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„Shaping the slow winds of Asymptotic Giant Branch stars
in binary systems“

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*Reicher Mann und armer Mann
Standen da und sahn sich an.
Und der Arme sagte bleich:
Wär ich nicht arm, wärst du nicht reich.*

Bertolt Brecht – “Alfabet” (1934)

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Introduction

1.1. Herschel Space Observatory

The thesis at hand is an observational study of the interactions that occur in the winds of asymptotic giant branch (AGB) stars and is based on observations carried out with the *Herschel Space Observatory* (*Herschel*; Pilbratt et al. 2010). *Herschel* is a space mission led by the European Space Agency (ESA) and dedicated to the far-infrared (IR) and sub-millimetre wavelength range, whose exploration was included in ESA’s long-term plan Horizon 2000 (Longdon 1984). By this time, it was called the Far-InfraRed and Submillimetre space Telescope (FIRST) until it received its present name *Herschel* in the year 2000; named after Friedrich Wilhelm Herschel (1738–1822), the discoverer of the infrared radiation. The *Herschel* mission was chosen as the successor of the Infrared Space Observatory (ISO; 1995–1998) and the realisation of the mission was decided in 1993 as the fourth cornerstone mission of ESA, after the X-ray Multi-Mirror-Mission (XMM-Newton; 1999–present), the Solar and Heliospheric Observatory (SOHO; 1995–present), and Rosetta (2004–present). Shortly after, the industrial production of the spacecraft began with a budget of 1.1 billion Euro.

Given the high costs of space missions, the reasons to operate a telescope outside earth must be vital and are found in the properties of the earth’s atmosphere. On the one hand, the atmospheric windows only allow ground-based observations in certain wavelength ranges (optical, near- to mid-infrared, and radio), while photons of other energies are absorbed and scattered by several molecules like ozone, carbon dioxide, and water (vapour) in the earth’s atmosphere. On the other hand, the thermal conditions and instability of the atmosphere hinders ground-based observations. This is especially the case in the far-IR regime ($\lambda > 15 \mu\text{m}$), where the thermal emission of the atmosphere dominates the observations. To explore the universe in this wavelength range means to reveal its cool and dusty places. The far-infrared covers a wavelength

range of roughly 15–1000 μm , equivalent to the peaks of the black body radiation curve between 300 K and 3 K. This is the temperature domain of newly born stars, planets and galaxies, active galactic nuclei (AGN), and evolved stars. Prior IR space missions like the Infrared Astronomical Satellite (IRAS), ISO, Spitzer Space Observatory, and AKARI delivered spectacular results in these scientific fields. *Herschel* is able to add a new level of detail to the far-IR universe due to its high sensitivity and spatial resolution. With a wavelength range of 55–671 μm , it is the first mission going beyond 200 μm (besides the Cosmic Background Explorer (COBE) and Wilkinson Microwave Anisotropy Probe (WMAP), which are used solely for cosmological studies).

On 14 May 2009, *Herschel* was finally sent to space with an Ariane 5-ECA rocket¹. After the separation from the carrier rocket, *Herschel* was manoeuvred to the second Lagrange point (L_2), which is located $\approx 1.5 \times 10^9$ m behind the earth, as seen from the sun. L_2 has the advantage that the sun, earth, and moon are on the same side which is handy in the sense that a sunshade is able to protect the spacecraft effectively. At this location, the spacecraft moves with the same orbital period as the earth. On 14 June 2009, while moving to L_2 , the Photodetector Array Camera & Spectrometer (PACS) on-board *Herschel* obtained first light: an image of M51, the Whirlpool Galaxy. After several commissioning phases the first routine operations were executed on 18 October 2009. In March 2013, nearly four years after launch and 3.5 years of successful observations, the liquid helium needed to cool the *Herschel* detectors was almost completely evaporated. This lack of helium prevented the detectors from working accurately and on 29 April 2013 ESA declared the *Herschel* mission to be completed.

1.1.1. Spacecraft

The Herschel Space Observatory has a total size of about $4\text{ m} \times 4\text{ m} \times 7\text{ m}$ with a mass of 3400 kg at launch. This includes 600 kg of liquid helium that is used to cool the instruments². The telescope itself is of Cassegrain-type with a 3.5 m primary and a 0.31 m secondary mirror.

The set-up of the spacecraft is shown in Fig. 1.1 and consists of four main structures: the payload module (PLM), the service module (SVM), the sunshade, and the telescope. The PLM houses the cryostat cooling and the optical

¹An extended description of the launch and the manoeuvre to the observation point can be found in the Herschel Observer’s Manual (<http://herchel.esac.esa.int/Docs/Herschel/html/Observatory.html>), on which also this paragraph is based.

²Pilbratt et al. (2010) give a full description of the spacecraft. This paragraph is based on this publication.

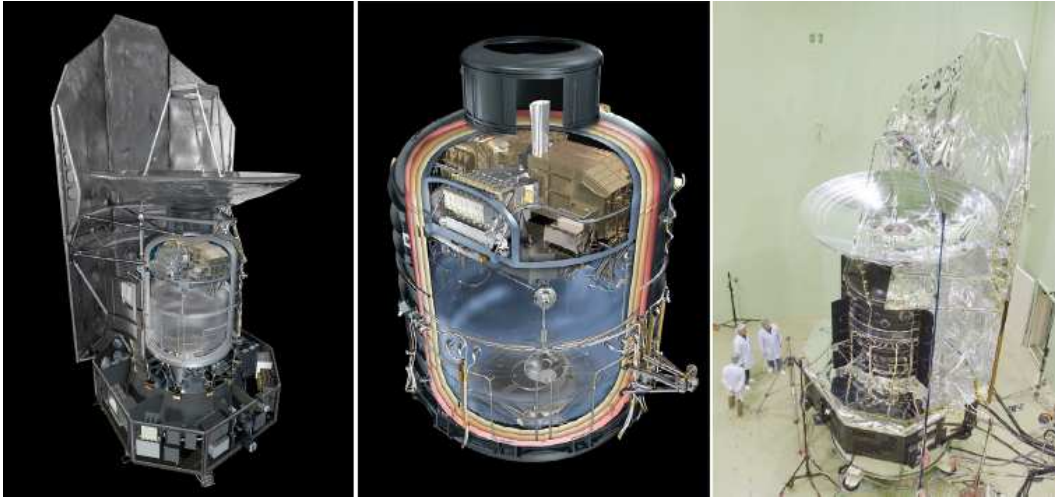


Figure 1.1.: Overview of the *Herschel* spacecraft given by Pilbratt et al. (2010). *Left*: schematic view of *Herschel* with the PLM (dominated by the cryostat), the SVM and the sunshade. *Middle*: schematic view of the cryostat with the optical bench on top. *Right*: *Herschel* before acoustic tests at the European Space Research and Technology Centre (ESTEC) in 2008.

bench with its three main instruments. As noted above, special attention has to be turned to the cooling of the instruments, otherwise the thermal emission dominates the observations. Therefore, the instruments at the PLM are cooled with liquid helium to a temperature of 1.65 K (except for the bolometers which are kept at 0.3 K). The cryostat technology was adopted from the successful ISO mission but the lifetime was extended from 2.5 years to almost 4 years³. The SVM carries instruments that provide the satellite with power, altitude and orbit control, communication, and on-board data handling, which all do not have to be actively cooled (Pilbratt et al. 2010). The same applies for the telescope which operates at a temperature of about 85 K.

³The cryostat was partly developed by RUAG Austrian Aerospace

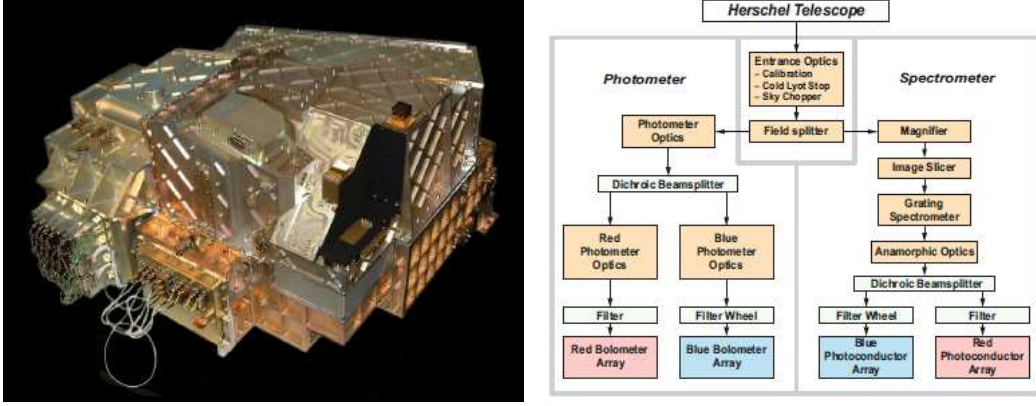


Figure 1.2.: Layout of the PACS focal plane unit (left) and a diagram of the light path through the instrument (right) by Poglitsch et al. (2010).

1.1.2. The Photodetector Array Camera and Spectrometer (PACS)

The focal plane houses three instruments: the Photodetector Array Camera and Spectrometer (PACS; Poglitsch et al. 2010), the Spectral and Photometric Imaging REceiver (SPIRE; Griffin et al. 2010), and the Heterodyne Instrument for the Far-Infrared (HIFI; de Graauw et al. 2010). The images used in this thesis were taken with PACS, whose photometer is described in the following based on Poglitsch et al. (2010).

PACS (see left panel of Fig. 1.2) is a general purpose instrument, which works in a wavelength range of $57\text{--}210\,\mu\text{m}$, divided into three bands: blue, green, and red. PACS features a photodetector, a spectrometer, and a front optics section, which is the first part of the instrument in the light path (see right panel of Fig. 1.2). The front optics section contains a blocking filter, grey body calibrators, and a focal plane chopper, which allows to switch between a chopped field of view (FoV) on the sky and two calibration sources (Poglitsch et al. 2010). The final part of the front optics is the field splitter, which routes the light to the photometer or spectrometer.

The photometer is set-up in way that the light is again split up into short-wave (blue or green) and long-wave (red) channels by a beam-splitter, with peaks of the filter transmission curves at $70\,\mu\text{m}$ (blue), $100\,\mu\text{m}$ (green), and $160\,\mu\text{m}$ (red). The light then falls onto the two bolometer arrays with a total number of 64×32 pixels in the blue/green array and 32×16 pixels in the red array. The bolometers cover a FoV of $\approx 3.5' \times 1.75'$ on the sky with a full

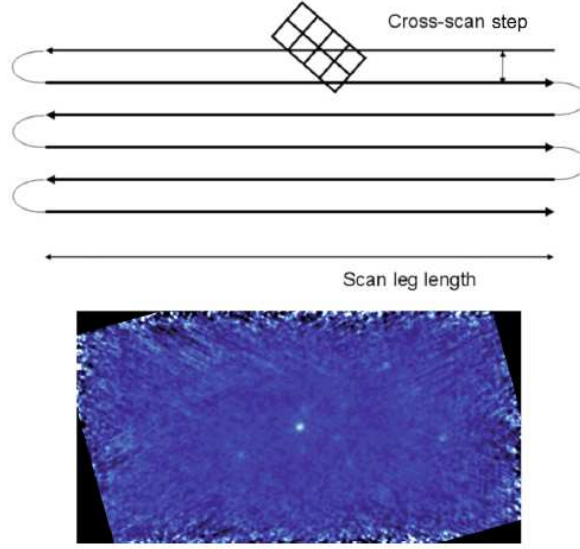


Figure 1.3.: Sketch of the scan map technique (upper panel) and a combined image from the cross scan mini maps (lower panel) by Poglitsch et al. (2010).

width of half maxima (FWHM) of $5.6''$ in the blue, $6.8''$ in the green, and $12.1''$ in red channel (Poglitsch et al. 2010). In general, the blue and red bolometer arrays are used simultaneously, while the green channel is only used for specific observations and can be selected by another filter wheel.

PACS offers three observation modes, of which the scan map technique is the most commonly used to map larger areas. The observations presented in this thesis were obtained with this technique, which is depicted in Figure 1.3. Prior to the actual observations on the target, a 30 s calibration phase is initialised where the chopper moves between the two internal calibration sources. In the scan map technique, the spacecraft moves along parallel lines with a constant speed (usually $20'' \text{ s}^{-1}$) over the target area and takes several frames along one scan leg (Poglitsch et al. 2010). In general, two scan directions (orthogonal) are combined and the number of parallel scans, their separation, the length of one scan leg, and the number of repetitions are chosen by the observer. With this method, PACS achieves an absolute photometric uncertainty of 10% and 20% in the blue/green and red channel, respectively, with a point source sensitivity of 3.7 mJy (blue), 5.0 mJy (green), and 9.5 mJy (red) (Poglitsch et al. 2010).

1.1.3. Data processing

Before data is transferred from the satellite to earth, several on-board data reduction and compression steps are necessary to handle the large amount of data (Poglitsch et al. 2010). The development of the on-board data reduction and compression is part of the Austrian contribution to *Herschel*/PACS and was led by the Department of Astrophysics of the University of Vienna⁴ (Ottensamer & Kerschbaum 2008). The task of the software is to compress the arising data from the detectors by a factor of 40. Without this procedure the amount of data would be too large to effectively transfer it to the ESA tracking station network, which comprises ten stations in seven countries.

In the scan map mode, four subsequent frames are averaged and compressed on-board. At this point the data is in a “Level 0” stage and can be retrieved from the Herschel Science Archive (HSA)⁵. Level 0 products also contain the calibration tree, which is needed to apply the following data reductions steps. Poglitsch et al. (2010), Groenewegen et al. (2011), and Roussel (2013) describe in detail the data reduction steps from Level 0 to the final maps that are presented in this thesis. The following paragraph only provides a short overview and is based on the above mentioned publications.

From the Level 0 stage on, the Python based Herschel Interactive Processing Environment (HIPE⁶; Ott 2010) is the designed tool for the data reduction since many reduction steps, especially for the scan map mode, are implemented in the pipeline. In the next step, Level 0.5, information are added like bad pixels, conversion of digital readouts to Volts/s, and sky coordinates for every pixel. The calibration block, a chopped measurement of the internal calibration sources created at the beginning of every scan, is removed. In addition, electronic glitches and crosstalk artefacts (reflection of a saturated pixel to another) are masked (Groenewegen et al. 2011).

For Level 1, the flux is calibrated, UTC added from on-board time, and the masked artefacts from Level 0.5 are removed. At this level, the standard data reduction ends and the data should be free from instrumental effects. In the next steps images (maps) are produced from the reduced frames.

Six major map making methods, *PhotProject*, *MADmap* (Cantalupo et al. 2010), *Scanamorphos* (Roussel 2013), *UNIMAP*, *Tamasis* (Barbey et al. 2011), and *JScanam* are available to create a final image. Each of the methods has its advantages and disadvantages, depending on the nature of the observed object

⁴with further contributions by the Technical University of Vienna and Joanneum Research, Graz

⁵http://herschel.esac.esa.int/Science_Archive.shtml

⁶A documentation of HIPE and all of its implemented functions is found at <http://herschel.esac.esa.int/hipe/>

and the observation method. The PACS bolometer show large sensitivity drifts during the observation and since the bolometers are multiplexed only the mean signal can be set to zero, which causes significant pixel-to-pixel variations (Mečina et al. 2014b). AGB stars which are the topic of this thesis need special attention since the central source is extremely bright in the far-IR and at the same time, the extended emission around the stars is very faint. A comparison among the available map-makers has shown that Scanamorphos⁷ (Roussel 2013) and its HIPE implementation JScanam perform best for these peculiar objects (Mečina et al. 2014b).

The advantage of Scanamorphos (and JScanam) is that it was coded especially for scan map observations and accounts for the fact that the signal received by the bolometer is superimposed on a drift that is much longer than the sampling time (Roussel 2013). The signal drift of a pixel can therefore be extracted from the source signal. Scanamorphos is able to handle the low-frequency noise, which manifests itself by the presence of stripes in the maps. The low-frequency noise is composed of thermal drift and flicker noise (Mečina et al. 2014b). While the thermal drift is similar for all bolometers an average time series over the whole array can be extracted and compared to a reference map. The flicker noise is treated similarly but not over the whole array but for each bolometer (Mečina et al. 2014b).

Scanamorphos was developed in the Interactive Data Language (IDL) by Helene Roussel and is working like a black box with only little possibility to adjust the code. However, this changed with the implementation of the algorithm into HIPE as JScanam. Although Scanamorphos and JScanam are based on the same principles, the resulting map can be quite different in certain points. Nevertheless, both tasks manage well to preserve the brightness distribution of the extended emission and produce a much smoother background compared to Photproject and MADmap and without cross artefacts that appear on the Tamasis maps.

The use of Scanamorphos is straight forward and most of the tasks are fully automatic. The algorithm picks up the Level 1 data produced by HIPE and slices it into spatial blocks of the size of the FWHM of the point spread function (PSF). Subsequently, the scan speed is determined, a time grid is put on the dataset, and high-frequency noise is removed (Roussel 2013). The first step of the drift correction is the determination of the average drift by comparing pairs of bolometers that observed the same position on the sky. The brightness difference between each pair is equal to the difference of the drifts between the two sampled times. This is done for all pixels and then subtracted from the

⁷*Scanamorphos* is available at <http://www2.iap.fr/users/roussel/herschel/>

signal series of the bolometer (Roussel 2013). A new map is produced and the correction of the average drift starts again until the drift amplitude (3σ) has become smaller than the white noise level of the bolometers. Afterwards, the individual drifts of the bolometers are removed by comparing the signal of a bolometer to the average bolometer signal at any given position of the sky. This is again done for all pixels in several iterations and subtracted from the signal. In the final step, the algorithm creates a sky map together with a weight map, including the inverse of the white noise, an error map of the high-frequency noise, and a low-frequency map, which includes the previously described drifts (Roussel 2013). These maps are finally exported to a FITS data cube.

In the last year of this PhD project, one of the tasks of the Viennese AGB group was to improve the quality of the Herschel maps, as part of the *Herschel Imaging Legacy* (HIL; Mečina et al. 2014b) project. Two domains were chosen to achieve this aim, namely to improve the astrometry and provide a deconvolution package. The *Herschel* astrometry suffers from poor pointing precision, which could cause smearing of about $5''$ in the scan map mode, much larger than the usual $1''$ jitter. This problem was solved using a new version of the star tracker flat field in combination with information from the gyroscopes.

A universal deconvolution package is still under development. Mostly because the manifold of observed PSFs complicates finding a universal PSF model. Generally, an image is characterized by its intensity distribution (I), which is the real image affected by the imaging system or rather the real signal (O) is convolved with the response function (PSF; P) of the imaging system:

$$I(x, y) = (O * P)(x, y) + n(x, y), \quad (1.1)$$

where n is additive noise. This convolution causes a smearing of the signal by the imperfection of the imaging system. Convolutions are treated best in the Fourier space, since the Fourier transform of a convolution of two functions is equal to the products of their Fourier transform, or

$$\hat{I}(u, v) = \hat{O}(u, v)\hat{P}(u, v) + \hat{n}(u, v). \quad (1.2)$$

The main problem to obtain O is the additive noise. Hence, the most simple method is to ignore the noise and obtain the real signal by dividing $\hat{I}$ by $\hat{P}$ (Starck & Murtagh 2006). This method is fast but the results are unusable. Generally, the division by $\hat{P}$ amplifies the high-frequency noise, which counteracts the deconvolution aim and lowers the details of the signal. For the *Herschel* images we therefore follow the scheme of Ottensamer et al. (2011) and Hollis et al. (1992) with a maximum entropy method (MEM; Jaynes 1957).

The MEM uses Bayes' theorem, meaning that the aim is to maximise the probability that the result of the deconvolution is O when using I and P :

$$P(O|I, P) = \frac{P(I|O, P)P(O|P)}{P(I|P)}. \quad (1.3)$$

For a set of $i = 1, 2, \dots, N$ states one obtains

$$\sum_{i=1}^N O_i = 1, \quad (1.4)$$

where $O_1, O_2, \dots, O_N$ is the normalized probability distribution (Hollis et al. 1992) and

$$\sum_{i=1}^M O_i P_{k,i} = I_{k,i}, \quad (1.5)$$

where $k = 1, 2, \dots, M$. If $M + 1 < N$, then a unique solution is not provided and one has to define the entropy

$$S(O) = - \sum_{i=1}^N O_i \ln(O_i). \quad (1.6)$$

The normalized probability function O in the i th state can then be written after Hollis et al. (1992) as

$$O_i = \exp \left(-\lambda_0 - \sum_{k=1}^M \lambda_k P_{k,i} \right) \quad \text{for } i = 1, 2, \dots, N, \quad (1.7)$$

where λ are Lagrange multipliers. The equation can be rewritten to

$$\sum_{i=1}^N (P_{k,i} - I_k) \exp \left(- \sum_{s=1}^M \lambda_s P_{s,i} \right) = 0 \quad \text{for } k = 1, 2, \dots, M, \quad (1.8)$$

where O is absent (Hollis et al. 1992). The multipliers can be solved by minimising the function F :

$$F = \lambda_0 + \sum_{k=1}^M \lambda_k I_k, \quad (1.9)$$

which is equivalent to a point wise subtraction of the image I_k with the object O_i convolved with $P_{k,i}$ (Alhassid & Levine 1979).

In the Herschel deconvolution task (Ottensamer et al. 2011), the multiplier is convolved with the PSF. At the beginning, the multiplier is an empty array

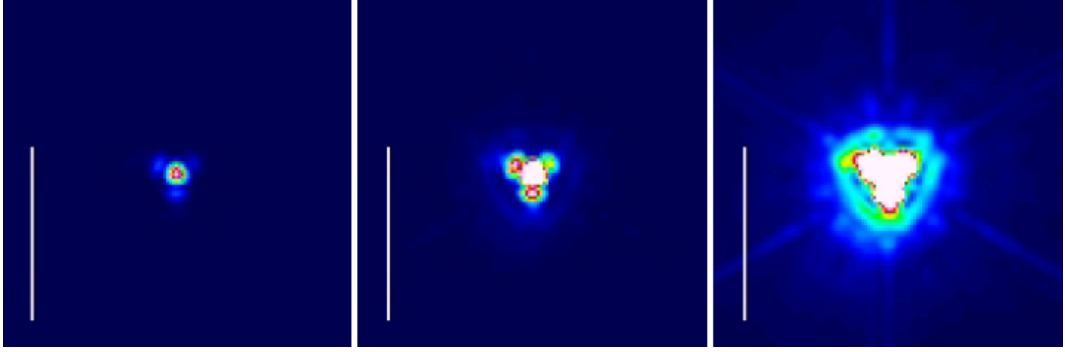


Figure 1.4.: Model PSF of a Rayleigh source in the $70\,\mu\text{m}$ band. From left to right: scaled to peak, 1% of peak, and 10% of peak. The bar indicates $60''$. *Image courtesy of Dieter Lutz.*

with the dimensions of I , thus the product is the PSF itself, which then gets scaled by the flux ratio of the image and the PSF and finally re-convolved. At each iteration step the fluxes are compared and the residuals become part of the new multipliers. As a result, extended and blurry emission gets soaked up and concentrated, which sharpens the image.

Technically, the deconvolution of Herschel images starts by selecting an appropriate PSF model, which is in our case an observation of a point source, preferentially taken at the same map scan angle and speed. However, *the* perfect point source observation does not exist, therefore each image has to be tested with various or averaged PSF models. Fig. 1.4 shows a PSF model⁸. We found that a few of the objects in our sample are useful PSF candidates, although these stars are all variable AGB stars. In our work, we used the following MESS objects as PSFs: AFGL 190, AFGL 3068 (see Fig. 3.20), OH 127, AFGL 618, IRAS 11385, IRAS 22036, IRC 10420, HD 179821, and HD 161796.

The task starts with preparing the PSF model observation, i.e. cropping the central part with a certain radius, rotating this part by an angle that it matches the map scan angle of I and pasting it onto a blank array of the same size as I . This PSF image is then passed on to the maximum entropy routine described above.

⁸Taken from “PACS photometer point spread function” by Dieter Lutz, available at http://herschel.esac.esa.int/twiki/pub/Public/PacsCalibrationWeb/bolopsf_20.pdf

1.1.4. Mass-loss of Evolved StarS (MESS) program

The goals of the *Herschel* mission are expressed in the selection of the observing key programmes. 21 guaranteed time key programmes (GTKP) and 21 open time key programmes (OTKP) have been awarded together 57% of *Herschel*'s $\approx 20\,000$ h observing time to explore the far-IR universe. The topics cover a very diverse range, e.g., from the Transneptunian region (Müller et al. 2010) to the galaxy formation history in the universe (Oliver et al. 2012).

The observations that are discussed in this thesis are part of the Mass-loss of Evolved StarS (MESS, Groenewegen et al. 2011) GTKP. Although the mass loss of evolved stars is studied since the 1960s many fundamental questions are still under investigation. For example, the evolution of the mass loss rate (MLR) when the AGB star enters the thermal pulse (TP) phase, the formation of specific dust species at a certain location in the stellar wind, the morphology of the mass loss itself, and, what is related to this thesis, the interactions the stellar wind faces after it is ejected by the AGB star (Groenewegen et al. 2011). The MESS GTKP aims to improve the understanding of the mass loss process by observing a sample of 108 evolved stellar objects: 78 AGB stars and Red Supergiants (RSGs), 20 post-AGB stars and planetary nebulae (PNe), five massive stars, such as luminous blue variables (LBVs) and Wolf-Rayet (WR) stars, and five supernova remnants (SNRs). The PACS and SPIRE instruments with their imaging and spectroscopy modes were used for these observations. A full list of the sampled objects and the corresponding observational properties are found in Groenewegen et al. (2011).

The target selection of the AGB part is predominantly based on results of previous space mission such as ISO and IRAS. From the latter, Young et al. (1993b) studied a data set of 512 evolved stars and found 76 of them showing extended emission in the 60 and 100 μm bands. Many of these extended objects were chosen to be observed again by *Herschel*. The final MESS sample consists of 30 oxygen-rich AGB stars and RSGs, nine S-stars, 37 carbon-rich stars, and two post-RSGs (Groenewegen et al. 2011) which were all imaged with PACS. A sub-sample of 26 bright objects were additionally imaged with SPIRE. Spectroscopic observations were carried out for 25 objects of the sample.

The MESS GTKP is a large collaboration of 19 institutes from nine countries and has proven to be very successful regarding the scientific output that was generated from these observations. Up to now, more than 20 peer-reviewed articles have been published based on the MESS observations.

1.2. Asymptotic giant branch stars

The work that is presented here treats the influence of an accompanying star on the wind of an AGB star. The general properties and physical aspects of this stellar class are topic of this section, which is based on a book by Habing & Olofsson (2003) and a review by Herwig (2005).

The term *asymptotic giant branch* star is derived from a location on the Hertzsprung-Russell-diagram (HRD; Hertzsprung 1911; Russell 1914), which relates the spectral class, or in other words, the effective temperature of stars, to their absolute brightness. During the production of the famous Henry Draper (HD) catalogue, about a decade before the HRD was devised, several peculiar stars were observed with narrow and deep absorption lines and high luminosities. These stars were named giants, since it was already understood, that they must be more extended than others to reach these luminosities. The physical understanding of what happens inside a star had to wait until the 1920s, when Arthur Stanley Eddington proposed that stars are spheres where the gas pressure and the gravitation force are in equilibrium and gas pressure might be created by the conversion of hydrogen to helium (Eddington 1926). This was a brave statement given the fact, that it was generally assumed that the composition of stars is similar to that of the earth's atmosphere. It was Unsöld (1928) who finally realized that the sun and all other stars are mainly composed of hydrogen when he analysed the solar chromosphere. A decade later, von Weizsäcker (1938) and Bethe (1939) identified the nuclear processes in the stellar core that account for the gas pressure. Sandage & Schwarzschild (1952) took this thought further and calculated models of low mass stars that finished the core conversion of hydrogen to helium. An active hydrogen burning layer manifests around the core, the stellar envelope expands to large sizes, and the luminosity increases strongly. The giant stars in the HD catalogue were finally understood.

From the observational side, the location of giant stars along the red giant branch (RGB) on the HRD was known since Arp et al. (1953) analysed precise photometric data of 1100 stars and found that the giant branch shows a bifurcation. The authors named the new branch the *asymptotic giant branch*, due to its alignment with the giant branch. The evolution of stars to the giant phase was completed when Hoyle & Schwarzschild (1955) proposed that the stars ascend the giant branch until they reach a maximum luminosity (the helium-flash) and subsequently burn quietly helium to carbon on the horizontal branch. When the helium is depleted in the core, a thin layer of active helium burning establishes and the star ascends the AGB on the HRD.

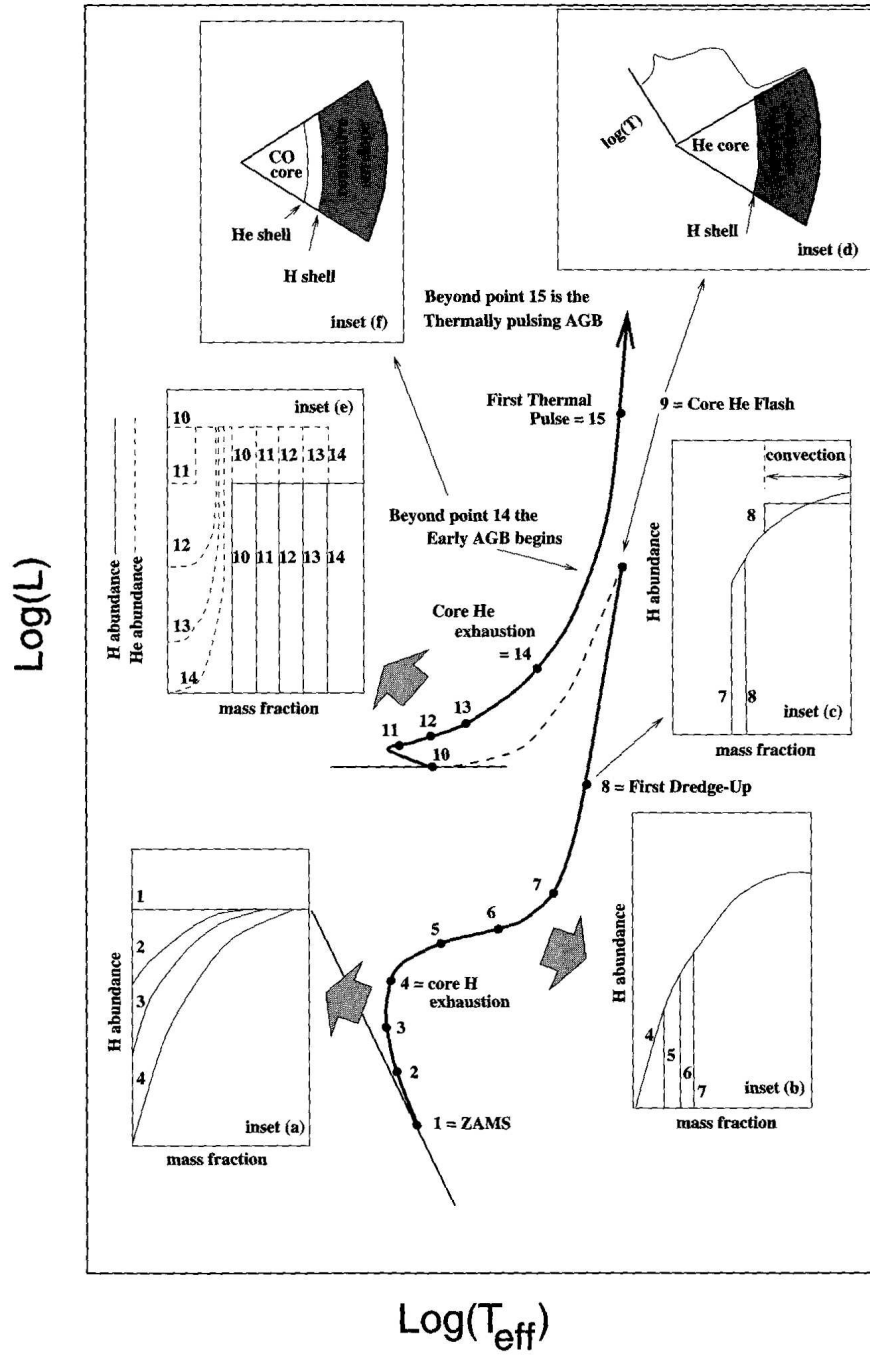


Figure 1.5.: Evolutionary track of a $1 M_{\odot}$ star from the zero-age main sequence (ZAMS) to the end of the AGB on the HRD (Habing & Olofsson 2003).

1.2.1. Stellar structure and evolution

Today we know that stars are born from giant molecular clouds, which are composed of the same material as the resulting stars: over 70 % hydrogen, 25 % helium, and less than 5 % heavier elements. A useful review of this topic is given by Kippenhahn & Weigert (1990), Iben (1991), Habing & Olofsson (2003), and Herwig (2005), on which this section is based.

When stars are formed, the gravitational force becomes so strong that the stellar core contracts and heats to a temperature where hydrogen nuclei start to undergo fusion to helium. This fusion can be done by two different processes. In massive stars, hydrogen merges with an already present carbon nucleus to form, via nitrogen and oxygen, a helium nucleus (and carbon). This is known as the carbon-nitrogen-oxygen cycle (CNO; von Weizsäcker 1938). It needs carbon to be already present in the star, thus the CNO cycle was not used by population III stars right after the first galaxies had formed. The CNO cycle is very effective in producing energy but is not used by low mass stars, since it needs a temperature of 1.4×10^7 K to trigger the fusion of carbon with hydrogen. For those stars, Bethe (1939) found the respective mechanism, the proton-proton (PP) chain, which begins at a temperature of 4×10^6 K and does not need carbon as seed nuclei.

Figure 1.5 shows the track of a $1 M_{\odot}$ star on the HRD through its evolution. When the hydrogen burning ignites in the stellar core, the star moves to the zero-age main sequence (ZAMS) and remains at the MS for the majority of its lifetime. The reason for this is the extremely slow nature of the start reaction of the PP chain where a beta-plus decay forms ${}^2\text{H}$ from ${}^2\text{He}$. The conversion of a hydrogen core to helium takes on average several billion years in low- and intermediate-mass stars. When hydrogen in the core is depleted, the star ascends the RGB.

At this stage, the helium core contracts and heats the surrounding hydrogen until it ignites and an active burning shell is established. Here, hydrogen is fused to helium via the CNO cycle due to the higher temperature provided by the helium core. This leads to an expansion of the whole star with convective outer layers that penetrate deep into the star, close to the hydrogen burning shell. This is called the *first dredge-up* and brings new nuclei, like ${}^{13}\text{C}$ and ${}^{14}\text{N}$, up to the atmosphere where they are observed. The core contraction ends with the sudden ignition of helium in a very short helium flash. In this few seconds the majority of helium in the core is burnt and a high luminosity is reached. This flash occurs in all stars of $0.8\text{--}1.8 M_{\odot}$. Lower mass stars do not create enough heat to fuse helium and the cores of stars above $1.8 M_{\odot}$ are so massive that the helium ignites right after the hydrogen is depleted (Habing

& Olofsson 2003).

To fuse helium and assemble the next stable nucleus a few difficulties have to be bypassed, because the product of two ${}^4\text{He}$ cores is ${}^8\text{Be}$, which has a half-life of only 6.7×10^{-17} s and decays to its base products. However, this is still longer than the time needed to form ${}^8\text{Be}$, thus a large amount of beryllium is present in the stellar core and can react with another alpha particle to ${}^{12}\text{C}$. This is called the triple-alpha process and is an extremely unlikely reaction. It is only possible because the sum of ${}^8\text{Be} + {}^4\text{He}$ has almost exactly the same energy as the excited state of ${}^{12}\text{C}$. This resonance which increases strongly the probability of the reaction was primarily proposed by Fred Hoyle and the reaction rates calculated by Salpeter (1952). The helium burning phase is about 10 times shorter than the H-core burning phase. Subsequently, oxygen is produced from carbon and leftover helium in the core.

On the HRD (see Fig. 1.5), the star is now on the horizontal branch. When the helium is depleted in the core, low and intermediate mass stars below $8 M_{\odot}$ do not have enough mass to further process carbon or oxygen and the fusion stops. The core contracts to the size of a white dwarf (WD; $\approx 10^6$ m) and is stabilised by the pressure of degenerated electrons, which transport away energy by neutrino emission. A thin He-burning shell and farther outside a H-burning shell establish around the core (see Fig. 1.7). In this phase, the star begins to ascend the AGB. Figure 1.6 shows the different processes occurring in the MS and AGB phase according to the stellar mass.

The ratio of stars which evolve through the AGB, can be derived from the initial mass function (IMF; Salpeter 1955),

$$N(m) dm \propto m^{-\alpha} dm \quad (1.10)$$

where $N(m) dm$ is the number of stars with masses between m and $m + dm$ within a certain volume. Kroupa (2001) determined α to be:

$$\alpha = \begin{cases} 0.3 & \text{if } M < 0.08 M_{\odot} \\ 1.3 & \text{if } 0.08 < M(M_{\odot}) < 0.5 \\ 2.3 & \text{if } M > 0.5 M_{\odot}. \end{cases} \quad (1.11)$$

By assuming that stars with masses between $0.8\text{--}8 M_{\odot}$ are able to fuse helium but stop after oxygen is formed, then over 90 % of all stars evolve through the AGB.

