clumpy structures and high DoLP observed within a few stellar radii further support a highly inhomogeneous and time-variable dust formation process.

3.2.12. Omi Ceti

Mira Ceti (or Omi Ceti) is the prototype star of the Mira variables, an AGB giant of type M5-9IIIe located at 92 ± 10 pc ([van Leeuwen 2007](#)). It forms a binary system with a white dwarf (Mira B) at ~ 70 -80 AU, with an orbital period of approximately 500 years ([Priour et al. 2002](#); [Planesas et al. 2016](#)). Mira has a pulsation period of 333 days and a visual amplitude of approximately 8 mag ([Templeton & Karovska 2009](#)), with a temperature of 2900–3200 K, a radius of 21 mas, and a mass-loss rate of $2\text{--}3 \times 10^{-7} M_\odot \text{yr}^{-1}$ ([Khouri et al. 2018](#); [Ryde & Schöier 2001](#)). Its circumstellar envelope shows complex dynamics, pulsational shocks, and inhomogeneous dust formation ([Wong et al. 2016](#); [Khouri et al. 2018](#)). ALMA observations of Mira Ceti reveal fragmented morphology and preferential outflows ([Ramstedt et al. 2014](#); [Hoai et al. 2020](#)). The detection of neutral atomic carbon (CI) emission around Mira, shifted by $\sim 4 \text{ km.s}^{-1}$, suggests an origin related to photodissociation by Mira B ([Saber et al. 2018](#)). The visible morphology of Mira A, observed with SPHERE/ZIMPOL, revealed a marginally resolved stellar disk with a radius of about 21 mas corresponding to 2.15 AU at 102 pc (the distance estimated by [van Leeuwen \(2007\)](#)), as well as polarized dust structures around the star and its companion ([Khouri et al. 2018](#)). For this object, our observations (program ESO 100.D-0737(B), PI: T. Khouri, Cnt820 filter) show an asymmetrical structure located at a radius of $17 R_\star$ (~ 305 mas) and $1.8 R_\star$ (~ 32 mas).

The recent study by [Khouri et al. \(2026\)](#), based on the same SPHERE/ZIMPOL observing program but using V-band data, shows a broadly similar polarized morphology. Differences in wavelength sensitivity lead to variations in contrast and apparent spatial extent, but both datasets are consistent with a highly structured and asymmetric dust environment around Mira A.

This asymmetric distribution, characterized by arcs and localized condensations, is consistent with a perturbation of the stellar wind induced by a gravitational interaction with the companion. Such structures are in line with ALMA interferometric observations, which reveal pulsation-driven shocks and strongly inhomogeneous dust formation in the close environment of Mira Ceti ([Wong et al. 2016](#); [Khouri et al. 2018](#)).

3.2.13. W Hya

W Hydrae (W Hya) is an AGB star of type M7IIIe, located at 78 ± 7 pc ([Vlemmings et al. 2003](#)), a semi-regular variable (SRa) with a period of 382 days and a visual amplitude of 6 to 10 mag ([Lebzelter & Hron 2003](#)). The star exhibits SiO, H₂O, and OH maser emissions (1612, 1665, and 1667 MHz),

but the OH maser emission at 1612 and 1665 MHz is weak, typical of SRa ([Etoka et al. 2003](#)). Analysis with the Infrared Space Observatory Short Wavelength Spectrometer (ISO-SWS) reveals a rich molecular inventory (CO, H₂O, OH, CO₂, SiO, SO₂) around the star, with excitation temperatures of 300 to 3000 K ([Justtanont et al. 2004](#)). Spectral modelling indicates the presence of amorphous silicates, Al₂O₃ and Mg_{0.1}Fe_{0.9}O, with a dust mass loss rate of $3 \times 10^{-10} M_\odot \text{yr}^{-1}$ and a gaseous mass loss rate of $(3.5\text{--}8) \times 10^{-8} M_\odot \text{yr}^{-1}$. VLT/MIDI observations reveal an asymmetric structure of W Hya with a photospheric diameter of 42 ± 2 mas, correlated with a detached shell and a north-easterly jet observed by the Herschel Space Observatory's Photodetector Array Camera and Spectrometer (Herschel-PACS). The masers trace different asymmetric regions of the envelope, suggesting non-spherical mass loss ([Zhao-Geisler et al. 2015](#)). The star is listed as an optical double, but no physical companion has been confirmed. The dust envelope traced by visible polarization extends to about 30 AU from the centre ([Khouri et al. 2020](#)), with a DoLP reaching a maximum of about 2.5%, observed very close to or within the visible photosphere. Similar structures have also been reported in previous studies ([Ohnaka et al. 2016, 2017, 2024](#)). These multi-epoch and multi-wavelength studies of W Hya ([Ohnaka et al. 2016, 2017, 2024](#); [Khouri et al. 2020](#)) reveal a highly time-variable and clumpy dust environment within a few stellar radii. Although the overall asymmetric and inhomogeneous nature of the envelope is consistently observed, the detailed morphology (e.g. location, number, and contrast of clumps, as well as apparent large-scale asymmetries) varies significantly with time and wavelength, reflecting both dynamical evolution and phase-dependent dust formation. Our DoLP map, based on the same dataset as ([Khouri et al. 2020](#)) (ESO program 096.D-0930(B), PI: Theo Khouri), reveals a generally bipolar morphology, oriented at a position angle of $\sim 0^\circ$. Within this bipolar envelope appear four main clusters, distributed asymmetrically around the star and organized into two perpendicular structures, one of which is aligned with the global axis. These clusters exhibit high degrees of local polarization (up to $\sim 34\%$). The entire structure is contained within a radius of approximately $5 R_\star$ (~ 200 mas), with matter being detected as low as $\sim 1 R_\star$ (~ 40 mas).

3.3. Newly resolved objects

Among the objects classified as clearly resolved, AK Hya, SW Col, and W Peg are presented here for the first time in high-resolution polarized visible light. In this section, we describe these sources.

3.3.1. AK Hya

AK Hydrae (AK Hya) is an M6III-type AGB star ([Percy et al. 2001](#)). It is classified as a semi-regular variable (SRb), with a pulsation period of 50–75 days and a photometric amplitude of 1.16 mag in V ([Percy et al. 2001](#)). Its mass loss is moderate, probably less than $10^{-7} M_\odot \text{yr}^{-1}$ ([Kerschbaum & Olofsson 1999](#)), and the gas expansion velocity is 4.6 km.s^{-1} , typical of AGBs with low expansion velocities. The CO observations of AK Hya show detections in CO (1–0), CO (2–1), and CO (3–2) transitions with integrated intensities of 0.43, 2.79, and 6.11 K.km.s^{-1} ([Kerschbaum & Olofsson 1999](#)). The parabolic line profile and expansion velocity indicate an optically thick envelope and a moderate mass loss rate, typical of red SRVs with periods < 200 days. The American Association of Variable

Star Observers (AAVSO) observations over more than 3100 days confirm a complex multi-periodic variability of this star, characteristic of AGBs in the thermal pulsation phase (Percy et al. 2001).

The AK Hya polarized intensity maps reveal a bipolar circumstellar structure around the central source. The degree of linear polarization remains relatively low with a maximum of $\sim 3.5\%$, indicating an object with observed scattering activity that is less intense than other objects in the sample. The inner circle represents $5 R_\star$ (33.7 mas) and the large one $20 R_\star$. The circumstellar material we detect starts as close as $5 R_\star$ (~ 35 mas). The structure is elongated along the north-south direction, with a P.A. $\sim 5^\circ$. Weak polarized structures are revealed at the top and bottom of this structure and are concentrated toward its edges. This is more clearly seen in the northern part (~ 135 mas) of the bipolar shell. The bipolar structure is twice as narrow along the equator.