At the early stage of the AGB (E-AGB), both shells are established but the He-fusion produces most of the energy which leads to an expansion of the envelope and pushes the H-shell farther outside what almost entirely extinguishes it. The size of the envelope reaches about 10^{11} m while the effective

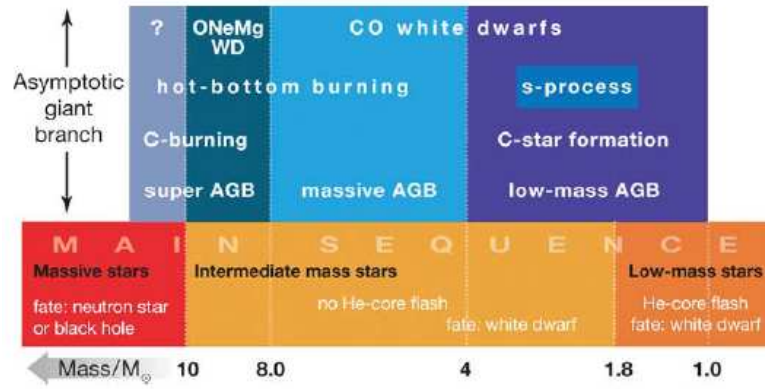


Figure 1.6.: The different processes that occur in the MS (lower part) and AGB phase (upper part) according to initial stellar mass (Herwig 2005).

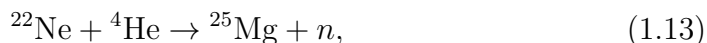
temperature at the atmosphere drops below 3000 K (Habing & Olofsson 2003). The envelope is highly convective and accounts for almost the entire volume. Stars between 4 and $8 M_{\odot}$ undergo a phase of strong convection, which digs deep into the inactive H-shell and mixes products of the CNO cycle (mostly ^4He , ^{12}C , and ^{14}N) to the surface. This is the *second dredge-up* phase.

In stars below $4 M_{\odot}$ the He-burning shell expands up to the *intershell* (see Fig. 1.7) where fresh helium from the H-burning shell is located. The temperature rises therein, the H-burning is strongly enhanced, and the He-burning shell declines in luminosity. The active H-burning shell again heats up the He-shell which leads to oscillations when the He-shell becomes more prominent and the H-burning shell simultaneously becomes inactive (Schwarzschild & Härm 1965; Weigert 1966). The star now shows *thermal pulses* (TPs), a main characteristic of the late stage on the AGB. TPs last for a short time (in the order of 10^3 yr) and are repeated several times, with about 10^5 yr between the TPs, depending on the core mass (Vassiliadis & Wood 1994). TPs are observable as episodes of strong changes in the surface luminosity of the star. When the He-burning is active, the amount of produced energy by the temperature sensitive 3α -process is larger than the energy that can be transported away by radiation. Convection appears in the intershell above the He-shell and mixes products of the He-burning (^4He and ^{12}C) almost to the H-burning shell. When the He-burning shell becomes inactive, the intershell expands and pushes the H-shell outside where it cools down and nearly extinguishes. A *third dredge-up* occurs and transports ^4He and ^{12}C to the surface and, after some cycles, the star changes its spectral type to a carbon star (Iben 1975; Sugimoto & Nomoto 1975).

In the same event a smaller convection zone establishes at the bottom of the H-shell which transports protons down to the ^{12}C rich region where ^{12}C captures the proton to produce ^{13}C by a beta-plus decay from ^{13}N (e.g. Kaepeler et al. 1990; Straniero et al. 1995). Afterwards, the star contracts and the H-shell, and subsequently also the He-shell, become active again. The newly assembled ^{13}C captures an alpha particle to produce oxygen:



but more importantly, a free neutron is generated. In stars above $2 M_{\odot}$, where temperatures of $3 \times 10^8 \text{ K}$ are reached, ^{14}N is mixed downwards and captures two alpha particles to make ^{22}Ne . When ^{22}Ne captures another alpha particle:



magnesium is formed and again a free neutron (Burbidge et al. 1957). These free neutrons are the source for the *slow neutron capture process* (s-process; Burbidge et al. 1957), which assembles nuclei heavier than iron. Compared to the rapid neutron capture, which occurs in supernovæ, the neutron density in AGB shells is quite low. The β^- -decay occurs faster than the neutron capture and nuclei close to the stability strip are produced. The s-process is together with the r-process the major source of elements heavier than iron, making AGB stars crucial production sites for these elements. The s-process ends with the assembly of ^{210}Po , which decays to ^{206}Pb by α -decay and starts a cycle around ^{209}Bi where as a net result four neutrons are always converted to an alpha particle.

In each of the TPs a lot of mass is lost by the increased radiation pressure produced in the He-shell – the number of TPs is limited. At the very end of the AGB phase the MLR increases up to $10^{-4} M_{\odot} \text{ yr}^{-1}$. A so-called superwind establishes. The mechanism that leads to such a high MLR is not fully understood yet but might be explained by the cumulative amount of opaque carbon in the envelope (e.g., Bowen & Willson 1991; Lagadec & Zijlstra 2008). At the end of the superwind phase, the mass of the envelope is reduced to $10^{-3} M_{\odot}$ and the star shrinks. The stellar luminosity at this stage is still provided by the radiative H-shell but the core heats the surrounding material. The star moves horizontally on the HRD towards higher temperatures, passing the regions of post-AGB stars and pre-PNe (Habing & Olofsson 2003). During the passage, which lasts for about 1000 years (Vassiliadis & Wood 1994), the remaining envelope is lost through nuclear burning and mass loss (which is also not fully understood). The result is the bare stellar C/O core, at this phase known as a WD. The ejected material is ionized by the high energy photons of the WD and becomes observable in all kind of wavelengths as a PN while the WD cools down and descends in the HRD.

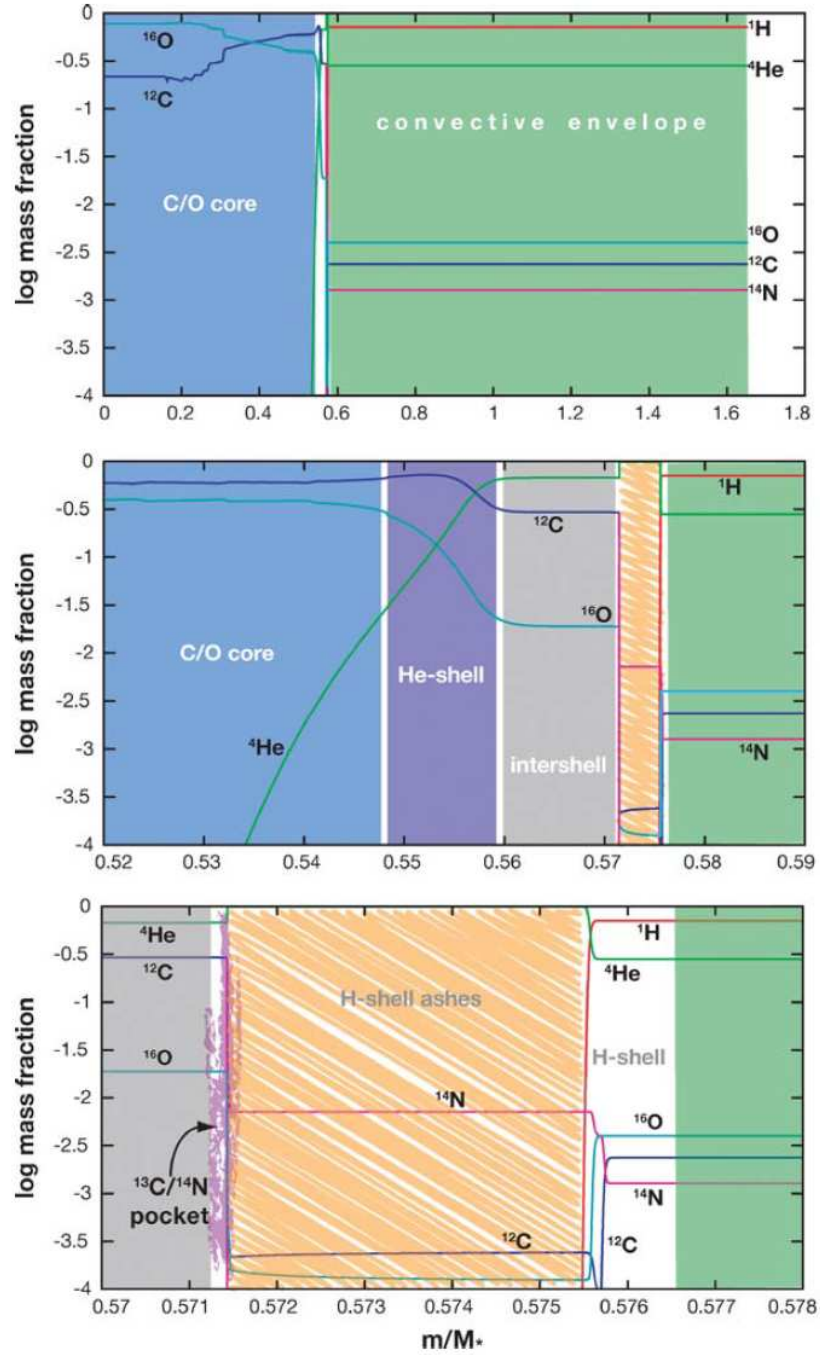


Figure 1.7.: Internal structure of a $2 M_{\odot}$ AGB star with a metallicity $Z = 0.01$ by Herwig (2005).

1.2.2. Dust formation & mass loss

AGB stars lose mass of the order of 10^{-8} to $10^{-4} M_{\odot} \text{ yr}^{-1}$. This high MLR goes along with the amount of solid particles (dust) assembled in the gaseous stellar atmosphere. The atmosphere of a star is thereby the region where the envelope changes from optically thick to optically thin, i.e. where photons are able to leave the star and become observable. An extensive description of the AGB atmosphere and the dust formation is given by Habing & Olofsson (2003), on which this paragraph is based.

In general, a star on the AGB has a radius of about $100\text{--}400 R_{\odot}$ and an effective temperature of $2000\text{--}3500 \text{ K}$ (Habing & Olofsson 2003). At such a large size, gravity is low and convection becomes strong and dredge-up events mix newly formed atoms to the atmosphere where the temperature is low enough to bind the atoms to molecules. Depending on the evolutionary stage and number of thermal pulses, the atmosphere changes from oxygen rich ($\text{C/O} < 1$), to an S-type star ($\text{C/O} \approx 1$), and finally to carbon rich ($\text{C/O} > 1$). Since CO has a very high dissociation energy of 11.1 eV , it is after H_2 the most common molecule in the envelopes of both, carbon and oxygen rich stars (Russell 1934). After either C or O is depleted, other molecules are formed. Table 1.1 shows the ten most abundant molecules of O-rich and C-rich stars (Habing & Olofsson 2003). S-type stars show as a speciality also strong bands of ZO, LaO, and YO in their spectrum since almost all C and O atoms are captured in CO and the TiO and H_2O bands become much weaker (Scalo & Ross 1976).

The deep convection zone is therefore important for the formation of molecules but it plays also a role on larger scales. The motion of matter is also visible as huge granules on the stellar surface as shown by 3D hydrodynamic simulations of Freytag & Höfner (2008), Freytag et al. (2010), and Chiavassa et al. (2010). These granules deform the stellar surface on large scales. In the stellar interior the periodically convection creates sound waves that move radially outwards. Close to their origin, the motion is slow but changes from subsonic to supersonic, when the wave propagates the less dense and cooler regions farther outside. The wave becomes a shock wave, which is steepened as it moves outwards since the local sound speed decreases. The shock wave compresses the gas and pushes it outwards. When it reaches the photosphere, it is strong enough to levitate the surface and creates a layer of dense gas at a region which is comparatively cool. After a certain time, the gas is decelerated by gravity and falls back towards the centre (Habing & Olofsson 2003). The

Table 1.1.: Ten most abundant molecules produced in O-rich and C-rich AGB stars. $f(X)$ gives the abundance relative to H_2 (Habing & Olofsson 2003).

Rank	O-rich		C-rich	
	Species	$f(X)$	Species	$f(X)$
1	H_2	1	H_2	1
2	CO	1.1(-3)	CO	1.6(-3)
3	H_2O	2.9(-4)	C_2H_2	2.2(-4)
4	N_2	1.3(-4)	C_2H	1.1(-4)
5	SiO	6.9(-5)	N_2	9.5(-5)
6	OH	9.0(-6)	HCN	8.5(-5)
7	SH	7.7(-6)	CS	2.3(-5)
8	H_2S	7.2(-7)	SiS	9.8(-6)
9	HCl	3.4(-7)	C_3H	9.5(-6)
10	SiS	2.0(-7)	CN	1.6(-6)

maximum distance of such a gas shell is given by

$$\frac{r_0}{r_{\max}} = 1 - \left(\frac{u_0}{u_{\text{esc}}} \right)^2, \quad (1.14)$$

where $r_0 = r(t_0)$ is the starting value of the radius of a gas shell, $r_{\max}$ its maximum radius, u_0 the velocity of the outflowing material, and u_{esc} the local escape velocity. For typical values $u_0 = 15 \text{ km s}^{-1}$ and $u_{\text{esc}} = 35 \text{ km s}^{-1}$ one obtains $r_{\max}/r_0 = 1.2$ (Habing & Olofsson 2003).

These strong shock fronts and the subsequent levitation of the outer atmospheric layers are crucial for the formation of solid particles. It provides a special environment that has on the one hand a high density ($\approx 10^{-14} \text{ g cm}^{-3}$), which ensures that enough atoms and molecules collide to grow dust grains, and on the other hand a low temperature ($\approx 1000 \text{ K}$) making the condensate stable against evaporation. The region where these dust grains are formed is described by the condensation radius r_c (Höfner 2007):

$$\frac{r_c}{R_*} = \frac{1}{2} \left(\frac{T_c}{T_*} \right)^{-\frac{4+p}{2}} \quad (1.15)$$

where R_* and T_* are the stellar radius and temperature, respectively, T_c the condensation temperature of the dust species, and p a parameter, which describes its wavelength dependent opacity. With typical values of $T_c = 1500 \text{ K}$, $T_* = 3000 \text{ K}$ and $p = 1$ one obtains $r_c/R_* = 3$ for amorphous carbon grains

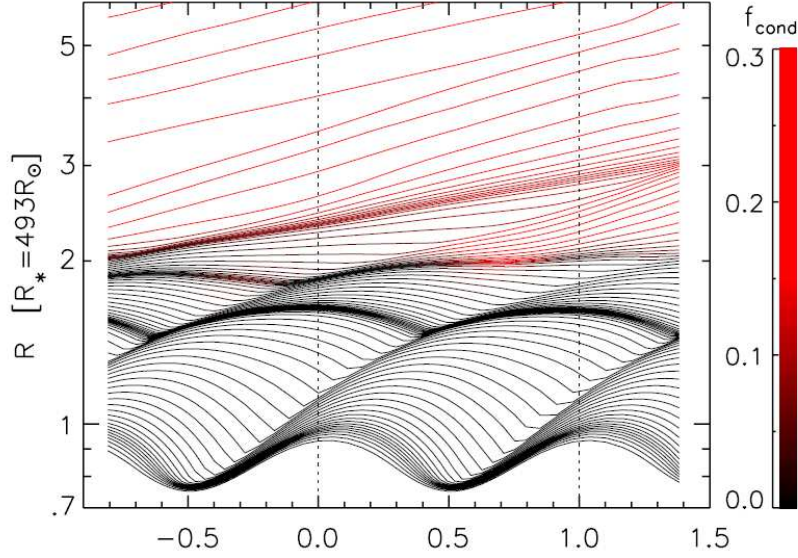


Figure 1.8.: Movement of atmospheric layers over two light cycles. The colour illustrates the degree of condensation of carbon into dust grains (Nowotny et al. 2013).

(Höfner 2007). The size of a typical carbon grain is about 10^{-8} m and contains about 10^8 atoms (Habing & Olofsson 2003). The time needed to form such a grain is of the order of 10^7 s, comparable to the time scales of the pulsation period. Thus, the wake of the shock wave is an ideal place for grain growth. Figure 1.8 pictures the levitation of the atmospheric layers and the region of dust formation over two light cycles (Nowotny et al. 2013).

With the growth of dust grains, the mass loss becomes an important factor of AGB stars. The opacity of dust grains is much higher than gas and the radiation pressure from the stellar interior is very efficient. The particles are pushed outwards and drag gas along via momentum transfer and friction of gas-dust collisions. To form a stellar wind, the velocity of the material has to exceed the escape velocity and overcome the gravity of the star. In AGB stars, the terminal velocity v_t of the stellar wind is quite low ($5\text{--}20\text{ km s}^{-1}$), but the MLRs are high (10^{-8} to $10^{-4} M_\odot \text{ yr}^{-1}$) compared to the wind of a MS star (typically $10^{-13} M_\odot \text{ yr}^{-1}$). The importance of the radiation pressure on dust grains is thereby quantified by the ratio of the momentum carried away by the wind to the radiation field of the star

$$\beta = \frac{v_t c \dot{M}}{L}, \quad (1.16)$$

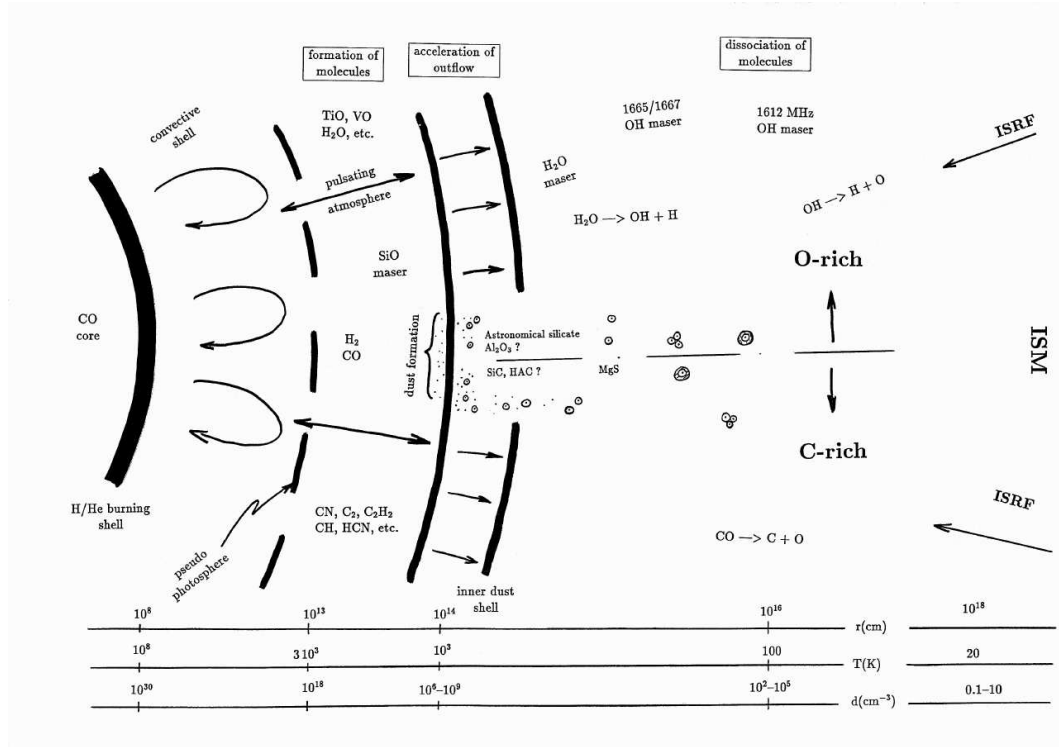


Figure 1.9.: Schematic view of the circumstellar envelope (CSE) of an AGB star with the respective scales (Le Bertre 1997).

where $\dot{M}$ is the MLR, c the speed of light, and L the luminosity (Habing & Olofsson 2003). For $\beta > 1$, the wind is optically thick and driven by gas pressure (thermal winds), for $\beta < 1$, the wind is optically thin and driven by radiation pressure. Knapp (1986) and Lefevre (1989) showed that $\beta < 1$ for most AGB stars. However, dust is needed to create such large MLR, and pulsations are needed to create dust in a numerable amount. Therefore, the winds of AGB stars are called *pulsation-enhanced dust-driven winds*. The stellar wind is composed of (molecular) gas and dust grains, which make up $\approx 1\%$ of the wind mass. While the grains are relatively stable, the remaining molecules in the wind get dissociated by ultraviolet (UV) photons or cosmic rays as they approach a distance from the star where the stellar wind is not dense enough to shield the molecules. Figure 1.9 gives an overview of the here discussed processes in the circumstellar envelope, from the core to the outer parts of the stellar winds. The expansion of stellar winds is discussed in Section 1.4 together with the occurring interactions.

1.2.3. Observational properties

As described earlier, when stars enter the giant phase, they become enormously bright. Many of them can be observed with the naked eye, like Antares (α Scorpii), Betelgeuse (α Orionis), Arcturus (α Bootis), Dubhe (α Ursæ Majoris), Pollux (β Geminorum), and Ras Algheti (α Herculis), which are all known since the ancient world. At that time, people must have recognized that these stars are significantly redder than others. This is the case because they are cool and surrounded by dust, thus their maximum flux is shifted to longer wavelengths.

Another physical discovery for AGB stars was made by the Dutch astronomer Johannes Holwarda, when he found that Mira (*o* Ceti) changes its brightness with a period of about eleven months. Today this brightness variation is one of the fundamental properties of all AGB stars and is a visible sign for the pulsations that are triggered in the stellar interior (see Section 1.2.1). The periods are quite long compared to other stellar types and are categorized in the General Catalogue of Variable Stars (GCVS; Samus et al. 2004) according to the amplitude and shape of the stellar light curves. AGB stars show four major types of variability: Mira-like stars (class M) are long-period variables (80–1000 days) with regular variations and a large amplitude in the V-band ($2.5 < V(\text{mag}) < 11$). Second are semi-regular stars of type A (SRa) with relatively regular periodicity between 35 and 1200 days and an amplitude $V < 2.5$ mag. Third are semi-regular stars of type B (SRb) with a poorly defined periodicity between 20 and 2300 days (Samus et al. 2004). Many of these stars show a second or third period overlaid. Last are the slow irregular type stars (class L), which do not show any evidence for periodicity in their light curves (Samus et al. 2004). The long periods observed for AGB stars are a common criterion to determine AGB stars. Another very useful effect of the period was recognised by Glass & Evans (1981). The authors studied the periods of Mira-type variables in the large magellanic cloud (LMC) and empirically found a strong correlation with the luminosity:

$$M_K = \rho(\log P - 2.38) + \delta, \quad (1.17)$$

where M_K is the absolute magnitude in the K -band, P the period of the Mira star in days, ρ the slope of the period-luminosity (PL) curve, and δ its zero-point (Feast et al. 1989; Whitelock et al. 2008). This is an extremely valuable tool to determine distances throughout the universe, since AGB stars are bright and easy to detect.

The most common way to distinguish whether a star is on the RGB or AGB, is to derive the luminosity

$$L = 4\pi R^2 \sigma T_{\text{eff}}^4, \quad (1.18)$$

where R is the stellar radius, σ the Stefan-Boltzmann constant, and T_{eff}^4 the effective temperature. RGB stars have a well defined maximum luminosity $L = 2900 L_{\odot}$ when they reach the tip of the RGB. Every evolved star with a similar colour that is more luminous must therefore be an AGB star or a RSG, which are, however, much rarer and brighter than AGB stars. AGB stars show luminosities of $2200 < L(L_{\odot}) < 55\,000$ corresponding to masses between $0.85\text{--}8 M_{\odot}$ (Habing & Olofsson 2003). Below the RGB tip luminosity, one must look for other clear indications for the AGB phase. One possibility is to obtain spectra and look for isotopes, which are produced in the s-process (see Section 1.2.1) and brought to the surface by dredge-up events. Good candidates are zirconium, vanadium, lithium, and especially technetium, which has no stable isotope. ^{99}Tc is produced exclusively by the s-process and has a half-life of 2.1×10^5 years. Thus, if ^{99}Tc is found in a stellar spectrum, it had to be produced in situ. Another indication is mass loss, which is much more prominent in the AGB phase (10^{-8} to $10^{-4} M_{\odot} \text{yr}^{-1}$) than in the RGB ($\approx 10^{-9} M_{\odot} \text{yr}^{-1}$). The MLR is thereby derived by fitting the mm-CO line profiles or dust emission of CSE (see e.g., Groenewegen et al. 2007).

The spectra of AGB stars are very rich in lines. With the study of circumstellar CO lines at different vibration-rotation bands it is possible to get properties of different layers of the CSE. While the gaseous part of the outflow manifests itself mainly in line emission, the dust is represented by broad features and continuum emission (Habing & Olofsson 2003). In the cold environment of the star, the dust cools down to a few 10–100 K and emits most of the energy in the mid- and far-IR. Therefore, observing the CSEs of AGB stars became possible not until the rise of IR observations in the late 1960s (Neugebauer & Leighton 1969). However, due to the difficulties of ground-based observations in the far-IR, it was the first operating astronomical IR satellite, IRAS, that enabled observations of the cool CSEs. These observations are discussed in Section 1.4, which deals with stellar winds. Another interesting technique to observe AGB stars is interferometry (in the near- and mid-IR), which enables to resolve the actual diameter of a star and is a valuable hunter for companions.

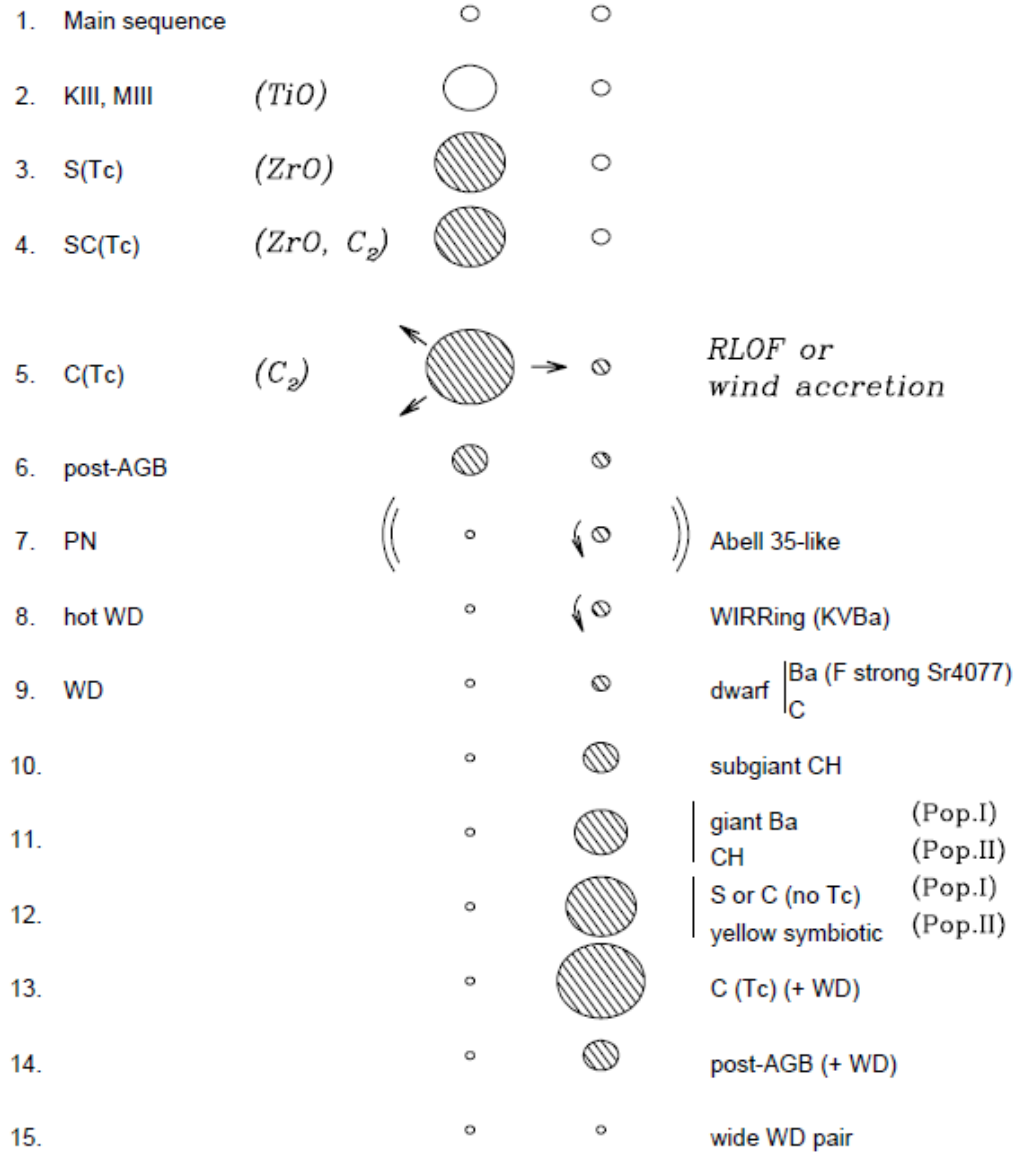


Figure 1.10.: Evolution of a low mass binary system from the MS to the WD phase of both stars. The series shows the ascent on the AGB and the on-setting of the mass transfer. The left column describes the normal single star evolution and the right the chemical peculiarities that can be caused by mass transfer (Jorissen 1999).

1.3. AGB stars in binary systems

So far, the introduction dealt with the evolution of a single star. However, a significant number of stars tend to be born in pairs, with a big dispute regarding the fraction. While Duquennoy & Mayor (1991) give a fraction of 57:38:4:1 for single:double:triple:quadruple G-type stars in the solar neighbourhood, Delfosse et al. (2004) find only 26% of the M-type stars to have (at least) one companion. And for all stellar types Lada (2006) finds a fraction of 33%. In any case, binary or multiple systems are common and their behaviour adds a few interesting points to the description of AGB stars. A detailed review of this topic is given by Habing & Olofsson (2003).

Since the bright AGB star dominates the visible and IR spectrum of a binary system it is referred as the *primary* star, while the other star is the *secondary* or *companion*. Due to the mass dependent time-scales of stellar evolution, the stellar type of the companion is quite restricted. A massive star with more than $8 M_{\odot}$ evolves much faster and its stellar life ends much earlier than an AGB progenitor, so it is impossible to have an AGB and an O-star in a binary system at the same time. An exception is the unlikely scenario that both stars were born as singles and the binarity was formed later on by gravitational capture between the two stars. But generally spoken, the companion could either be another giant star, a MS star with a slightly lower initial mass, or a WD, which had a higher initial mass and already evolved through the AGB. The evolutionary tracks of low mass binary systems are a complex field due to mass transfer processes, which alter the properties of both stars. A typical evolutionary track of a low mass binary system from the MS to the WD phase is depicted in Fig. 1.10.

The effects that occur in a binary system are of gravitational nature, which follows an r^{-2} relation. Thus, the distance in correlation with the two masses is the most important parameter of a binary system. Duquennoy & Mayor (1991), and most recently Tokovinin (2014), studied the orbital periods of solar type stars in the solar neighbourhood and found the Gaussian distribution to peak at a period of about 173 years ($10^{4.8}$ days). Figure. 1.11 shows the distribution of the binary orbits by Duquennoy & Mayor (1991).

Assuming a $2 M_{\odot}$ system, with an orbital period $P = 10^{4.8}$ days and applying the third Kepler law

$$P^2 = a^3 \frac{4\pi^2}{G(M_1 + M_2)}, \quad (1.19)$$

where G is the gravitational constant, and M_1 and M_2 are the masses of the primary and companion, respectively, one obtains a separation $a \approx 39$ au. However, one has to keep in mind that the primary star is not steady but

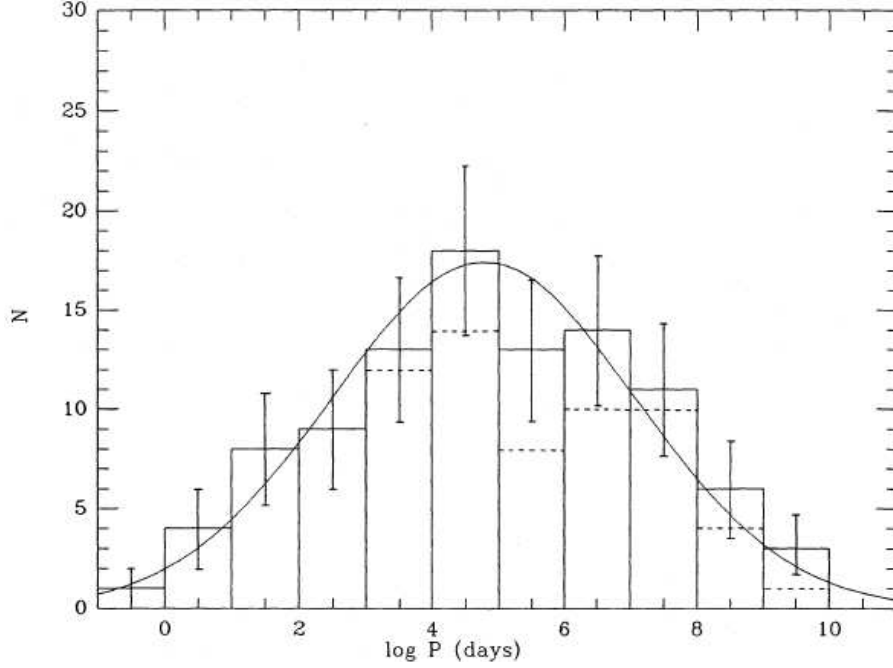


Figure 1.11.: Orbital period distribution of nearby G-dwarf stars over-plotted with a Gaussian. The median is at $P = 10^{4.8}$ days, equivalent to 173 years (Duquennoy & Mayor 1991).

also performs an orbital motion around the centre of mass (CoM) of the two bodies. The distance of the primary to the CoM is given by

$$r_1 = \frac{a}{1 + (M_1/M_2)}, \quad (1.20)$$

where $a = r_1 + r_2$ is the separation of the two stars.

An important concept in studying binary systems is the Roche equipotential surface after Édouard Roche, who studied extensively this phenomenon (see Fig. 1.12). By assuming that both stars are point sources, the gravitation field of the system is characterised by five Lagrangian points, where the gravitational forces of the masses provide the angular momentum for the orbit. For the inspection of the binary system, the inner Lagrangian point (L_1), which lies between the two masses, plays an important role. L_1 is the intersection of the equipotential, which has an ∞ -shape. The two lobes (with both stars at their centre) are called *Roche-lobes*.

1.3.1. Mass transfer in binary systems

Generally, one differentiates between three classes of binary (AGB star) systems: *wide (detached)* binaries, *semi-detached* binaries, and *common envelope* (CE) binaries. The division is mainly based on the behaviour of the mass transfer and the properties of the Roche-lobe, which depends on the separation.

When a binary system evolves, the more massive star ascends first the RGB, and subsequently the AGB. During the evolution, the atmosphere expands to huge size and when it reaches L_1 mass is transferred through the Lagrange point to the companion. Paczyński (1971) determined the Roche-lobe radius R_1 around the primary as

$$\frac{R_1}{a} = \begin{cases} 0.38 + 0.2 \log q & \text{if } 0.5 < q < 20 \\ 0.46224 \left(\frac{M_1}{M_1 + M_2} \right)^{1/3} & \text{if } 0 < q < 0.5, \end{cases} \quad (1.21)$$

with $q = M_1/M_2$. Eggleton (1983) later refined this description to

$$\frac{R_1}{a} = \frac{0.49q^{2/3}}{0.6q^{2/3} + \ln(1 + q^{1/3})}, \quad (1.22)$$

for all ranges of q . This mass transfer is called *Roche-lobe overflow* (RLOF).

Some very rough estimates can be drawn from this equation and the orbital period distributions (Duquennoy & Mayor 1991). For a system with $q = 1.5$, the Roche lobe radius is $0.41a$. A typical AGB star with a radius of about $300 R_\odot$ (1.4 au) then fully fills the Roche lobe if the orbital separation is shorter than 3.4 au. This separation would translate to an orbital period of $10^{3.21}$ days (4.4 years) in a $2 M_\odot$ system, which is much shorter than the average period of binaries in the solar neighbourhood (see Fig. 1.11). Applying the Gaussian-type relation for solar type binaries by Duquennoy & Mayor (1991) one finds that about 22% of the G-dwarf binary systems have separations of 3.4 au or shorter.

In such close systems, the primary fills quickly the small Roche-lobe and keeps expanding. Material falls over L_1 on the secondary, which accumulates steadily the oncoming mass. These systems, in which only one star fills the Roche-lobe, are called semi-detached. If much more material falls over L_1 than the companion can steadily accrete, a circumstellar disk establishes around the secondary, which starts to expand as well due to the large amount of oncoming mass (Benson 1970). The star fills its own Roche-lobe and both atmospheres start merging to share a flattened common envelope (CE; Paczyński 1971, 1976). Friction causes the orbit to shrink with the result that the companion

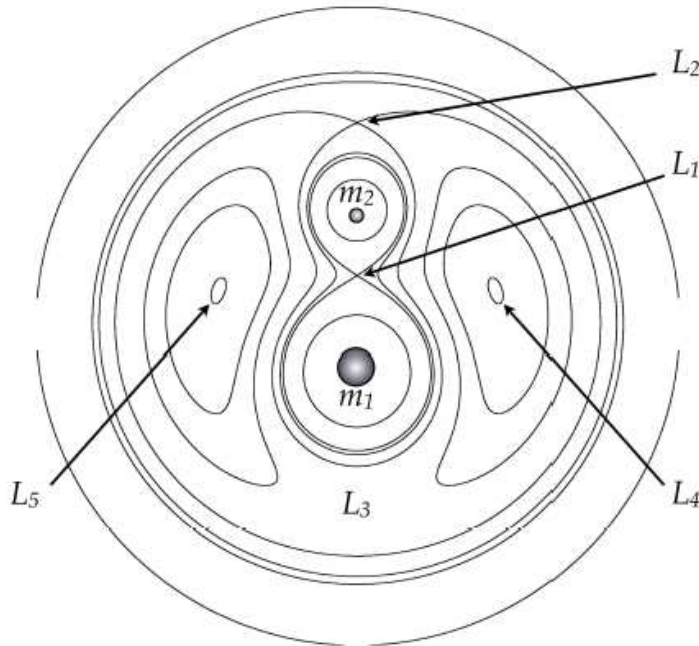


Figure 1.12.: Roche equipotential surface in the orbital plane of a binary system with a mass ratio $q = 2.5$ (Benacquista & Downing 2013).

spirals towards the primary (Kastner et al. 2000; Podsiadlowski 2001). Energy is lost from the orbit to the envelope, which in turn inflates (Izzard et al. 2012). Meanwhile an accretion disk forms around the secondary star and a large fraction of the disk mass is launched in two opposite jets (Akashi & Soker 2008; Soker 2014b). At this stage the separation of the system is only about 0.1 au. Finally, the CE is ejected, revealing a pair of hot stellar cores surrounded by a circumbinary disk that also might launch jets. The whole CE phase only lasts for a very short time (few years), and if the in-spiralling of the companion is quicker than the envelope ejection, both stars merge. This scenario is also supposable after the ejection of the envelope (Soker 2013). Until now, the CE phase has only been proven indirectly by binary systems inside PNe, which are so close that they must have shared a CE. However, Chesneau et al. (2014) found evidence for a CE around the yellow hypergiant HR 5171 A. Recently, Soker (2014a) postulated another mechanism, where the companion grazes the AGB envelope and accretes mass at high rates. A jet is launched, which carries away momentum and energy and the orbit shrinks together with the radius of the AGB star. The CE phase is therefore omitted in this scenario and the result is again a close binary system (Soker 2014a).

The last class of binaries, the detached systems, are usually separated by more than 5 au and represent by far the largest group of binary systems (Duquennoy & Mayor 1991). The radius of the star is in this case smaller than the Roche-lobe radius. But also here, mass is transferred from the primary to the companion; however, at much smaller rates. Karovska et al. (2005) observed a mass-transfer bridge in the Mira (*o* Ceti) binary system, where both components are separated by 55 au. This implies a Roche-lobe size that a Mira star could not reach. Mohamed & Podsiadlowski (2007, 2011) performed hydrodynamic simulations for the Mira AB system and realised a new form of mass transfer. In this scenario it is not the atmosphere of the Mira-type star that fills the Roche-lobe but its slow stellar wind. This is called *wind Roche-lobe overflow* (WRLOF) or *gravitational focussing* (de Val-Borro et al. 2009). The WRLOF manages to transmit a significant fraction of the primary wind to the companion. For the *o* Cet system, the accretion efficiency $\beta = \dot{M}_{\text{acc}}/\dot{M}_*$, which gives the ratio between the accumulated mass by the companion and the mass lost by the primary, is about 10%. The highest accretion efficiency of the WRLOF (45%) is achieved for systems with a separation of about 20 au (Mohamed & Podsiadlowski 2011). At smaller separations a larger fraction of the wind escapes through L_2 and L_3 , and is not accreted by the companion (Abate et al. 2013).

Another form of mass transfer in detached systems is described by the Bondi-Hoyle-Lyttleton (BHL) accretion (Hoyle & Lyttleton 1941; Bondi & Hoyle 1944). This mass transfer describes the gravitational potential of the companion to attract surrounding matter. Theuns & Jorissen (1993) formulated the accretion efficiency of the BHL accretion as

$$\beta = -\alpha\mu^2 \frac{k^4}{[1 + k^2 + (c_s/v_w)^2]^{3/2}}, \quad (1.23)$$

where α is a parameter describing the uncertainty in the parametrization of the mass accretion rate,

$$\mu = \frac{M_{\text{comp}}}{M_{\text{comp}} + M_{\text{prim}}}, \quad (1.24)$$

and $k = v_{\text{orb}}/v_w$, where v_{orb} is the orbital velocity and v_w the wind velocity. However, the mass transfer rate of the BHL accretion is only of the order of a few percent in a detached binary like Mira, and thus much more inefficient than the WRLOF (Abate et al. 2013).

1.3.2. Observing binary AGB star systems

As shown before, AGB stars are very bright in the optical and IR and surrounded by dusty envelopes, while the companion is generally much fainter at these wavelengths. Systems with a directly observed companion (*visual binaries*) are therefore rare. The same fact holds for the light curves of binary AGB stars, which can appear shallow or with wide and flat minima but this method is restricted to sufficiently bright companions. Nevertheless, a few other methods are available to detect binary systems involving an AGB star. A more extensive overview is given in Chapter 9 of Habing & Olofsson (2003), on which this part is based.

One of the most common methods for hunting out companions is measuring the radial velocity (RV) of a star to see if there are periodical variations that can indicate the orbital motion. These are called *spectroscopic binaries*. The gravitational force of the companion leads to a motion of the primary around the common CoM and the spectrum shows Doppler shifts, which change periodically from red- to blue-shift. However, these observations bear many difficulties. One is the time line of the observation, since the RV of a detached system has to be monitored over a long period to obtain a certain detection of the orbital motion. The other source of troubles is the pulsation period of the primary. As previously discussed, AGB stars show strong envelope pulsations, which can be confused with the extrinsic variations from the orbital motion (Habing & Olofsson 2003). A typical Mira-type pulsation causes RV variations that are larger than the extrinsic variation caused by the orbital motion of the detached binary. Previous observations have only been successful in detecting a few spectroscopic binaries (e.g., Van Winckel et al. 1999; Hinkle et al. 2002), mainly owing to limitations in resolution. New instruments, like the HERMES spectrograph (Raskin et al. 2011) at the Mercator telescope, are becoming useful tools for this task (e.g., Van Winckel et al. 2010, 2014; Merle et al. 2014).

A similar method to measure the Doppler shifts is the analysis of astrometry data of the binary system. For this approach, one uses the fact that the primary star pulsates, which produces a non-linear motion around the photocentre of the binary system. The photocentre moves back and forth along the connection line of the two stars. If the measurements are carried out over a time-scale that is comparable to the orbital period it is possible to detect the delicate wavy orbital motion of the photocentre with respect to the CoM (Wielen 1995). The accuracy provided by the Hipparcos satellite is sufficient and these stars are flagged as *variability-induced movers* (VIM; Wielen 1996) in the Hipparcos catalogue (van Leeuwen 2007). However, Pourbaix et al. (2003) showed in an

extensive analysis that 85 % of the VIM could also be explained by a single-star solution. This dispute will hopefully end when the Gaia satellite, launched in December 2013, is fully operating. Its high precision data will dramatically increase the number of VIMs and allow to separate pulsation from photocentre motion.

Meanwhile, another astrometric approach can help to find companions: the $\Delta\mu$ method described by Makarov & Kaplan (2005) and Frankowski et al. (2007). The basic idea behind is that the proper motions of binaries recorded by Hipparcos over a timespan of 3.2 years (van Leeuwen 2007) are polluted by the orbital motion of the photocentre. The Hipparcos proper motion value is therefore different from the Tycho-2 value, which includes proper motions covering one century (Høg et al. 2000). In the Tycho-2 catalogue, the photocentre motion is smeared out over time and therefore closer to the motion of the CoM. Frankowski et al. (2007) have shown that binary systems with orbital periods of 1500–30 000 days can be detected by their proper motion difference. Furthermore, Makarov & Kaplan (2005) showed that the difference also allows to determine a few orbital parameter following

$$\Delta\mu \leq \frac{2\pi\varpi R_0 M_2}{(M_1 + M_2)^{2/3} P^{1/3}}, \quad (1.25)$$

where ϖ is the parallax, and R_0 a time-dependent orbital phase term. The exact solution stands for a face-on orbit, the projected $\Delta\mu$ of an inclined orbit is therefore always smaller. In Section 2.3, a proper motion analysis is performed for the binary system π^1 Gruis.

Another possibility to identify AGB binary systems is the detection of composite spectra (Habing & Olofsson 2003). These stars are also known as *symbiotic* binaries and are defined by having a spectrum, which shows low-excitation absorption features (CO, H₂O, TiO) together with high-excitation emission lines (e.g., He II), but also forbidden lines are frequent in the stellar wind (Boyarchuk 1967; Puetter et al. 1978; Habing & Olofsson 2003). These phenomena are found in binary systems consisting of a cool Mira-type AGB star (3000 K) and a hot WD (10⁵ K) companion. The systems are detached, so the AGB star does not fill its Roche-lobe. The absorption lines are a characteristic of the giant while the hot continuum is emitted when the companion accretes and heats up material from the Mira star. A maximum mass of $\approx 10^{-3} M_\odot$ of hydrogen is moved to the surface of the WD, where it ignites and provides steady fuel for a few thousand years (Kwok 1997). In contrast to a classical nova, where the cool component is a MS star, which fills the Roche-lobe, the brightness increase of a symbiotic nova is mainly due to recombination lines of hydrogen and collisionally excited lines of metals (Kwok 1997). The brightness

maximum is in the IR and lasts for a few decades. One of the most famous symbiotic stars, R Aquarii, is discussed in Section 2.2.

The transfer of matter from an AGB star to a companion also allows to observe the binary system in the UV and X-ray wavelength. This kind of emission is unusual for AGB stars since the flux decreases rapidly for $\lambda < 2800 \text{ \AA}$, and is below any detection limit shorter than $2000 \text{ \AA}$ (Wood & Karovska 2004). However, Sahai et al. (2008) found nine AGB stars, in a sample of 21, to have significant UV emission in the GALEX FUV ($1344\text{--}1786 \text{ \AA}$) and NUV ($1771\text{--}2831 \text{ \AA}$) bands. The fluxes are by a factor 10^5 larger than expected for the photosphere of an AGB star and show a significant photometric variability. This is most likely caused by accretion of matter by a WD. Matter falls over L_1 towards the potential well of the hot companion and starts to orbit the star and collides with itself since more material is transferred to the companion. Shocks cause the accreted material to form a disk, and friction and viscosity processes become important and convert gravitational energy into radiation (Frank et al. 2002). The energy loss leads to an approach of the particles towards the WD. The accretion disk becomes circular and heats up to half of the WD temperature (few 10^4 K ; Pringle 1981). Therefore the emission of the accretion disk peaks in the UV and X-ray, where it is detected for, e.g., the Mira AB system (Karovska et al. 2005), as described earlier.

Another possibility for the accretion disk to lose angular momentum is to trigger a high velocity bipolar outflow or jet along the rotation axis. These outflows can be identified by high resolution spectroscopy of the binary system. Variations in the line shape of monoxide molecules at different locations on the sky are evidence of a complex velocity structure within the CSE. Studies are mostly done for the CO and SiO molecules, which are abundant and observable from ground in the (sub-)millimetre wavelength domain. Characteristic shapes indicating the presence of a disk with a bipolar outflow, are a narrow central peak with broad shoulders and wings on each side (Kahane & Jura 1996; Jura & Kahane 1999) and a double-horned non-parabolic profile with a velocity gradient along one direction (Sahai 1992; Knapp et al. 1999; Chiu et al. 2006). Several objects, of which some are also discussed in this thesis, show this kind of asymmetries in the molecular line shape.

Finally, it is also possible to detect a companion and determine some of the orbital parameters by observing asymmetries in the large-scale wind morphology caused by the interaction of the stellar wind with the gravitational force of the companion. This is shown in Section 1.4.3.

1.4. Stellar winds

The previous parts of the introduction demonstrated how dust particles are formed and how AGB stars lose mass at remarkable rates. This part deals with the expansion of the stellar wind, its structure, and, if special circumstances meet, how interactions occur. An extensive description is given in a review book of (Lamers & Cassinelli 1999), which is also a base of this section.

Generally, for single stars one can assume that mass loss forms a spherically expanding wind that can be described by the *wind equation* of an isothermal wind (Parker 1958):

$$\frac{1}{2} \left(1 - \frac{c_s^2}{v_w^2} \right) \frac{dv_w^2}{dr} = -\frac{GM}{r^2} \left(1 - \frac{2c_s^2 r}{GM} \right). \quad (1.26)$$

The equation has a critical point at

$$r = r_{\text{crit}} = \frac{GM}{2c_s^2}, \quad (1.27)$$

where the right side of Eq. 1.26 becomes equal zero. This leads to four stable solutions of the wind equation (Lamers & Cassinelli 1999). The first solution describes a wind that is ejected subsonically and is mildly accelerated to the critical point and slows down again beyond the point. Hence, the wind always stays subsonic. The second solution is ejected subsonically but accelerated to c_s at r_{crit} and is moving supersonically beyond r_{crit} . This describes a typical stellar wind scenario. The wind equation gives $v_w \propto (\ln r)^{1/2}$ which means that the velocity becomes infinite at an infinite distance. Instinctively, this seems wrong and is due to the isothermal approach of the equation. In reality, the wind velocity is reduced by shock waves and the wind leaves the isothermal condition. A large fraction of the kinetic energy is converted to heat. The remaining two solutions are the inversions of the previous solutions, the stellar wind is ejected supersonically and stays supersonic or is decelerated to subsonic motion. The latter describes the BHL accretion flow, which was described in Section 1.3.1 (Hoyle & Lyttleton 1941; Bondi & Hoyle 1944). A deeper discussion of the wind equation and its solutions is given in a review book on stellar winds by Lamers & Cassinelli (1999).

The stellar wind beyond r_{crit} is freely expanding and moving supersonically. Freely in this context, however, is relative since the expansion has to work against the interstellar medium (ISM) surrounding the star. The stellar wind pushes away and piles up the ISM like a snowplough why it was named the *snowplough phase* by Oort (1951) who aimed to describe the expansion of a

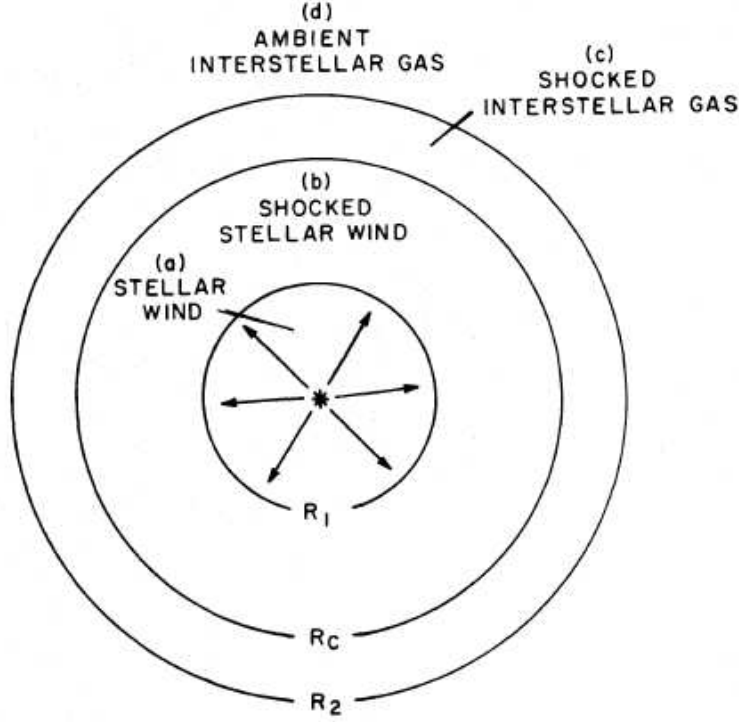


Figure 1.13.: Concept of a stellar wind bubble, or astrosphere, by Weaver et al. (1977). The astrosphere is divided into four parts, which are described in the text.

SNR in this way. Due to the pile-up of the ISM, the structure of the stellar wind becomes more complex as shown in Fig. 1.13. The wind bubble, or *astrosphere*, can be divided into four parts (Weaver et al. 1977). These are from inside to outside: (i) the freely expanding supersonic wind with small thermal pressure. For a constant MLR, the wind velocity is constant and the density in this region drops with r^{-2} . The border where the wind changes from supersonic to subsonic is called *termination shock*. A shock front can be understood in the way of a discontinuity which propagates through the stellar wind and changes the medium irreversible. The shock front can be described by the *Rankine-Hugoniot conditions*:

$$\frac{P_1}{P_0} = \frac{(\gamma + 1)V_0 - (\gamma - 1)V_1}{(\gamma + 1)V_1 - (\gamma - 1)V_0} \quad (1.28)$$

and

$$\frac{\rho_0}{\rho_1} = \frac{v_1}{v_0} = \frac{(\gamma - 1)P_1 + (\gamma + 1)P_0}{(\gamma + 1)P_1 + (\gamma - 1)P_0} \quad (1.29)$$

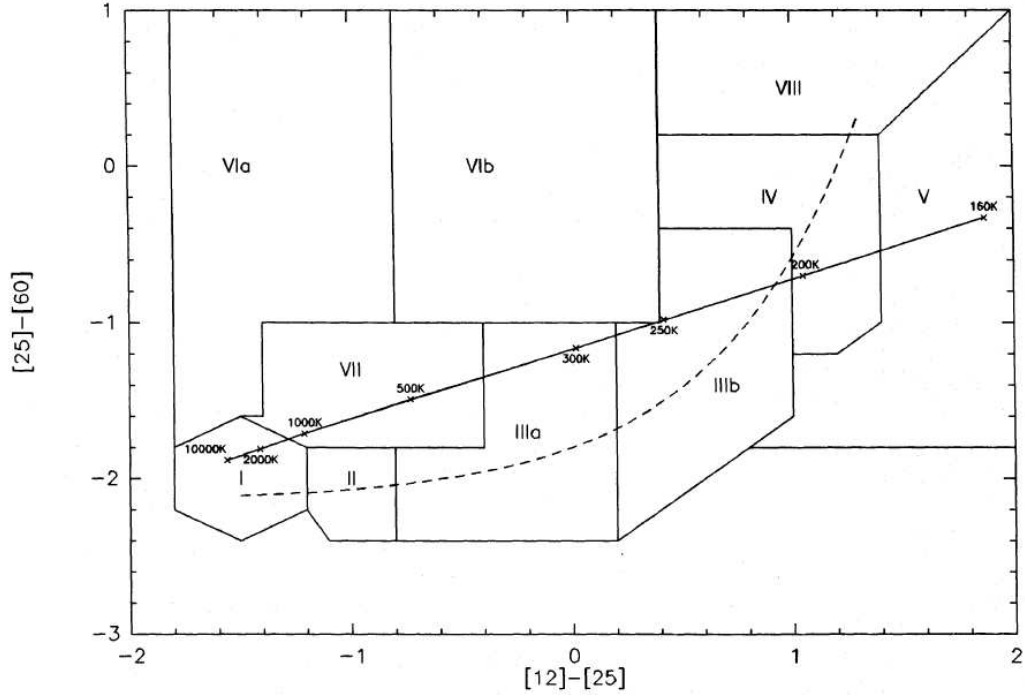


Figure 1.14.: IRAS two-colour diagram of AGB stars. The dashed line represents the evolutionary track from an oxygen-rich to carbon-rich AGB star (van der Veen & Habing 1988).

where 0 and 1 depict the conditions before and after the shock, respectively. P is hereby the pressure, $V = 1/\rho$ the specific volume, γ the specific heat coefficient of the gas, v the velocity, and ρ the density. A strong shock converts most of the kinetic energy of the wind to thermal energy and the temperature in the shock front can be approximated by

$$T \approx \frac{3\bar{m}v^2}{16k}, \quad (1.30)$$

where $\bar{m}$ is the mean weight of a particle in the shocked medium. For an isothermal hydrogen gas ($\gamma = 1$) the thickness of a shock front is given as

$$\frac{\Delta R}{R} = \frac{1}{3\mathcal{M}^2}, \quad (1.31)$$

where $\mathcal{M}^2 = \rho_1/\rho_0$ is the Mach number (Comeron & Kaper 1998).

In region (ii), the stellar wind exists in a shocked condition. Radiative cooling causes a steep increase of the density. The contact discontinuity parts the

shocked wind from the shocked ISM, but dissolves due to thermal conduction of both layers. Farther outside follows region (iii), where the shocked and piled-up ISM is located. This layer dominates the mass balance of the astrosphere although the size of the shell is small compared to rest of the bubble. The expansion of the stellar wind can therefore be described as a thin shell expansion with a velocity of the shell proportional to $t^{-2/5}$. The shocked ISM is surrounded by region (iv) where the undisturbed ISM is located (Falle 1975; Weaver et al. 1977).

For AGB stars, the shocks are very mild since the wind velocity is only $5\text{--}20\text{ km s}^{-1}$. The shock front of a continuous AGB wind that runs into the ambient medium does not heat up the dust grains significantly. However, if the star is not at rest but moves with respect to the ISM, the additional velocity component can be much larger than the wind velocity and causes stronger shocks. This, along with other forms of interactions, will be discussed in the next sections. The photometric observations of stellar AGB winds is therefore biased towards observing interactions.

With the rise of IR space observations, it became possible to observe the circumstellar environment of AGB stars. First it was van der Veen & Habing (1988) who studied the IRAS observations in the 12, 25 and $60\text{ }\mu\text{m}$ bands and derived an evolutionary track of the AGB star in the *IRAS two-colour diagram* (see Fig. 1.14). The star starts oxygen-rich without a circumstellar shell at region I and evolves to region VII where the C-rich envelopes are located. However, the IRAS two-colour diagram only describes the composition of the CSE. Young et al. (1993b) examined an IRAS sample of 512 evolved stars and found 76 of them to show an extended envelope, of which some seemed to be asymmetric. The resolution of IRAS, however, is too low to specify the shape of the asymmetries. In the past decade the winds of AGB stars were studied extensively. The next sections discuss some of these observations.

1.4.1. Interaction of two winds: detached shells

As shown earlier in Section 1.2.1, the TP phase is an essential part of the stellar evolution on the AGB. The mass loss is enhanced during that time which is equivalent to an increase of the wind velocity (Maercker et al. 2012). This means that during the TP phase a wind is triggered that is denser and faster than on the E-AGB. The TP wind sweeps up the slower wind from the E-AGB phase. What forms is a dense region and a shock front where both winds collide (Maercker et al. 2010; ?). The layer of swept up and dense material collisionally heats dust grains but also shields molecules from photo-dissociation and the wind bubble becomes observable as a projected ring, called *detached shell*. Since this phenomenon is triggered by TPs, all of the detached shell objects are carbon rich.

The first indications of the interaction of winds were expressed by Olofsson et al. (1987, 1988, 1990) when the authors found thin shells around a handful of carbon stars in the molecular CO($J=1-0,2-1$) radio emission. The CO maps showed that the shells were located at a distance of about 10^4 au from the star, much farther away than the zone where the molecules are formed. The high bond energy of CO prevents photo-dissociation by the interstellar radiation field up to large distances from the star. This makes CO emission a great tracer for detached shells, but also other abundant molecules like CS, HCN, and CN have been found in detached shells (Olofsson et al. 1993; Lindqvist et al. 1996). Interferometric CO observations showed that the shells are only produced during a very short period of a few hundred years (Lindqvist et al. 1999; Olofsson et al. 2000). This result, however, only gives the lower limit since it does not account for the deceleration of the shell when it sweeps up the old wind.

Observations of AGB stars with ISO demonstrated that detached shells are also observable in the far-IR, the regime of thermal emission from cold dust grains. Izumiura et al. (1996) found a detached CSE around Y CVn located $\approx 4 \times 10^4$ au away from the central star in the ISOPHOT $90 \mu\text{m}$ and $160 \mu\text{m}$ bands. However, the images suffer massively from ISO's low resolution. This changed when observations were carried out with *Herschel*/PACS using its high resolution and sensitivity. Cox et al. (2012) identified 15 detached shell objects in the MESS sample while Kerschbaum et al. (2010) and Mečina et al. (2014a) were able to determine the dust temperature in a number of shells. Figure 1.15 shows S Scuti in the PACS $70 \mu\text{m}$ and $160 \mu\text{m}$ bands (Mečina et al. 2014a). The rim of the wind bubble is brightened where the interaction with the old wind occurs. Farther outside in north-east direction, a bow shock structure is visible, which is an indication for the interaction of the stellar

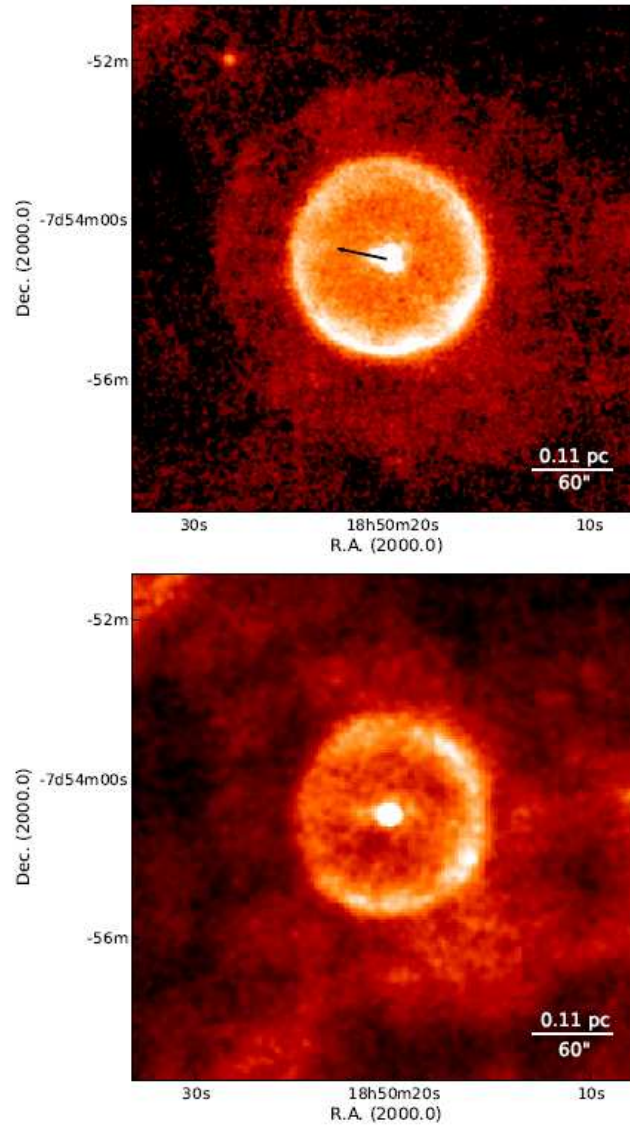


Figure 1.15.: *Herschel*/PACS maps of S Scuti at $70\,\mu\text{m}$ and $160\,\mu\text{m}$ by Mečina et al. (2014a). The images show the spherically symmetric detached shell which is surrounded in the NE by a faint bow shock caused by ISM interaction (upper panel). The black arrow indicates the direction of the space motion, in accordance with the bow shock location.

wind with the ISM. This feature is discussed in the following section.

1.4.2. Interaction with the interstellar medium: bow shocks

So far, spherically symmetric stellar winds were described using a wind bubble model that expands uniformly into the surrounding ISM. This simple scenario is valid if the star is at rest with respect to the ambient medium. Feast & Whitelock (2000) however found that an AGB star typically moves with a velocity of 30 km s^{-1} but can reach in extreme cases also over 100 km s^{-1} (e.g., *o Ceti*; Martin et al. 2007). The stellar motion adds an asymmetry to the wind velocity profile, since certain parts of the wind face the ISM with different relative velocities. The strength of the asymmetry depends of course on the stellar velocity v_* , and for the typical AGB star velocity of 30 km s^{-1} the spherically symmetric wind bubble is still a valid approach. For $v_* \gtrsim 50 \text{ km s}^{-1}$ the stellar wind is deformed severely in a surrounding medium with an ordinary density.

When a star moves at a certain direction, the outermost layer of the stellar wind bubble faces the ISM highly supersonic. A shocked layer in the wind bubble forms that is bound on the side where it hits the undisturbed ISM by the *bow shock* and further inside by the *termination shock*. Thus, the material in the bow shock is of interstellar origin while the termination shock heats up the stellar wind material.

A basic model for the stellar wind–ISM interaction was given by Baranov et al. (1970) when the authors described the bow shock around the sun, that was discovered earlier by Strong (1968). Gurzadian (1969) argued that also stellar objects with gaseous surroundings, like PNe, should show bow shocks and tail structures. The model by Baranov et al. (1970) included an essential formulation of the *stand-off distance*, the distance from the star to the apex of the bow shock (see Fig. 1.16). It is given as:

$$R_0 = \sqrt{\frac{\dot{M}v_w}{4\pi\rho_0v_*^2}}, \quad (1.32)$$

where ρ_0 is the density of the ISM which follows roughly

$$n_H(z) = 2.0e^{-\frac{|z|}{100 \text{ pc}}}, \quad (1.33)$$

where n_H is the number density of hydrogen and z the galactic height (Mihalas & Binney 1981). Thus, the distance of the star to the apex of the bow shock is defined by the MLR, the wind velocity, the ISM density, and the stellar velocity. The analytic shape of the bow shock was later determined by Wilkin (1996) who studied the vector momentum of the ISM and the stellar wind on

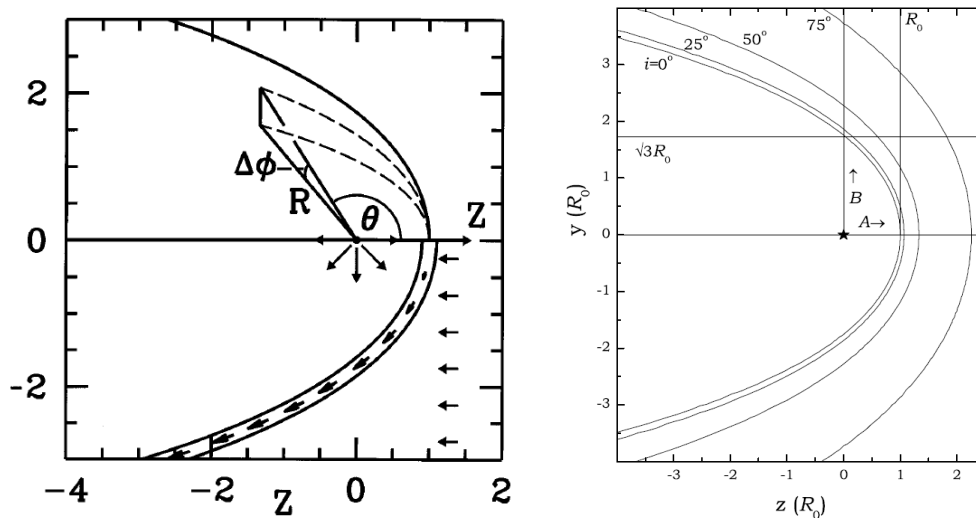


Figure 1.16.: *Left panel:* analytic solution of a thin shell bow shock by Wilkin (1996). The upper part gives the overall shape of the bow shock with the star at (0,0). The lower part shows the wind flow of the oncoming ISM through the bow shock. *Right panel:* projected shapes of the analytic bow shock solution with different inclination (viewing) angles i (Cox et al. 2012).

a small wedge of the bow shock. The shape is thereby given as

$$R(\theta) = \frac{R_0}{\sin \theta} \sqrt{3(1 - \theta \cot \theta)}, \quad (1.34)$$

where θ is the polar angle measured from the axis of symmetry (a straight from the star to the bow shock apex, see left panel of Fig. 1.16). According to Eq. 1.34, the shape is linearly dependent on the stand-off distance, thus only the size of the bow shock changes with R_0 but the outline remains the same. As Cox et al. (2012) demonstrated, this is valid for all viewing angles up to 70° . At higher inclinations, the bow shock cone broadens (see right panel of Fig. 1.16).

Observationally, stellar wind bow shocks were for a long time limited to main sequence stars. The first stellar bow shocks were found around LL Orionis and ζ Ophiuchi, where the first moves fast through the star forming Orion Nebula and the latter is a runaway O-star that expels its wind with a velocity over 1000 km s^{-1} . Both show very strong bow shocks observable in the optical and UV. The launch of IRAS in 1983 allowed for observations in the far-IR, which is according to Draine (1981) the domain of dust emission in shocked gas. At

moderate energies, electrons and ions collide with the dust grains, penetrate the outer layers and kinetic energy is converted to heat. The wavelength peak is given as

$$\lambda_{\text{peak}} = 75 \mu\text{m} \left(\frac{n_{\text{H},0}}{\text{cm}^{-3}} \right)^{-0.18} \left(\frac{v_s}{100 \text{ km s}^{-1}} \right)^{-0.3}, \quad (1.35)$$

where $n_{\text{H},0}$ is the wind density before the shock and v_s the shock wave speed (Draine 1981). Subsequently, van Buren & McCray (1988) presented 15 unambiguous bow shocks around runaway O-stars observed with IRAS. However, the satellite did not provide enough sensitivity to image bow shocks around AGB stars (Stencel et al. 1988). This had to wait until Ueta et al. (2006) used Spitzer/MIPS to observe R Hydræ at $70 \mu\text{m}$ and $160 \mu\text{m}$ and found an arclike structure about 0.08 pc away from the AGB star. The curvature of the arc in combination with the direction of motion allow the conclusion that the arc is indeed caused by the interaction with the ISM. The dust emission most likely traces the termination shock rather than the bow shock, which consists of (less dusty) shocked ISM. Nevertheless, for reasons of simplicity, the overall interaction structure is furthermore named bow shock.

An unambiguous detection of an AGB star bow shock was found around *o* Cet by Martin et al. (2007) on GALEX images. The star is moving so fast that material, which is stripped off from the bow shock head, collisionally excites the downstream H_2 gas and becomes observable in the UV as a 4 pc long tail. Section 2.1 provides a more detailed view of the environment of *o* Cet. UV emission of the large-scale stellar environment of AGB stars is very rare and so far only found for Mira, CW Leonis (IRC +10 216), and CIT 6 (Martin et al. 2007; Sahai & Chronopoulos 2010; Sahai & Mack-Crane 2014).

The high sensitivity and resolution of *Herschel*/PACS mean a great leap in the field. Cox et al. (2012) identified more than 30 new bow shock objects in the MESS sample – a large number compared to the handful known objects from previous observations (Geise et al. 2010). The spatial resolution of PACS allows to obtain a deeper insight into the wind–ISM interaction than previous observations. The observations of α Orionis, for example, revealed that the material between the star and the bow shock consists of multiple shells created by turbulent mass loss events, while the interaction region is completely smooth (Decin et al. 2012). In contrast, Jorissen et al. (2011) studied the environments of TX Piscium and X Herculis and found the interaction region not to be smooth but heavily distorted by wiggles, wings and bends (see Fig. 1.17).

These phenomena are found for the majority of bow shocks in the MESS sample and is caused by effective cooling in the shocked region (Cox et al. 2012). If the bow shock cools rapidly, it collapses to a thin and dense shell, as used in the analytic solution of Wilkin (1996). Its efficiency is determined by

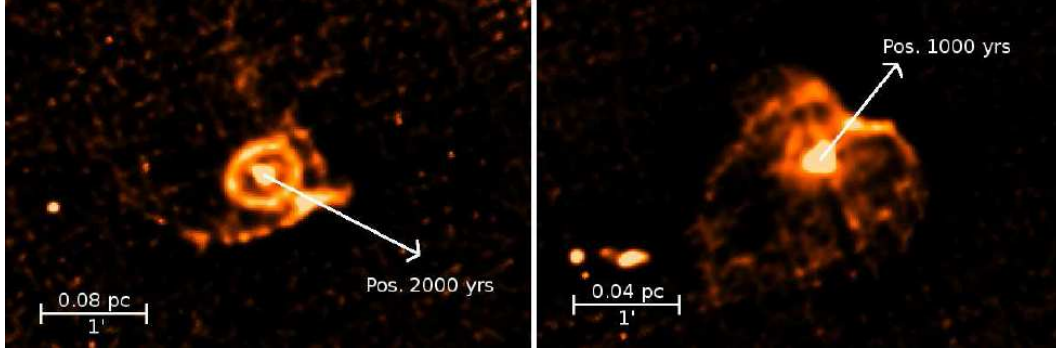


Figure 1.17.: Deconvolved $70\,\mu\text{m}$ *Herschel*/PACS images of TX Psc (left) and X Her (right). The arrow indicates the direction of the space motion and the position after a given time in the future (Jorissen et al. 2011).

the cooling length

$$L_c = \frac{3\bar{m}^2 v_*^3}{256\rho_0\Lambda}, \quad (1.36)$$

where Λ is the volume cooling rate (Blondin & Koerwer 1998). The cooling length, however, is far smaller than the stand-off distance of all AGB bow shocks found in the MESS sample (Cox et al. 2012). The gas cools rapidly and the bow shocks around AGB stars can be described as thin shell shock fronts. These shock fronts are susceptible to a number of instabilities like the non-linear thin shell instability (NTSI; Vishniac 1994) which is formed when the shock front is bended. Opposing gas flows occur in the inner parts of the shock front creates non-linear wiggles and ripples (Blondin & Koerwer 1998). Another instability is the transverse acceleration instability (TAI; Dgani et al. 1996), which is caused by additional mass elements on the shock surface and the change of momentum flux when the shock front collides with the ISM. Unlike the NTSI, the TAI operates mainly in the bow shock wings and not at the apex. The most common instability is the Kelvin-Helmholtz instability (KHI), which is caused by a shear at the boundary between two fluids and produces ripples and waves. Either one or a combination of these instabilities are influencing the shape of stellar AGB bow shocks in the MESS sample.

1.4.3. Interaction with a companion: Archimedean spirals

The last type of interaction described in this introduction has to do with the presence of a companion. As shown in Section 1.3.1, mass transfer is a subject to AGB binary systems. The crucial parameters for the mass transfer is the MLR, the mass of the companion, and the separation of the components. In one of the binary types the companion is so close, that both stars fill their Roche-lobes and form a CE which is eventually ejected, or the two stars merge. The CE phase irreversibly changes the stellar wind morphology, also on large scales. Until now, this was however not observed for AGB stars but is one of the most accepted explanations for shaping asymmetric PNe (e.g., De Marco et al. 2008; Hall et al. 2013; Jones et al. 2014).

The vast majority of binary systems have larger separations and the mass transfer and outflow shaping proceeds differently. These semi-detached and detached systems transfer mass via (W)RLOF or BHL accretion (see Sect. 1.3.1). Extensive hydrodynamic modelling of this situation has been carried out by Theuns & Jorissen (1993), Mastrodemos & Morris (1998, 1999), Mohamed & Podsiadlowski (2007, 2011), Abate et al. (2013), and Kim & Taam (2012b,c). Mastrodemos & Morris (1998, 1999) studied the effects of mass transfer with the widest parameter range, including 18 models varying in the size of the primary, wind velocity, orbital period and separation; from semi-detached systems of $a = 3.6$ au to wide binaries of $a = 50.4$ au. These simulations are the base for the more recent work of Mohamed & Podsiadlowski (2007, 2011) and Kim & Taam (2012a,c), and are therefore explained in more detail.