3.3.2. SW Col

SW Columbae (SW Col) is an M1III giant star on the AGB with an estimated distance of 92 pc by Dumm & Schild (1998). SW Col is a variable AGB star with a luminosity of $921 L_\odot$ and an effective temperature of 3660 K (McDonald et al. 2012). It has a visual amplitude of 0.33 mag in the V band and a main pulsation period of 78.7 days (Tabur et al. 2009). Characterized by multi-periodic pulsations and moderate amplitudes, this behaviour is typical of SRVs (Tabur et al. 2009). Although the majority of the local M giants are variable, SW Col does not exhibit extreme variability (Adelman 2000). At the circumstellar level, SW Col shows a moderate IR excess, indicative of dust production and an active stellar wind (McDonald et al. 2012).

Due to its remarkable morphology, SW Col constitutes one of the most fascinating objects in our sample. The DoLP map reveals relatively moderate values of the degree of linear polarization, reaching $\sim 4.5\%$. The revealed structure is highly bipolar and extends up to $120 R_\star$ (300 mas) in both directions. The circumstellar material we detect starts as close as $20 R_\star$ (~ 50 mas).

3.3.3. W Peg

W Pegasi (W Peg) is a Mira variable with a photometric amplitude of five magnitudes (8–13 mag) and a period of 344.9 days (Wyatt & Cahn 1983). Its average spectral type is M7e at maximum light, characterized by TiO bands, Balmer emission lines, and weak metallic lines (Keenan et al. 1974). Its position and radial velocity associate it with the Galactic disk. In addition, IR measurements ($J = 1.1$, $H = 0.2$, $K = 0.1$) confirm a cold atmosphere of this star ($T_{\text{eff}} \sim 2800$ K) (Cutri et al. 2003). W Peg has estimated angular diameters of 8.2 ± 0.1 mas and 9.6 ± 0.1 mas in the H and K bands (Millan-Gabet et al. 2005), reflecting the effects of molecular opacity. It has an estimated distance of 310 ± 31 pc, which corresponds to a linear diameter of about 1.2 AU in K (Wyatt & Cahn 1983). To date, no binary companion has been detected for W Peg.

Its polarization map reveals an extended structure around the central star. The structure is oriented along a P.A. $\sim 120^\circ$ and is larger in the south-east than in the north-west and extends up to $16 R_\star$ (~ 180 mas). The overall DoLP remains relatively low in the circumstellar environment of the star, reaching a maximum of $\sim 5.3\%$. The degree of polarization is very low perpendicu-

larly to the extend structure, as seen in other bipolar structures such as SW Col.

3.4. Representativeness of the sample

In order to identify possible discriminating parameters between our sample of 45 stars studied and the McDonald's catalogue, we applied two methods. We used first principal component analysis (PCA) to explore the data structure. Thus, we applied the Kolmogorov-Smirnov test (KS-test) to quantify the difference in the distribution of each parameter between the two groups. We conducted these two methods on a set of 11 stellar parameters: the distance (D), the luminosity (L), the effective temperature (T_{eff}), the stellar radius ($R_\star$), the interstellar extinction (A_V), the IR excess (E_{IR}), the fraction of reprocessed light in IR ($L_{\text{IR}}/L_\star$), the magnitude in the V, J, and K bands (M_V , M_J , M_K), and the colour index ($J - K$). More details on these two methods and the definitions of the relevant parameters are given in Section A.1.

The results of the PCA analysis reveal the ability of these methods to distinguish our sample of 45 stars studied from the rest of the red giants. The 2D PCA (Figure 3) projection shows that our sample of 45 stars is not representative of the large sample of red giants. Most of the stars in the subsample appear offset to the same side relative to the majority of the stars in the large sample in the PCA projected space. This suggests the existence of discriminating physical parameters between the two samples. This result confirms the specificity of our sample in the physical parameter space.

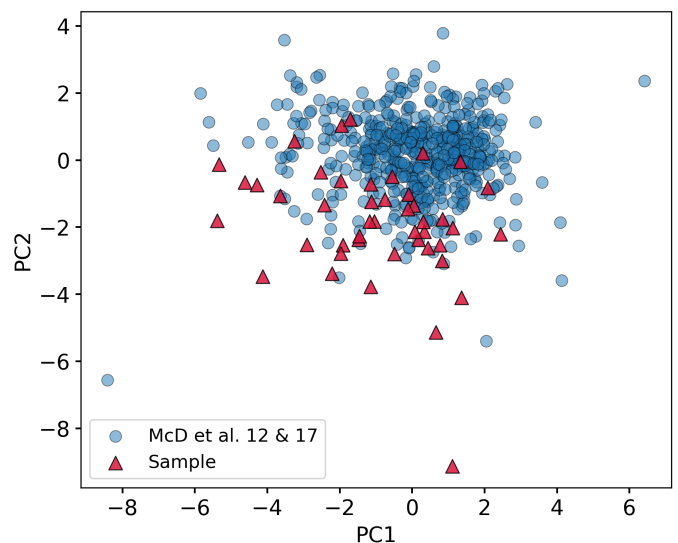


Fig. 3: Bi-dimensional projection of the PCA of the full sample (McDonald et al. 2012, 2017) in blue, and the selected subsample in red. The axes correspond to the first two principal components (PC1, PC2), which explain most of the variance in the data. This visualization highlights the distribution and separation of the selected stars in parameter space.

3.5. Prediction of the resolved nature of star envelopes

To propose some physical criteria for predicting the resolved nature of circumstellar envelopes by SPHERE in visible wavelengths, we applied a multi-step approach, combining machine

Table 3: Overview of stellar, variability, mass loss, and polarimetric properties for the 18 resolved AGB stars observed with SPHERE/ZIMPOL.

Star	Stellar type	Distance (pc)	Var	P (d)	T_{eff} (K)	L ($L_{\odot}$)	Mass-loss rate ($M_{\odot} \text{ yr}^{-1}$)	Max. DoLP(%)	R_{out} ($R_{\star}$)	Companion (sep.)
S Pav	AGB O-rich	470 (1)	SRa	–	–	–	1.0×10^{-7} (1)	~5	12	suspected
V PsA	AGB O-rich	278 (2)	SRb	148 (3)	2400 (2)	–	4.8×10^{-7} (2)	~7	34	–
R Hya	AGB O-rich	165 (4)	Mira	385 (4)	2830 (6)	–	$\sim 3 \times 10^{-7}$ (4)	~5	10	3500 AU (23)
W Aql	AGB S-type	395 (7)	Mira	490 (7)	–	–	3.0×10^{-6} (7)	~39	53	0.46'' (24)
GY Aql	AGB O-rich	–	Mira	461.5 (8)	–	–	–	~30	17	–
π^1 Gru	AGB S-type	163 (9)	SR	–	3100 (9)	7240 (9)	(7.7×10^{-7}) (9)	~11	20	6.05 AU (25)
U Her	AGB O-rich	–	Mira	–	–	–	–	~18	8	–
SW Vir	AGB O-rich	143 (10)	SRb	154 (10)	2990 (11)	4500 (11)	$(1.7\text{--}9.8) \times 10^{-7}$ (10)	~9.5	16.5	–
R Crt	AGB O-rich	–	SRb	~160 (12)	–	–	$(0.7\text{--}1) \times 10^{-7}$ (12)	~6.5	40	–
L_2 Pup	AGB O-rich	64 (13)	Mira	–	–	–	–	~40	25	~2 AU (26)
R Dor	AGB O-rich	59 (14)	–	–	–	–	–	~10	4.5	–
Mira Ceti	AGB O-rich	92 (10)	Mira	333 (15)	2900–3200 (15)	–	$(2\text{--}3) \times 10^{-7}$ (15)	~5	17	~70 AU (27)
W Hya	AGB O-rich	78 (16)	SRa	382 (16)	–	–	$(3.5\text{--}8) \times 10^{-8}$ (16)	~34	5	–
AK Hya	AGB O-rich	–	SRb	50–75 (17)	–	–	$< 10^{-7}$ (17)	~3.5	20	–
BK Vir	AGB O-rich	180 (18)	–	–	2920 (18)	2700 (18)	$\sim 2 \times 10^{-7}$ (18)	~2	35	–
RT Vir	AGB O-rich	226 (19)	SRb	153–320 (19)	2902 (19)	~6000 (19)	$10^{-7}\text{--}10^{-6}$ (19)	~7	23	–
SW Col	AGB O-rich	92 (20)	SRV	78.7 (20)	3660 (20)	921 (20)	–	~4.5	120	–
W Peg	AGB O-rich	310 (21)	Mira	344.9 (21)	~2800 (21)	–	–	~5.3	16	–

Notes. R_{out} denotes the maximum detected radius of polarized dust expressed in stellar radii. All objects listed in this table are resolved in polarized visible light.