Generally, a secondary with an accretion disk orbits the primary with a velocity higher than the sound speed. The attracted material around the accretion disk then forms a small bow shock in direction of the orbital motion. The bow shock is steady approximately 1 au ahead of the companion and is formed no matter if the accretion occurs in form of BHL accretion or (W)RLOF (Mohamed & Podsiadlowski 2007). Material is stripped from the bow shock head and forms a narrow and stable wake due to the high Mach number. Figure 1.18 shows the velocity field of the primary's wind with the bow shock and accretion wake of the secondary by Mastrodemos & Morris (1998). After the accretion wake is formed, it is pushed away from the system by the remaining wind expelled from the primary. The accretion wake forms a spiral pattern, which winds around the binary system due to the orbital motion of the companion. Due to the geometry of the accretion wake and the distance to the mass losing star the spiral pattern is confined to the orbital plane. The shape of the spiral pattern is a true Archimedean spiral. Depending on the orbital velocity of the secondary, v_s , the spiral is tighter the larger the ratio v_s/v_w is

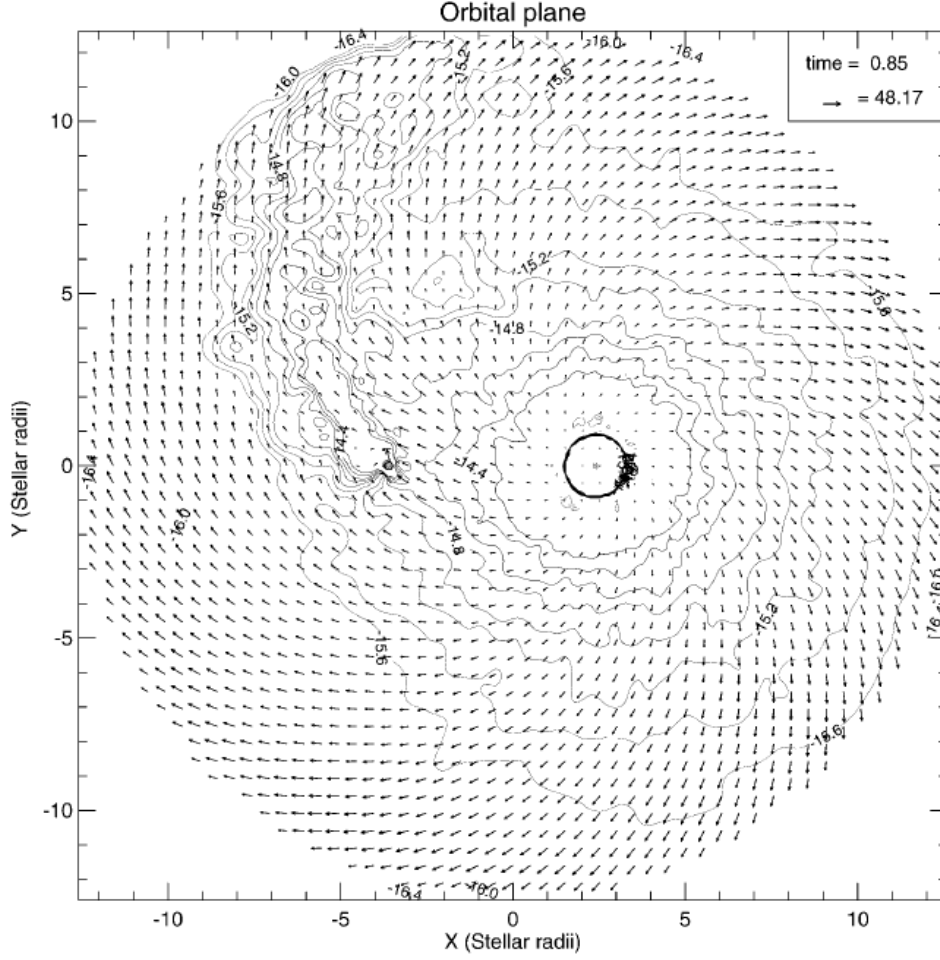


Figure 1.18.: Velocity field of the primary's wind in the orbital plane by Mastrodemos & Morris (1998). In their model M4, the companion is located ≈ 13 au from the primary. The wind losing star orbits around the CoM at (0,0) while the companion accumulates mass and forms an accretion wake and a bow shock head.

(Mastrodemos & Morris 1999).

What happens in the following strongly depends on the separation of the system and the mass of the companion. In systems which are semi-detached or the separation is only slightly larger (see models M1, M2, and M17 of Mastrodemos & Morris 1999), the gravitational effect of the companion does not allow the primary wind to accelerate effectively and the outflow is focused onto the orbital plane. A disk is formed around the system which mimics

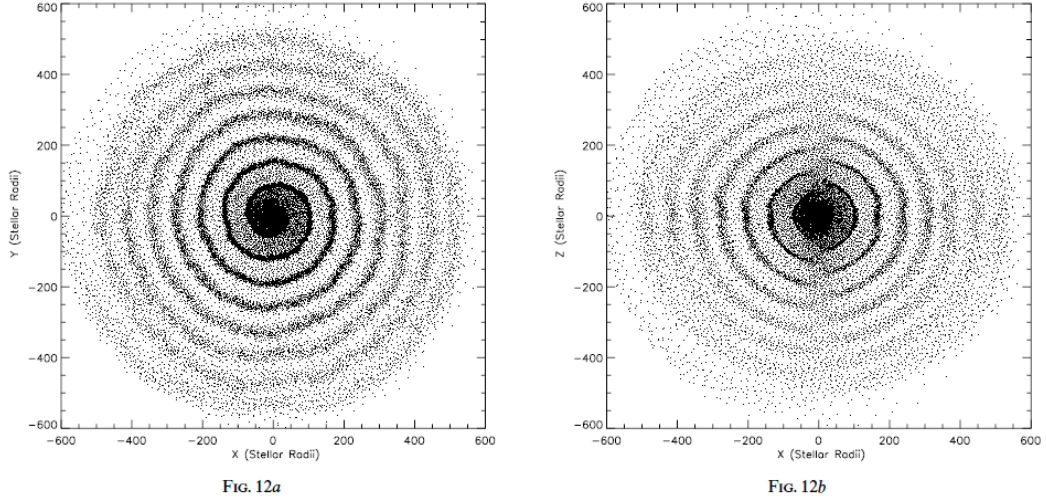


Figure 1.19.: Spiral pattern formed by a wide binary system. The *left panel* shows the spiral pattern in the orbital plane, while the *right panel* is perpendicular to the orbital plane (Model M4 of Mastrodemos & Morris 1999).

the shape of a bipolar outflow and the spiral pattern is not recognizable any longer. Mastrodemos & Morris (1999) have shown that this is the case for systems with separations up to ≈ 10 au and a companion more massive than $0.5 M_{\odot}$. Systems with less massive companions behave like wide binaries since the gravitational force is much weaker (see M18 of Mastrodemos & Morris 1999).

In wide binary systems ($a \gtrsim 10$ au), a cut perpendicular to the orbital plane reveal that the spiral pattern is visible as broken concentric arcs (see Fig. 1.19). This reflects an edge-on view of the system. The arcs are caused by the motion of the primary around the CoM. This motion adds a velocity component (the primary's orbital velocity) to the wind velocity (of the order of a few km s^{-1}) depending on the location of the companion. At this point the faster wind starts to overtake the slower and the symmetry of the primary wind is broken. A spiral shaped shock front forms which extends to high latitudes. Thus, the wind morphology in the wide binary systems is affected by two processes, the formation of an accretion wake of the companion and the primary's motion around the CoM. The observation of the wind morphology in binary systems is thus a superposition of this two effects. Kim & Taam (2012c) studied both separately and found them to result in a similar single-armed spiral. The spiral caused by the accretion wake, however, is attached to the companion

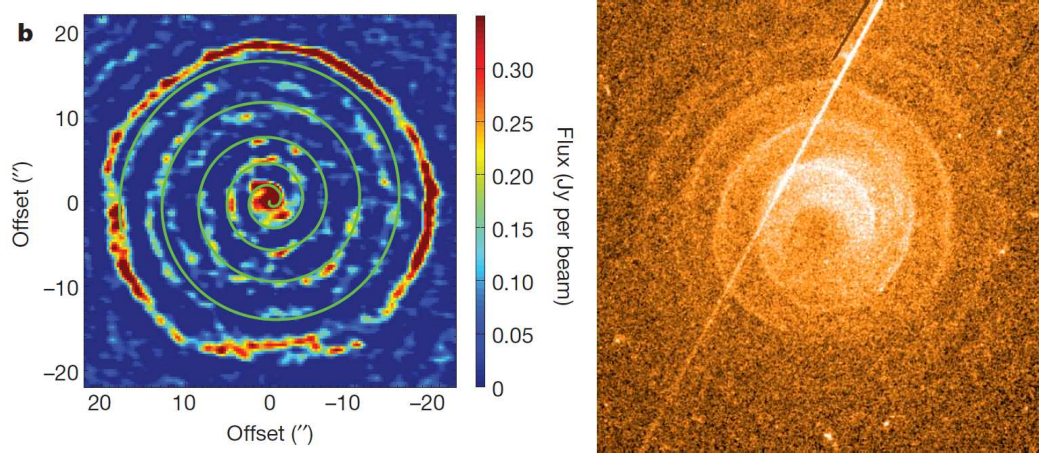


Figure 1.20.: *Left panel:* ALMA observations of R Sculptoris in the CO(3-2) transition (Maercker et al. 2012). The spiral separation indicate an orbital period of 350 years. *Right panel:* first observation of a spiral pattern around an AGB star (AFGL 3068) in scattered galactic light with the Hubble Space Telescope (HST) by Mauron & Huggins (2006). The FoV is $25.6'' \times 25.6''$. The companion was later detected by Morris et al. (2006) separated by 109 au from the primary.

and is somewhat more contracted to the orbital plane but the shape difference becomes insignificant at higher latitudes (Kim & Taam 2012c). Overall, in the orbital plane of wide binaries, the spiral shock is narrower than in close systems (but with a wider spacing) and the propagation of the shock in the wind can be traced for several thousand au (M4–M7 of Mastrodemos & Morris 1999). The spiral pattern broadens with distance from the binary system but the large extent in all directions enables the observation of those systems. Furthermore, Mohamed & Podsiadlowski (2011) showed that even very wide binary systems with separations over 50 au are forming strong spiral shocks when the mass transfer is enhanced by the WRLOF. The wind morphology in binaries with eccentric orbits was studied by He (2007) who found it to appear like broken spiral arms or incomplete spherical shells.

The first observational evidence of a spiral pattern around an AGB star was found for AFGL 3068 (LL Pegasi) on HST-ACS images at 606 nm by Mauron & Huggins (2006). This wavelength seems odd at first glance, since the spiral shocks are not strong enough to be visible in the optical. But in this case, the spiral is illuminated by galactic light which is scattered in the dusty spiral arms. Figure 1.20 shows the HST image of Mauron & Huggins (2006). The

spiral can be traced out to a distance of $12''$ from the star with a density contrast up to five between spiral arm and inter-arm region. The spacing of the arms is constant at $2.29''$ and is given by

$$\theta = v_w \times P, \quad (1.37)$$

which allows to determine $P = 830$ yr corresponding to a separation $a = 120$ au for $M_1 = 2 M_\odot$ and $M_2 = 0.5 M_\odot$ (Mauron & Huggins 2006). Morris et al. (2006) was indeed able to identify the companion on Keck II images in the near-IR at a distance of 109 au from the AGB star. This shows that spirals occur also for systems which are much wider than predicted by the models of Mastrodemos & Morris (1999).

Dinh-V.-Trung & Lim (2009) and Claussen et al. (2011) used the (extended) Very Large Array (VLA) for high angular resolution sub-mm observations of $\text{HC}_3\text{N}(5-4, 4-3)$ emission around the carbon star CIT 6 (RW Leonis Minoris). The authors found shell-like asymmetries which seem to be connected with each other and could reflect a spiral pattern. However, the poor resolution only allowed for speculations that the disrupted rings might be part of a spiral caused by a companion with an orbital period of about 600 years (Dinh-V.-Trung & Lim 2009). Kim et al. (2013) revised the observations of Claussen et al. (2011) and used hydrodynamic simulations to fit the channel maps. The authors found a system with $M_1 = 0.8 M_\odot$, $M_2 = 2.2 M_\odot$, $a = 68$ au, and $i = 60^\circ$ matching the observations best.

The connection between observed properties of the spiral pattern and orbital parameters was described by Kim & Taam (2012a). The inclination i of the system is thereby given as

$$\sin^2 i = \frac{(a/b)_{\text{proj}}^2 - 1}{(a/b)^2 - 1}, \quad (1.38)$$

where a/b is the aspect ratio of the spiral pattern

$$a/b = 1 + \frac{2v_p}{3\langle v_w \rangle}, \quad (1.39)$$

where v_p is the orbital velocity of the primary and $\langle v_w \rangle$ the average wind velocity (Kim & Taam 2012a). The inclination can therefore be estimated from the aspect ratio of the spiral, the wind velocity, and the orbital velocity of the primary. The latter can be derived from the spiral spacing and the distance of the primary from the CoM, r_p , as

$$\Delta r_{\text{arm}} = \left(\langle v_w \rangle + \frac{2v_p}{3} \right) \times \frac{2\pi r_p}{v_p}. \quad (1.40)$$

In reality it is difficult to evaluate v_p since it requires knowledge of the binary properties from additional observational data (e.g., RV measurements). Nevertheless, with the obtained inclination it is possible to determine the separation of the binary system as

$$a = (r_p + r_{\text{comp}}) = \frac{(r_p + r_{\text{comp}})_{\text{proj}}}{(1 - \sin^2 \Theta_p \sin^2 i)^{1/2}}, \quad (1.41)$$

with

$$\tan \Theta_p = \frac{\tan \theta}{\cos i}, \quad (1.42)$$

where θ is the position angle (P.A.) of the binary axis (Kim & Taam 2012a). Finally, the stellar masses can be determined by

$$M_1 = q(1 + q)^2 v_p^2 r_p / G \quad (1.43)$$

$$M_2 = M_1 / q. \quad (1.44)$$

This method, however, requires high-resolution and -sensitivity observations to accurately trace the spiral shape. A facility that is able to obtain such maps is the Atacama Large Millimetre/submillimetre Array (ALMA). Maercker et al. (2012) demonstrated first its capabilities with the observations of R Sculptoris in CO(3-2) (see left panel of Fig. 1.20). The authors aimed to study the formerly known detached shell around the object but revealed a spiral with five windings embedded in the shell. Furthermore, the authors were able to show that the MLR and wind velocity changed during the expansion time of the spiral, which in turn affects the spiral spacing. The picture Maercker et al. (2012) draw is a TP-AGB star that creates a detached shell during the TP when the MLR is peaking and the wind is quite fast. Between the TPs the companion accretes enough material to imprint a spiral pattern in the AGB wind. Also R Scl is a wide binary system with an orbital period of about 350 years.

An ALMA follow-up study of the *Herschel* results on Mira (*o* Ceti; Section 2.1) by Ramstedt et al. (2014) revealed the exceedingly complex environment of the system seen in the CO(3-2) line emission (see also Section 2.4.4 for an abstract of this study). The observations confirm the *Herschel* results (Mayer et al. 2011) with an environment of the star that is shaped by several interacting processes like mass loss, binary shaping, wind–wind interaction, and accretion (Ramstedt et al. 2014). A more detailed study of the ALMA data is part of an upcoming publications by the same authors.

Recently, Decin et al. (2015) presented ALMA Band 9 observations of the carbon star IRC +10 216 (CW Leonis). The ALMA data were taken near

maximum light and the channel maps of the $^{13}\text{CO}(6-5)$ line displays a complex structure in the vicinity of the star, including spiral-like arcs. These arcs are incomplete and seen on scales between $1''$ and $3''$. The position-velocity diagrams display a typical S-shape around zero offset which Decin et al. (2015) compare to the modelling efforts by Kim et al. (2013). The S-shape is encountered in these simulations as a sign for an inclined spiral pattern seen from a P.A. that differs from the orbital axis. Such a shape can not be reproduced by any other model. The spiral arcs around IRC +10 216 are seen almost edge-on ($i = 60 - 80^\circ$) with a thickness of about 300 mas (Decin et al. 2015). From the arm separation ($1.12''$) and wind velocity (14.5 km s^{-1}), the authors derive an orbital period of 55 yr . With $M_1 = 4 M_\odot$ and $M_2 \approx 0.6 M_\odot$ the binary separation is $\approx 25 \pm 2 \text{ au}$ (Decin et al. 2015). Cernicharo et al. (2014) probed the molecular CO(2-1) emission of the star on a wider scale ($400'' \times 400''$) with the IRAM 30 m telescope. The authors support the spiral origin of the CSE morphology but with $a = 130 \text{ au}$, $P = 800 \text{ yr}$, and a system mass of $3 M_\odot$.

Besides the gaseous component of the outflow, it must be possible to trace also the dusty component, since the spiral shocks are not strong enough to destroy all the grains. Edgar et al. (2008) assumed that crystalline dust is produced in binary-induced spiral shocks of AGB stars by annealing amorphous grains. The thermal emission of the dust grains, which peaks in the far-IR, could therefore be detectable. Fortunately, it turned out that *Herschel* is sensitive enough to trace these faint structures. With the number of AGB stars in the MESS sample, it is possible to draw a more comprehensive picture of the binary interaction compared to the starting point of only two known interaction cases (AFGL 3068, CIT 6). As it will be shown in the following, the interactions that are happening in AGB binary systems are more complex than initially thought.

At this point the introduction ends. Hopefully all necessary information have been provided to understand the following chapter which demonstrates how *Herschel* traces the complex interactions of the AGB wind with a companion.

Publications

In this chapter, the main results of the PhD project are presented, i.e., three peer-reviewed first author publications in chronological order as well as a section on publications as co-author. The involvement of the Viennese AGB work group in the *Herschel*-MESS observations offered a chance to work with first class data of some of the best known AGB stars. The group gathered important expertise in the reduction of the PACS imaging data which helped to become a key member of the MESS group, especially for morphology studies of circumstellar environments.

At the beginning of this PhD project, an overview of all MESS objects with emphasis on the ISM-interaction cases (see Section 1.4.2) was assembled by Cox et al. (2012) (see Section 2.4.1), which raised the pressure to work fast on individual objects. In the collaboration I took care of the highly asymmetric objects, which were classified as *irregular* by Cox et al. (2012). As discussed in Section 1.4.3, a companion can have a large influence on the CSE of an AGB star and deform it massively. The morphology these deformations cause are very unique and differ from other interaction features. At the beginning of this work, only two AGB stars were known to show a (non-symbiotic) binary interaction, namely AFGL 3068 (Mauron & Huggins 2006) and CIT 6 (Dinh-V.-Trung & Lim 2009). The research field was dominated by theory and hydrodynamic simulations, which predicted large-scale spiral patterns around binary systems (Theuns & Jorissen 1993; Mastrodemos & Morris 1998, 1999; Mohamed & Podsiadlowski 2007). Although the binary fraction of AGB stars suggests that the interaction is a common phenomenon, observations of these patterns were lacking and questioned the validity of the simulations.

The lack of observations was a motivation to dig deeper into the asymmetric morphologies revealed by the MESS sample. With its high resolution and sensitive observations of the CSEs of 78 AGB stars the MESS program offers a great possibility to explore the binary interaction at a wavelength range that was not covered so far (AFGL 3068 was observed in the optical and CIT 6 at

sub-mm). With the expiration of the *Herschel* mission, observations in far-IR regime will not be repeated in the next 10-15 years. The following examples will therefore be a starting point for future investigations with facilities like ALMA, the Very Large Telescope Interferometer (VLTI), VLT/SPHERE, and the VLTI to map the interactions closer to the regions where they develop.

2.1. Herschel’s view into Mira’s head

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In the first publication we studied the CSE of *o* Cet (Mira). Mira is famous for its 4 pc long head-tail structure, which is caused by the fast motion of the star and revealed on GALEX images (Martin et al. 2007). In addition, Mira is a well known double star system, where mass transfer was observed in the X-ray even though the system is separated by 55 au (Karovska et al. 1997). On the *Herschel*/PACS images we recognised a structure similar to the one obtained with GALEX but, in addition, arcs are visible around the star, which indicates that Mira’s companion interacts with the primary’s wind.

With help of smoothed particle hydrodynamics (SPH) simulations, which model the outline of the observed far-IR emission (Mohamed & Podsiadlowski 2011), we were able to show that a companion with such a large separation can imprint a spiral pattern in the AGB wind. This observation also confirmed that spiral pattern can be traced by thermal dust emission. Given the spectacular results and the high profile of the object we decided to publish this work as a letter. Based on these results an ALMA study on Mira was recently published by Ramstedt et al. (2014) confirming the structures seen with *Herschel*.

Individual contributions: Herschel data analysis, textual work, comparison with GALEX observations (A. Mayer); role of the binary system, general supervision (A. Jorissen); SPH simulations (S. Mohamed); general supervision (F. Kerschbaum); data reduction (R. Ottensamer).

Herschel's view into Mira's head[★]

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ABSTRACT

Herschel's PACS instrument observed the environment of the binary system Mira Ceti in the 70 and 160 μm bands. These images reveal bright structures shaped as five broken arcs and fainter filaments in the ejected material of Mira's primary star, the famous AGB star *o* Ceti. The overall shape of the IR emission around Mira deviates significantly from the expected alignment with Mira's exceptionally high space velocity. The observed broken arcs are neither connected to each other nor are they of a circular shape; they stretch over angular ranges of 80 to 100 degrees. By comparing *Herschel* and GALEX data, we found evidence for the disruption of the IR arcs by the fast outflow visible in both H α and the far UV. Radial intensity profiles are derived, which place the arcs at distances of 6–85'' (550–8000 AU) from the binary. Mira's IR environment appears to be shaped by the complex interaction of Mira's wind with its companion, the bipolar jet, and the ISM.

Key words. stars: AGB and post-AGB – stars: mass-loss – binaries: general – infrared: stars – ISM: general

1. Introduction

Centuries ago *o* Ceti confused the astronomers all over the world with its appearance and disappearance on the night sky and was therefore named *Mira*, the wonderful, by *Hevelius* (1662).

Today we know that Mira is a wind-accreting binary star system (Reimers & Cassatella 1985) at a distance of 91.7 pc (corresponding to a parallax of 10.9 ± 1.2 mas; van Leeuwen 2007) consisting of the primary star Mira A (*o* Ceti) and its companion Mira B (VZ Ceti). Mira A is an M-type oxygen-rich star with a pulsation period of 331 d and a brightness amplitude in the visible of 8 mag. Moreover, Mira A is the prototype of stars in their late stage of evolution residing on the asymptotic giant branch (AGB). The nature of Mira B has been unknown for long; with an effective temperature of about 10 000 K, it might either be a main-sequence star or a white dwarf (Karovska et al. 1997), but recent observations show strong evidence in favour of a white dwarf (Sokoloski & Bildsten 2010). From a Hubble Space Telescope observation, Karovska et al. (1997) found the separation of Mira AB to be $\approx 0.6''$, which corresponds to 55 AU. A very uncertain orbit, based on astrometric measurements since 1923, which has a period of ≈ 500 yr, has been published by Prieur et al. (2002).

Stars on the AGB loose a significant fraction of their mass in the form of a stellar wind. For Mira A, a moderate mass loss rate of $10^{-7} M_{\odot} \text{ yr}^{-1}$ was determined by Maun & Caux (1992), which corresponds to a dust mass-loss rate of about $5.5 \times$

$10^{-10} M_{\odot} \text{ yr}^{-1}$ (Meixner 2011, priv. comm.). From mm-CO lines, Josselin et al. (2000) found a wind expansion velocity of 4 km s^{-1} and a molecular envelope around the binary system with a size of about $20''$. This envelope is disrupted by a slow bipolar outflow of about 8 km s^{-1} (Josselin et al. 2000), but a high-velocity component at 160 km s^{-1} has been observed by Meaburn et al. (2009). In the outer environment of Mira, a spectacular observation with the GALEX ultraviolet satellite (Martin et al. 2007) revealed a cometary-like structure with an extension of more than 2° (≈ 4 pc) from head to tail. Martin et al. (2007) attribute this tail to Mira's exceptionally high space velocity of $\approx 110 \text{ km s}^{-1}$ and the resulting strong interaction of the stellar wind with the interstellar medium (ISM). This structure was also observed in the 21 cm H I line (Matthews et al. 2008) and is well reproduced by the hydrodynamic simulations of Wareing et al. (2007), Raga & Cantó (2008) and Esquivel et al. (2010). In the vicinity of the binary system, knot-shaped enhancements of the UV and H α emission were found at a distance of $1'$ to $2'$ from the binary (Martin et al. 2007; Meaburn et al. 2009), corresponding to 5500 to 11 000 AU, and in a direction consistent with that of the bipolar outflow observed by Josselin et al. (2000). In the far IR Ueta (2008) resolved with the *Spitzer* Space Telescope the contours of Mira's astropause including the circumbinary envelope, termination shock, and astrosheath.

The present study offers a detailed view of Mira's circumstellar shell(s) thanks to the high spatial resolution of the PACS instrument (which has a point-spread function of $5''.6$ full-width at half-maximum at $70 \mu\text{m}$) onboard the *Herschel* satellite. The images presented here reveal clumpy broken arcs (see Sect. 3.1)

[★] *Herschel* is an ESA space observatory with science instruments provided by European-led Principal Investigator consortia and with important participation from NASA.

Table 1. Kinematic data for Mira.

$b(^{\circ})$	-58	ϖ (mas)	10.9 ± 1.2^a
$\mu_{\alpha, \text{LSR}}$ (mas yr $^{-1}$)	-20.93 ^a	$\mu_{\delta, \text{LSR}}$ (mas yr $^{-1}$)	-222.39 ^a
RV_{LSR} (km s $^{-1}$)	47.2 ^f	$V_{\text{space, LSR}}$ (km s $^{-1}$)	107.9
$V_{\text{space, LSR PA}}$ ($^{\circ}$)	185.4	$V_{\text{space, LSR } i}$ ($^{\circ}$)	25.9
V_{wind} (km s $^{-1}$)	4 ^c	V_{outflow} (km s $^{-1}$)	160 ± 10^d
Bipolar flow PA ($^{\circ}$)	168–180 ^d	Bipolar flow i ($^{\circ}$)	-69 ^d
Orbital pole PA ($^{\circ}$)	228 ^e	Orbital pole i ($^{\circ}$)	$\pm 22^e$
P (yr)	$\approx 500^e$	a (AU)	$\approx 100^{a,e}$
$M_1 + M_2$ ($M_{\odot}$)	4.4 ^e	$\dot{M}$ ($M_{\odot}$ yr $^{-1}$)	10^{-7b}

Notes. Negative inclinations are towards the observer. The various vectors are displayed in a 3D view in Fig. 4. The adopted solar motion to convert heliocentric velocities in LSR velocities is $(U, V, W)_{\odot} = (11.10, 12.24, 7.25)$ km s $^{-1}$ (Schönrich et al. 2010). The matrix to convert equatorial velocities into galactic velocities is taken from Johnson & Soderblom (1987).

References. ^(a) van Leeuwen (2007); ^(b) Maun & Caux (1992); ^(c) Josselin et al. (2000); ^(d) Martin et al. (2007); Meaburn et al. (2009); ^(e) Priour et al. (2002); ^(f) Fong et al. (2006).

that result from the complex interactions of the wind with the ISM, the companion, and the fast outflow.

2. Observations and data reduction

The observations of Mira took place on February 9, 2010, using the PhotoArray Camera and Spectrometer (PACS; Poglitsch et al. 2010) onboard *Herschel* as part of the MESS (Mass-loss of Evolved StarS) guaranteed time key program (Groenewegen et al. 2011).

The PACS camera observed at 70 μm and 160 μm simultaneously, covering a field of $30' \times 30'$ on the sky with a scan-map mode. For the basic data processing to produce the images displayed in Fig. 1, the *Herschel* Interactive Processing Environment (HIPE) was used (Ardila & Science Ground Segment Consortium 2010) together with Scanamorphos, an IDL software for building scan maps from PACS (and SPIRE) observations (Roussel 2011). Finally, we deconvolved the images as described by Ottensamer et al. (2011). Although the PACS instrument offers a resolution of $3.2''$ per pixel in the 70 μm (blue) band and $6.4''$ per pixel at 160 μm (red band), the images shown in Fig. 1 are oversampled by a factor 3.2, resulting in a sampling of $1''$ and $2''$ per pixel (at 70 and 160 μm , respectively), to be compared with the *FWHM* of $5''.6$ and $11''.4$ at those wavelengths. We estimate the average background emission to be 1.5×10^{-4} Jy pixel $^{-1}$ in the blue and 3×10^{-4} Jy pixel $^{-1}$ in the red band, yielding the 1σ sensitivity.

3. Results and discussion

3.1. IR images

Mira's environment is remarkably structured and exhibits arc-like structures in the surrounding of the binary system, labelled A to E in Fig. 1c. The best-defined and brightest arc, C, stretches over position angles (PAs) $\sim 190^{\circ}$ – 270° (south-west to west), is well detached from the star and covers a range of angular separation from $67''$ (6100 AU) at the closest point to $85''$ (7800 AU) at the most distant point from the star. The intensity was integrated over this PA range and the resulting radial intensity profile (Fig. 2) clearly shows the arc as a plateau in the diagram. The extension of this plateau confirms that the arc is non-circular or,

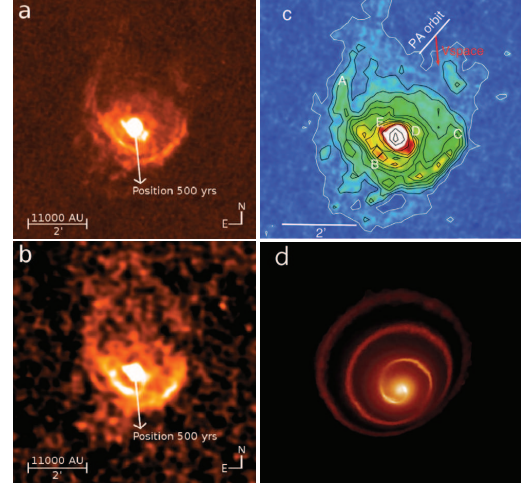


Fig. 1. Panel **a**) deconvolved PACS image at 70 μm . The arrow indicates the space motion and the position in 500 yrs; **b**) is the same for the 160 μm band and **c**) is the 70 μm deconvolved PACS image with contours and arcs labelled A, B, C, D and E. The lowest contour is the 3σ threshold (and is depicted in white), the arrow labelled with V_{space} shows the direction of the space motion, the bar labelled PA orbit gives the orientation of the major axis of the apparent orbit, orthogonal to the node line. Panel **d**) results from the “toy model” described in Sect. 3.3 that is based on the hydrodynamical simulations of Mohamed & Podsiadlowski (2007, 2011).

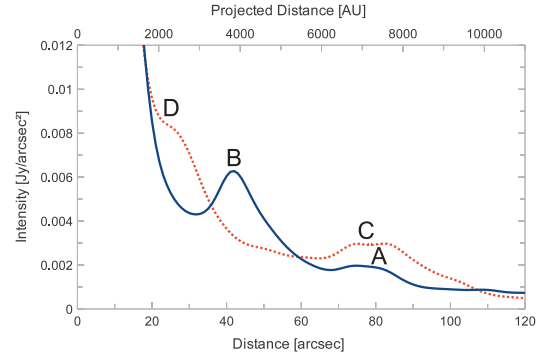


Fig. 2. Radial intensity profiles of Mira in the 70 μm band as a function of the distance to the star. Continuous (blue) line: integrated intensity across the arcs B and A ($75^{\circ} \leq \text{PA} \leq 180^{\circ}$). Dashed (red) line: across the arcs D and C ($190^{\circ} \leq \text{PA} \leq 270^{\circ}$). The top scale gives the distance from the star computed from Mira's distance of 91.7 pc.

if circular, is not centred on the position of the star. We found another arc, D, in the same direction as arc C but much closer to the star and stretching over much smaller PAs. In the radial intensity profile, arc D is visible as a bump located at a distance of 21 – $28''$ (1900–2600 AU). East of Mira more arcs are visible. In the south-east direction, we see arc B close to the star. It stretches over PAs 75° to 180° and is more circular than arc C and therefore appears as a narrow peak in the radial intensity profile at a distance of $41''$ (3800 AU) from the binary (Fig. 2).

2.1. Herschel's view into Mira's head

A. Mayer et al.: *Herschel's view into Mira's head*

Farther out, directly to the east, we find another structure, arc A, stretching towards north-east. In the integrated intensity profile, it can be recognized as a small plateau representing its fairly faint nature at a distance of 68–89'' (6200–8200 AU). This matches the distance of arc C, which leads to the suggestion that both arcs are somehow related to each other.

It is also possible that another arc, E, is present in the south-east direction, very close to the binary at a distance of less than 15'' (1400 AU), of which we only see the edge at a PA of about 65°. It is noteworthy that the arc sequence E-D-B-C-A is a sequence of both increasing distance from the star and increasing PA range, arc E being the shortest and closest to the star, and A the longest and farthest.

The overall 3σ emission above the $70\ \mu\text{m}$ IR background of Mira, visible in Fig. 1c as the outermost contour, spans as far as 157'' towards the south-east. It is remarkable that the extension of the emission is towards a position angle of $\approx 160^\circ$ because one would expect the emission to be aligned with Mira's space motion, but that motion is in the direction of PA = 185° . In Fig. 1c we also indicated the orientation of the major axis of the apparent orbit, which is oriented along a PA of $\approx 140^\circ$ (Prieur et al. 2002). As discussed in more detail in Sect. 3.3, the orbital motion and the mass transfer from the binary can also shape its environment. Nevertheless, the extension of the IR emission lies between both values and makes a distinct attribution difficult.

3.2. Comparison with GALEX UV observations

Before drawing conclusions from the structures observed in the IR, it is interesting to confront these IR observations with GALEX ultraviolet observations of Mira in the far and near UV (152.8 nm and 227.1 nm, respectively; Martin et al. 2007). In the far UV image, Martin et al. (2007) found emission knots arranged north-west and south (Fig. 3). The axis of the streams is consistent with the direction of the bipolar outflow detected by Josselin et al. (2000), and moreover, the UV knots are exactly coincident with similar knots seen in H_α (Meaburn et al. 2009). In contrast, Fig. 3 reveals that in the PACS $70\ \mu\text{m}$ image the southern stream exactly corresponds to a region with an IR flux below the 3σ threshold¹. It thus looks as if the southern stream is penetrating and disrupting the material responsible for the IR emission. According to Meaburn et al. (2009), the southern stream is indeed inclined at an angle of 69° with respect to the plane of sky towards us. Put together, all these arguments clearly indicate that the IR emission must come from a 3D structure and is not confined to the orbital plane; otherwise, there could be no explanation for the anti-coincidence between the GALEX far UV/ H_α emission and the IR emission.

Another interesting clue is that the northern lobe of the bipolar flow remains visible even though it is located behind the IR shell. The dust present in the shell will efficiently absorb the far UV radiation, so that the intensity of the northern lobe measured by GALEX should be smaller than that of the southern lobe, which has no intervening dust. In the far UV, the peak intensity of the northern lobe is indeed about 1.5 times fainter than the peak intensity of the southern lobe. Assuming that the northern and southern jets carry the same energy, this ratio may then be seen as resulting from dust extinction:

$$1/1.5 = \exp(-N\pi a^2 Q_{\text{ext,UV}}), \quad (1)$$

¹ The “hole” in the IR emission located about 1' to the East is less significant than the one considered, with fluxes about twice smaller for the latter.

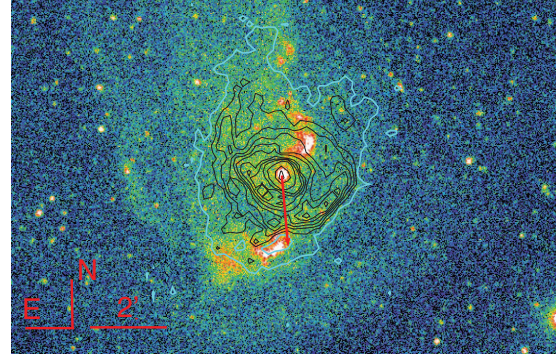


Fig. 3. GALEX far UV image of Mira obtained by Martin et al. (2007) overplotted with contours of the *Herschel* $70\ \mu\text{m}$ image, the thick blue contour corresponding to an IR flux just 3σ above background. The bright white regions correspond to strong UV emission at both ends of the fast jet. Note the absence of IR emission at the end of the southern jet. The red arrow indicates the position of the star in 500 yrs. The bow shock is the faint structure in the background in the south-west.

where N is the dust column density, a is the grain radius, and $Q_{\text{ext,UV}}$ is the ratio between the extinction cross section and the geometrical section. This constraint can be inserted in Kirchhoff's law for the IR emission j_{IR} , leading to

$$j_{\text{IR}} = B_{\text{IR}}(T_{\text{dust}}) \ln(1.5) Q_{\text{abs,IR}}/Q_{\text{ext,UV}}, \quad (2)$$

where B_{IR} is the Planck intensity function at the dust temperature and $Q_{\text{abs,IR}}$ the ratio of the absorption cross section and the geometrical section. From Draine (1985), $Q_{\text{abs},70\ \mu\text{m}}/Q_{\text{ext},0.15\ \mu\text{m}} \sim 10^{-3}$ (almost independent of the grain size), which leads to

$$j_{\text{IR}} = 4.2 \times 10^{-4} B_{\text{IR}}(T_{\text{dust}}). \quad (3)$$

From the measured intensity ratio at 70 and $160\ \mu\text{m}$ for the northern lobe, we find a dust temperature of 36 K; combining $B_{70\ \mu\text{m}}(36\ \text{K})$ with the measured $j_{70\ \mu\text{m}} = 4.42 \times 10^7\ \text{Jy/sr}$, we obtain $j_{70\ \mu\text{m}}/B_{70\ \mu\text{m}}(36\ \text{K}) = 1.2 \times 10^{-4}$, which agrees well with the value predicted by Eq. (3).