References: (1) (Heras & Hony 2005); (2) (Wallström et al. 2024); (3) (Aringer et al. 1999); (4) (Zijlstra et al. 2002); (5) (Wenger et al. 2000); (6) (Feast 1996); (7) (Ramstedt et al. 2018; Danilovich et al. 2014); (8) (Pardo et al. 2004); (9) (Mayer et al. 2014; Doan et al. 2017; Winters et al. 2003); (10) (van Leeuwen 2007); (11) (Ohnaka et al. 2019); (12) (Kholopov et al. 1987; Szymczak et al. 1999; Kahane & Jura 1994); (13) (Kervella et al. 2014); (14) (Van de Sande et al. 2018); (15) (Templeton & Karovska 2009; Khouri et al. 2018); (16) (Vlemmings et al. 2003; Lebzelter & Hron 2003; Justtanont et al. 2004); (17) (Percy et al. 2001; Kerschbaum & Olofsson 1999); (18) (Perrin et al. 1998; Ohnaka et al. 2012; Winters et al. 2003); (19) (Zhang et al. 2017; Kudashkina & Andronov 2022; Brand et al. 2020); (20) (Dumm & Schild 1998; McDonald et al. 2012; Tabur et al. 2009); (21) (Wyatt & Cahn 1983; Keenan et al. 1974; Cutri et al. 2003); (22) (van Langevelde et al. 2000; Vlemmings et al. 2002); (23) (Homan et al. 2021) (24) (Ramstedt et al. 2014); (25) (Montargès et al. 2025); (26) (Kervella et al. 2015b); (27) (Karovska et al. 1997).

learning and optimal threshold analysis on our sample of 45 stars. The main objective of this study is to identify, from the observed and/or calculated parameters, the most discriminating factors for resolved nature, and to propose simple and interpretable rules for the prediction of whether the dust envelope of a star will be resolved by SPHERE or not. The following methodology is structured into three steps: global modelling, identification of discriminating parameters, and determination of optimal thresholds.

Examination of the most discriminating principal components of the PCA, as well as analysis of the most important variables according to the KS test, indicate that luminosity, IR excess (E_{IR}), effective temperature, and magnitude in the K band are the most important contributors to the differentiation of our sample (see Figure 4). These results confirm that the subsample selection allows us to isolate a subset of stars with distinct physical characteristics, thus justifying the adopted multivariate approach. In addition, the visual magnitude M_V and the near-infrared colour $J-K$ also appear as significant parameters separating the two samples.

These results show that, beyond the parameters that initially guided the selection of our 45 stars studied (luminosity, M_V , and E_{IR}), other stellar properties such as $J-K$, M_K , and T_{eff} contribute significantly to distinguishing our sample of 45 AGB stars from the larger population of red giant stars. From a physical perspective, this reflects differences in both stellar temperature

and circumstellar dust content, as redder colours and brighter near-IR magnitudes are indicative of cooler, more evolved stars surrounded by dust-rich environments.

4. Discussion

4.1. Resolved envelope properties and classification criteria

All 45 nearby AGB stars observed in our sample display a clear departure from spherical symmetry, with the presence at large scale (more than $10 R_{\star}$) of arcs, bipolar structures, or clumps. Since convection and pulsation can produce asymmetries in the immediate vicinity of single stars (Höfner & Freytag 2019; Freytag & Höfner 2023; Wiegert et al. 2024), our observations alone do not always allow us to distinguish unambiguously between intrinsic stellar processes and shaping by a companion. In particular, although large-scale arcs, clumps, or bipolar structures are often interpreted as signatures of binarity, similar non-spherical morphologies can also arise from asymmetric mass ejection in single stars.

The high fraction of large-scale asymmetric structures among the resolved envelopes indicates that additional shaping mechanisms are at play beyond a purely spherical steady wind. Although such morphologies are often associated with the influence of a (sub-)stellar companion, our data do not allow us to unambiguously establish binarity for all resolved systems. In

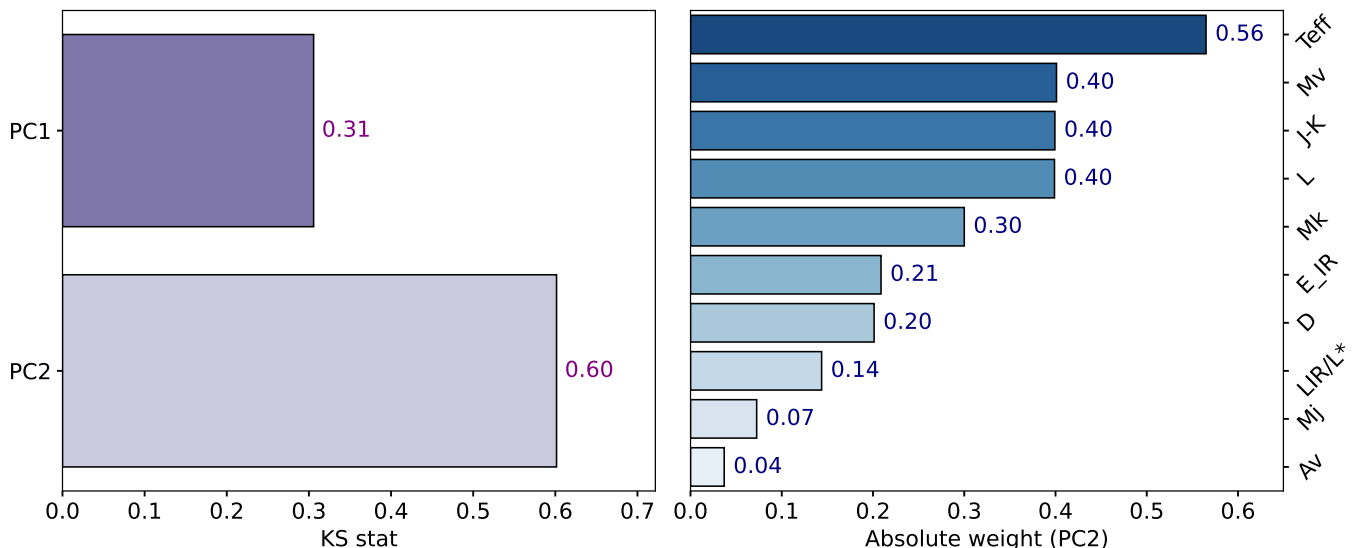


Fig. 4: Variables most discriminative between the full sample and the selected subsample, identified via the KS test in the 2D PCA space. Left: KS test comparing PC1 and PC2; the KS statistics are 0.60 for PC2 and 0.31 for PC1, showing that variables loading heavily on PC2 drive the separation between the samples. Right: Absolute variable weights in PC2.

several cases, the observed large-scale arcs, clumps, or bipolar-like features may therefore result from either binary interactions or intrinsically asymmetric mass ejection. Moreover, certain envelopes present a pronounced clumpiness, confirming that dust formation and mass loss processes are neither spatially nor temporally homogeneous.

Based on these morphological characteristics, we defined three observational classes: clearly resolved envelopes, marginally resolved envelopes, and unresolved objects. This classification allows us not only to distinguish between envelopes that are spatially resolved and those that remain unresolved with SPHERE but also to separate resolved envelopes according to the degree of morphological complexity. Of the 45 stars in our sample, 16 exhibit clearly resolved circumstellar envelopes, while 11 show marginally resolved structures, and 18 remain unresolved with SPHERE. For the purpose of predicting the resolved nature of circumstellar envelopes, the clearly resolved and marginally resolved objects were grouped into a single class of resolved envelopes.