3.3. Role of the binary system

The arcs observed around Mira (Sect. 3.1) are (almost) unique in the MESS sample² (Groenewegen et al. 2011; Cox et al., in prep.) which makes it tempting to relate them to the binary nature of Mira.

In binary systems involving a mass-losing component, nested half-shells are seen when the orbit is orientated close to edge-on (He 2007), and they represent the 3D structure extending above the Archimedian spiral present in the plane of a circular orbit (for eccentric orbits, the spiral becomes broken). The latter was predicted by the hydrodynamics simulations of Theuns & Jorissen (1993),

² The prototypical carbon star IRC +10216 is surrounded by a large number of thin and faint arcs, known for quite some time in the optical (Mauron & Huggins 1999, 2000), and now identified in *Herschel* images as well (Decin et al., in prep.). Their appearance is, however, quite different from the few thick arcs seen around Mira, in line with the fact that there is so far no evidence that IRC +10216 belongs to a binary system (Huggins et al. 2009).

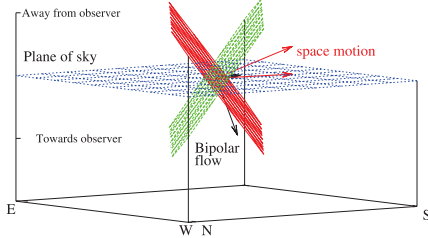


Fig. 4. Various vectors entering the discussion in a 3D view, with the red and green planes corresponding to the two possible orbital orientations. Because bipolar flows are generally perpendicular to the orbital plane, the green orientation seems the most likely. The sky plane is depicted in blue. The thick arrows are projections onto the sky plane. The observer is located on the bottom plane and looking upwards.

Mastrodemos & Morris (1999), Mohamed & Podsiadlowski (2011), and detected around AFGL 3068 by Maunon & Huggins (2006) and Morris et al. (2006). In Mira, the observed arc structure resembles neither an Archimedian spiral, nor nested half-shells; its interpretation must therefore be more complex, involving two supplementary physical processes at play, namely the presence of a bipolar jet, and the interaction with the ISM (to fix the ideas, Fig. 4 presents the respective orientations of all relevant vectors involved in the Mira system). We already argued in Sect. 3.2 that the fast bipolar outflow (160 km s^{-1} ; Martin et al. 2007; Meaburn et al. 2009) seems to cut a hole in the IR shell (see Fig. 3). Similarly, it could easily disrupt the arcs with its high velocity, and may actually be responsible for cutting the edges of arcs B, C, and D, because all these edges are located along the southern jet, at a position angle close to 180° .

On the other hand, it is likely that the interaction with the ISM, more precisely, the termination shock, plays some role in shaping (at least) arc C, as already suggested by Ueta (2008) from lower-resolution *Spitzer* images, and confirmed in the *Herschel* images by the sharp ridge seen on the contour levels in Figs. 1c and 3. Arc C is indeed located almost upstream along Mira's space motion. On the $160 \mu\text{m}$ image (Fig. 1b), arcs A and C extend towards the north and join with each other, exactly opposite to the space motion of Mira, in a tail-like or bullet-like structure, as seen in the hydrodynamic simulations by Wareing et al. (2007) and Esquivel et al. (2010). This is clear evidence that the outer arcs feel the space motion and interact with the ISM. Another indication thereof is provided by the curvature of the bipolar-outflow southern stream, which Martin et al. (2007) attribute to its deceleration by the post-shock flow. Therefore, the arcs seen around Mira likely result from a combination of the projected 3D structures resulting from the interaction of Mira's wind with its companion on one hand, and with the ISM on the other hand.

As a first exploration of this combination, we used the simulations of Mohamed & Podsiadlowski (2007, 2011) of an AGB star nearly filling its Roche lobe in a system 10 AU -wide³, and losing mass through a slow wind. The 3D structure resulting from the expanding wind disturbed by the companion's gravitational pull was then intersected with a paraboloid representing the bow shock. All particles within a thin shell along the paraboloid surface were kept and the resulting particle density

projected onto the sky plane (the respective orientations of the paraboloid, the orbital plane, the sky plane, and the companion were taken into account, as represented in Fig. 4). If the IR emission observed by *Herschel* around Mira results from the reheating of the wind by the shock, this “toy model”, presented in Fig. 1d, should then give a fair account of the situation. Fig. 1d shows that there are indeed promising resemblances between the *Herschel* image and the one from the “toy model”, apart from the absence of brightening of the south-west arc C (where the compression from the ISM – not included in our model – is maximum), and apart from the ISM-swept appearance of the outermost northern arc. Hydrodynamical simulations of mass transfer in the Mira system, including the ISM interaction, are thus badly needed.

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³ Although this separation is much smaller than the actual orbital separation of Mira system, this difference should not impact our conclusions, because the spiral properties are largely scale-invariant.

2.2. Large-scale environments of binary AGB stars probed by Herschel – I. Morphology statistics and case studies of R Aquarii and W Aquilæ

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For the second publication we wanted to approach the sample of MESS binary stars in a more systematic way. In the first part of the paper we present all 18 objects which show evidence to be part of a physically related binary system. For this task we searched the literature for direct detections of a companion, proper motion variations, composite nature of the spectrum, shallow light curves with wide and flat minima, eclipses, and asymmetries in the CSE (spirals, double CO line profile). We subsequently had a look to the CSEs of the resulting 18 binary systems and divided their morphology into the classification scheme of Cox et al. (2012). We found with statistical methods that the irregular type is significantly over-abundant for binary systems.

The second part of the paper provides case studies of two MESS AGB stars, namely R Aquarii and W Aquilæ. Both objects are known binary systems, however, their far-IR CSE morphologies are completely different. R Aqr is

one of the best studied and brightest symbiotic systems with an orbital period of 44 years (Gromadzki & Mikołajewska 2009). The object is known to be surrounded by a ring shaped nebula visible in the optical (Solf & Ulrich 1985) and an X-ray jet (Wallerstein & Greenstein 1980). On the *Herschel*/PACS images, R Aqr shows an opposing arm structure which is, after comparison with optical images, the far-IR counterpart of the ring nebula. With help of spectral energy distribution (SED) fitting and modelling of the stellar wind we were able to de-project the arm structure using the temperature profile from the model. We found that the structure is rather non-circular, located in the orbital plane.

W Aql is at first sight a typical ISM interaction case, given the elongation of the asterosphere. However, the brightened region of the CSE does not fit to its major axis and the proper motion catalogues list doubtful or no values (e.g., Hipparcos, Tycho-2). We therefore performed a proper motion analysis using position measurements of the last century. We found that the proper motion is indeed in direction of the major axis; however, with large error bars. Interestingly, a spiral pattern with the properties of the companion can be fitted to the outline of the CSE. Most likely, a combination of ISM- and binary-interaction shape the wind of W Aql.

Individual contributions: Herschel data analysis, textual work, literature search for binarity, comparison of optical and far-IR emission, proper motion analysis (A. Mayer); statistics and textual work of Section 3, evolutionary tracks, general supervision (A. Jorissen); general supervision (F. Kerschbaum); data reduction (R. Ottensamer, M. Mečina); SED fitting, atmosphere/wind modelling, textual work of Section 4.1.2 (W. Nowotny, B. Aringer).

Large-scale environments of binary AGB stars probed by *Herschel*

I. Morphology statistics and case studies of R Aquarii and W Aquilae^{*}

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ABSTRACT

The Mass loss of Evolved StarS (MESS) sample offers a selection of 78 asymptotic giant branch (AGB) stars and red supergiants (RSGs) observed with the PACS photometer on-board *Herschel* at 70 μm and 160 μm . For most of these objects, the dusty AGB wind is not spherically symmetric and the wind shape can be subdivided into four classes. In the present paper we concentrate on the influence of a companion on the morphology of the stellar wind. Literature was searched to find binaries in the MESS sample, which were subsequently linked to their wind-morphology class to assert that the binaries are not distributed equally among the classes. In the second part of the paper we concentrate on the circumstellar environment of the two prominent objects R Aqr and W Aql. Each shows a characteristic signature of a companion interaction with the stellar wind. For the symbiotic star R Aqr, PACS revealed two perfectly opposing arms that in part reflect the previously observed ring-shaped nebula in the optical. However, from the far-IR there is evidence that the emitting region is elliptical rather than circular. The outline of the wind of W Aql seems to follow a large Archimedean spiral formed by the orbit of the companion but also shows strong indications of an interaction with the interstellar medium. We investigated the nature of the companion of W Aql and found that the magnitude of the orbital period supports the size of the spiral outline.

Key words. stars: AGB and post-AGB – binaries: general – stars: winds, outflows – infrared: stars – circumstellar matter

1. Introduction

When low- to intermediate-mass stars evolve off the main sequence and finally up the asymptotic giant branch (AGB) in the Hertzsprung-Russell diagram, they successively strip off their envelope and lose most of their mass in the form of a dust-enriched stellar wind. These dusty outflows are eventually dissipated into the interstellar medium (ISM) where they contribute essentially to the chemical enrichment of our Galaxy since the vast majority of stars evolve through this stage.

In the simplest manner the dusty winds expand with a velocity of 5–15 km s⁻¹ as spherically symmetric wind bubbles that push away the surrounding ISM and lead to extended circumstellar envelopes (CSEs) around AGB stars (Young et al. 1993). However, observations of post-AGB objects in the infrared (IR) and optical (Meixner et al. 1999; Ueta et al. 2000) showed that at least at the end of the AGB phase the envelopes differ from spherical symmetry while Olofsson et al. (1988) with CO observations and Kerschbaum et al. (2010) in the far-IR

found shells that are detached from the star. In addition, asymmetric shells were observed at many wavelengths: UV (e.g. Martin et al. 2007; Sahai & Chronopoulos 2010), 21 cm H I (e.g. Gardan et al. 2006; Matthews et al. 2008, 2011), CO (e.g. Kahane & Jura 1996; Castro-Carrizo et al. 2010), and mainly IR (e.g. Ueta et al. 2006, 2008; Geise et al. 2010; Ladjal et al. 2010; Jorissen et al. 2011; Cox et al. 2012).

One major trigger for asymmetries is the presence of a companion to the mass-losing AGB star. The impact of binary on the shaping of the AGB mass loss depends on the binary separation. In close binaries, where the AGB star fills its Roche lobe (Paczynski 1971), mass transfer is usually considered to be dynamically unstable (e.g., Ritter 1996; Soberman et al. 1997; Jorissen 2004), provided that the AGB star is more massive than its companion, which results in the formation of a common envelope when the accreting star cannot adjust fast enough to accommodate the arriving matter (e.g. Livio & Soker 1988; Taam & Bodenheimer 1989; Soker 1991; Hjellming & Taam 1991; Rasio & Livio 1996). This common envelope is eventually ejected and the system then looks very much like a planetary nebula (most likely bipolar) with a binary (or even coalesced-binary) nucleus (e.g., Miszalski et al. 2012, and references therein).

^{*} *Herschel* is an ESA space observatory with science instruments provided by European-led Principal Investigator consortia and with important participation from NASA.

A less violent variant of this scenario involves a wider system where it is not the stellar photosphere, but rather a dense AGB wind that is filling the Roche lobe. Mohamed & Podsiadlowski (2007, 2011) dubbed this situation “wind Roche-lobe overflow”. The mass transfer is non conservative and matter escapes from the system through an Archimedean spiral, a situation already encountered in hydrodynamical simulations of mass transfer in detached systems by e.g. Sawada et al. (1986), Theuns & Jorissen (1993) and Mastrodemos & Morris (1998, 1999), where this feature was called “spiral arm” (see also Huggins et al. 2009; Kim & Taam 2012a,b,c; Wang & Willson 2012). Observationally, such large-scale spirals were observed around LL Peg (AFGL 3068; Maun & Huggins 2006; Morris et al. 2006), RW LMi (CIT 6; Dinh-V.-Trung & Lim 2009), and recently R Scl (Maercker et al. 2012), and also in a bruised version around *o* Cet (Mira; Mayer et al. 2011). Estimates of the orbital separation are available for three (AFGL 3068, CIT 6, and Mira) of these four systems, flagging them as wide binaries given their projected separations of 109, 70, and 55 AU (Morris et al. 2006; Dinh-V.-Trung & Lim 2009; Karovska et al. 1997). In the framework of this paper, which interprets *Herschel* observations, it is important to report the finding by Edgar et al. (2008). The authors suggested that the spiral shock associated with mass-losing AGB stars in binary systems may anneal the amorphous grains to form crystals, as is often seen in the discs around post-AGB binaries (Gielen et al. 2011).

Finally, one should mention the frequent occurrence of bipolar jets in binary AGB stars (e.g., Huggins 2007), such as *o* Cet (Meaburn et al. 2009), R Aqr (Wallerstein & Greenstein 1980; Kafatos et al. 1989), π^1 Gru (Sahai 1992), and V Hya (Hirano et al. 2004).

In this paper, we examine a sub-sample of the 78 AGB stars from the Mass loss of Evolved StarS (MESS; Groenewegen et al. 2011) guaranteed-time key program (GTKP) for *Herschel* and give new observational insights into this topic. In Sect. 3.2, we give a short statistical overview of the morphology of circumstellar envelopes of binaries in the sample. The focus is then set on two prominent examples: R Aqr and W Aql. Each of them shows remarkable structures in the CSE that point to various forms of interaction.

2. Observations and the MESS sample

2.1. Observations

The observations presented here were carried out with the Photodetector Array Camera and Spectrometer (PACS; Poglitsch et al. 2010) on-board *Herschel* in 2009–2011. PACS is operating in the far-IR wavelength range in three channels, 70 μm (blue channel), 100 μm (green channel), and 160 μm (red channel) two of which are used simultaneously. Usually, these are the blue and red bands. The pixel size in the two channels is $3''.2 \times 3''.2$ in the blue band and $6''.4 \times 6''.4$ in the red band with a typical field of view of $5' \times 5'$, but the images presented here are oversampled by a factor of 3.2, resulting in a resolution of $1'' \text{ pix}^{-1}$ in the blue and $2'' \text{ pix}^{-1}$ in the red band. This image resolution has to be compared to the FWHM of $5''.7$ and $11''.4$ at these wavelengths.

The data processing was performed using the standard reduction steps in the *Herschel* interactive processing environment (HIPE) and the map-making program *Scanamorphos*. Both are described in detail by Groenewegen et al. (2011) and Roussel (in prep.). In addition, deconvolution was applied to

all images. A detailed analysis of this process can be found in Ottensamer et al. (2011).

2.2. MESS program

The MESS GTKP (Groenewegen et al. 2011) performed with the *Herschel* Space Observatory (Pilbratt et al. 2010) strives to investigate the CSE and the mass loss history of evolved stellar objects, benefits from the high spatial resolution of *Herschel*’s PACS and SPIRE instruments (Poglitsch et al. 2010; Griffin et al. 2010).

Earlier results of this program included the detections of multiple shells together with a bow shock around CW Leo (IRC +10216) by Ladjal et al. (2010) and Decin et al. (2011) and of detached shells around AQ And, U Ant and TT Cyg (Kerschbaum et al. 2010). Jorissen et al. (2011) examined the envelopes of TX Psc and X Her. The envelopes are massively shaped by the interaction of the stellar winds with the oncoming ISM due to their high space velocity.

Mayer et al. (2011) discussed the circumstellar environment of *o* Cet and found it to be shaped by a combination of several processes: wind-ISM interaction, a bipolar outflow, and in the interior, the orbiting motion of the companion that forms a spiral that appears to be broken. The broken appearance results from the bipolar outflow that pierces the dust shells.

2.3. MESS sample categories

For this study on binary-induced structures, we concentrate on the 78 AGB stars and RSGs in the MESS sample. The composition of this sample is well-balanced since it contains all major spectral classes of late-type stars. More specifically, the sample consists of 37 C-rich, 32 O-rich stars and 9 S-stars.

Recently, Cox et al. (2012) reviewed the properties of the whole MESS sample with the aim to classify the different CSE morphologies and to relate them to the influence of the interacting ISM. In short, five main morphology classes were identified:

- the *fermata* type, which is characterised by a strong bow shock in the direction of the space motion of the star;
- the *eye* type, or double-fermata, which has two elliptically shaped density-enhanced regions;
- the *ring* type, which is in general a detached shell (see e.g. Kerschbaum et al. 2010);
- the *irregular* type, which has a completely asymmetric morphology. This can be due, for example, to very strong instabilities that destroy the bow shock or to strong interactions with a companion;
- a *point source*, which shows no resolved CSE at all.

A detailed discussion is provided by Cox et al. (2012) and will not be repeated here. The strong indications of ISM interaction and the wide variety of morphologies motivated us to investigate the possible role of companions that shape the CSE in more detail. A discussion of that role based on the PACS images is the topic of the present paper. We refer to the above-mentioned categories throughout.

3. Physical binaries in the MESS sample

As described above, the FWHM of the PSF is $5''.7$ and $11''.4$ at 70 μm and 160 μm , respectively. However, these resolutions are insufficient to resolve the individual components of a binary

2.2. Large-scale environments of binary AGB stars - I.

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system even for relatively nearby objects. For this reason, the literature was thoroughly searched to find other possible evidence for binarity among the 78 AGB stars and RSGs in the MESS sample. The result of this search is listed in Table 1, resulting in 18 objects that show strong indications for physical binarity in their spectra, proper motion history, or observed morphology. In addition, the table also lists the objects of the MESS sample that are part of the visual binary catalogue by Proust et al. (1981), but we stress that most of these visual binaries are likely to be optical pairs given their large angular separations.

Table 1 also provides the general and kinematic data of the targets. In the penultimate column, the detection method of the binarity is listed.

3.1. Difficulties and limitations of binary detection

Flagging an AGB star as a binary is a difficult endeavour, mainly because the main binary-detection method – variable radial velocities – is not very efficient in the case of AGB stars (no convincing case of a spectroscopic binary involving a genuine AGB star¹ is currently known). This lack of efficiency results from the fact that orbital radial-velocity variations are confused by the intrinsic variations associated with the atmospheric dynamics (e.g., Hinkle et al. 1982, 2002; Nowotny et al. 2010), especially since the large radii of AGB stars impose their orbits to be rather wide, and hence the velocity amplitude to be small.

Other methods of binary detection should thus be used in the case of AGB stars, of which we list:

- detection of the companion itself (visually, interferometrically or through lunar occultations);
- composite nature of the spectrum and/or symbiotic activity;
- X-ray emission;
- shallow light curve of a Mira variable, with wide and flat minima;
- light variations associated with orbital motion (eclipses, Algol);
- asymmetries in circumstellar envelopes (especially spiral features, or double CO line profile);
- proper-motion variations.

A detailed description of these methods (with appropriate references) may be found in Jorissen (2004) and Jorissen & Frankowski (2008). The selection of putative binaries among the MESS targets is based on these different methods, as indicated in the penultimate column of Table 1. The confidence level for a target to be a possible binary varies from one target to another. In the case of visual binaries with a small angular separation (*o* Cet, π^1 Gru, W Aql), there can be no doubt; there is very little doubt in the case of UV-excess detection (*o*¹ Ori, VY UMa, TW Hor, V Eri), but the confidence is lowest for the double CO profile (EP Aqr). To account for these profiles, a bipolar geometry accompanying a Keplerian circumbinary disc has been proposed for instance for BM Gem (Kahane & Jura 1996), whose companion was later detected by Izumiura et al. (2008). But a double wind (fast and slow), as originally suggested by Knapp et al. (1998) for instance for the MESS target EP Aqr is an alternative to the binary model. The recent CO map of the circumstellar environment of that object by Nakashima (2006) casts doubt on the binary nature of that star, since it does not reveal any signature of a circumbinary disc. In those cases, other binary diagnostics,

such as the effect of binarity on the shaping of the CSE can dispel doubts.

3.2. Distribution of binaries according to morphological categories

In this section, we investigate the statistical frequency of binaries among the different morphological categories to see whether some categories are more often associated with binaries than others.

Before embarking on this comparison, we emphasize, however, that our ability to detect complex structures around AGB stars depends upon their distance, since it is obviously easier for nearby objects. This is reflected in the statistics derived from the Cox et al. (2012) morphologies: the number of point sources drops from 30/78 (38.5% of the total sample) to 15/59 (25.4%) for the $d < 500$ pc objects, as seen in Table 2. For this reason, the binary frequency among the different morphologies is only investigated for the 59 objects within 500 pc from the Sun.

Only three among the 18 binaries are farther away than 500 pc, which yields a binary frequency of 25.4% in the MESS $d < 500$ pc sample. This value is not so different from the 30% of binaries detected by van Winckel (2003) among post-AGB stars.

Furthermore, seven objects of the MESS sample show multiple morphologies, and two of them are binary stars: *o* Cet, whose extended structure was already discussed in detail by Mayer et al. (2011), and R Scl (Maercker et al. 2012).

The most common morphology type within 500 pc of the sample is the *fermata*: 23 out of the 59 objects (39.0%) show this kind of strong AGB wind – ISM interaction. Of these 23 objects, 5 (or 21.7%) are physical binaries. Do these five binary stars have a *fermata* morphology, which would suggest that the main shaping agent is indeed the interaction of the fast moving AGB wind with the ISM, which would mean in turn that the binary motion is negligible? In fact, the classification is not as clear-cut as it might seem. For instance, the binary nature of EP Aqr is subject to debate, as discussed in Sect. 3.1, and should thus not be included in the present discussion. For *o* Cet and R Scl, *fermata* is not the sole morphological type, because Cox et al. (2012) also associate them with types “irregular” and “ring”, respectively. Since *o* Cet is the nearest binary target, it is not really surprising that this system shows the most conspicuous impact of the binary motion, in the form of broken arcs and of a symmetry axis tilted with respect to the space motion (Mayer et al. 2011). θ Aps and W Aql, like *o* Cet, are other cases where signatures of binary motion and ISM interaction seem to co-exist in the CSE appearance: we show in Sect. 4.2 that an Archimedean spiral fits the CSE of W Aql well, even though the spiral also shows some signs of interaction with the ISM. In a forthcoming paper, we will demonstrate that the CSE of θ Aps shows indications for a jet bumping into the wind – ISM bow shock. Thus, there is not one single pure *fermata* morphology among the binary stars.

The *eye* type is a comparatively small group of seven objects (representing 11.9% of the $d < 500$ pc sample) two of which are binaries (28.6%). Given the small-number statistics, no conclusion can be drawn for this category.

The *ring* category contains 13 members within 500 pc (22.0%). Ring objects in general are slowly moving through the ISM, and most of them are carbon stars. In some cases, however, a bow shock forms beyond the ring structure, supporting the assumption that the rings are rather due to wind-wind interaction, probably associated to the transition from an O-rich to a

¹ A star is defined as an AGB star if it is a Mira variable, carbon-rich, or exhibits spectral lines from the unstable element technetium.

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Table 1. Properties of the suspected binaries in the MESS sample.

Object	Morphology	Spec. Type	d [pc]	$\dot{M}$ [$10^{-7} M_{\odot} \text{ yr}^{-1}$]	v_w [km s^{-1}]	$v_{l,SR}$ [km s^{-1}]	Binary detection	References
<i>o</i> Cet	Fermata and Irregular	M7 IIIe	91 ± 10	2.5	8.1	107.7	visual: $\rho = 0''.6$, PA $\approx 90^\circ$	(1),(2),(3)
θ Aps	Fermata	M6.5 III	113 ± 6	1.1	4.5	34.2	HIPPARCOS variability-induced mover (VIM)	(1),(2),(4),(5)
EP Aqr	Fermata	M8 IIIv	114 ± 8	3.1	11.5	40.2	complex CO profile	(1),(2),(6),(7)
π^1 Gru	Irregular	S6e	163 ± 20	8.5	30.0	11.9	jets, visual: $\rho = 2''.45$, PA = 200.4°	(1),(2),(8)
<i>o</i> ¹ Ori	Irregular	M3	200 ± 28	<0.4	–	38.8	UV excess	(9),(10),(11)
R Aqr	Irregular	M7 IIIpev	214	0.6	16.7	39.7	symbiotic	(12),(13),(14),(15),(16),(17)
Y Lyn	Point source	M6 Slb-II	253 ± 61	5.6	5.4	13.9	HIPPARCOS VIM	(1),(9),(5)
TW Hor	Point source	C	322 ± 38	0.24	7.5	52.4	UV excess	(1),(18),(19),(16)
W Aql	Fermata	S6.6	340	130	20.0	21.6	composite spectrum/CO profile, visual: $\rho = 0''.47$, PA = 209°	(20),(2),(1),(21),(18),(22)
R Scl	Fermata and Ring	C	370	16	17.0	66.3	spiral arm	(2),(1),(23)
VY UMa	Eye	C	380 ± 51	0.7	7.9	28.2	UV excess	(1),(4),(24),(10)
TX Cam	Point source	M8.5	380	65	21.2	–	spiral arm	(2),(19)
U Cam	Eye	C	430	10	20.6	9.8	HIPPARCOS DMSA/C: $\rho = 0''.17$, PA = 79°	(25),(26),(27),(1)
V Eri	Point source	M5/M6 IV	439 ± 133	1.5	13	39.8	UV excess	(1),(26),(24),(10)
RW LMi	Point source	C	440	59	20.8	–	spiral arm	(6),(2),(28)
VY CMa	Point source	M3/M4 III	562	2800	46.5	42.9	UV excess	(26),(2),(1),(10)
V Hya	Point source	C	600	610	30	27.9	rapid rotation	(14),(2),(1),(29)
LL Peg	Point source	C	980	310	16.0	–	spiral arm, visual: $\rho = 0''.11$	(2),(30),(31)
R Dor	Point source	M8 IIIe	55 ± 3	6.1	6.0	39.4	visual: $\rho = 32''.3$	(32),(33),(34)
W Hya	Ring	C	104 ± 12	0.78	7.5	48.2	visual: $\rho = 74''.5$	(1),(2),(34)
R Hya	Fermata	M7 IIIe	124 ± 11	1.6	12.5	25.3	visual: $\rho = 21''.2$	(1),(2),(34)
R Cas	Fermata	M7 IIIe	127 ± 16	4.0	13.5	44.0	visual: $\rho = 27''.8$	(1),(2),(34)
R Crt	Eye	M7 III	261 ± 65	6.9	10.8	23.8	visual: $\rho = 65''.4$	(1),(2),(34)
VX Sgr	Point source	M5/M6 III	262 ± 187	610	24.3	8.5	visual: $\rho = 0''.7$	(1),(2),(34)
UU Aur	Fermata	C	341	2.7	11.0	17.9	visual: $\rho = 18''.2$	(32),(2),(34)
V Pav	Eye	C	370 ± 73	3.4	16.0	24.0	visual: $\rho = 15''.0$	(1),(14),(24),(34)
S Sct	Ring	C	386 ± 85	1.4	8.0	17.5	visual: $\rho = 14''.3$	(1),(2),(34)
TT Cyg	Ring	C	436	50	12.6	38.3	visual: $\rho = 71''.0$	(32),(35),(36),(34)

Notes. The table is subdivided into two parts. The upper part lists the physical binaries, the lower part the visual binaries without indicating physical association. The space motion $v_{l,SR}$ is calculated following Johnson & Soderblom (1987). The adopted solar motion to convert heliocentric motion into LSR motion is $(U, V, W)_{\odot} = (11.10, 12.24, 7.25) \text{ km s}^{-1}$ (Schönrich et al. 2010). The objects are ordered by increasing distance. Although VX Sgr is associated with entry ADS 11078 in Proust et al. (1981), the Washington Double Star Catalog (<http://ad.usno.navy.mil/wds/wdtext.html>) does not list any measurement for that system, which is thus most likely spurious.

References. (1): van Leeuwen (2007), (2): De Beck et al. (2010), (3): Karovska et al. (1997), (4): Schöier & Olofsson (2001), (5): Pourbaix et al. (2003), (6): Knapp et al. (1998), (7): Winters et al. (2007), (8): Sahai (1992), (9): Groenewegen & de Jong (1998), (10): Sahai et al. (2008), (11): Ake & Johnson (1988), (12): Kamohara et al. (2010), (13): Matthews & Reid (2007), (14): Groenewegen et al. (2002), (15): Willson et al. (1981), (16): Hinkle et al. (1989), (17): Gromadzki & Mikolajewska (2009), (18): Culver et al. (1974), (19): Castro-Carrizo et al. (2010), (20): Guandalini & Busso (2008), (21): Herbig (1965), (22): Ramstedt et al. (2011), (23): Maercker et al. (2012), (24): Loup et al. (1993), (25): Knapp et al. (2003), (26): Young et al. (1993), (27): Lindqvist et al. (1999), (28): Dinh-V-Trung & Lim (2009), (29): Barnbaum et al. (1995), (30): Maun & Huggins (2006), (31): Morris et al. (2006), (32): Cox et al. (2012), (33): Olofsson et al. (2002), (34): Proust et al. (1981), (35): Olofsson (1996), (36): Olofsson et al. (2000)

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2.2. Large-scale environments of binary AGB stars - I.

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Table 2. Distribution of morphologies in the MESS sample.

Type	Number	Number within 500 pc	Physical binaries within 500 pc
Fermata	25 [32.1%]	23 [39.0%]	5/23 [21.7%]
Eye	7 [9.0%]	7 [11.9%]	2/7 [28.6%]
Ring	15 [19.2%]	13 [22.0%]	1/13 [7.7%]
Irregular	8 [10.3%]	7 [11.9%]	4/7 [57.1%]
Point source	30 [38.5%]	15 [25.4%]	5/15 [33.3%]
Total	78	59	15/59 [25.4%]

Notes. Seven objects, of which two are binaries (*o* Cet and R Scl), show multiple morphologies and are counted for two types. Of these seven objects, six are within 500 pc. For details see Cox et al. (2012).

C-rich atmosphere (Cox et al. 2012). If for one reason or another, the wind from the C-star becomes faster than the wind formerly present around the O-star (for instance because of the change in opacity of the carbon grains with respect to oxygen-based grains, or because of the increase in luminosity accompanying the thermal pulse responsible for the carbon synthesis), the fast wind will catch the old slower wind and interact with it (Mattsson et al. 2007), probably forming the observed ring. Currently, only one (R Scl) of the 13 ring objects shows indications of binarity, in the form of an Archimedean spiral (Maercker et al. 2012).

The shaping influence of binarity is best revealed by the *irregular* type stars. Their circumstellar environment exhibits no symmetry and cannot be related to ISM or to wind-wind interaction. There are seven objects belonging to the irregular category, four of which are binaries (57.1%), which is by far the highest percentage. The number of objects is too small though to conclude that binaries are the only cause for an irregular morphology. The four binary objects in the irregular category are *o* Cet, *o*¹ Ori, *π*¹ Gru, and R Aqr. *o* Cet was already discussed by Mayer et al. (2011) and for *o*¹ Ori there is doubt whether the very faint emission seen at the sky noise level with PACS is indeed real and associated to the central star (see Fig. 4. in Cox et al. 2012). The CSE of *π*¹ Gru shows an arm structure, which is strong evidence for the influence of a companion. This target will be discussed together with *θ* Aps in a forthcoming paper. The IR emission of R Aqr, dominated by two opposing arms, is discussed in Sect. 4.1. The remaining stars in the irregular category with no evidence so far for binarity are AFGL 278, ST Her, and V Cyg (Cox et al. 2012). Despite the small number of objects, it is possible to compare the binary frequency in the whole sample ($p_B = 15/59 = 0.254$) with that in the “irregular” category ($p_{B,irr} = 4/7 = 0.571$) and check the null hypothesis H_0 that the two frequencies are indeed identical and their difference only due to sampling fluctuations. If the null hypothesis is true, the expected number of binaries among irregular morphologies is

$$\tilde{x} \equiv \tilde{N}_{B,irr} = p_B N_{irr} = 1.78, \quad (1)$$

as may be estimated from the fraction of binaries in the total sample (denoted p_B) applied to the number of stars in the irregular category (N_{irr}). The corresponding standard deviation on $\tilde{x}$ (denoted σ_x) is computed from its expression for a hypergeometric distribution, which characterises the variable $\tilde{x}$, given the total number of stars in the sample, N_{all} , the total number of binaries, $p_B N_{all}$, and the number of stars with irregular morphologies, N_{irr} :

$$\sigma_x = [N_{irr} p_B (1 - p_B) (N_{all} - N_{irr}) / (N_{all} - 1)]^{1/2} = 1.08. \quad (2)$$

The reduced, squared difference c^2 between the estimated number of binaries with irregular morphologies ($\tilde{x} = 1.78$) and the observed number ($x = 4$) is

$$c^2 = [(\tilde{x} - x) / \sigma_x]^2 = 4.225, \quad (3)$$

and its significance is computed from the χ^2 distribution with one degree of freedom. The corresponding significance level is then

$$\alpha = 0.5 P(\chi^2 > c^2) = 0.02. \quad (4)$$

Thus, the probability that the difference between the expected number of binaries with irregular morphologies (1.78) and the observed number (4) is due to random fluctuations amounts to only 2%, and may be considered as insignificant.

The last type of objects are the *point sources*, representing 15 of the 59 objects within 500 pc (25.4%). Five of them are binaries (33.3%), which is about the average percentage of binaries in the whole sample (23.7%).

Finally, we stress that the sample selection, as sketched by Cox et al. (2012), should not interfere with the above statistics, since that statistics is based on the distribution of binaries among morphological categories defined a posteriori.

According to these results, a companion to an AGB star would most likely produce circumstellar structures that are ascribed to the irregular morphology type. However, a closer look at the images, which we report in Sect. 4 for R Aqr and W Aql, leads to the conclusion that the irregular category hides morphologies specific to binary systems, such as jets (R Aqr) or spiral arms (W Aql and *o* Cet; Mayer et al. 2011, for the latter). But apparently nothing prevents this binary-induced morphology from coexisting with a bow shock that might result from interaction with the ISM, which is observed on a larger scale, as in the latter two systems.

4. Case studies of binary AGB stellar winds: R Aqr and W Aql

In this section, the new *Herschel*-PACS far-IR observations of the large-scale environment of R Aqr and W Aql are discussed with emphasis on how the binary interplay shapes the AGB wind morphology. These objects were selected because of the complex morphology of their envelope, which suggests a prominent role of binary interaction. This section attempts to elucidate that role.

4.1. R Aqr

4.1.1. Background

R Aqr is one of the best-studied and brightest symbiotic systems (Whitelock et al. 1983), probably observed for almost 1000 years, as suggested by a nova record in Korean history books (1073–1074 A.D.; Yang et al. 2005). The system consists of an M7III Mira variable primary star with a pulsation period of 387 days (Mattei & Allen 1979) and a hot companion (Merrill 1921, 1950) that is most probably a magnetic white dwarf with $M \approx 0.6\text{--}1 M_\odot$ (Nichols et al. 2007; Gromadzki & Mikołajewska 2009). The companion was resolved by Hollis et al. (1997) with a separation of 55 ± 2 mas from the primary (11.8 AU at 214 pc) at a position angle of $18^\circ \pm 2^\circ$.

The orbital period of 44 yr was first determined by Willson et al. (1981) from eclipses in the light curves in 1928–1934

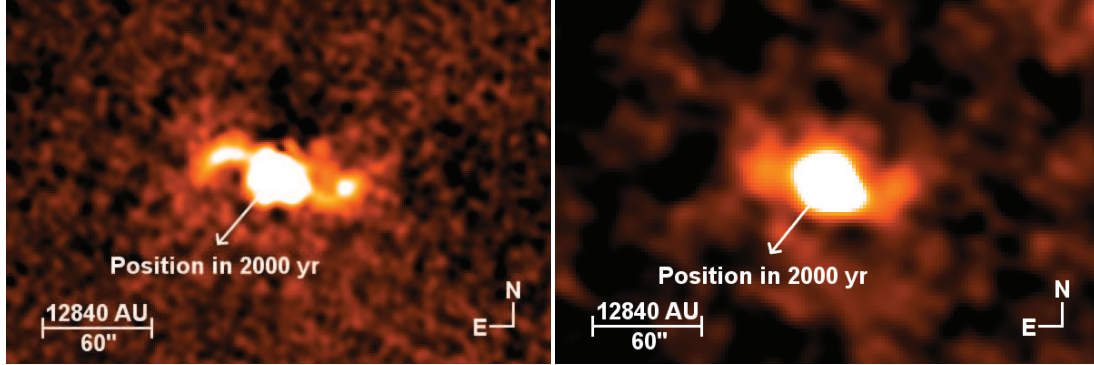


Fig. 1. Deconvolved PACS images of R Aqr at 70 μm (left) and at 160 μm (right). The arrows indicate the direction of space motion and the position of the star in 2000 yr. The proper motion values are taken from Kamohara et al. (2010).

and 1974–1980 and was refined later to 43.6 yr (Gromadzki & Mikołajewska 2009). The orientation of the orbit during the eclipse is uncertain, however. From the duration of the eclipse, Mäkinen et al. (2004) claimed that it occurs at apastron, while McIntosh & Rustan (2007) suggested that it happens during periastron passage. The latter authors also obtained an orbital period of 34.6 yr, significantly shorter than the other estimates.

The orbit is highly eccentric, with $e \approx 0.6$ –0.8, and it is seen nearly edge-on with $i = 70^\circ$ as noted by Solf & Ulrich (1985), Wallerstein (1986), Hinkle et al. (1989), and Hollis et al. (1997).

The distance to the system is fairly well established and ranges from 363 pc (HIPPARCOS; van Leeuwen 2007) to 214 pc (SiO maser spots; Kamohara et al. 2010), with an intermediate value at 240 pc (period–luminosity relation; Whitelock et al. 2008). Throughout this discussion, the distance of 214 pc is used since Kamohara et al. (2010) were also able to derive new proper motion values with a small error bar ($\mu_\alpha \cos \delta = 32.2 \pm 0.8 \text{ mas yr}^{-1}$ and $\mu_\delta = -29.5 \pm 0.7 \text{ mas yr}^{-1}$).

In the optical, the system is surrounded by two jets and a nebular structure with the shape of a double hourglass (Solf & Ulrich 1985). The NE optical jet (PA = 46°) was discovered first (Wallerstein & Greenstein 1980) at a distance of about $6''$ from the binary system, while the second (SW) jet was discovered as knots in the radio emission (Kafatos et al. 1989). Subsequently, the jets were intensively studied (e.g. Hollis et al. 1990, 1991; Viotti et al. 1987; Mäkinen et al. 2004; Nichols et al. 2007). Kellogg et al. (2007) observed both jets in X-ray and radio emission and found the NE jet to be curved and dominated by a bright spot $8''$ from the star. The bright spot is tilted away from the observer (Nichols & Slavin 2009). The SW jet, with PA = 211° , is not directly opposite, with a bright spot $26''$ away from the binary system (Kellogg et al. 2007).

Interestingly, Mäkinen et al. (2004) found that parts of the NE jet broke apart within a timespan of 7 yr probably due to a collision with a more massive cloud.

In addition to the jet, the circumstellar environment features an hourglass structure (discovered by Solf & Ulrich 1985), extending to about $2'$. It is centred on the binary system and might be linked to a possible previous explosion on the white dwarf 660 yr ago. The structure of the nebula consists of a ring with a radius of $42''$ inclined by 18° with respect to the plane of the sky. Hollis et al. (1989) compared 6-cm radio continuum emission with observations in the optical and found them to be morphologically similar and spatially related.

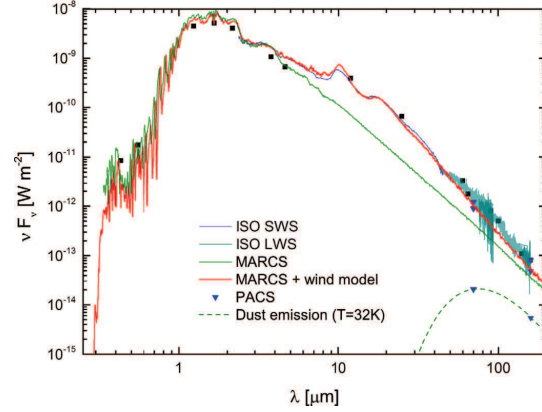


Fig. 2. SED of R Aqr described by single-band photometry (filled squares) compiled from the literature as well as the available ISO-SWS (blue line) and -LWS (cyan line) spectra. Overplotted are the synthetic spectra based on models for the photosphere (MARCS; green line) and the combined photosphere + wind (red line; see Section 4.1.2 for details). In addition, aperture photometry of the PACS 70 μm and 160 μm bands (triangles) is included. There are three data points for each of these measurements. From bottom to top: aperture photometry (i) of the eastern arm; (ii) of the central source; and (iii) of the whole IR-emitting region. The dotted line represents the model for the dust emission of the eastern arm.

4.1.2. Characterising R Aqr and its inner wind region

To understand *Herschel*'s observations of the outer regions of the environment of R Aqr, it is important to derive characteristics of the star, its present-day mass loss and the region where the outflow is triggered. For this reason, the literature was searched to derive a spectral energy distribution (SED) of R Aqr. Photometric data were adopted from the ASCC-2.5 catalogue (B, V bands), the 2MASS catalogue (J, H, K bands), Fouque et al. (1992) [L, M bands], the Infrared Astronomical Satellite (IRAS; 12, 25, 60 and 100 μm), and the AKARI satellite (65, 90, 140 and 160 μm). Valuable information is provided by the spectra obtained by the Infrared Space Observatory [ISO; 2–45 μm (SWS) and 43–160 μm (LWS)]. Figure 2 shows the resulting SED of R Aqr. The short-wavelength band (SWS) of ISO is dominated by pronounced emission of an optically thin dust shell

2.2. Large-scale environments of binary AGB stars - I.

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Table 3. Proper motion values of R Aqr and W Aql from various catalogues sorted according to their mean epoch. μ_{α^*} stands for $\mu_{\alpha} \cos \delta$.

R Aqr	GC ⁽¹⁾ 1903.2	SAO ⁽²⁾ 1903.2	Tycho-2 ⁽³⁾ 1903.2	UCAC3 ⁽⁴⁾ 1991.27	PPMXL ⁽⁵⁾ 1994.60	USNO ⁽⁶⁾ 2000.0	HIP2 ⁽⁷⁾	ASCC-2.5 ⁽⁸⁾	SiO maser ⁽⁹⁾
μ_{α^*} [mas/yr]	27	29 ± 5	33 ± 1.4	30.8 ± 1.6	28.6 ± 1.7	32	33.00 ± 1.53	28.95 ± 1.52	32.2 ± 0.8
μ_{δ} [mas/yr]	-20	-21 ± 5	-32.6 ± 1.2	-31.5 ± 2.1	-31.8 ± 1.6	-34	-25.73 ± 1.30	-32.61 ± 1.85	-29.5 ± 0.7
W Aql	GC ⁽¹⁾ 1913.2	SAO ⁽²⁾ 1913.2	YZC ⁽¹⁰⁾ 1933.60	W550 ⁽¹¹⁾ 1968.55	CPIRSS ⁽¹²⁾	UCAC3 ⁽⁴⁾ 1981.86	CMC ⁽¹³⁾ 1993.68	ASCC-2.5 ⁽⁷⁾	PPMXL ⁽⁶⁾ 2002.26
μ_{α^*} [mas/yr]	27	30 ± 20	26	30	33	-5.2 ± 48.1	15.9 ± 1.8	15.06 ± 1.70	-21.0 ± 20.8
μ_{δ} [mas/yr]	7	8 ± 22	0	10	8	17.6 ± 48.1	-0.9 ± 2.0	-0.58 ± 2.00	-36.5 ± 20.8

References. (1): General Catalogue of Stars (Boss 1937), (2): Smithsonian Astrophysical Observatory Star Catalog (Smithsonian Astrophysical Observatory Staff 1966), (3): Tycho-2 (Høg et al. 2000), (4): Third US Naval Observatory CCD Astrograph Catalog (Zacharias et al. 2010, based on HIPPARCOS and Tycho-2 for bright and SPM and SuperCosmos for faint stars), (5): PPMXL (Roeser et al. 2010, combining USNO-B1.0 and 2MASS), (6): USNO-B1.0 (Monet et al. 2003, taken from 7435 Schmidt plates over the last 50 yr), (7): New HIPPARCOS Reduction (van Leeuwen 2007), (8): All-Sky Compiled Catalogue-2.5 (Kharchenko & Roeser 2009, merging e.g. HIPPARCOS, Tycho-1, Tycho-2 and PPM), (9): Kamohara et al. (2010), (10): Yale Zone Catalogue (Fallon 1983), (11): Washington 550, results of observations with the six-inch transit circle 1963-1971 (Hughes & Scott 1982), (12): The US Naval Observatory Catalog of Positions of Infrared Stellar Sources (Hindsley & Harrington 1994), (13): Carlsberg Meridian Catalogs Number 1–11 (Carlsberg Meridian Catalogues Staff 1999)

that contains amorphous silicate grains. No signs of crystalline dust features have been found in R Aqr so far. In ISO's long-wavelength range (LWS), the spectrum shows no prominent features. The ISO spectrograph had a wavelength-dependent field of view of $\approx 25'' \times 25''$, thus not covering the outer regions observed by *Herschel*. To derive the *Herschel*-PACS fluxes of the central star, aperture photometry with a radius of $10''$ was applied. The resulting fluxes are $F_{\nu,70} = 20.980$ Jy and $F_{\nu,160} = 2.569$ Jy at $70 \mu\text{m}$ and $160 \mu\text{m}$, respectively, and coincide well with the predictions of the combined photosphere and wind model (to be described below).

Three PACS fluxes are plotted in Fig. 2. The first (highest) one corresponds to the overall IR emission (aperture photometry on a circle of radius $50''$ with resulting fluxes of $F_{\nu,70} = 28.220$ Jy and $F_{\nu,160} = 4.320$ Jy at $70 \mu\text{m}$ and $160 \mu\text{m}$, respectively). The intermediate flux value corresponds to the above described measurement of the central source, while the third (weakest) one corresponds to the flux of the eastern arm. An elliptical aperture with a size of $40'' \times 20''$ tilted by 45° was chosen to fully cover the arm. The resulting fluxes for the arm are $F_{\nu,70} = 0.481$ Jy and $F_{\nu,160} = 0.288$ Jy at 70 and $160 \mu\text{m}$, respectively. As discussed in more detail in Sect. 4.1.3, this flux measurement in the CSE of R Aqr may be interpreted as astronomical silicate dust emission. Adopting absorption coefficients $Q_{\text{abs},70} = 3 \times 10^{-3}$ and $Q_{\text{abs},160} = 5.9 \times 10^{-4}$ at $70 \mu\text{m}$ and $160 \mu\text{m}$, respectively (Draine 1985), the $70 \mu\text{m}$ and $160 \mu\text{m}$ fluxes observed at the eastern tip of the eastern arm then correspond to a temperature of 37 K (see Jorissen et al. 2011, for details). Because there is a temperature gradient in the arm (see Sect. 4.1.3), the average temperature of the arm is ≈ 32 K. The corresponding dust-emission spectrum – computed via $\nu\pi B_\nu(T = 32 \text{ K})Q_{\text{abs}}(\nu)f$, where f is a scaling factor – is also shown in Fig. 2.

To characterize R Aqr, we modelled the atmosphere and the inner wind region using methods of proven reliability. The model parameters, listed in Table 4, were chosen according to values compiled from the literature where available. With an angular diameter of $\theta_* = 0''.015$ (van Belle et al. 1997), a distance of $D = 214$ pc (Kamohara et al. 2010), and assuming the star to have a mass of $1 M_\odot$, one can estimate $\log(g_*)$. Together with the effective temperature adopted from Contini & Formigini (2003), the luminosity of R Aqr can be derived. Metallicity and C/O ratio were assumed to be solar-like following the abundance pattern derived by Caffau et al. (2008, 2009). For the stellar

Table 4. Input parameters used for modelling the atmosphere and wind of R Aqr.

Luminosity $L_\star [L_\odot]$	4780
Effective temperature $T_{\text{eff}} [\text{K}]$	2800
Mass $M_\star [M_\odot]$	1
Surface gravity $\log(g_*) [\text{cm s}^{-2}]$	-0.5
Metallicity $Z [Z_\odot]$	1
C/O ratio	0.55
Mass-loss rate $\dot{M} [M_\odot \text{ yr}^{-1}]$	7×10^{-7}

atmosphere, we computed a COMARCS model atmosphere following Aringer et al. (2009). This was then complemented with a model for the stationary outflow containing amorphous silicate dust particles, calculated as described in detail by Ferrarotti & Gail (2006), including recent improvements of the wind code (Gail et al., in prep.). Based on this combined model, we carried out detailed radiative transfer calculations similar to previous works (Aringer et al. 2009; Nowotny et al. 2011).

This led to a synthetic spectrum that simulates an unresolved object with spectral contributions from the photosphere and the inner-wind region (but not from any extended circumstellar material farther than the eastern arm of R Aqr), just as can be assumed for the observational data in Fig. 2. The resulting model spectra were normalised to the flux of the ISO-SWS spectrum at $3.8 \mu\text{m}$ for a direct comparison. Overplotted in the figure is the best-fitting model after iterating the mass-loss rate. While the COMARCS model is able to reproduce the SED of R Aqr in the visual and NIR reasonably well, an additional emission due to the circumstellar dust is clearly needed for a proper description beyond $\approx 4 \mu\text{m}$. Figure 2 illustrates that our wind model with a final mass-loss rate of $7 \times 10^{-7} M_\odot \text{ yr}^{-1}$ is also able to reproduce the emission features due to amorphous silicates at 9.7 and $18 \mu\text{m}$ quite well. This successful model will be used in Sect. 4.1.3 to compare the dust temperatures resulting from the wind model to the corresponding ones estimated from PACS fluxes.

4.1.3. Infrared arms in R Aqr: Jets, expanding nova, or ISM interaction?

R Aqr was observed on the 16th of May 2011 with the PACS photometer of *Herschel* at $70 \mu\text{m}$ and $160 \mu\text{m}$. Figure 1 shows

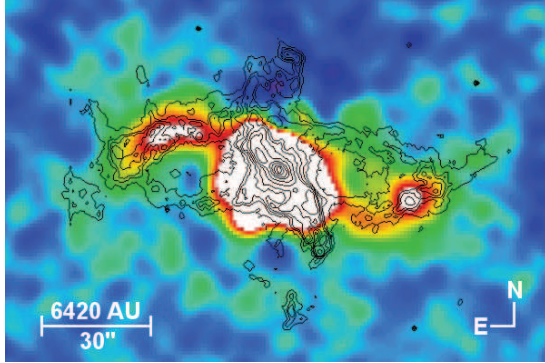


Fig. 3. Deconvolved $70\ \mu\text{m}$ PACS image of R Aqr overplotted with contours from an ESO Multi-Mode Instrument (EMMI) 2007 observation at $653\ \text{nm}$ [N II]. The contours clearly show a ring structure while the far-IR image renders only a part of this structure.

the first successful attempts to image the far-IR emission around R Aqr. Both images reveal the same features. Since the $70\ \mu\text{m}$ image offers a better resolution, however, it will be the base for the following discussion (unless otherwise noted).

The far-IR circumstellar environment is basically characterised by two arms, one approximately in north-east direction and the other in south-west direction. In the $160\ \mu\text{m}$ band, the eastern arm suffers from the lower resolution and is only visible as a bright clump, whereas the western arm sustains its shape.

The arms of R Aqr are exactly opposite at $\text{PA} = 61^\circ$ and 241° and seem to be connected with the binary system. However, owing to the saturation of the central source, a look farther inside a region closer than $\approx 18''$ from the star is not possible. The overall size of the IR emission structure around R Aqr is about $95'' \times 35''$ ($\approx 20\,330 \times 7490\ \text{AU}$). While both arms are aligned nearly symmetrically with respect to the central star, the light distribution is not. The western arm is brightest at its end, in the form of a light spot, whereas the eastern arm is clearly dominated by emission from the curved region. We now discuss three possible origins for the arms observed in the infrared.

Bipolar jet?

The first hypothesis naturally arises from the morphology of the IR emission and assumes that the arms trace the bipolar jet from the symbiotic system (Sect. 4.1.1). This hypothesis is not well supported because of the discrepancy between the position angles of the IR arms (61° and 241°) and of the optical-UV-X jet (46° and 211° ; Kellogg et al. 2007). Observations in the UV by Meier & Kafatos (1995) indicate that the direction of the bipolar wind is not stable due to the precession of the accretion disk. Although such a precession effect could perhaps account for the above discrepancy, we do not engage in discussing the possible association of the infrared arms with the jet, since the hypothesis cannot be validated with our observations.

Nova nebula?

The second hypothesis about the nature of the infrared arms thus stems from their good agreement with the structures seen for instance in [N II] $653\ \text{nm}$, as shown in Fig. 3, which correspond to

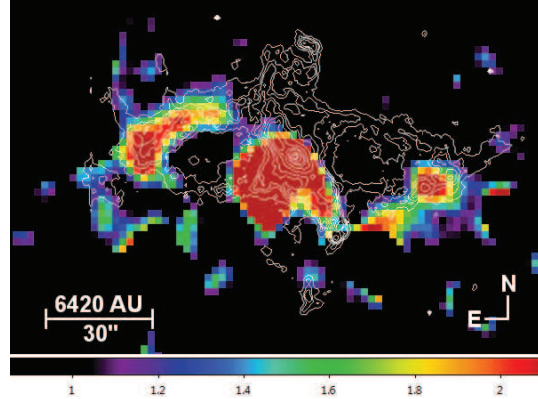


Fig. 4. Map from the ratio of flux values between the deconvolved $70\ \mu\text{m}$ and $160\ \mu\text{m}$ PACS images of R Aqr overplotted with contours from an EMMI observation at $653\ \text{nm}$ [N II]. The colour code represents the flux ratio between 70 and $160\ \mu\text{m}$. Both arms show gradients in the flux ratio, which is a signature of continuum dust emission. Furthermore, the highest flux ratio occurs at the ends of both arms.

the equatorial plane of the outer hourglass structure first outlined by Solf & Ulrich (1985) (see Sect. 4.1.1)².

In the eastern arm, the optical emission is stronger on the northern half, which is moving away from the observer (Hollis et al. 1999). There it fits its far-IR counterpart well. In the southern part of the eastern arm, far-IR emission is missing, but the optical emission is also much weaker. Similar conclusions hold for the western arm: this time, it is the southern part of the ring that matches the IR emission (even the IR spot at the arm's end has a well-defined optical counterpart), whereas the northern part of the ring is missing IR emission. This close match between optical and far-IR features raises the question of the origin of the far-IR emission. There are two possibilities: either scattering of light from the central source by the gas or dust, or else continuum dust emission. In the first case, the good match between the optical and far-IR images is a natural consequence of the model. The high degree of polarization observed from the nebula around R Aqr (Yudin & Evans 2002) is in favour of this model. The second hypothesis requires the dust to be strongly coupled with the gas: it must either have formed in the nova ejecta traced by the gas seen in the optical image, or it must have been piled up by the ejecta in the Mira wind pre-existing to the explosion.

To distinguish between the two models – light scattering or continuum dust emission – a map of the $70\ \mu\text{m}$ to $160\ \mu\text{m}$ flux ratio was derived (Fig. 4). Fluxes below 4σ of the background noise in either band were set equal to zero to prevent artefacts originating from background fluctuations. The part of the western arm closest to the star suffers from artefacts in the $160\ \mu\text{m}$ band, which are not entirely eliminated by the 4σ clipping. The image clearly shows gradients in both arms, which are not expected in the scattered-light scenario, since the flux ratio is a

² The jets at $\text{PA} = 46^\circ$ and 211° (Kellogg et al. 2007) are clearly visible in the contour plot of Fig. 3 and do not match the far-IR emission. In the optical, the jets extend up to $20''$ north and $30''$ south from the star, well beyond the PACS far-IR emission, and have no IR counterpart, which is also true for the detached clump seen in the optical approximately $40''$ south of the star and for the (non-detached) clump $37''$ north.

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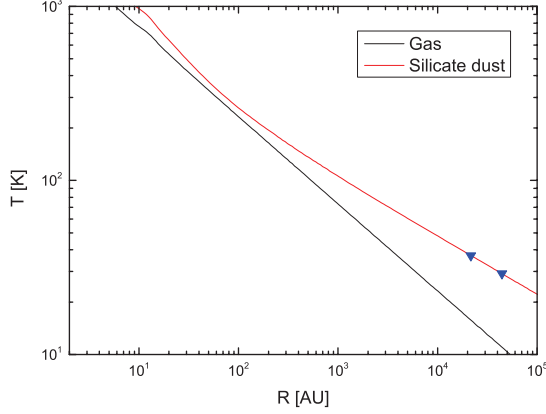


Fig. 5. Temperature gradient delivered by the stationary wind model (see Sect. 4.1.2). The dust temperatures of the eastern arm derived from the PACS band photometry (37 K and 29 K; blue triangles) correspond to distances of 21 500 AU and 43 700 AU in the wind model.

function of the scattering cross section only (provided that the scattering centres are the same throughout the arms) and is thus expected to be constant throughout the arms. The flux ratio image of Fig. 4 thus seems in favour of dust emission rather than light scattering. Even more surprising, the map reveals that the highest ratio occurs at the end of both arms, which are situated opposite each other much more accurately than in Fig. 3. At the end of the arms, the flux ratio is ≈ 2.5 while at the northernmost part of the eastern arm, the ratio drops to ≈ 1.1 . To constrain the temperature from these flux ratios, it is necessary to specify the dust species in the arms. Assuming the dust to be constituted only of silicates with absorption coefficients $Q_{\text{abs},70} = 3 \times 10^{-3}$ and $Q_{\text{abs},160} = 5.9 \times 10^{-4}$ at $70 \mu\text{m}$ and $160 \mu\text{m}$, respectively (Draine 1985), the flux ratios observed in the eastern arm correspond to temperatures of 37 K and 29 K (see Jorissen et al. 2011, for details). Because astronomical silicate has a very low opacity according to Draine (1985), these values represent the lowest possible ones.

The temperature of the eastern arm tip may now be compared with the predictions from the modelling at the same distance, since the model for photosphere and dusty outflow has been shown to describe the resulting SED of central source and inner wind region quite satisfactorily (Fig. 2). The wind model yields a silicate dust temperature of 49 K at a distance of 9200 AU. These values compare reasonably well to the estimates based on the observational data (see above), and the successful application of the wind model to predict the dust temperature implies moreover that the dust is heated by the radiation from the central star rather than by some form of shock.

The temperature gradient predicted by the wind model (Fig. 5) may now be used to de-project the geometry of the eastern arm. Since the (logarithmic) gradient appears to stay constant for distances larger than 500 AU from the central star (i.e., well encompassing the location of the eastern arm), it is more robust than the temperature prediction itself (the dust temperature of 37 K observed at a distance of 9200 AU differs somewhat from the 49 K value predicted by the model). The observed temperature ratio of 1.27 ($=37/29$) along the eastern arm is thus equivalent to a (de-projected) distance variation by a factor of 2.03 [$=d(29 \text{ K})/d(37 \text{ K})$]. Since the tip of the arm is its warmest part,

it may be assumed that it is located closest to the star, by the factor 2.03 derived above, as compared to the coolest, northernmost point on the eastern arm. On the image, however, the corresponding (projected) distances are $d_{\text{proj}}(29 \text{ K}) = 4300 \text{ AU}$, and $d_{\text{proj}}(37 \text{ K}) = 9200 \text{ AU}$, or a ratio of 0.467. This is in contrast to the de-projected one, thus suggesting that the arm is strongly inclined onto the plane of the sky. To fix the ideas, we assume that the warmest tip of the eastern arm [at $\text{PA} = 90^\circ$, corresponding to $d_{\text{proj}}(37 \text{ K})$] lies in the plane of the sky (basically because the western and eastern tips are almost exactly opposite). With this assumption, we obtain $d_{\text{proj}}(37 \text{ K}) = d(37 \text{ K})$ and $d_{\text{proj}}(29 \text{ K})/d(29 \text{ K}) = \cos i = 0.467/2.03 = 0.23$, or $i = 77^\circ$. Incidentally, this value is close to the 72° inclination of the orbital plane found by Solf & Ulrich (1985). Therefore, the picture emerging from our analysis for the arms is that of a non-circular structure located in the orbital plane.

Interaction with the ISM?

A third possible interpretation of the arm feature relates to its orientation with respect to the space motion of the star. Adopting the proper motion from the SiO maser measurements (Kamohara et al. 2010) and removing the solar motion ($U, V, W)_\odot = (11.10, 12.24, 7.25) \text{ km s}^{-1}$ obtained by Schönrich et al. (2010), we found that the star moves with $v_{\text{LSR}} = 39.7 \text{ km s}^{-1}$ along $\text{PA} = 145.1^\circ$ with an inclination $i = -40.2^\circ$ with respect to the plane of the sky. In Fig. 1, the space motion is indicated by an arrow and its length gives the position of the star 2000 years in the future. The space motion thus appears to be almost perpendicular to the arms ($\text{PA} = 61^\circ$). It is worth noting that a similar orthogonality has been found between the jet and the space motion of X Her (Jorissen et al. 2011). However, unlike the situation prevailing for X Her, the arm structure does not seem to be linked to the space motion, since ram pressure would bend the arms in the direction opposing the star motion, unlike what is observed for the eastern arm. Because of this, it is very unlikely that the ISM shapes the arm structure.

As a conclusion to the discussion of these three possible models, the arms seem to be the IR counterpart of the expanding nebula associated with the outer hourglass observed in the optical and the emission is caused by radiation-heated dust grains. However, the temperature gradient within the eastern arm, along with the exactly opposing locations of the highest temperatures, seems to contradict the circular geometry of the expanding ring proposed by Solf & Ulrich (1985), since this model would imply if not a uniform temperature distribution, at least a more arbitrary one than that observed. Although Solf & Ulrich (1985) clearly favoured the interpretation of an inclined ring ejecta, they also mentioned (their Sect. 4.3) the possibility that the nebula could be elliptical, based on kinematic arguments. This interpretation is supported by the temperature map of the *Herschel* observations.

4.2. W Aql

4.2.1. Background

W Aql is a Mira variable star of spectral type S6.6 with a period of 490 days (Feast & Whitelock 2000) at a distance of 340 pc (Guandalini & Busso 2008). W Aql was found to be a binary star by Herbig (1965), who noticed that the spectrum at minimum light acquired spectral characteristics of an F5 or F8 star. Ramstedt et al. (2011) recently presented an archive HST 435 nm image from 2004 that clearly shows the companion

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Table 5. Images of W Aql retrieved from the HST archives, with column labelled ID providing the HST program number.

Instr. Filter	Date	ID	Δm	V	V_{comp}	δ (")
WFPC <i>F487N</i>	1993-05-25	3603	+0.30			
WFPC <i>F502N</i>	1993-05-25	3603	-0.99	13.8	14.8	0.47
ACS <i>F435W</i>	2004-10-12	10185	-3.53			
ACS <i>F606W</i>	2004-10-12	10185	-3.82	11.1	14.9	0.47

Notes. Column Δm provides the magnitude difference ($m_{\text{WAql}} - m_{\text{comp}}$) as estimated from aperture photometry. Columns labelled V and V_{comp} provide the visual magnitudes of W Aql as derived from the AAVSO (for 1993) or ASAS (for 2004) databases (Pojmanski 2002), and of its companion, respectively. The last column gives the measured separation δ .

south-west of W Aql at a distance of $0''.47$. This angular separation corresponds to a projected distance of 160 AU at 340 pc.

W Aql shows strong emission lines of SiO and HCN with a parabolic shape indicating that the emission is optically thick (Bieging et al. 1998). In addition, Ramstedt et al. (2009) found weak wings extending beyond the parabolic profile. They could be caused by recent mass-loss-rate modulations or asymmetric outflows.

The mid-IR spectrum of W Aql is also dominated by emission from amorphous silicate grains, with an additional contribution from amorphous alumina dust. Both emissions result in a peak position (for the blended silicate plus alumina bands) of about $10.5 \mu\text{m}$ (Yang et al. 2007).

The circumstellar environment was studied at $11.15 \mu\text{m}$ by Danchi et al. (1994) and Tatebe et al. (2006). The former authors detected dust shells at 8 and 19 stellar radii while the latter found the dust to be unevenly distributed, with a clear excess eastward.

4.2.2. Nature of the companion

The suspicion of binarity based on the composite spectrum at minimum light discovered by Herbig (1965) was later confirmed by the *Hubble* Space Telescope (HST) images of Ramstedt et al. (2011). The log file of the available HST images is given in Table 5. Two sets of images separated by 11 yr are available and can be used to check for a possible relative motion of the two components. None has been detected, though, within the error bar set by the pixel size, which is $0''.04$ for the WFPC, about two times larger than that of the ACS image. At a distance of 340 pc, this pixel size corresponds to 13.6 AU. Assuming a circular orbit with a radius of 160 AU (as derived from the angular separation of $0''.47$), the pixel size represents about 1.3% of the orbital circumference. Over a 11 yr timespan, a motion would be detectable with the HST if the orbital period were shorter than about 800 yr.

A coincidental accord with a background source can also be excluded. The distance covered over 11 yr at a distance of 340 pc by an AGB star moving (rather slowly) with $v_{\text{LSR}} = 20 \text{ km s}^{-1}$ is more than a factor of 3 larger than the pixel size of the WFPC image ($0''.04$ compared to $0''.13$ covered by the star). To derive the nature of the companion, aperture photometry has been performed on the two continuum images (obtained with filters *F502N* and *F606W*), and the results are listed in Table 5 in the form of a magnitude difference with respect to W Aql.

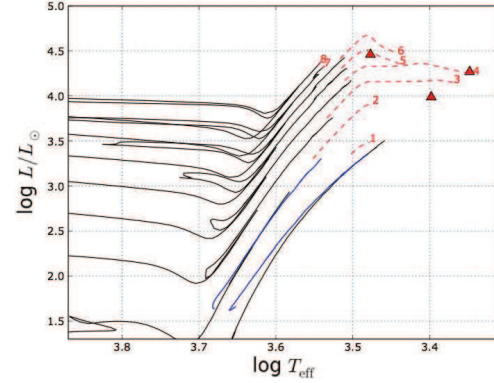


Fig. 6. Evolutionary tracks from the Padova set (Bertelli et al. 2008, 2009) for $Y = 0.26$ and $Z = 0.017$, with masses between 1 and $8 M_{\odot}$, as indicated (in red) at the end of each track. The asymptotic giant branches are depicted with dashed (red) lines. The location of W Aql as derived from the interferometric radii measured by Danchi et al. (1994) and van Belle et al. (1997) are depicted by (red) triangles.

The magnitude of the Mira variable at the time of the HST observations was obtained from the AAVSO database (for the 1993 observation) or from the ASAS database (Pojmanski 2002) (for the 2004 observation). It is remarkable that both epochs yield a consistent value for the visual magnitude of the companion (about 14.8), and that this magnitude is well below the magnitude of W Aql at minimum light ($V_{\text{WAql,min}} \approx 14.0$). This explains the absence of a flat minimum for the light curve, which would be caused by the companion becoming brighter than the variable star around minimum light.

Therefore, adopting an apparent magnitude of 14.8 for the companion and a distance of 340 pc, the resulting absolute visual magnitude is $M_V = 7.1$, corresponding to a K4V main-sequence star with a mass of $\approx 0.7 M_{\odot}$. This result contrasts with the F5 or F8 spectral type inferred by Herbig (1965) from the composite spectrum observed at minimum light; but the spectrum quality was quite poor.

We now estimate the mass of W Aql to evaluate the orbital period. Danchi et al. (1994) and van Belle et al. (1997) determined the angular diameter θ and effective temperature of W Aql. Van Belle et al. (1997) observed the star at maximum light and found $\theta = 11.58 \text{ mas}$ and $T_{\text{eff}} = 2230 \text{ K}$, which yields $L = 18\,590 L_{\odot}$ at a distance of 340 pc. Danchi et al. (1994) observed the star at maximum and minimum light and found $\theta_{\text{max}} = 8.6 \text{ mas}$ at $T_{\text{eff,max}} = 3000 \text{ K}$ and $\theta_{\text{min}} = 7.2 \text{ mas}$ at $T_{\text{eff,min}} = 2500 \text{ K}$, corresponding to $L_{\text{max}} = 28\,885 L_{\odot}$ and $L_{\text{min}} = 9\,740 L_{\odot}$. These values are widely spread and lead to a stellar mass in the range 2 to $5 M_{\odot}$ using the Padova stellar evolutionary tracks for a solar composition (Fig. 6). This yields a total system mass in the range $2.7\text{--}5.7 M_{\odot}$. Adopting a circular orbit of radius 160 AU ($0''.47$ at 340 pc and $i = 0$), a minimum orbital period in the range 850–1230 yr is found from Kepler's third law. This estimate agrees with that based on the absence of any relative motion on the HST image and has to be seen as the lowest bound, since the de-projected radius of the orbit can be much larger than 160 AU.

4.2.3. Space motion

Unfortunately, the space motion of W Aql is not clearly defined, as shown in Table 3, which collects proper-motion values from

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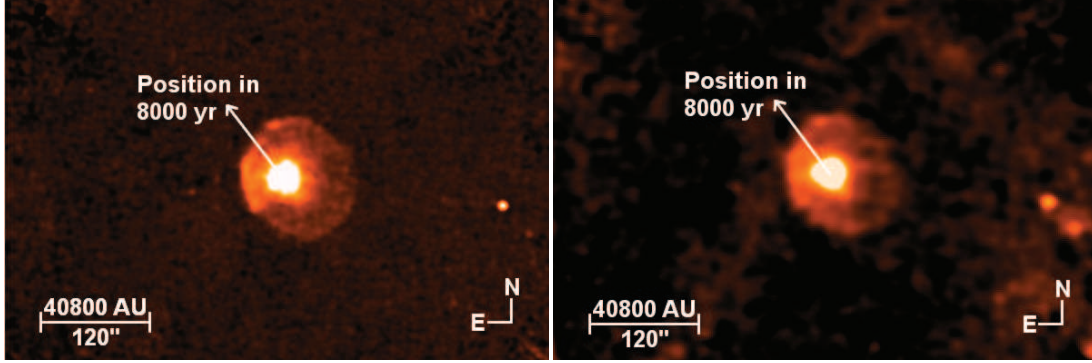


Fig. 7. Deconvolved PACS images of W Aql at 70 μm (left) and at 160 μm (right). The arrows indicate the direction of space motion and the position of the star 8000 yr in the future.

various catalogues. Unlike the situation prevailing for the proper motions of R Aqr, also listed in Table 3, the proper motion of W Aql varies significantly from one catalogue to the other, with no trend with the mean epoch spanning almost a century.

This behaviour very likely results from the combination of the Mira pulsation and the presence of a companion. During the variability cycle of the Mira, the photocenter of the binary system moves along the path that joins the two stars (separated by $0.47''$), according to the respective contribution of the two components to the total light (according to AAVSO, the Mira variable varies from $V = 7$ to 14, while the companion has $V \sim 14.8$ as shown above). The proper motion, of the order of a few tens of milliarcseconds per year, can therefore not be reliably derived, since the individual position measurements on which it relies are varying over a range of about 400 milliarcseconds, with a periodicity of 490 d. This behaviour is denoted as “variability-induced mover” (VIM) in the context of the HIPPARCOS catalogue (see also Pourbaix et al. 2003).

Nevertheless, on a century-long time span, one may hope that the long-term proper motion will dominate over this short-term variability-induced motion. For this reason one can try to derive the proper motion from the positional data of the seven catalogues in Table 3 (see references within) for which an observation epoch is stated. The SAO Star Catalog has to be excluded because W Aql’s position is far off from that of the other catalogues and seems erroneous. Instead, the positions from the HST Guide Star Catalog (obs. epoch 1987; Lasker et al. 1996), the Tycho-2 Catalog (obs. epoch 1991; Høg et al. 2000) and the USNO-B Catalog (obs. epoch 2000; Monet et al. 2003) are added. They are not listed in Table 3 because they do not feature proper motion values for W Aql. The result are nine data points that cover nearly one century (1913–2002). Figure 8 shows the right ascension and declination values with respect to the observation epoch. The diagrams clearly show a trend for the stellar motion of W Aql. Linear curve fitting was performed to obtain the proper motion from the slopes of the curves. The resulting proper motion values are $\mu_{\alpha} = 11.8 \pm 4.1 \text{ mas yr}^{-1}$ and $\mu_{\delta} = 4.5 \pm 2.1 \text{ mas yr}^{-1}$ for right ascension and declination, respectively. These values are different from all stated in Table 3 but reflect observations of the stellar position over a timespan of nearly one century, essentially longer than the observations for every catalogue in the table. In addition, the direction of motion is largely supported by the IR observations of the CSE, which are discussed in Sect. 4.2.4.

Although the scatter around the linear fit seems large at first sight, it is $\approx 2 \times 10^{-4}$ degrees or ≈ 0.7 , which is about the separation of the binary system ($0.5''$). This is exactly what is expected for a variability-induced movement, whose amplitude must be of the order of the angular separation on the sky.

Adopting a distance of 340 pc (Guandalini & Busso 2008), a radial velocity $V_r = -20.80 \pm 3.10 \text{ km s}^{-1}$ (Kharchenko et al. 2007) and the solar motion $(U, V, W)_{\odot} = (11.10, 12.24, 7.25) \text{ km s}^{-1}$ (Schönrich et al. 2010), the resulting proper motion values are $\mu_{\alpha} = 7.9 \pm 4.1 \text{ mas yr}^{-1}$ and $\mu_{\delta} = 10.0 \pm 2.1 \text{ mas yr}^{-1}$ for right ascension and declination, respectively. The space velocity of W Aql is $v_{\text{LSR}} = 21.6 \pm 4.1 \text{ km s}^{-1}$ at $\text{PA} = 38^\circ$ with an inclination $i = -17^\circ$ with respect to the plane of the sky. However, due to the large uncertainties of the positions, the results thus obtained may include large errors.

4.2.4. Binary vs. ISM interaction

W Aql was observed with PACS on October 2011. Figure 7 presents the 70 μm and 160 μm images. Since they exhibit the same features, the discussion below relies on the 70 μm image.

In the IR, the CSE is at first sight a typical *fermata* case and was classified as such by Cox et al. (2012). The elliptical envelope shape is to be expected from the interaction of the stellar wind with the oncoming ISM and the orientation of the envelope with its symmetry axis at $\text{PA} \approx 35^\circ$ (with the star offset by $8''$ though) nicely fits the space motion of the star along $\text{PA} = 38^\circ$ (see right panel of Fig. 9).

A feature that does not directly fit with this interpretation though is the brighter region east of the star, at a distance of $42''$. This feature suggests a bow shock but its location and the space motion/symmetry axis of the ellipse do not match: the bright region eastward extends from $\text{PA} = 55^\circ$ to 140° while the stellar motion and the CSE have their symmetry axis along $\text{PA} \approx 35^\circ$. However, it is imaginable that a strong ISM flow blowing from the east modifies the CSE morphology and creates a *fermata*. Another possible scenario is an ISM flow from the south that pushes material to the east. A feature supporting this is the bending of the IR emission $\approx 28''$ south of the star towards the star. Such ISM flows combined with the proper motion of the star were proposed for α Ori by Ueta et al. (2008). To infer the direction of the ISM flow, it is necessary to know the three-dimensional orientation of the bow shock, which is virtually

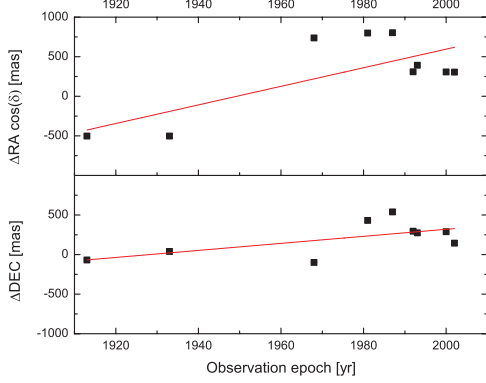


Fig. 8. Positional data of W Aql. The positions are taken from 9 catalogues (see Table 3 and text) and cover the years 1913 to 2002. The (red) lines indicate the linear fit to the data points. The scatter is of the order of the angular separation of the binary system on the sky that is expected for a variability-induced movement. The positions of W Aql in the last century show a trend for a movement along PA = 38° with a space velocity $v_{LSR} = 21.6 \pm 4.1 \text{ km s}^{-1}$.

impossible since the inclination of the bow shock cone has almost no effect on the (observed) projected outline (Mac Low et al. 1991; Cox et al. 2012). Thus, the hypothesis of an ISM flow that interacts with the CSE at the bright region could be adequate, but it is hardly verifiable.