Moreover, the analysis of circumstellar envelopes, illustrated by the ellipticity histogram (see Figure 5), reveals that all 16 clearly resolved envelopes analyzed exhibit a strictly non-zero ellipticity. This result indicates that none of these envelopes is compatible with a perfectly spherical geometry but instead displays systematic departures from sphericity, even when these deviations remain moderate. From a physical point of view, high ellipticity can result from several mechanisms: the presence of a stellar companion favours the formation of elongated structures by gravitational interaction or mass transfer; binary systems can induce preferential matter flows and circumbinary disks; finally, magnetic fields or asymmetric pulsations can channel mass loss in certain directions. These factors contribute to the observed morphological diversity and testify to the complexity of mass loss processes in the last phases of stellar evolution. This classification scheme also forms the basis for the random forest analysis presented in the following sections.

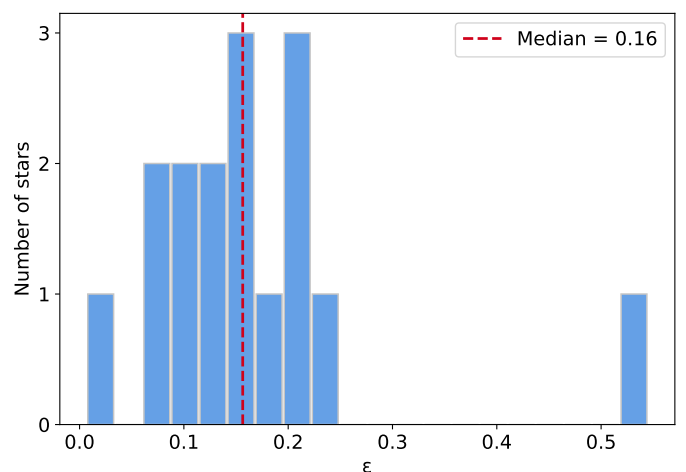


Fig. 5: Histogram of ellipticities ϵ of the 16 clearly resolved circumstellar envelopes, calculated for each star from the filter with the largest apparent diameter. The dotted red line indicates the median of the distribution. The ellipticity values reflect the level of elongation or flattening of the observed envelopes.

4.2. Impact of stellar physical properties on the morphology and extent of the dust shell

Our random forest model, trained on the physical parameters of AGB stars, identifies favourable conditions for observing a resolved envelope (for stars located within a radius of 300 pc) with the SPHERE instrument (see Table A.2).

Using the set of discriminating parameters, the optimal thresholds indicate that stellar luminosity plays a primary role in envelope detectability. The decision rule shows that the probability of resolving a circumstellar envelope increases when the luminosity exceeds the optimal threshold ($L > 4681 L_{\odot}$), a trend that is consistent with the higher median luminosity measured for resolved objects. Physically, more luminous AGB stars are

expected to sustain stronger mass loss rates, leading to the development of more extended and brighter dust shells.

The apparent angular size, corresponding to the angular radius of the central star and quantified by $R_\star$, is another strong discriminant. The envelopes are more likely to be resolved when $R_\star$ exceeds the threshold value (> 9 mas). Larger values correspond to more evolved and intrinsically larger AGB stars, which are statistically more likely to host extended circumstellar dust shells detectable with SPHERE.

Visual extinction (A_v) appears as a secondary discriminant. According to the decision rule, the probability of resolution is higher for values below the threshold ($A_v < 0.02$), while the median values remain very similar for resolved and unresolved objects. This suggests that A_v mainly traces line-of-sight effects rather than the global spatial extent of the circumstellar envelope and therefore plays a limited role in determining resolution. Overall, these results indicate that the most favourable targets for resolved observations are luminous AGB stars surrounded by extended dust shells, whose large apparent sizes enhance their detectability with SPHERE.

4.3. Observational criteria to select resolved targets

Our analysis also shows that several observational parameters play a determining role in the detection and characterization of the circumstellar envelopes of AGB stars with SPHERE (see Table A.2). A significant fraction of stellar luminosity reprocessed in the IR ($L_{IR}/L_\star$) is found to be a strong discriminant: the probability of resolution increases when $L_{IR}/L_\star$ exceeds the optimal threshold (> 0.007). This reflects the presence of substantial amounts of circumstellar dust, which enhances both thermal emission and scattered-light signals from extended envelopes.

The IR excess E_{IR} also appears as a relevant discriminating parameter. According to the decision rule, the probability of resolving a circumstellar envelope increases for values above the threshold ($E_{IR} > 1.42$), consistent with the slightly higher median value measured for resolved objects. A larger IR excess traces the presence of warm circumstellar dust and is therefore indicative of more developed dust envelopes that are more likely to be spatially resolved.

The contrast parameter (C_{tr}), which quantifies the brightness contrast between the circumstellar envelope and the central star, plays an important role in envelope detectability. In this work, C_{tr} is directly taken as the optimal height $\hat{h}$, determined from the radial profile of the polarized intensity map (PIL). This height corresponds to the relative polarized signal associated with the circumstellar envelope with respect to the peak polarized intensity in the image. The probability of resolution increases when the contrast exceeds the optimal threshold ($C_{tr} > 0.04$). Higher contrast values improve the visibility of circumstellar emission relative to the stellar PSF, facilitating the detection of extended structures in polarimetric imaging.

Finally, the axis ratio b/a provides insight into the morphology of the circumstellar envelope. In this case, the decision rule indicates a higher probability of resolution for values below the threshold ($b/a < 0.97$). We emphasize that this threshold should be regarded as an empirical criterion derived from our classification procedure rather than as a strict physical boundary. This suggests that departures from spherical symmetry, such as elongated or flattened dust distributions, produce stronger spatial signatures and are therefore more readily detected with high angular resolution imaging. However, we note that asymmetries may also be present in envelopes that remain unresolved, and that

part of the measured deviation from circular symmetry can be influenced by residual PSF anisotropies. Therefore, the axis ratio alone should not be interpreted as a definitive indicator of intrinsic envelope morphology. Together, these observational criteria indicate that SPHERE preferentially resolves circumstellar envelopes that are extended, dust-rich, and often morphologically asymmetric, where both angular size and contrast play a decisive role.

5. Conclusion

In this study, we presented the largest catalogue (45) of AGB stars observed in polarized light at high angular resolution. Polarization maps enabled us to resolve 16 dusty circumstellar envelopes, including three for the first time. All of these envelopes clearly show a departure from spherical symmetry. Such asymmetries may arise either from intrinsically asymmetric mass loss processes in single stars or from shaping by (sub)stellar companions. While binarity provides a natural explanation for some of the most pronounced morphologies (e.g. large-scale arcs or bipolar structures), our data do not allow us to determine in all cases which mechanism dominates. Moreover, certain envelopes present a pronounced clumpiness, confirming that dust formation and mass loss processes are neither spatially nor temporally homogeneous. Finally, using a random forest model applied to our sample, we determine the most important stellar parameters to use to be able to predict which star should have a resolved envelope or not. This should be useful for future surveys that aim to characterize dust shells around AGB stars.

Data availability

- (i) The supplementary polarimetric maps associated with this article, including the degree of linear polarization (DoLP) and polarized intensity (PIL) maps for all 45 AGB stars in the sample, are publicly available on Zenodo at DOI: [10.5281/zenodo.20607881](https://doi.org/10.5281/zenodo.20607881).
- (ii) The reduced SPHERE/ZIMPOL polarimetric images (DoLP and PIL maps) for the 45 AGB stars presented in this catalogue are available at the CDS via <http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/>.

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Appendix A: Samples comparison and star classification methods

A.1. Comparison between our catalogue and the parent sample

In this section, we compare our catalogue of 45 AGB stars observed in polarized light with SPHERE/ZIMPOL to the parent catalogue of 558 nearby giant stars compiled by (McDonald et al. 2012, 2017) and introduced in Section 2. As explained in the Section 2, the selection of our catalogue from the parent sample was guided by four main criteria: infrared excess, luminosity, observability with SPHERE, and AGB type. To evaluate how these criteria shape our catalogue relative to the parent population, we investigated whether additional stellar parameters could further discriminate between the two samples.