It is hard to imagine, however, that an ISM flow that creates such a strong shocked interface does not modify the overall symmetry of the CSE, which is aligned with the (quite slow) space motion of the star. The binary nature of W Aql made us check whether a companion-induced Archimedean spiral could fit the outline of the CSE, as seen around RW LMi (Mauron & Huggins 2006) and LL Peg (Dinh-V.-Trung & Lim 2009). Mastrodemos & Morris (1999) showed in their hydrodynamic simulations that for large binary separations, such spirals even appear as broken arcs or concentric shells when seen edge-on (Mayer et al. 2011). The fact that such structures are not restricted to face-on orbits increases the probability to observe them.

Given the orbital period $P \geq 1000 \text{ yr}$ and the wind velocity $v_w = 20 \text{ km s}^{-1}$ (Sect. 4.2.2 and Table 1), an arm separation

$$\rho = v_w \times P \geq 12''5 \quad (5)$$

is estimated. Within this range, we indeed find two solutions, as drawn on the left panel of Fig. 9, with arm separations of 26'' or 52'', the former being about twice the estimated (minimum) winding separation. On the western side, the shell around W Aql exhibits three equidistant sharp ridges that are quite clearly delineated by the 26'' Archimedean spiral. That spiral is broken on its southern side, however. An orbital period of 2000 yr is thus required to match the Archimedean spiral, which is certainly not impossible, given the uncertainties associated with the distance and the orbital inclination.

In addition, as indicated by Raga et al. (2011), the starting point of the spiral structure ought not to be at the centre of the binary, but is offset by a distance

$$R_0 = \frac{r_{\text{orb}} \times v_w}{v_{\text{orb}}}, \quad (6)$$

where r_{orb} is the orbital separation, and v_{orb} is the orbital velocity. Within this distance, the wind propagates shock-less. For

the W Aql binary, the estimated orbital separation is 160 AU and the orbital velocity 2.4 km s^{-1} (assuming an orbital period of 2000 yr). This gives a shock-free radius of 1330 AU or 4''.

In summary, there are good arguments to support both hypotheses of a binary-induced spiral and of a wind-ISM interaction. Although the Archimedean spiral nicely fits the CSE, it cannot explain the bright region in the east. Similarly, an ISM flow alone cannot explain the CSE shape that follows an Archimedean spiral. Therefore, it is suggested that an ISM flow, preferentially from east or south direction, interacts with a part of the spiral and forms the bright region. A similar combination of orbital spiral and ISM interaction was already reported around *o* Cet (Mayer et al. 2011).

5. Conclusions

We have analysed the properties of the 18 targets among the 78 AGB stars and RSGs in the MESS sample that are suspected of being binaries. Based on the Cox et al. (2012) classification of the circumstellar morphology into five groups, the binary objects tend to be dominantly of *irregular* type (no imprint of the wind-ISM interaction on the circumstellar morphology). In contrast, the *ring*-type category contains only one binary star, which suggests that the interaction of the companion with the stellar wind decisively alters the spherical symmetry of the wind. However, despite the small number of binary stars in the sample, we showed that the null hypothesis of a similar binary fraction among the irregular shells and among the total sample can be rejected at a 98% confidence level.

Among the 17 binary AGB stars of the sample, a detailed analysis of the PACS images at 70 μm and 160 μm was performed for the two objects R Aqr and W Aql.

R Aqr, a symbiotic star, shows two arms extending over a region $95'' \times 35''$ wide. The arms are exactly opposite at PA = 61° and 241°, but their position does not fit the X-ray jets (PA 41° and 211°; Kellogg et al. 2007). However, a contour plot drawn from an ESO Multi-Mode Instrument (EMMI) optical image shows that the IR arms partly fit the ring nebula described by Solf & Ulrich (1985). A map of the flux ratios between 70 μm and 160 μm , which is equivalent to a temperature map, reveals a gradient in both arms with the highest temperature at their ends. This result dismisses a circular-ring structure, which would not show any temperature gradient in the arms, and favours an elliptically-shaped nebula. In addition, the SED of R Aqr (constructed with observational data compiled from the literature) was fitted with the help of a combined model for photosphere and dusty outflow, the latter having a mass-loss rate of $\dot{M} \approx 7 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$. A silicate dust temperature of 37–49 K for the tip of the eastern arm could be estimated from the PACS photometry as well as from the modelling of the stellar wind. The temperature gradient delivered by the wind model results in an inclination of the arms by 77°, which agrees well with the inclination of the orbital plane (72°; Solf & Ulrich 1985). Therefore, the arms are part of a non-circular structure located in the orbital plane.

For the second object, W Aql, Ramstedt et al. (2011) presented an HST 435 nm-image of the companion, which was previously detected spectroscopically as an F5 or F8 star (Herbig 1965). The quality of Herbig's spectrum is quite poor, however. Aperture photometry on archive HST images at other wavelengths (502 and 606 nm) and light-curve data reveal that the companion has an absolute magnitude $M_V = 7.1$, corresponding to a K4 main-sequence star with a mass of $\approx 0.7 M_{\odot}$. With a mass for W Aql between 2 and 5 $M_{\odot}$ (as determined from

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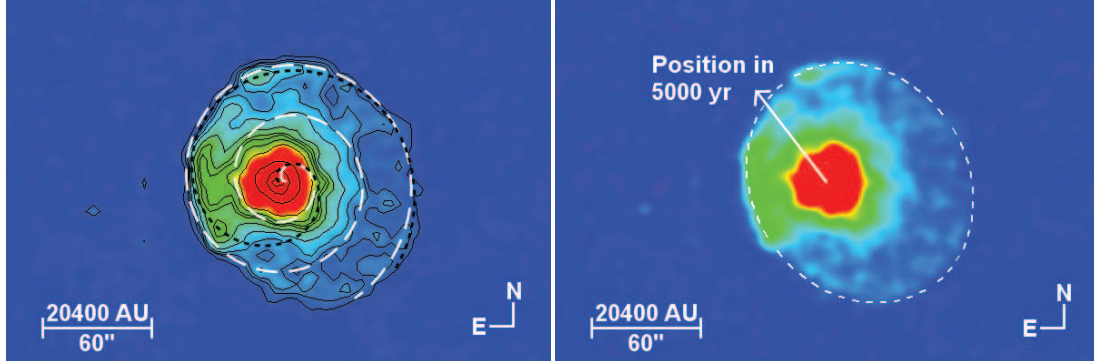


Fig. 9. *Left panel:* contour plot of the deconvolved $70\ \mu\text{m}$ PACS image of W Aql. Two Archimedean spirals matching the outline of the IR emission are recognizable. The (black) dotted spiral has one winding to cover the emission with a separation distance $\theta = 52''$ while the (white) dashed spiral has two windings with a separation distance $\theta = 26''$. *Right panel:* the same image overplotted with an ellipse fitted to the IR emission. The axes lengths of the ellipse are $69''$ and $59''$, respectively, with the major axis oriented along $\text{PA} = 35^\circ$.

HRD track matching on luminosity and angular diameter data by Danchi et al. 1994 and van Belle et al. 1997), one derives an orbital period of at least 1000 yr assuming a separation of 160 AU. The outline of W Aql's far-IR emission can be reproduced by an Archimedean spiral that has either one or two windings, with an arm separation of $52''$ or $26''$, respectively. A separation of $26''$ would imply that the orbital period is about twice as large as the inferred 1000 yr. However, this value for the period assumed an orbit seen face-on, but the binary separation (and hence the orbital period) may be much larger if the orbital plane is inclined with respect to the plane of the sky. The two-arm Archimedean spiral thus appears as a viable solution. But the CSE also shows some features, especially a bright region east of the star that can only be explained by the interaction with the ISM. Although the symmetry axis of the IR emission is along the space motion at $\text{PA} = 36^\circ$ and differs from the bright region at $\text{PA} 55\text{--}140^\circ$, an ISM flow from the east or south-east directions is a valid explanation for this feature. Thus the wind of W Aql is most probably shaped both by the companion, which produces the spiral, and by the ISM, which is responsible for the spiral brightening upstream of the ISM flow. In a forthcoming paper, the binaries θ Aps and π^1 Gru will be analysed along similar guidelines.

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2.3. Large-scale environments of binary AGB stars probed by *Herschel* – II. Two companions interacting with the wind of π^1 Gruis

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The third publication is a detailed analysis of the AGB star π^1 Gruis, one of the brightest intrinsic S stars and a known binary system with a separation of about 460 au ($P \approx 6200$ yr). The *Herschel*/PACS images of this object show an elliptical CSE with an arc emerging at its eastern edge. The elliptical CSE is known from CO observations with similar properties and explained as a disc tilted by 35° to the plane of the sky. However, we found it hard to explain the presence of both structures, the elliptical CSE and the arc, since the properties of the companion match well the size of the arc but the companion is too far away from the primary and of too low mass to efficiently focus the AGB onto the orbital plane. We therefore investigated archival observations and found π^1 Gru to show proper motion variations that can only be caused by a companion with an orbital period between 1500 and 30 000 days, thus much closer to the star than the known companion. In addition, the Hipparcos IAD show an orbital motion of the photocentre with a period between 5 and 10 years. We used archival data of the Astronomical Multi-BEam combineR (AMBER) at the VLTI to prove whether a tidal deformation of the primary is present.

We found signatures in the closure phase that could be fitted by a Roche lobe model. However, also stellar spots or flares can produce such signatures. Nevertheless, the VLTI/AMBER data may support the proper motion analysis which point to a close companion, making π^1 Gru a hierarchical triple system, where both companions interact with the primary's wind.

Individual contributions: Herschel data analysis, textual work, proper motion analysis (A. Mayer); evolutionary tracks, analysis of the CO data, general supervision (A. Jorissen); general supervision (F. Kerschbaum); *Herschel*/PACS data reduction (R. Ottensamer, M. Mečina); VLTI/AMBER data analysis, Roche lobe model (C. Paladini, C. Siopis, G. Sadowski); Hipparcos IAD analysis (D. Pourbaix).

Large-scale environments of binary AGB stars probed by *Herschel*

II. Two companions interacting with the wind of π^1 Gruis^{*,**}

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ABSTRACT

Context. The Mass loss of Evolved StarS (MESS) sample observed with PACS on board the *Herschel* Space Observatory revealed that several asymptotic giant branch (AGB) stars are surrounded by an asymmetric circumstellar envelope (CSE) whose morphology is most likely caused by the interaction with a stellar companion. The evolution of AGB stars in binary systems plays a crucial role in understanding the formation of asymmetries in planetary nebulae (PNe), but at present, only a handful of cases are known where the interaction of a companion with the stellar AGB wind is observed.

Aims. We probe the environment of the very evolved AGB star π^1 Gruis on large and small scales to identify the triggers of the observed asymmetries.

Methods. Observations made with *Herschel*/PACS at 70 μm and 160 μm picture the large-scale environment of π^1 Gru. The close surroundings of the star are probed by interferometric observations from the VLTI/AMBER archive. An analysis of the proper motion data of HIPPARCOS and Tycho-2 together with the HIPPARCOS Intermediate Astrometric Data help identify the possible cause for the observed asymmetry.

Results. The *Herschel*/PACS images of π^1 Gru show an elliptical CSE whose properties agree with those derived from a CO map published in the literature. In addition, an arc east of the star is visible at a distance of 38'' from the primary. This arc is most likely part of an Archimedean spiral caused by an already known GOV companion that is orbiting the primary at a projected distance of 460 au with a period of more than 6200 yr. However, the presence of the elliptical CSE, proper motion variations, and geometric modelling of the VLTI/AMBER observations point towards a third component in the system, with an orbital period shorter than 10 yr, orbiting much closer to the primary than the GOV star.

Key words. stars: AGB and post-AGB – binaries: general – circumstellar matter – stars: winds, outflows – stars: individual: π^1 Gruis – infrared: stars

1. Introduction

The evolution of low- and intermediate-mass stars ends with an ascent of the asymptotic giant branch (AGB) in the Hertzsprung-Russell diagram. This phase involves an increase of mass loss that strips off the envelope through a slow and dust-enriched wind ($v_w = 5\text{--}20\text{ km s}^{-1}$) blown into the interstellar medium (ISM), where it ranks among the dominant contributors of heavy elements in the Galaxy. Finally, at the end of

the AGB phase, the remaining envelope as a whole is ejected. The hot remnant stellar core ionizes the ejecta, forming what is known as a planetary nebula (PN). PNe show a manifold of morphological diversity, including highly asymmetric and bipolar forms that can only be adequately described by a binary star model (e.g. Nordhaus et al. 2007; De Marco et al. 2008; Miszalski et al. 2009a,b).

Paczyński (1971), Livio & Soker (1988), and Theuns & Jorissen (1993) have theoretically shown that already in the AGB phase the stellar winds must be heavily distorted in binary systems depending on the size of the system and the evolutionary type of the companion. For binary systems with small separations, the primary AGB star fills the Roche lobe and transfers mass onto the companion (Paczyński 1965, 1971).

In detached systems, the stellar AGB wind fills the Roche lobe, and up to half of the material is accreted by the companion (named wind Roche lobe overflow – WRLOF, Mohamed & Podsiadlowski 2011; Abate et al. 2013). Jets and bipolar

* *Herschel* is an ESA space observatory with science instruments provided by European-led Principal Investigator consortia and with important participation from NASA. This paper makes use of data from ESO programmes 076.D-0624, 077.D-0620, 078.D-0122, 080.D-0076, 187.D-0924.

** Maps of Fig. 4 are only available at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via <http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/570/A113>

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outflows have also been observed for some of these systems, e.g., α Cet (Meaburn et al. 2009), R Aqr (Wallerstein & Greenstein 1980; Kafatos et al. 1989), and V Hya (Hirano et al. 2004), where the accretion disc of the companion is fed by a strong wind from the AGB primary (e.g. Morris 1987; Soker & Rappaport 2000; Huggins 2007). But in general, the companion affects the circumstellar envelopes (CSEs) of the AGB star in two ways. First, the material that is transferred via the WRLOF is focused by the gravitational potential of the companion and forms a density wake that trails the orbital motion of the companion. The result is a wind pattern shaped as an Archimedean spiral, as predicted by hydrodynamic simulations in Theuns & Jorissen (1993), Mastrodemos & Morris (1998, 1999), and Kim & Taam (2012b). Second, the presence of the companion also manifests itself via the gravitational force that it exerts on the primary, causing it to move around the centre of mass of the binary system (Soker 1994; Kim & Taam 2012c,a). Furthermore, Kim & Taam (2012c) and Kim et al. (2013) recently demonstrated that the combination of the two effects leads to a spiral wind pattern exhibiting knots where the two structures intersect.

Observationally, spiral patterns were found around a small number of AGB or proto-PN objects: AFGL 3068 (Mauron & Huggins 2006), CIT 6 (Dinh-V.-Trung & Lim 2009; Kim et al. 2013), α Cet (Mayer et al. 2011), R Scl (Maercker et al. 2012), and W Aql (Mayer et al. 2013), all of which are wide binary systems with an orbital separation in the range of ≈ 50 –160 au. Recently, Mauron et al. (2013) found that 50% of a sample of 22 AGB stars have elliptical emission, which the authors attributed to binaries whose envelopes are flattened by a companion.

This work continues our study of large-scale environments of binary AGB stars from the *Herschel* Mass loss of Evolved StarS sample (MESS; Groenewegen et al. 2011). Contrary to Mayer et al. (2013, hereafter Paper I), which concentrated exclusively on *Herschel*/PACS observations of the large-scale structures (around R Aqr and W Aql), here we also explore the close surroundings of the star using HIPPARCOS Intermediate Astrometry Data (IAD; van Leeuwen & Evans 1998) as well as unpublished archive observations obtained with the Very Large Telescope Interferometer Astronomical Multi-BEam combineR (VLTI/AMBER, Petrov et al. 2007). We do this by analysing the structures around the binary AGB star π^1 Gru at angular scales from $0''.02$ to $60''$. Section 2 discusses the fundamental properties of π^1 Gru. In Sect. 3, the observations of *Herschel*/PACS and VLTI/AMBER are described, with their results presented in Sect. 4. The different interaction scenarios that can produce asymmetries in the extended environment of the star on both small and large scales are discussed in Sect. 5.

2. General properties of π^1 Gruis

The S5,7 star π^1 Gru (HIP 110478) is an SRb variable, and because of its proximity ($d = 163$ pc; van Leeuwen 2007) one of the brightest and best studied intrinsic¹ S stars (Keenan 1954). The intrinsic nature of the S star π^1 Gru is defined from the presence of spectral lines of the element Tc (Jorissen et al. 1993). The pulsation period of the star was initially derived to be ≈ 150 days by Eggen (1975) and used in various publications since then. A new derivation of the period based on the light curve provided by the All Sky Automated Survey (ASAS) Photometric V-band Catalogue (Pojmanski & Maciejewski 2005) revealed, however, π^1 Gru varies with a pulsation period of 195 days (see Fig. 1).

¹ About intrinsic S stars, see Van Eck & Jorissen (1999).

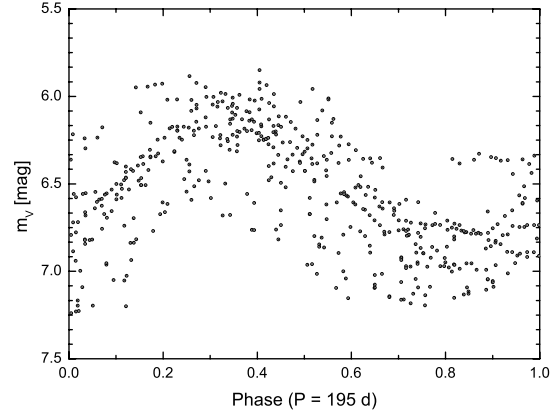


Fig. 1. ASAS-3 light curve of π^1 Gru with an adopted pulsation period of 195 days covering 14 cycles.

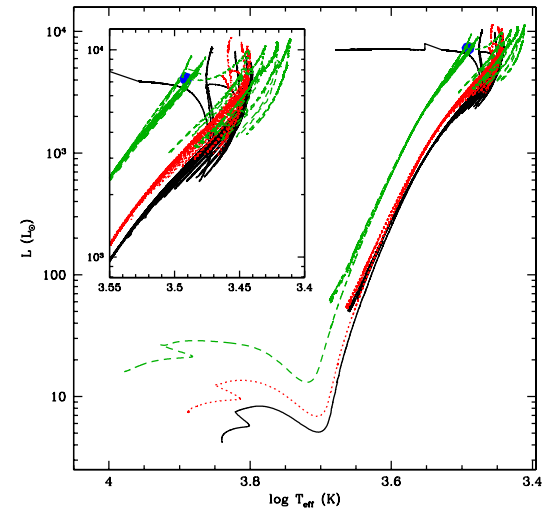


Fig. 2. Evolutionary tracks from STAREVOL for stars with initial masses $1.5 M_{\odot}$ (black line), $1.7 M_{\odot}$ (red dotted line) and $2.0 M_{\odot}$ (green dashed line) from the pre-main-sequence to the end of the AGB. π^1 Gru is represented by the large blue circle.

The Hertzsprung-Russell diagram for HIPPARCOS S stars from Van Eck et al. (1998) point to the very evolved nature of this star, close to the tip of the AGB. With values of $T_{\text{eff}} = 3100$ K and $\log L/L_{\odot} = 3.86$ (Van Eck et al. 1998), the location of π^1 Gru in the Hertzsprung-Russell diagram can be compared with evolutionary tracks (Fig. 2) computed from the STAREVOL code (Siess 2006; Siess & Arnould 2008) with a metallicity $Z = 0.02$. It appears that π^1 Gru falls on the track of a star of initial mass $2.0 M_{\odot}$, but by the time that star has reached $\log L/L_{\odot} = 3.86$, its mass has dropped to about $1.5 M_{\odot}$.

From CO(1–0) observations, a present-day mass loss rate of $\dot{M} = 2.73 \times 10^{-6} M_{\odot} \text{ yr}^{-1}$ (Winters et al. 2003), an expansion velocity of 14.5 km s^{-1} (Guandalini & Busso 2008), and a gas-to-dust ratio of 380 (Groenewegen & de Jong 1998) is derived.

2.3. Large-scale environments of binary AGB stars - II.

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Table 1. Journal of the AMBER observations of π^1 Gru.

Date and UT time	Config.	Baselines [m]	PA [deg]	Seeing ["]	Airmass
09 Oct. 2007 T23:51:44.10	E0-G0-H0	16–31–47	230	0.68–0.71	1.18
10 Oct. 2007 T00:53:41.50	"	16–32–48	242	0.70–0.78	1.09
10 Oct. 2007 T01:05:39.23	"	16–32–48	244	0.67–0.63	1.08
10 Oct. 2007 T01:50:37.99	"	16–32–48	252	1.05–1.10	1.07
10 Oct. 2007 T03:05:37.54	"	15–30–45	265	0.67–0.68	1.11
10 Oct. 2007 T03:54:47.47	"	14–28–42	274	0.56–0.47	1.18
10 Oct. 2007 T04:39:09.68	"	13–26–39	283	0.57–0.56	1.30

π^1 Gru is known to have a faint G0V companion with an apparent visual magnitude of 10.4 (Feast 1953; Ake & Johnson 1992). From the HIPPARCOS parallax (6.13 ± 0.76 mas or 163 pc; van Leeuwen 2007), the distance modulus is 6.1, yielding an absolute visual magnitude of 4.3 for the G0V star, in accordance with its spectral classification. The companion must thus be physically associated with the S star, but the orbital period is quite long, since the relative position did not change significantly over the past century, according to the list of relative positions collected by the Washington Double Star Observations catalogue, and kindly communicated to us by B. Mason (see Appendix A.2 and Table A.2). Assuming that the observed angular separation ($\approx 2''.8$) corresponds to the semi-major axis and adopting $2.5 M_{\odot}$ as the total mass of the system (π^1 Gru+G0V companion), the system parallax implies an orbital separation of the order of 460 au and an orbital period of about 6200 yr.

3. Observations

3.1. *Herschel*/PACS

The observations presented here are part of the MESS guaranteed time key programme (Groenewegen et al. 2011) for the *Herschel* Space Observatory (Pilbratt et al. 2010) using the Photodetector Array Camera and Spectrometer (PACS, Poglitsch et al. 2010) and the Spectral and Photometric Image Receiver (SPIRE, Griffin et al. 2010) on board the spacecraft. π^1 Gru was observed on May 21 2010. For the following analysis, we exclusively used the PACS data since the instrument offers a resolution that best suits our purpose. Observations of π^1 Gru were obtained at 70 and 160 μm at a FWHM of $5''.6$ and $12''$, respectively. The adopted data processing and image reconstruction for π^1 Gru was made in the same way as for the data presented in Paper I, following Groenewegen et al. (2011) and Roussel (2013). We oversampled the reconstructed images by a factor 3.2 to achieve a pixel size of $1''$ in the blue and $2''$ in the red band.

An overview of the MESS objects is given by Cox et al. (2012) and detailed studies of individual objects are presented in Ladjal et al. (2010a), Kerschbaum et al. (2010), Jorissen et al. (2011), Mayer et al. (2011, 2013), Decin et al. (2011, 2012), van Hoof et al. (2013), and Mećina et al. (2014).

3.2. VLTI/AMBER

π^1 Gru was observed with VLTI/AMBER and VLTI/MIDI in the framework of ESO programmes 076.D-0624, 077.D-0620, 078.D-0122, 080.D-0076, and 187.D-0924. The detailed description of the MIDI data reduction and modelling is given in Sacuto et al. (2008) and Paladini et al. (in prep.). The MIDI observations do not deviate from spherical symmetry. These

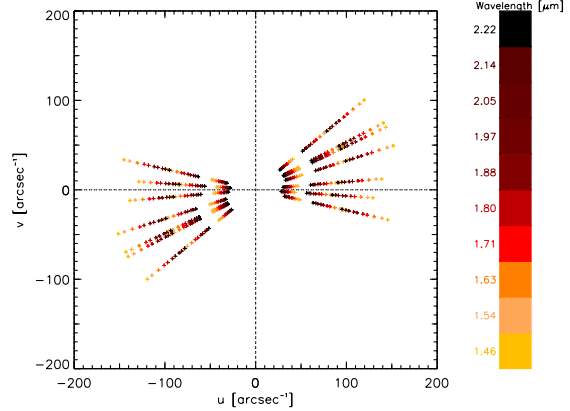


Fig. 3. uv -plane coverage of the VLTI/AMBER data of π^1 Gru.

data, however, sample only the low spatial frequencies, and it is known that for AGBs, asymmetric structures are usually detected at high spatial frequencies. The only information that we can extract from the MIDI observations is the overall size of the envelope. For this reason the MIDI data are not discussed here.

We retrieved seven VLTI/AMBER observations from the ESO archive. The data were recorded in low-resolution mode ($R = 30$) on the night of October 9, 2007 and cover the J , H , and K bands. The log of these observations is presented in Table 1, while Fig. 3 shows the corresponding uv -plane coverage.

We reduced the data with amdlib v.3.0.8 (Tatulli et al. 2007; Chelli et al. 2009) using the K3III star λ Gru as calibrator (Bordé et al. 2002; Cruzalèbes et al. 2010, with a stellar diameter of 2.62 ± 0.03 mas). The data analysis is limited to the H and K bands because reliability for the wavelengths shorter than $1.46 \mu\text{m}$ is not guaranteed by the current pipeline version.

The medium- and long-baseline visibilities sample the second and even third lobe, meaning that the star is fully resolved. There is evidence for deviation from centro-symmetry (or rather left/right symmetry for this triplet of aligned baselines), as judged from the non-zero closure phase. We return to this in Sect. 5.3.2.

4. Results

Figure 4 depicts the images obtained with *Herschel*/PACS at 70 μm (blue band) and 160 μm (red band)². Since the blue band

² Both maps are available as FITS files from CDS/VizieR at <http://cdsweb.u-strasbg.fr/>

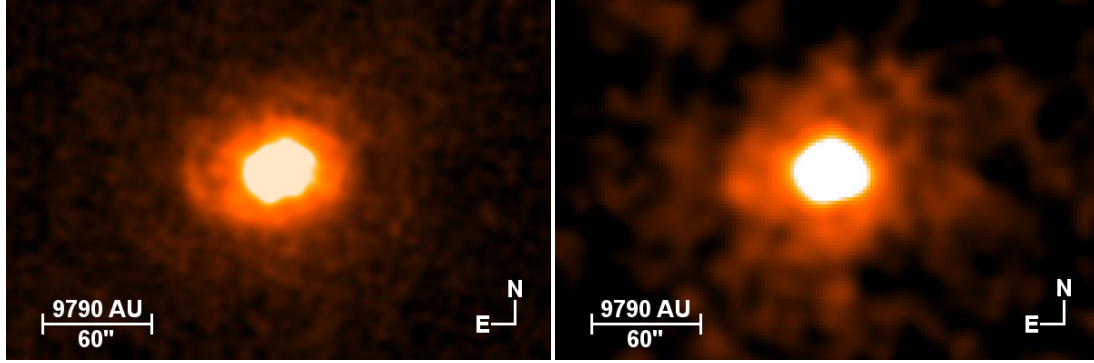


Fig. 4. Deconvolved *Herschel*/PACS images of π^1 Gru at 70 μm (left panel) and 160 μm (right panel).

offers a better spatial resolution, all following discussions are based on this image unless stated otherwise. The PACS 70 μm image is dominated by two features, an elliptical CSE and an arc east of the star, which are described in the remainder of this section.

The elliptical CSE is oriented east-west with its major axis at PA $\approx 105^\circ$. The total size of the emission is $\approx 72'' \times 60''$ [$11\,750 \times 9\,790$ au]. A confirmation of the CSE size is provided by the 870 μm image of π^1 Gru obtained with the APEX bolometer LABOCA (Ladjal et al. 2010b). The authors found an elongation of the CSE in east-west direction with a total size of the structure of about $60'' \times 40''$.

The size of the CSE obtained from the PACS 70 μm image is much smaller than that inferred by Young et al. (1993) from the IRAS 60 μm dust emission ($4'.9$). A similar discrepancy for the CSE sizes obtained from IRAS and *Herschel* data was found for the targets X Her and TX Psc analysed previously (Jorissen et al. 2011), most likely owing to the size of the IRAS PSF ($\text{FWHM} = 1'.6$ at 60 μm), which causes difficulties in probing asymmetries of the order of $1'$ as found in the *Herschel* data.

The second main feature visible in the far-IR emission of π^1 Gru is an arc east of the central star. It emerges $38''$ away from the stellar system, in the direction of the major axis ($\approx 105^\circ$). This finding diminishes the probability that the elliptical emission is caused by the interaction with the ISM. The observed arc is curved towards the north and extends in that direction for almost $25''$ and $16''$ to the east. On the PACS 160 μm image, the arc suffers from the low resolution but remains recognisable as a clump. We further note that in Fig. A.2 of Ladjal et al. (2010b), a spike is visible on the eastern side, that might reflect the arc seen on the 70 μm PACS image.

5. Discussion

5.1. Origin of the far-infrared dust arc

Arcs or arms around AGB stars were found recently for CIT 6 (Dinh-V.-Trung & Lim 2009; Kim et al. 2013), TX Cam (Castro-Carrizo et al. 2010), α Cet (Mayer et al. 2011), and W Aql (Mayer et al. 2013). They are most likely part of Archimedean spirals caused by a combination of (i) the accretion wake of the companion when it orbits the mass-losing primary and the wind pushes the wake radially outwards (Theuns & Jorissen 1993; Mastrodomos & Morris 1998, 1999); and (ii) the motion of the primary around the centre of mass caused by the

gravitational drag of the companion (Soker 1994; Kim & Taam 2012c,a). Spectacular examples of complete Archimedean spirals have been observed around AFGL 3068 (Mauron & Huggins 2006) and R Scl (Maercker et al. 2012).

It is not clear, however, whether the far-infrared arc seen around π^1 Gru has anything to do with a spiral pattern produced by the orbital motion of a companion. If it does, the properties of the arc have to be consistent with the properties of the π^1 Gru+G0V binary system. From the orbital period $P \approx 6200$ yr, the parallax $\varpi = 6.13$ mas, and the wind velocity $v_w = 14.5$ km s $^{-1}$, one derives an arm separation of

$$\rho = v_w P \varpi = 116''.$$

This is more than twice as large as the separation of $52''$ between the central part of the arc and π^1 Gru as seen on the PACS 70 μm image. If the arc is part of a spiral, it only represents a part of the first spiral twist.

In the upper panel of Fig. 5 we plot a spiral with $\rho = 116''$ over the PACS image that seems to match the observed arc well. However, this assumption has to be made with care since the curvature of the arm allows many solutions. A unique solution is obtained when the start of the spiral coincides with the current position of the G0V star. The lower panel of Fig. 5 displays the same scenario in a polar-radial diagram, which facilitates the illustration of the Archimedean spiral (dashed line). The current position of an anticlockwise orbiting companion is given by

$$\Phi_{\text{comp}} = \Phi_{\text{arc}} + \frac{2\pi R}{\rho},$$

where R is the distance from a given part of the spiral to its origin, and Φ_{arc} the PA of that given part³. Assuming $R = 52'' - 2''.8$, $\Phi_{\text{arc}} = 85^\circ$, and $\rho = 116''$, the PA of the companion is $\approx 240^\circ$, which has to be compared with the observed PA $\Phi_{\text{comp}} = 203^\circ$ (see Table A.2).

A spiral that matches both the slope of the arc and the position of the G0V star has an arm spacing $\rho = 168''$. This value is about 45% higher than that derived from the wind velocity of the primary, however, and the orbital period and this difference may originate from the uncertainties on these values.

³ This is a simplification since the origin of the Archimedean spiral is the primary. For a binary system this wide, it is assumed, however, that the accretion wake of the companion causes the spiral, not the reflex motion of the primary. The spiral thus follows the involute of the circular orbit. Since the outcome is almost identical (Kim & Taam 2012c), we keep the description of an Archimedean spiral.

2.3. Large-scale environments of binary AGB stars - II.

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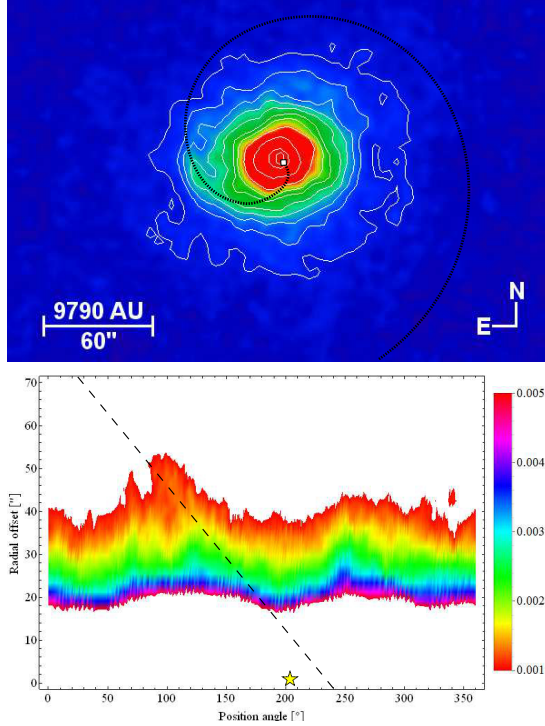


Fig. 5. Upper panel: contour plot of the *Herschel*/PACS 70 μm image of π^1 Gru over-plotted with an Archimedean spiral. The spiral spacing of 116'' was derived from the wind velocity and the orbital period of the known G0V companion. Lower panel: polar-radial intensity profile of the same image. The position angle is measured north over east and the colour code is given in Jy arcsec^{-2} . The dashed line shows the same Archimedean spiral as in the upper panel. The (yellow) star illustrates the current position of the G0V companion.

Maercker et al. (2012) remarked that the arm separation of the spiral around R Scl changed significantly during the past 1800 yr. The outer (older) part of the spiral shows a larger separation than the inner (younger) part. For the authors, this indicates a modulation of the mass-loss rate by a factor of 30 caused by a thermal pulse. At the beginning of that phase, the wind velocity increased by 40% and subsequently declined to the present-day value within 1200 yr. This is measurable in the spiral-arm separation, which varied by this value.

Such a thermal pulse presumably also occurred in π^1 Gru given its location at the tip of the AGB. Furthermore, Knapp et al. (1999) suggested that the mass-loss rate of π^1 Gru has increased in the past 1000 years to explain the presence of the CO disc.

The second uncertainty on the arm separation ρ stems from the assumption that the observed orbital separation of the π^1 Gru+G0V system ($\approx 2''.8$) is de-projected, meaning that the binary orbit is seen face-on. For instance, to obtain an arm spacing of 168'' with a constant wind velocity of 14.5 km s^{-1} , an orbital period of 9000 yr is required, which implies an inclination $i = 46^\circ$ of the orbit w.r.t. the plane of the sky.

The appearance of inclined spirals was studied in the hydrodynamic simulations of Mastrodemos & Morris (1999), Mohamed & Podsiadlowski (2011), and Kim & Taam (2012c).

The authors found that the spiral shape is preserved up to an inclination angle of $\approx 70^\circ$ and then changes its appearance to broken concentric shells. Hence, a spiral pattern inclined by 46° would still be recognisable as such.

5.2. Origin of the elliptical emission

A puzzling fact is the presence of the elliptical emission together with the spiral arc. While the arc can be explained by the G0V companion interacting with the primary's wind (see Sect. 5.1), this cannot be the case for the elliptical emission.

An inclined disc structure around π^1 Gru was proposed by several CO and SiO line studies in the past 20 years (e.g. Sahai 1992; Winters et al. 2003; Knapp et al. 1999; Chiu et al. 2006). In all of the observations, the CO(2–1) profiles show an asymmetric, double-peaked structure and extended emission wings. On a corresponding map (Chiu et al. 2006), the envelope is elongated in the east-west direction with a size of $\approx 40''$ [6530 au] and a velocity gradient in the north-south direction.

Knapp et al. (1999) interpreted these observations in terms of an expanding disc with a radius of 3340 au [20''] inclined by 35° to the plane of the sky with the northern part of the disc tilted away from the observer. The same inclination was found from the axis ratio of the PACS far-IR emission along with the same orientation of the projected major axis, which assumes that both structures are identical, but visible on different scales. A similar conclusion was drawn by Ladjal et al. (2010b) from the APEX/LABOCA observations where the authors mention an inclination of the structure of about 70° (a probable misprint for $48^\circ = \arccos[40/60]$).

According to Knapp et al. (1999), the disc is produced by a constant mass-loss rate of $1.2 \times 10^{-6} M_\odot \text{ yr}^{-1}$ expanding in the plane of the disc with a velocity of $13 \pm 2 \text{ km s}^{-1}$, in agreement with the velocity of the SiO(6–5) line. The expansion velocity derived from the CO lines increases steadily to 18 km s^{-1} towards the pole. In addition, a fast molecular wind (with velocities of at least 70 km s^{-1}) is observed, which is most likely a continuation of the velocity increase towards the poles. This is in conflict with Sahai (1992), who interpreted the spatially-separated horn features in the CO lines as arising from a bipolar flow perpendicular to the disc. In the most recent study of the CO emission, Chiu et al. (2006) adhered to the Knapp et al. (1999) model and found, moreover, that the high-velocity outflow is oriented along $\text{PA} = 30\text{--}210^\circ$.