To this end, we conducted an in-depth analysis based on a set of 11 stellar parameters: the Distance (D), the luminosity (L), the effective temperature (T_{eff}), the stellar radius ($R_{\star}$), the interstellar extinction (A_V), the infrared (IR) excess (E_{IR}), the fraction of reprocessed light in IR ($L_{\text{IR}}/L_{\star}$), the magnitude in V, J, and K bands (M_V , M_J , M_K), and the color index ($J - K$).

Of these 11 parameters, 10 were determined using the Python Stellar Spectral Energy Distribution (PySSED) code (McDonald et al. 2024). The code corrects for interstellar extinction affecting the stellar flux in observational data using the 3D GTOMO map of A_V . It then fits the corrected flux with BT-Settl stellar atmosphere models (Johns-Krull et al. 2011) to determine physical parameters such as T_{eff} , L, and $R_{\star}$. The distance and extinction adopted for the fits correspond to those reported by the code, with the Hipparcos 2007 parallax being favored. The magnitudes M_V , M_J , M_K are obtained from catalogue queries.

The remaining parameters, E_{IR} and $L_{\text{IR}}/L_{\star}$, are determined from the following equations,

$$E_{\text{IR}} = \sum_{\lambda > 2.2\mu\text{m}} \frac{F_{\lambda}^{\text{obs}}/F_{\lambda}^{\text{model}}}{n_{\text{obs}}}, \quad (\text{A.1})$$

$$\frac{L_{\text{IR}}}{L_{\star}} = \frac{\int_{2.2\mu\text{m}}^{\infty} (F_{\nu}^{\text{obs}} - F_{\nu}^{\text{model}}) d\nu}{\int_0^{\infty} F_{\nu}^{\text{obs}} d\nu}, \quad (\text{A.2})$$

where F_{λ}^{obs} and $F_{\lambda}^{\text{model}}$ (resp. F_{ν}^{obs} and F_{ν}^{model}) represent the flux of the star from observation and its model derived with PySSED for a given wavelength (resp. a given $\mu = c/\lambda$) with c , the light velocity. In order to identify possible discriminating parameters between our sample of 45 stars studied and the McDonald's catalogue, we applied two multivariate analysis methods:

- (i) Principal Component Analysis (PCA) to explore the data structure and visualize the distribution of stars in the principal parameter space;
- (ii) Kolmogorov-Smirnov test (KS-test) to quantify the difference in the distribution of each parameter between the two groups.

A.2. Global modelling

A.2.1. Dataset for the Random Forest

To predict the resolved nature of the star envelope, we trained a Random Forest (Ho 1995; Breiman 2001) model on 14 avail-

able variables i.e. the 10 variables previously defined in Section A.1, excluding the effective temperature (since its contribution is already largely captured by the luminosity), plus the envelope-to-star contrast (Ctr), the axis ratio (b/a), the linear ellipticity $\varepsilon = 1 - b/a$, and the eccentricity $e = \left(1 - (b/a)^2\right)^{1/2}$, resulting in a total of 14 parameters). The Random Forest is a machine learning algorithm that builds an ensemble of decision trees using random samples of the data and random subsets of variables, in order to improve prediction accuracy and reduce overfitting. We chose it in this study because of its robustness to correlations between variables, its ability to handle moderately sized datasets as in our case, and its ability to provide a direct measure of the importance of each parameter. Specifically, the Random Forest computes variable importance by measuring the average decrease in impurity (Gini importance) across all trees: each time a variable is used to split a node, the reduction in classification error is recorded, and the total contribution of that variable is averaged over the ensemble. Variables with higher cumulative impurity decrease are deemed more discriminant.

Given the limited sample size ($N=45$), we did not adopt a standard train/test split approach. While such a split (e.g., 80/20) yields a single trained model that can be applied to new data, it risks overfitting or underfitting when the training subset is very small, and it provides only a single performance estimate that may be highly sensitive to the particular random partition. Instead, we focused on a repeated stratified cross-validation strategy, which offers a more robust assessment of model stability and generalization.

To ensure a reliable evaluation and avoid overfitting, we adopted the following approach:

– *5-fold cross-validation stratified, repeated 30 times.* To assess prediction stability and quantify performance variability, we repeated this entire 5 fold procedure 30 times with different random partitions, yielded 150 independent models (30 repetitions $\times$ 5 times), and each star was tested 30 times under varying training sets. Performance metrics (accuracy, precision, recall, F1-score) were averaged over all test predictions to obtain robust estimates, and their standard deviations quantified inter-split variability.

We also compared the cross-validation 3 times (test size 15 stars per fold, training size ~ 30) with 5 times across multiple repetition counts (5, 10, 30, 50, and 100). Both strategies yielded nearly identical mean performance (accuracy and F1-score differed by less than 0.01 at 100 repetitions), and the set of systematically misclassified objects remained identical. We retained 5-fold as our primary approach because (i) it maximizes the size of the training set per fold (36 stars vs. 30 for 3-fold), which is beneficial for small samples; and (ii) it exhibited slightly lower performance variance (standard deviations ~ 0.03 vs. ~ 0.04 for 3-fold).

– *Performance evaluation metrics.* The performance of the model was evaluated using several complementary metrics, defined as follows:

(i) *Confusion matrix M:* a cross-tabulation 2×2 of predicted versus true labels, which serves as the basis for all other metrics. The four elements are: (a) True Negatives (TN): unresolved stars correctly classified as unresolved; (b) False Positives (FP): unresolved stars incorrectly classified as resolved; (c) False Negatives (FN): resolved stars incorrectly classified as unresolved; and (d) True Positives (TP): resolved stars correctly classified as resolved. The matrix provides a detailed view of classification errors by class.

(ii) *Accuracy*: the proportion of correctly classified stars (both resolved and unresolved) among all test predictions, derived from the confusion matrix as $\text{Accuracy} = (\text{TP} + \text{TN}) / (\text{TP} + \text{TN} + \text{FP} + \text{FN})$.

(iii) *Precision*: the fraction of predicted resolved stars that are truly resolved, $\text{Precision} = \text{TP} / (\text{TP} + \text{FP})$. High precision indicates few false alarms.

(iv) *Recall* (or sensitivity): the fraction of truly resolved stars that are correctly identified, $\text{Recall} = \text{TP} / (\text{TP} + \text{FN})$. High recall indicates few missed detections.

(v) *F1-score*: the harmonic mean of precision and recall, $\text{F1} = 2 (\text{Precision} \times \text{Recall}) / (\text{Precision} + \text{Recall})$, which balances both metrics and is particularly useful for imbalanced classes.

(vi) *Macro-average* and *Weighted-average*: aggregate metrics across the two classes. Macro-average treats each class equally, computing the unweighted mean of per-class metrics; this is useful for assessing whether the model performs equally well on minority and majority classes. Weighted-average weights each class by its support (number of samples), providing a global performance estimate that reflects the class distribution in the data. Both are reported to ensure transparency on the model's behavior across classes.

The primary goal of this repeated cross-validation is to (1) assess the stability and robustness of the Random Forest classifier under different training/test partitions, (2) identify which variables are consistently discriminant (via variable-importance rankings averaged across all 150 models), and (3) detect objects that are systematically misclassified regardless of the training set, signaling intrinsic ambiguity in feature space.

A.2.2. Identification of discriminating parameters

To identify the physical parameters that contribute most to predicting the object's resolved nature, we employed the Random Forest variable importance rankings as a complementary validation step.

The Random Forest computes importance via Mean Decrease in Impurity (MDI), a Gini-based measure. For each variable X , we measured its contribution to reducing classification error by tracking the decrease in Gini impurity across all splits using X in the ensemble. The Gini impurity is defined as

$$\text{Gini}(D) = 1 - \sum_{k=1}^K p_k^2 \quad (\text{A.3})$$

where p_k is the proportion of class k in a node; a lower Gini indicates a more homogeneous (pure) node. We summed X contributions to Gini reduction across all 150 trained models (30 repetitions $\times$ 5 folds), then normalized to obtain a fractional importance score for each parameter.

While Random Forest importances indicate which variables the model uses most, they do not provide decision rules or thresholds for classifying new sources. Our core methodology for parameter selection and threshold determination therefore relies on a model-independent ROC/AUC approach.

A.2.3. ROC/AUC approach

As noted above, repeated 5-fold cross-validation does not produce a single final model suitable for prediction on new observations. We therefore adopt an alternative approach based on model-independent decision rules derived from ROC analysis

and the Youden criterion, which allows us to establish explicit, interpretable thresholds directly applicable to future sources.

For each variable X corresponding to a physical parameter, we calculated the optimal class-separation threshold using the ROC curve and the Youden criterion. This criterion consists of choosing the threshold (t_{opt}) that maximizes the difference between the true positive rate (TPR) and the false positive rate (FPR), that is, $J = \text{TPR} - \text{FPR}$. Only parameters whose ROC curves yield an area under the ROC curve (AUC) satisfying $\text{AUC} > 0.5$ are retained for the rule. Finally, to determine on which side of the optimal threshold (t_{opt}) a parameter must fall to likely support the object's resolved character, we compared the medians of the two classes ("resolved" class and "unresolved" class). Thus, for a given parameter X , if the class "resolved" has the smallest median (resp. the largest median), we consider that the parameter strongly supports the resolved character "if $X \leq t_{\text{opt}}$ " (resp. "if $X \geq t_{\text{opt}}$ ").

A.3. Discussion of model results

Model performance. Using stratified 5-fold cross-validation repeated 30 times, the classifier achieves a mean accuracy of 0.76 ± 0.03 , with a weighted F1-score of 0.75 ± 0.03 . The per-class metrics reported in Table A.1 indicate a better performance for the "resolved" class (precision 0.77, recall 0.85, F1-score 0.81; $n=27$) than for the "non-resolved" class (precision 0.73, recall 0.61, F1-score 0.67; $n=18$). The averaged confusion matrix is consistent with these values, with $\text{TN}=11$, $\text{TP}=23$, $\text{FP}=7$, and $\text{FN}=4$.

These results show that the model efficiently captures discriminant patterns between resolved and non-resolved envelopes (see the feature-importance and AUC analyses), while naturally reflecting the limitations imposed by a moderate sample size and a mild class imbalance. The higher recall and F1-score obtained for the resolved class are likely driven by both its larger representation in the dataset and the presence of more distinctive morphological and photometric signatures. In contrast, the non-resolved class exhibits a stronger overlap in feature space, as reflected by the larger number of false positives (7) compared to false negatives (4).

Crucially, repeating the 5-fold procedure 30 times provides a robust estimate of performance variability and prediction stability at the object level. Global metrics vary modestly across repetitions (standard deviations ~ 0.03), and the set of systematically misclassified objects remains stable, indicating that our conclusions do not depend on a particular random split. As emphasized by Hastie et al. (2009), the assessment of a supervised classifier depends on context, task difficulty, and class distribution. In our case, metrics around ~ 0.74 (accuracy and weighted F1) are consistent with the limited sample size and the intrinsic complexity of the problem, and they provide a sound basis for the rule-based predictions derived from AUC thresholds presented next. Nevertheless, caution is warranted when interpreting individual outcomes for the minority (unresolved) class.

Model stability and consistency at the object level. To assess the robustness of the results with respect to the choice of the training set, we repeated the stratified 5-fold cross-validation 30 times, so that each star is evaluated across a large number of independent training configurations. The relatively small dispersion of the global metrics (standard deviations of order ~ 0.03) demonstrates that the performance of the model is stable and not driven by a particular random split of the data.

Table A.1: Classification metrics and confusion matrix for 5-fold cross-validation repeated 30 times.

Class	Precision	Recall	F1-score	Support
Non-resolved	0.73	0.61	0.67	18
Resolved	0.77	0.85	0.81	27
Accuracy	0.76 (n=45)			
Macro	0.75	0.73	0.74	45
Weighted	0.75	0.76	0.75	45

Notes. The metrics shown are averaged over all repetitions to ensure robustness against training set variations.

Confusion matrix (averaged):

$$\begin{bmatrix} \text{TN} & \text{FP} \\ \text{FN} & \text{TP} \end{bmatrix} = \begin{bmatrix} 11 & 7 \\ 4 & 23 \end{bmatrix}$$

Table A.2: Optimal thresholds (t_{opt}) and associated statistics for the main discriminating variables in predicting the resolved nature of the circumstellar envelope.

Variable	Med_unres	Med_res	t_{opt}	Dir
L ($L_{\odot}$)	3098	6141	4681	>
Av (mag)	0.01	0.01	0.02	<
E _{IR}	1.80	1.81	1.42	>
LIR/L _★	0.004	0.011	0.007	>
Ctr	0.02	0.03	0.04	>
R _★ (mas)	5	14	9	>
b/a	0.89	0.86	0.97	<

Notes. The *Dir* column indicates the direction of the decision rule: “>” means that the probability of being resolved increases when the variable exceeds the threshold t_{opt} , while “<” indicates that the probability is higher below this threshold. The *Med_unres* and *Med_res* columns give the median of the variable for unresolved and resolved objects, respectively. The variables listed in this table account for a cumulative Gini importance of 54.81% in the Random Forest classifier.

Interpretation of systematic misclassifications. More importantly, by tracking the classification outcome for each individual star across all repetitions, we identify a limited subset of objects (12 out of 45, i.e. ~27%) that are systematically misclassified, with error rates exceeding 50%. These objects, summarized in Table A.3, can be separated according to their true morphological class.

This object-level analysis is based on the full set of 30 repetitions of the stratified 5-fold cross-validation and therefore differs from the averaged confusion matrix, which reflects the mean behaviour over a single 5-fold split and yields 11 misclassified objects.

Among the stars whose envelopes are intrinsically unresolved but are frequently misclassified as resolved, we identify S Lep, R Aql, RT Vir, R Peg, BK Vir, Bet Gru, T Cet, RX Lep, and R Hor. Conversely, three stars with intrinsically resolved envelopes SW Col, V Hya, and W Aql are predominantly misclassified as unresolved. This clear partition demonstrates that the

same objects are repeatedly affected across independent training subsets, indicating that the misclassifications are not driven by statistical noise or by the limited size of the training set, but rather by intrinsic stellar properties.

A detailed inspection of these problematic objects reveals two complementary regimes. In the case of unresolved stars misclassified as resolved, several objects exhibit high luminosities, large infrared excesses, or relatively large angular stellar radii, placing them close to the resolved population in the multidimensional feature space. These properties mimic the typical signatures learned by the classifier for resolved envelopes and naturally lead to confusion.

In contrast, resolved envelopes misclassified as unresolved tend to display global photometric or geometric parameters that overlap with those of the unresolved population, despite their clearly resolved morphology. This behavior is particularly well illustrated by SW Col, which is systematically misclassified despite exhibiting a strongly bipolar morphology. Its extreme elongation parameters make it morphologically unambiguous in direct imaging, yet its integrated photometric properties remain partially degenerate with those of unresolved stars.

An additional potential source of bias concerns the availability of a dedicated PSF observation for each target. Among the 12 systematically misclassified objects, 6 lack a dedicated PSF corresponding to 50% of the problematic subset, while the remaining 6 objects (50%) do have a dedicated PSF. This indicates that systematic misclassifications occur both with and without a dedicated PSF. Consequently, these errors cannot be primarily attributed to uncertainties in the PSF estimation, but rather reflect intrinsic ambiguities in the stellar properties themselves.

Overall, this analysis demonstrates that increasing the number of training repetitions would not fundamentally alter the conclusions: the same stars remain systematically misclassified, and the associated uncertainties are dominated by intrinsic stellar diversity and variability rather than by the choice of training set. Identifying and characterizing these objects, as summarized in Table A.3, is therefore a key outcome of the method, as it defines a well-motivated subset of targets for future observational and modelling efforts aimed at understanding the physical origin of their atypical properties. This object-level analysis complements the global performance metrics and reinforces the reliability and interpretability of the Random Forest approach adopted in this work.

Table A.3: Summary of the stars systematically misclassified by the Random Forest classifier (error rate > 50% across repeated cross-validation runs).

Name	True class	Error rate (%)	L ($L_{\odot}$)	E_{IR}	$R_{\star}$ (mas)	Dedicated PSF (Yes/No)	Comment
SW Col	Resolved	100	1059	2.45	3	No	strong asymmetry; low L
V Hya	Resolved	73	52698	6.18	6	Yes	extreme L + extreme E_{IR}
W Aql	Resolved	77	3698	1.30	10	No	low L
S Lep	Unresolved	77	3144	2.65	8	No	E_{IR} close to resolved
R Aql	Unresolved	100	32170	3.28	5	Yes	high L + high E_{IR}
RT Vir	Unresolved	100	2243	1.99	17	No	large $R_{\star}$; overlap regime
R Peg	Unresolved	90	4525	1.75	8	Yes	red colors; intermediate E_{IR}
BK Vir	Unresolved	90	3683	1.73	10	No	moderate E_{IR} ; elongation
Bet Gru	Unresolved	87	3052	1.22	17	Yes	very large $R_{\star}$
T Cet	Unresolved	73	7694	1.62	8	No	overlap in (L , E_{IR})
RX Lep	Unresolved	87	4122	1.31	10	Yes	$R_{\star}$ near resolved regime
R Hor	Unresolved	100	25564	5.76	25	Yes	extreme L + extreme E_{IR}

Notes. For each object, we report a subset of physical parameters that dominate the classification and misclassifications processes. The parameters L , E_{IR} , and $R_{\star}$ were retained because they are (i) among the most discriminant variables identified by the PCA, KS test, and Random Forest feature importance, and (ii) physically and observationally linked to the detectability and spatial resolvability of circumstellar envelopes with SPHERE. The error rate is defined as the fraction of individual cross-validation realizations (out of 30 repetitions of the stratified 5-fold cross-validation) in which a given star is misclassified. The last column indicates whether a dedicated PSF observation was available for the considered target.

Appendix B: Stellar observation and derived parameters

Table B.1: Stellar parameters used to train the prediction model.

Name	L	D	A _V	E _{IR}	LIR/L _★	Ctr	R _★	M _V	M _J	M _K	J-K	b/a	e	ε	Res_stat
-	(L _☉)	(pc)	(mag)	-	-	-	(mas)	(mag)	(mag)	(mag)	(mag)	-	-	-	-
Chi Cyg	12715	181	0.02	1.60	0.0078	0.02	23	6.96	0.17	-1.70	1.86	0.96	0.29	0.04	yes
Z Peg	752	201	0.01	1.63	0.0041	0.04	15	9.15	2.22	0.92	1.31	0.99	0.13	0.01	no
Y Pav	11213	403	0.02	2.18	0.0053	0.04	13	6.70	0.00	0.27	-0.27	0.90	0.44	0.10	yes
S Lep	3144	203	0.01	2.65	0.0053	0.01	8	7.00	0.80	0.00	0.80	0.82	0.57	0.18	no
R Aql	32170	422	0.24	3.28	0.0241	0.01	5	7.73	0.68	-0.83	1.51	0.95	0.31	0.05	no
U Her	4836	235	0.02	1.96	0.0159	0.01	25	8.43	0.86	-0.63	1.49	0.82	0.58	0.18	yes
R Crt	10371	261	0.01	1.81	0.0129	0.03	8	9.07	0.17	-1.40	1.58	0.80	0.60	0.20	yes
CW Cnc	2312	244	0.00	1.84	0.0029	0.08	5	9.27	1.42	0.11	1.31	0.91	0.42	0.09	no
S Pav	6083	184	0.01	1.58	0.0127	0.01	15	8.07	-0.20	-1.62	1.42	0.90	0.44	0.10	yes
R Dor	4681	55	0.00	1.46	0.0108	0.08	47	5.86	0.00	0.00	0.00	0.99	0.14	0.01	yes
U Del	16561	481	0.04	2.76	0.0165	0.08	5	7.00	1.03	-0.21	1.24	0.81	0.58	0.19	yes
W Peg	7639	294	0.04	1.64	0.0088	0.10	11	9.51	1.14	-0.16	1.30	0.84	0.54	0.16	yes
SW Col	1059	199	0.00	2.45	0.0050	0.01	3	5.94	2.12	1.06	1.06	0.46	0.89	0.54	yes
Pi.01 Gru	7970	163	0.00	1.77	0.0096	0.01	17	6.38	-0.66	-2.11	1.45	0.85	0.53	0.15	yes
W Hya	9944	104	0.01	1.71	0.0079	0.01	40	7.65	-1.74	-3.22	1.48	0.99	0.16	0.01	yes
Alpha Her	15009	110	0.02	1.42	0.0018	0.01	25	3.51	-2.30	-3.51	1.21	1.00	0.10	0.00	yes
Z Eri	2637	256	0.01	1.35	0.0011	0.01	5	6.90	1.59	0.00	1.59	0.96	0.29	0.04	no
R Leo	2093	71	0.00	1.59	0.0213	0.04	30	0.00	-0.72	-2.29	1.57	0.78	0.62	0.22	yes
RT Vir	2243	136	0.00	1.99	0.0097	0.01	17	8.72	0.36	-1.06	1.42	0.86	0.52	0.14	yes
R Peg	4525	287	0.03	1.75	0.0088	0.02	8	8.64	1.84	-0.05	1.89	0.91	0.42	0.09	no
BW Oct	3993	250	0.05	2.06	0.0118	0.06	8	8.85	1.08	0.00	1.08	0.75	0.66	0.25	yes
R Scl	6141	266	0.01	8.80	0.0206	0.02	15	7.10	1.44	-0.20	1.64	0.99	0.11	0.01	yes
L2 Pup	1651	64	0.00	5.03	0.0655	0.03	13	4.66	-1.06	-2.31	1.25	0.88	0.47	0.12	yes
Y Scl	1054	165	0.00	2.40	0.0117	0.07	7	8.59	1.57	0.00	1.57	0.89	0.46	0.11	yes
Mira	7760	92	0.00	6.48	0.0735	0.04	18	0.00	-0.73	-2.21	1.48	0.77	0.63	0.23	yes
SS Lep	6732	279	0.01	7.13	0.0033	0.09	3	4.99	2.90	1.67	1.23	0.75	0.66	0.25	no
T Mic	8679	211	0.03	1.33	0.0033	0.02	14	7.68	-0.36	-1.65	1.29	0.86	0.51	0.14	yes
R Hya	5824	124	0.01	1.66	0.0044	0.01	29	0.00	0.00	0.00	0.00	0.93	0.37	0.07	yes
BK Vir	3683	181	0.00	1.73	0.0132	0.02	10	8.36	0.54	-0.73	1.27	0.72	0.69	0.28	yes
DZ Aqr	2717	297	0.02	1.93	0.0161	0.02	4	8.98	1.85	0.56	1.28	0.77	0.64	0.23	no
AK Hya	2069	156	0.00	2.05	0.0107	0.04	7	6.81	0.64	0.00	0.64	0.99	0.12	0.01	yes
SW Vir	7634	143	0.01	1.62	0.0070	0.07	19	7.18	-0.36	0.00	-0.36	0.83	0.55	0.17	yes
Bet Gru	3052	54	0.00	1.22	0.0006	0.02	17	2.30	-1.97	-3.32	1.35	0.94	0.35	0.06	no
T Cet	7694	270	0.01	1.62	0.0043	0.03	8	5.90	0.50	-0.81	1.30	0.83	0.55	0.17	no
Psi Phe	1162	105	0.00	1.30	0.0004	0.01	5	4.61	0.45	0.00	0.45	0.78	0.62	0.22	no
V1943 Sgr	7403	197	0.04	1.46	0.0054	0.04	12	8.17	-0.08	0.00	-0.08	0.97	0.23	0.03	yes
Ups Cet	548	90	0.00	1.30	0.0060	0.01	3	4.18	1.00	0.10	0.90	0.83	0.56	0.17	no
RX Lep	4122	149	0.01	1.31	0.0019	0.03	10	5.84	-0.16	-1.40	1.24	0.91	0.42	0.09	no
R Hor	25564	210	0.00	5.76	0.0064	0.04	25	7.34	0.72	-0.61	1.33	0.90	0.43	0.10	no
GY Aql	2526	223	0.10	4.49	0.0648	0.01	22	12.95	1.29	-0.28	1.57	0.78	0.62	0.22	yes
V Hya	52698	694	0.01	6.18	0.0298	0.05	6	8.06	1.65	-0.69	2.34	0.92	0.40	0.08	yes
AC Cet	835	289	0.01	2.20	0.0058	0.01	3	8.04	3.11	1.85	1.26	0.89	0.45	0.11	no
W Aql	3698	372	0.22	1.30	0.0010	0.04	10	0.00	0.00	0.00	0.00	0.78	0.63	0.22	yes
SV Aqr	4525	430	0.01	2.08	0.0045	0.01	4	10.00	2.24	0.95	1.29	0.71	0.71	0.29	no
V PsA	7861	304	0.01	2.09	0.0108	0.04	9	8.95	0.75	0.00	0.75	0.94	0.34	0.06	yes

Notes. All displayed quantities are used for training, including the magnitudes (V , J , K , $J - K$). The distance adopted is that of the Hipparcos catalogue, with the exception of the three stars (W Aql, SV Aqr and V PsA) without Hipparcos IDs for which the Gaia DR3 distance was used. Note that Gaia distances present large uncertainties in the parallaxes for most AGB stars, as mentioned by Béguin et al. (2024). Therefore, we favored Hipparcos distances whenever possible in this study. Luminosity (L), and effective temperature (T_{eff}). Photometry sources: Hipparcos/Tycho (visible), SDSS and DENIS (visible and near-IR), 2MASS (near-IR), and MSX, AKARI, IRAS, WISE (thermal IR). Shape parameters: axial ratio b/a , eccentricity $e = \sqrt{1 - (b/a)^2}$, ellipticity $\epsilon = 1 - b/a$, and envelope resolution statute Res_stat . Columns shown: L ($L_{\odot}$), D (pc), A_V (mag), E_{IR} , $L_{\text{IR}}/L_{\star}$, Ctr , R_{mas} , M_V , M_J , M_K , $J - K$, b/a , e , ϵ , Res_stat .

Table B.2: Targets observation log with ZIMPOL.

Date	Time	Target	Program ID	Dedicated PSF	Filter 1	Filter 2	Seeing	Airmass
2015-09-22	06:00:05	Y Pav	095.D-0309(B)	No	V	N_R	0.8	1.6
2015-09-23	06:33:06	R Hor	095.D-0309(B)	Yes	V	N_R	0.8	1.6
	05:22:59	R Scl	095.D-0309(B)	Yes	V	N_R	0.8	1.6
	04:32:28	Y Scl	095.D-0309(B)	Yes	V	N_R	0.8	1.6
2015-12-19	06:56:44	R Crt	096.D-0930(E)	Yes	N_R	N_R	1.0	1.5
2016-02-19	02:00:31	SW Col	096.D-0252(A)	No	V	N_R	0.8	1.6
2016-03-08	07:53:40	W Hya	096.D-0930(B)	No	Cnt820	Cnt748	1.0	1.5
2016-03-09	07:35:37	SW Vir	096.D-0930(C)	No	N_R	N_R	1.0	1.5
2016-04-22	01:37:40	V Hya	097.D-0516(A)	Yes	V	N_R	0.8	1.6
2016-04-30	06:08:35	Alpha Her	097.D-0352(A)	Yes	V	Cnt748	0.8	1.5
2016-06-30	05:27:44	Chi Cyg	097.D-0352(A)	Yes	V	Cnt748	0.8	2.2
2016-07-22	10:13:16	Z Eri	097.D-0516(B)	No	V	N_R	1.4	1.6
	07:33:48	R Peg	097.D-0516(B)	Yes	V	N_R	1.4	1.6
	06:48:41	BW Oct	097.D-0516(B)	Yes	V	N_R	1.4	1.6
	09:09:48	AC Cet	097.D-0516(B)	Yes	V	N_R	1.4	1.6
	07:12:00	DZ Aqr	097.D-0516(B)	Yes	V	N_R	1.4	1.6
	08:40:12	Z Peg	097.D-0516(B)	Yes	V	N_R	1.4	1.6
	08:13:34	W Peg	097.D-0516(B)	Yes	V	N_R	1.4	1.6
2016-07-29	23:20:37	RT Vir	097.D-0443(A)	No	Cnt820	Cnt820	1.2	1.9
2016-10-04	06:33:30	RX Lep	098.D-0206(C)	Yes	CntHa	CntHa	1.0	1.5
2016-10-12	02:07:05	Beta Gru	098.D-0200(A)	Yes	V	N_R	1.4	1.6
	01:05:09	T Mic	098.D-0200(A)	Yes	V	N_R	1.4	1.6
2016-11-09	04:13:02	R Dor	098.D-0731(A)	No	Cnt820	Cnt748	1.2	1.8
2016-12-07	06:06:15	AK Hya	098.D-0206(D)	No	N_R	N_R	1.0	1.5
2016-12-14	08:47:36	R Leo	097.D-0352(A)	No	V	Cnt748	0.8	1.5
2017-03-07	04:08:12	BK Vir	097.D-0443(A)	No	Cnt820	Cnt820	1.2	1.9
2017-07-31	07:44:43	T Cet	099.D-0600(A)	No	CntHa	B_Ha	0.8	1.2
2017-11-27	03:03:26	Mira Ceti	0100.D-0737(B)	Yes	Cnt820	Cnt748	1.2	1.3
2019-07-05	05:09:14	U Del	0103.D-0772(A)	No	CntHa	CntHa	2.0	2.0
2019-07-08	01:55:17	U Her	0103.D-0772(A)	No	VBB	VBB	2.0	2.0
	09:20:26	π^1 Gru	0103.D-0772(A)	No	Cnt820	Cnt748	2.0	2.0
2019-07-09	04:53:58	W Aql	0103.D-0772(A)	No	VBB	VBB	2.0	2.0
	08:51:53	V PsA	0103.D-0772(A)	No	N_R	N_R	2.0	2.0
2019-07-27	01:35:53	R Hya	0103.D-0772(A)	No	CntHa	CntHa	2.0	2.0
2019-07-30	00:53:26	R Aql	0103.D-0772(A)	Yes	N_R	N_R	2.0	2.0
2019-09-24	03:38:22	S Pav	0103.D-0772(A)	No	N_R	N_R	2.0	2.0
2019-09-28	03:18:41	GY Aql	0103.D-0772(A)	Yes	VBB	VBB	2.0	2.0
2019-09-29	03:02:18	SV Aqr	0103.D-0772(A)	Yes	VBB	VBB	2.0	2.0
2019-10-16	03:26:11	Ups Cet	0104.D-0240(A)	Yes	V	N_R	2.0	2.8
	01:42:05	V1943 Sgr	0104.D-0240(A)	Yes	V	N_R	2.0	2.8
	02:46:51	Psi Phe	0104.D-0240(A)	Yes	V	N_R	2.0	2.8
2020-02-29	01:51:51	S Lep	0104.D-0240(B)	No	I_PRIM	I_PRIM	2.0	2.8
	00:10:45	SS Lep	0104.D-0240(B)	Yes	I_PRIM	I_PRIM	2.0	2.8
	00:48:30	L ₂ Pup	0104.D-0240(B)	No	V	N_R	2.0	2.8
	02:20:39	CW Cnc	0104.D-0240(B)	No	I_PRIM	I_PRIM	2.0	2.8