A natural explanation for the elliptical emission is that the wind of the AGB star does not propagate in a spherically symmetric fashion but is focused towards a plane. Three known mechanisms can account for this: (i) a fast differential internal rotation creates a gradient in the wind velocity between the equator of the star and its poles. However, only one AGB star is known to show a fast rotation (V Hya; Barnbaum et al. 1995), and generally slow rotation rates are found among white dwarf stars (Kawaler et al. 1999); (ii) a bipolar magnetic field causes the wind to become denser at the magnetic equator (Matt et al. 2000). Surface magnetic fields have been recently reported for some AGB stars (Vlemmings et al. 2011; Leal-Ferreira et al. 2013; Lèbre et al. 2014), but there is no observational evidence for stellar magnetic fields to shape stellar AGB winds; (iii) the most common explanation is gravitational focusing of the AGB wind on the orbital plane of a companion. This scenario is supported by hydrodynamic simulations (Mastrodemos & Morris 1999; Kim & Taam 2012a) and by observations (e.g. van Winckel et al. 2009).

If the elliptical emission is part of the primary's wind that is focused towards the orbital plane of the G0V companion, that star is orbiting *within* the disc. Since the high-velocity receding lobe is almost centred on the position of the secondary (see Fig. 4 of Chiu et al. 2006), it is hard to imagine that the G0V companion does not produce any disturbance in the low-velocity CO disc. Therefore, the orientation of the CO disc might not be aligned with the orbital plane of the G0V companion.

The enormous separation of the system ($d > 460$ au) additionally makes it unlikely that the main-sequence companion is able to focus the AGB wind towards the orbital plane. Mastrodemos & Morris (1999) used models with binary separations of 3.6 au to 50.4 au and $M_{\text{prim}}/M_{\text{comp}} = 0.75\text{--}6$ in their hydrodynamic simulations, but only the models up to 12 au were able to form bipolar or elliptical CSEs (see Table 2 of Mastrodemos & Morris 1999). The density contrast between the mass-accretion rate of the secondary and the mass-loss rate of the primary thereby defines the degree of focusing of the stellar wind and can be estimated after Morris (1990) as

$$\alpha_{\text{foc}} \equiv \frac{\dot{M}_{\text{acc}}}{\dot{M}_{\text{prim}}} = \left(\frac{GM_{\text{comp}}}{d} \right)^2 \frac{1}{v_w^2} \left(v_w^2 + \frac{G(M_{\text{comp}} + M_{\text{prim}})}{d} \right)^{-3/2}. \quad (3)$$

Assuming $M_{\text{prim}} = 1.5 M_{\odot}$, $M_{\text{comp}} = 1.0 M_{\odot}$, $v_{\text{wind}} = 14.5 \text{ km s}^{-1}$, and $d = 460$ au, the focusing ratio is $\alpha_{\text{foc}} = 8 \times 10^{-5}$. According to Han et al. (1995), strong and mild focusing is expressed by $\alpha_{\text{foc}} > 0.1$, which is more than three orders of magnitude higher than the value found for the π^1 Gru+G0V system. The shaping agent of the elliptical CSE observed by CO and dust emission might therefore be another object that is located much closer to the AGB star than the G0V companion. This hypothesis was first expressed by Chiu et al. (2006) and is discussed here in Sect. 5.3.

If the elliptical emission is indeed an inclined disc that is not located in the orbital plane of the G0V companion, the question arises whether the mass accreted by the star is large enough to form the arc. Given the large system separation of more than 460 au, the accretion rate on the companion is very low, even if the stellar AGB wind expands isotropically. The focusing ratio $\alpha_{\text{foc}} = 8 \times 10^{-5}$ is a factor of four lower than the lowest value simulated by Mastrodemos & Morris (1999) in their model M9. But even at this low rate, a spiral pattern is forming. Nevertheless, the accretion rate of the G0V star is surely enhanced when the star moves through the disc, that is, in the region where the orbital plane and the disc intersect. Unfortunately, the orbital parameters are unknown because of the long period of the G0V companion.

Another interpretation of the CSE ellipticity is that it represents a deformed asterosphere caused by the stellar wind interacting with the ISM. Ueta et al. (2006), Jorissen et al. (2011), and Cox et al. (2012) showed that fast-moving AGB stars can alter the wind bubble and produce a bow shock in the direction of the space motion at the interface of the wind and the ISM. For stars with a low space velocity, the CSE appears elliptical (Weaver et al. 1977). Adopting the long time-scale proper motion from the Tycho-2 catalogue (see Table 2), the direction of the space motion is at $\text{PA} = 103.1^\circ \pm 4.0^\circ$, which means that it is aligned with the major axis at $\text{PA} \approx 105^\circ$. However, the velocity of the space motion is only $15.0 \pm 2.8 \text{ km s}^{-1}$, which is comparatively low to cause the elongation. Cox et al. (2012) nevertheless showed that even stars with a space velocity similar to π^1 Gru are able to form bow shocks (R Leo and UU Aur). The presence of the arc in the direction of the space motion, however,

Table 2. Kinematic data of π^1 Gru from the HIPPARCOS (van Leeuwen 2007) and Tycho-2 (Høg et al. 2000) catalogues.

	HIPPARCOS	Tycho-2
μ_{α^*} (mas/yr)	28.48 ± 0.94	33.4 ± 1.1
μ_{δ} (mas/yr)	-12.14 ± 0.60	-17.7 ± 1.2
v_{LSR} (km s $^{-1}$)	11.7 ± 2.5	15.0 ± 2.8
i ($^\circ$)	-40.4 ± 15.0	-30.4 ± 13.2
PA ($^\circ$)	81.3 ± 2.9	103.1 ± 4.0

Notes. v_{LSR} is the velocity of the star corrected for the solar motion, i and PA the inclination to the sky plane and position angle of the space motion. The parallax $\varpi = 6.13 \pm 0.76$ mas from van Leeuwen (2007), the radial velocity $V_r = -5.7 \pm 1.5 \text{ km s}^{-1}$ from Van Eck et al. (2000), and the solar motion vector $(U, V, W)_{\odot} = (8.50 \pm 0.29, 13.38 \pm 0.43, 6.49 \pm 0.26)$ from Coşkunoğlu et al. (2011) were used to derive v_{LSR} , i , and PA.

diminishes the possibility that the elliptical emission is shaped by the oncoming ISM.

5.3. A hidden companion in the π^1 Gruis system?

As shown above, the elliptical emission around π^1 Gru cannot be shaped by the G0V companion given its distance and mass. Therefore, an object closer to the star might focus the primary wind on the orbital plane, making π^1 Gru a hierarchical triple system. Interestingly, Chiu et al. (2006) found a central cavity with a radius of 200 au ($1''.2$) in their CO map. The authors note that it is large enough to host a putative close companion, but not the G0V companion orbiting the S star at an angular distance of $2''.8$. In the following sections, we discuss further indications for a second companion from astrometric and interferometric observations.

5.3.1. $\Delta\mu$ behaviour and the HIPPARCOS Intermediate Astrometric Data

π^1 Gru is found to be a $\Delta\mu$ binary (Makarov & Kaplan 2005; Frankowski et al. 2007), meaning that its long-term proper motion (Tycho-2; Høg et al. 2000) is different from its short-term proper motion (HIPPARCOS; van Leeuwen 2007), because the latter is altered by the orbital motion while the orbital motion averages out on the long-term proper motion (see Table 2 and also Appendix A.1).

In the following we investigate whether the $\Delta\mu$ binary nature of π^1 Gru can be caused by the G0V companion separated by more than 460 au. The observed proper motion discrepancy is derived as

$$\Delta\mu = \left[(\mu_{\alpha^*}(\text{HIP}) - \mu_{\alpha^*}(\text{TYC2}))^2 + (\mu_{\delta}(\text{HIP}) - \mu_{\delta}(\text{TYC2}))^2 \right]^{1/2} = 7.4 \pm 1.4 \text{ mas yr}^{-1}. \quad (4)$$

Frankowski et al. (2007) have shown, thanks to a comparison with known spectroscopic binaries from the *Ninth Catalogue of Spectroscopic Binary Orbits* (SB_9 ; Pourbaix et al. 2004), that the binaries detectable by the $\Delta\mu$ approach must have orbital periods in the range of 1500 to 30 000 days. This already implies that the G0V companion with an orbital period of $\approx 2.2 \times 10^6$ days can hardly account for the proper motion variation. For a more detailed analysis, Makarov & Kaplan (2005) showed that $\Delta\mu$ is related to the orbital parameters in the following way:

$$\Delta\mu \leq \frac{2\pi\varpi R_0 M_2}{(M_1 + M_2)^{2/3} P^{1/3}}, \quad (5)$$

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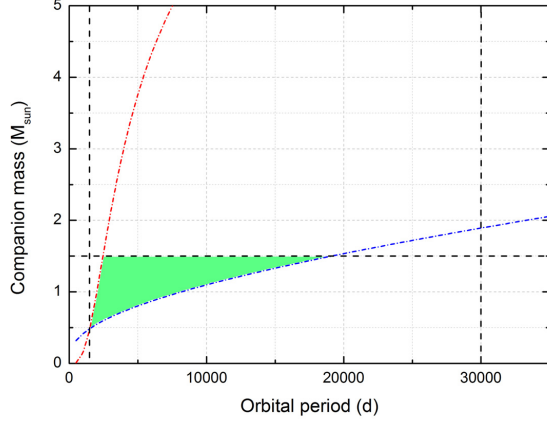


Fig. 6. Constraints on the orbital period and the companion mass M_2 set by the $\Delta\mu$ criterion (Eq. (7); above the blue line) and by the Roche lobe criterion (Eq. (10); below the red line) adopting a stellar radius of $420 R_\odot$ and a primary mass of $1.5 M_\odot$. The latter condition imposes the companion to be less massive than $1.5 M_\odot$ (below the dashed horizontal line). The ability to detect a $\Delta\mu$ binary moreover imposes $1500 < P(\text{days}) < 30\,000$ (between both vertical dashed lines). The admissible region is enclosed within these boundaries (green area).

where M_1 and M_2 are the primary and secondary masses, ϖ is the parallax, P is the orbital period, and R_0 is a time-dependent orbital phase term,

$$R_0 = \left(\frac{1 + e \cos E}{1 - e \cos E} \right)^{1/2}, \quad (6)$$

where e is the orbital eccentricity and E the eccentric anomaly. In the following, $R_0 = 1$ is assumed, equivalent to a circular orbit.

The equality in Eq. (5) corresponds to an orbit seen face-on, thus all our estimations in the remainder of this section correspond to lower bounds. With $\varpi = 6.13$ mas (van Leeuwen 2007) and $\Delta\mu = 7.4$ mas yr⁻¹, Eq. (5) yields

$$0.192 P^{1/3} \leq \frac{M_2}{(M_1 + M_2)^{2/3}}. \quad (7)$$

Another constraint on the orbital period comes from the Roche lobe radius R_1 (Paczynski 1971). Since π^1 Gru appears to be close to the tip of the AGB (Van Eck et al. 1998, and Sect. 2), its large radius limits the admissible orbital separation and period

$$R_1 \leq a \left(0.38 + 0.2 \log \frac{M_1}{M_2} \right). \quad (8)$$

By substituting a from the third Kepler law

$$P^2 = \frac{4\pi^2}{G(M_1 + M_2)} a^3, \quad (9)$$

one obtains

$$R_1 \leq P^{2/3} \left(\frac{G(M_1 + M_2)}{4\pi^2} \right)^{1/3} \left(0.38 + 0.2 \log \frac{M_1}{M_2} \right), \quad (10)$$

where G is the gravitational constant. Equations (7) and (10) allow us to restrict the range of possible values for P and M_2 (Fig. 6) if we adopt $420 R_\odot$ for the radius of π^1 Gru (12 mas

Table 3. Possible orbital solutions obtained from the analysis of the 55 HIPPARCOS Intermediate Astrometric Data of π^1 Gru (HIP 110478), by scanning a $P - e$ grid.

e	P (yr)	χ^2	$F2$	ϖ (mas)	$\mu_{\alpha*}$ (mas yr ⁻¹)	μ_δ (mas yr ⁻¹)
0.5	8.3	60.45	1.74	6.55	26.1	-19.1
0.5	4.6	59.28	1.64	6.53	26.4	-16.4
0.7	4.6	56.74	1.42	6.55	27.3	-17.8
0.9	9.7	55.66	1.32	6.55	34.3	-21.9
0.9	4.6	54.01	1.17	6.66	28.9	-17.9
0.9	6.3	53.18	1.09	6.68	31.2	-18.8

Notes. $F2$ is the goodness-of-fit, as defined by Eq. (11).

at 163 pc) as derived by Cruzalèbes & Sacuto (2006) from VLTI/MIDI observations, and $M_1 = 1.5 M_\odot$ for the primary mass from its location in the Hertzsprung-Russell diagram (Van Eck et al. 1998). Figure 6 presents these constraints in graphical form.

We thus conclude from this simple analysis that the G0V companion separated by at least 460 au with an orbital period of several thousand years cannot be the cause of the $\Delta\mu$ binary. A close second companion is required instead. An analysis of the HIPPARCOS IAD was performed along the method outlined by Pourbaix & Jorissen (2000)⁴ and especially by Jorissen (2004), to search for the possible presence of a close binary companion in the HIPPARCOS IAD *without any a priori knowledge of the orbital elements*. Basically, the routine scans a grid in eccentricity – period and searches for the best possible solution (in terms of χ^2 value) by including orbital motion at each grid point. Satisfactory solutions (i.e., with χ^2 in the range of 53 to 60, because 55 data points are available, or goodness-of-fit⁵ values between 1.0 and 1.8) are obtained for eccentricities higher than 0.5 and orbital periods in the range of 5 to 11 yr. Although the available data do not allow to fully constrain the orbit, confidence in the orbital solutions obtained from the HIPPARCOS IAD is bolstered because the proper motion derived from the analysis of the HIPPARCOS data now agrees with the long-term Tycho-2 proper motion. Possible solutions are listed in Table 3. The orbital arc corresponding to the best fitting among these possible solutions (last entry in Table 3) is presented in Fig. 7. Moreover, the favoured orbital periods (4.6–9.7 yr, or 1680–3540 d) are in the range considered to be likely from the analysis of Eqs. (7) and (10) (4.1–52.3 yr). According to Fig. 6, periods as short as 4.6 yr are only marginally possible, but solutions with orbital periods around 6 yr or longer are perfectly admissible and imply masses for the companion in the range of 0.5 to 1.5 $M_\odot$ that would correspond to spectral types K9 to F3 on the main sequence.

A system similar to π^1 Gru + close companion was modelled by Mastrodemos & Morris (1999) in their models M10 (1 $M_\odot$ companion) and M17 (0.5 $M_\odot$ companion). The radius of the primary ($R_p = 452.4 R_\odot$) and the separation of the system

⁴ Except for the fact that the condition imposing a positive parallax has since been found to be inappropriate and has been lifted in recent applications of the Pourbaix & Jorissen (2000) method.

⁵ If χ^2 does follow a chi-square distribution with ν degrees of freedom, the goodness-of-fit follows a $N(0, 1)$ -distribution irrespective of ν (see e.g., Pasquato et al. 2011):

$$F2 = \sqrt{\frac{9\nu}{2}} \left[\sqrt{\frac{\chi^2}{\nu}} + \frac{2}{9\nu} - 1 \right]. \quad (11)$$

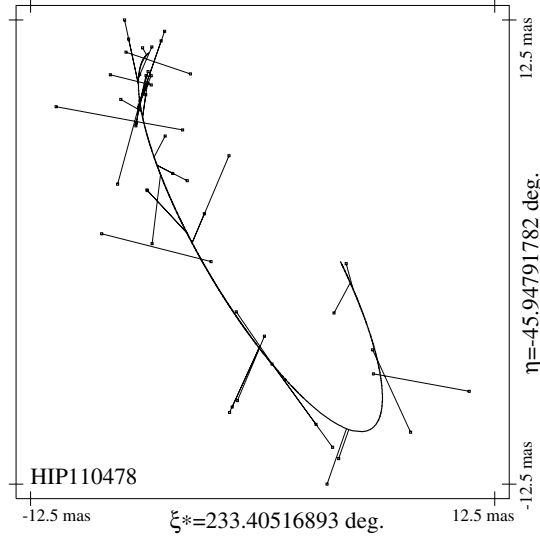


Fig. 7. Orbital arc derived from the analysis of the HIPPARCOS Intermediate Astrometric Data of π^1 Gru (see last entry in Table 3). The HIPPARCOS observations are 1D data, the bars therefore indicate the possible position of the photocentre perpendicular to the orbital segment.

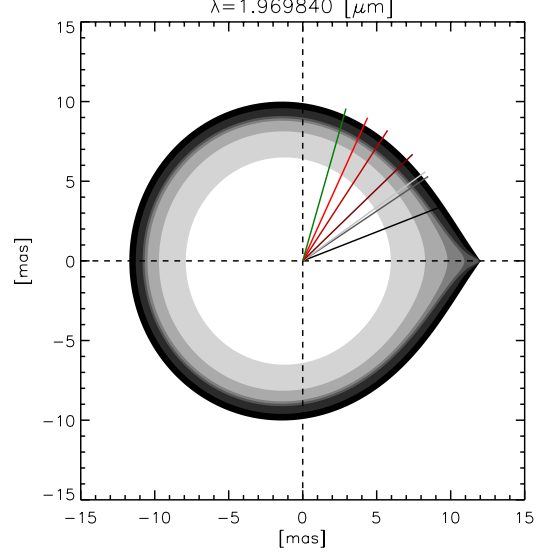


Fig. 8. Intensity map of the Roche lobe model for one of the AMBER low-resolution spectral channels. The lines represent the direction of the projected baselines used to simulate the interferometric data. Since the location of the close companion and the orientation of the orbital plane are unknown, the depicted Roche lobe orientation illustrates only one possible solution.

($a = 6.3$ au) are the same for both models and resemble the results obtained from interferometric observations (Sacuto et al. 2008) and the $\Delta\mu$ estimate above.

In model M10, the wind morphology is indeed collimated and oblate due to the gravitational force of the companion on the spherical wind of the AGB star. It is thus conceivable that a close $1 M_{\odot}$ companion is the cause for the disc observed in the CO and dust emission. A lower-mass companion, as in M17, however, prevents this behaviour and a well-defined spiral pattern occurs instead. The size of the spiral pattern can be evaluated with Eq. (1), and results in $\rho \approx 0''.2$ (≈ 33 au). This is much smaller than the $1''$ pixel size of the $70 \mu\text{m}$ PACS image, which does not allow us to favour either of the models.

5.3.2. Interferometric observations

The angular resolution of VLTI/AMBER is perfect to investigate the deformation of the envelope induced by a close secondary companion.

The usual first step for interpreting interferometric observations with limited uv -coverage, like the AMBER data presented here, is the comparison with geometric models. For this purpose we made use of the software GEM-FIND described by Klotz et al. (2012). It is sufficient here to report that none of the geometric toy models could fit the data in a satisfactory way. Given the presence of closure-phase signatures (i.e. asymmetric structures), 1D model atmospheres cannot reproduce the observations either. Therefore, we decided to switch to a more realistic physical model. The presence of a binary companion very close to the primary would trigger a tidal deformation of the primary star. If the primary is close to filling its Roche lobe (and this possibility is not excluded by the results presented in Sect. 5.3.1 since Roche lobe fitting giants are located along the left curve

of Fig. 6), the shape will resemble that of a pear, as shown in Fig. 8. This kind of geometry will produce a signature in the closure phase.

Siopis & Sadowski (2012) developed the software package *Gaia* Eclipsing System Simulator and Solver (GESSS) with the primary aim of modelling the light curve of eclipsing binaries for the *Gaia* survey. This tool is very flexible and can also be used to model other binary configurations. The code was recently adapted to extract interferometric observables (Paladini et al. 2014).

For our experiment, we used as starting point a MARCS model atmosphere (Gustafsson et al. 2008) with stellar parameters $T_{\text{eff}} = 3200$ K, $\log g = 0.3$, and solar metallicity. The *Gaia* eclipsing binary software identifies the stellar surface with Roche equipotentials, which are numerically computed for each component of the binary system using a dense mesh of points. This mesh defines a scalar field of intensities (calculated from the MARCS model that incorporates the limb darkening), which is then linearly interpolated to produce a synthetic 1020-by-1020-pixel image of the system. We produced a set of 27 intensity maps spread across the H and K bands, with the spectral resolution of AMBER ($R = 30$). This set of images was produced for two Roche lobe models, one with mass ratio $1/3$, and one with mass ratio 1 . As we do not know the orientation of the orbital plane, we assumed for simplification that for both models the companion is currently located at one of the orbital nodes, that is, at the intersection of the orbital plane with the plane of the sky. Thus, the Roche lobe is seen face-on. An example of the intensity maps in one of the AMBER low-resolution spectral channels is shown in Fig. 8.

The orientation of the π^1 Gru system on the sky with respect to the projected baselines is unknown. In principle, the

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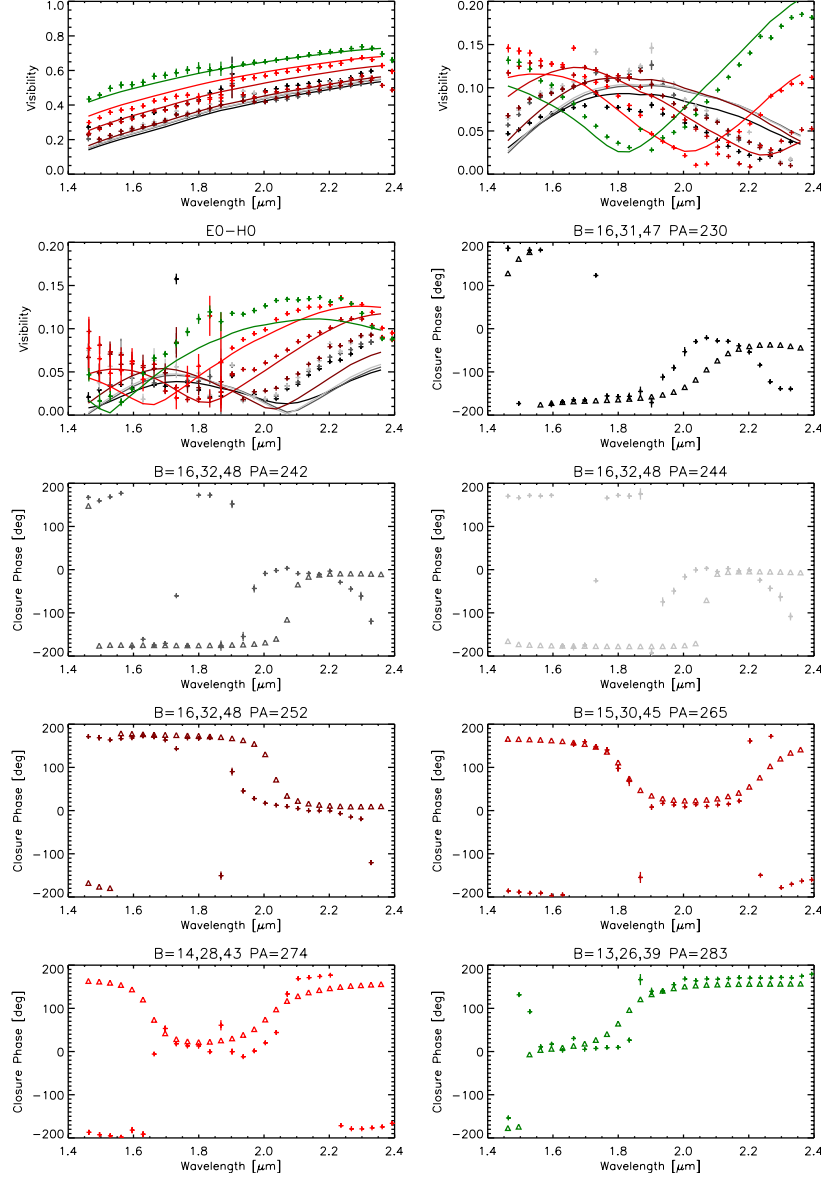


Fig. 9. Comparison between AMBER data (crosses) and the synthetic Roche lobe observations (full line for the *upper three panels*, triangles for the *others*; see Fig. 8). The *first three panels* depict the visibilities of the E0-G0-H0 configuration (see Table 1). The *other panels* show the closure phases produced by the triplet of baselines B at position angle PA.

full parameter space of azimuthal *and* polar angles describing the orientation of the system on the plane of the sky has to be explored. Together with the position angle of the baselines, similar images to that of Fig. 8 have to be generated for all these possible orientations to compute the corresponding visibilities and closure phases. This effort is beyond the scope of this paper, and we here restrict ourselves to showing that the Roche lobe model may yield closure-phase variations qualitatively similar to those observed. We chose the system orientation that yielded

the highest asymmetry (shown in Fig. 8), and searched for the baseline position angle that yielded closure phases that varied in the same way as the observations. Starting from a first baseline with a position angle of either -60 , -40 , 0 , 10 , 20 , or 30 degrees, we extracted visibilities and closure phases for the same baseline pattern as displayed in Fig. 3.

In Fig. 8, we show the orientation of the baseline pattern of Fig. 3 needed to obtain the model curves displayed in Fig. 9. These model curves should by no means be considered as best

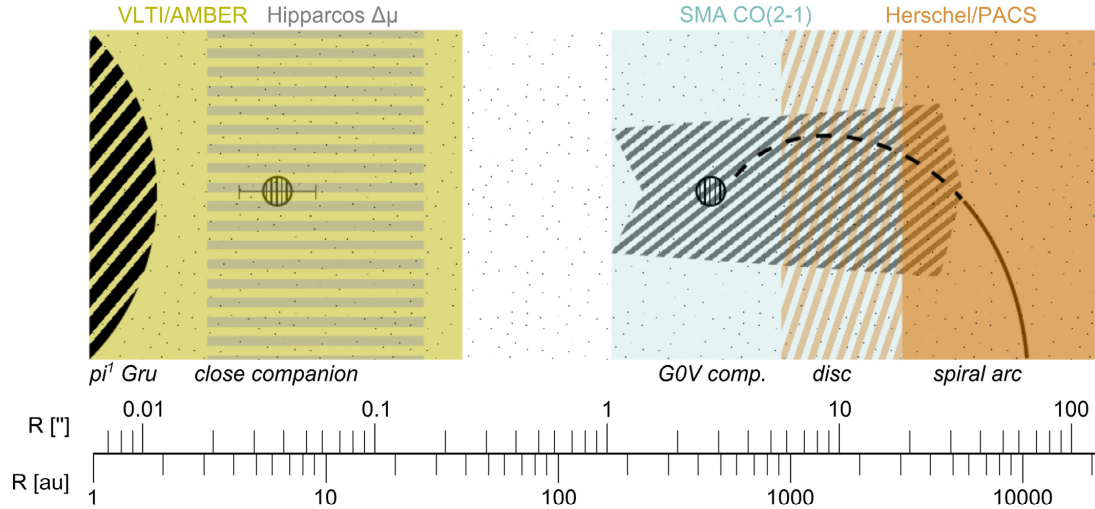


Fig. 10. Illustration of the surroundings of π^1 Gru including the close companion, the disc, the G0V companion, and the spiral arc. The coloured areas represent the field of view or detection range of the used instrument: olive represents the VLT/AMBER range, horizontal grey lines the HIPPARCOS $\Delta\mu$ constraint, light blue the SMA CO(2-1) observations, and dark orange the partly overlapping *Herschel*/PACS field of view.

fits, but they illustrate the good prospects offered by the Roche model. Nevertheless, it has to be kept in mind that not only the Roche lobe geometry can cause non-zero signatures in the closure phase, but so can stellar spots or flares (e.g.; [Chiavassa et al. 2010](#); [Wittkowski et al. 2011](#)).

The Roche lobe model suggests that a solution with the smallest orbital separation (red line in Fig. 6, corresponding to Roche lobe filling) is consistent with both the AMBER and HIPPARCOS data. The AMBER data do not allow us to unambiguously select one among the possible HIPPARCOS solutions (Table 3), but they offer confidence for the hypothesis of a close companion in the π^1 Gru system.

As a summary, the whole scenario including the close companion, the disc, the G0V companion, and the spiral arc are illustrated in Fig. 10. The coloured areas represent the field of view or detection range of the respective observing facility. The horizontal grey lines around the close companion indicate the range of acceptable orbital separations using the HIPPARCOS $\Delta\mu$ constraint. This is refined to the region indicated by the “error bar” which is based on the results from the HIPPARCOS IAD fitting (see Table 3).

6. Conclusions and summary

We have analysed the CSE of the highly evolved AGB star π^1 Gru based on *Herschel* observations at $70\ \mu\text{m}$ and $160\ \mu\text{m}$ as part of the MESS sample. The images show an asymmetric stellar wind morphology with two main features, namely an elliptical CSE and an arc east of the star. The arc emerges $38''$ away from the star along the major axis of the ellipse and is curved towards the north-east before it becomes too faint. The arc is most likely a small part of an Archimedean spiral caused by the interaction of the stellar AGB wind with a companion. π^1 Gru has a physically related G0V companion that has been known for over a century and is separated by $460\ \text{au}$ ($2''.8$) from the primary. We were able to fit the observations with a spiral given the properties of the G0V star. For a perfect match, however, the wind velocity

has to be adjusted to higher values, as was suggested by [Knapp et al. \(1999\)](#) to explain their CO observations.

The second far-IR feature, the elliptical CSE, stretches over $72'' \times 60''$ [$11\,750 \times 9\,790\ \text{au}$] and represents the dusty counterpart of CO emission with the same axis ratio, but it is slightly smaller ([Knapp et al. 1999](#); [Chiu et al. 2006](#); [Sahai 1992](#)). All of the authors interpreted their findings as a disc structure inclined by 35° to the plane of the sky, which is also supported by the axis ratio of the far-IR emission. In the CO map by [Chiu et al. \(2006\)](#) the disc has an inner radius of $1''.2$ and an outer radius of $\approx 20''$. Based on the focusing ratio, it can be ruled out that the known G0V companion focuses the AGB wind towards the orbital plane given the enormous separation of the system. Furthermore, the G0V companion would be orbiting within the disc without causing any observable disturbance. Because of this, we assumed that the disc is not located in the orbital plane of the G0V companion and followed the hypothesis of [Chiu et al. \(2006\)](#) that π^1 Gru may have a close second companion.

We found support for this assumption in several observations. π^1 Gru is a known $\Delta\mu$ binary, meaning that its long-term and short-term proper motions are significantly different ([Makarov & Kaplan 2005](#); [Frankowski et al. 2007](#)). An analysis of the HIPPARCOS ([van Leeuwen 2007](#)) and Tycho-2 ([Høg et al. 2000](#)) data eliminates the G0V companion as the source of disturbance and suggests a $0.5\text{--}1.5\ M_\odot$ companion with an orbital period in the range of $4\text{--}50\ \text{yr}$. This result is strengthened by the HIPPARCOS IAD, which reveal an orbital motion of the photocentre of π^1 Gru. This motion is best fitted by a highly eccentric orbit with a period of $4.6\text{--}9.7\ \text{yr}$. [Mastromaros & Morris \(1999\)](#) used this configuration in their hydrodynamic simulations where the companion was indeed able to focus the primary’s wind towards the orbital plane.

To obtain direct indications for the close companion we used archival data from VLT/AMBER that show closure-phase signatures. Although the interferometric observations can be qualitatively reproduced by a Roche lobe model, we cannot exclude

2.3. Large-scale environments of binary AGB stars - II.

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Table A.1. Positional data of π^1 Gru from various catalogues over the past century.

	SAO ⁽¹⁾	AC 2000.2 ⁽²⁾	PPM ⁽³⁾	YZC ⁽⁴⁾	CPC-2 ⁽⁵⁾	SHCB ⁽⁶⁾
Mean epoch of RA	1896	1903.7	1950.9	1961.8	1962.1	1974.6
Mean epoch of Dec	1890	1903.7	1951.0	1961.8	1962.1	1974.6
μ_{α^*} (mas yr ⁻¹)	9 ± 11	–	38.2 ± 4	39	38.6 ± 3	–
μ_{δ} (mas yr ⁻¹)	–7 ± 8	–	–17 ± 4	–22	–13 ± 3	–
RA at obs. epoch [°]	335.682791	335.682854	335.683458	335.683616	335.683791	335.684319
Error in RA [10 ⁻⁵ °]	5.833	7.056	2.5	–	1.361	6.111
Dec at obs. epoch [°]	–45.947583	–45.947530	–45.947752	–45.947802	–45.947802	–45.947926
Error in Dec [10 ⁻⁵ °]	5	2.694	2.5	–	1.778	5.556
	SPM4 ⁽⁷⁾	FOCAT-S ⁽⁸⁾	Tycho-2 ⁽⁹⁾	PPMXL ⁽¹⁰⁾	USNO-B ⁽¹¹⁾	
Mean epoch of RA [yr]	1983.3	1985.3	1991.4	1991.2	2000.0	
Mean epoch of Dec [yr]	1983.3	1985.3	1991.4	1991.2	2000.0	
μ_{α^*} [mas yr ⁻¹]	26.9 ± 4.8	32 ± 1	33.4 ± 1.1	35.3 ± 2	32	
μ_{δ} [mas yr ⁻¹]	–20.2 ± 4.3	–12 ± 4	–17.7 ± 1.2	–16.3 ± 2	–18	
RA at obs. epoch [°]	335.684025	335.684000	335.684094	335.684177	335.684203	
Error in RA [10 ⁻⁵ °]	1.183	5	0.111	0.056	–	
Dec at obs. epoch [°]	–45.947895	–45.947872	–45.947916	–45.947915	–45.947959	
Error in Dec [10 ⁻⁵ °]	1.025	6.667	0.111	0.056	–	

Notes. All positions are given in the J2000.0 system.

References. (1): Smithsonian Astrophysical Observatory Star Catalog (SAO Staff 1966); (2): The Astrographic Catalogue on the HIPPARCOS System (Urban et al. 2001); (3): Positions and Proper Motions – South (Bastian & Röser 1993); (4): Yale Zone Catalogues Integrated (Fallon 1983); (5): Cape Photographic Catalogue 2 (Nicholson et al. 1984); (6): Southern Hemisphere Catalogue of Bordeaux (Rousseau et al. 1996); (7): Yale/San Juan Southern Proper Motion Catalog 4 (Girard et al. 2011); (8): Pulkovo photographic Catalogue of Southern Hemisphere (Bystrov et al. 1994); (9): The Tycho-2 Catalogue of the 2.5 Million Brightest Stars (Høg et al. 2000); (10): The PPMXL catalog of positions and proper motions on the ICRS (Roesser et al. 2010); (11): The USNO-B Catalog (Monet et al. 2003).

that a more complex model including the presence of spots or flares will also be able to reproduce these observations. The main restriction comes from the uv -plane coverage. A VLTI/PIONIER imaging programme would probably help to break the degeneracy in the currently available data. Based on the current observational status, π^1 Gru is most likely a hierarchical triple system in which the close companion shapes the disc observed in CO and dust emission, while the (previously known) GOV companion is located farther outside and causes the spiral arc visible in the *Herschel*/PACS images.

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Appendix A: Positional data

A.1. π^1 Gru

The difference between the long- and short-term proper motions is illustrated in Fig. A.1, which shows the positions of π^1 Gru in the last 100 years from various catalogues (see Table A.1 for a list of these catalogue positions). The position at the observation epoch of a given catalogue, if not directly given by the *VizieR* database at the *Centre de Données Stellaires* (Strasbourg),

⁶ Available at <http://www.jmmc.fr/amberdr3>

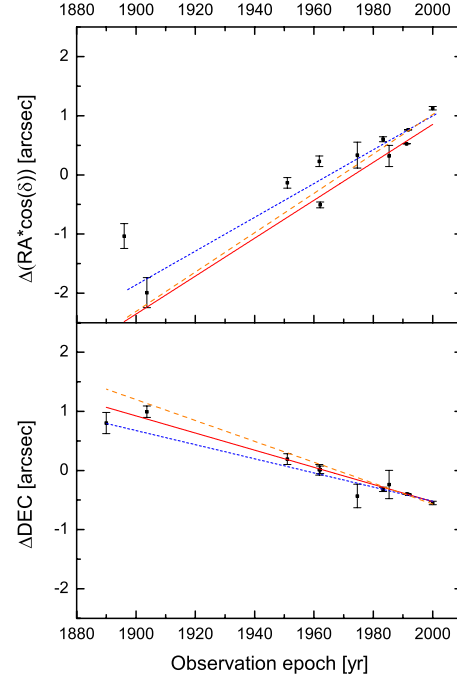


Fig. A.1. Positions of π^1 Gru from catalogues spanning more than 100 years. The solid red line corresponds to a linear fit through the positions, weighted by the inverse square of the position uncertainties. The dashed blue line shows the positions extrapolated according to the HIPPARCOS proper motion, while the dashed orange line represents the same for the Tycho-2 proper motion.

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Table A.2. Separations and position angles of the G0V companion of π^1 Gru, from the Washington Double Star Observations catalogue (courtesy of B. Mason).

Obs. Epoch (yr)	PA ($^\circ$)	d ($''$)	Reference
1896.8	190	2.5	Innes (1897)
1900.75	201.6	3.04	Innes (1905)
1900.76	201.4	2.70	Lunt (1908)
1912.63	201.4	2.27	Innes (1914)
1926.02	200.6	2.74	van den Bos (1928)
1929.02	200.4	2.78	Rossiter (1955)
1936.74	201.2	2.75	van den Bos (1938)
1943.49	202.1	2.71	Voûte (1955)
1956.446	200.83	2.831	The (1975)
1960.80	202.8	2.63	van den Bos (1961)
1966.81	201.0	2.82	Knipe (1969)
1975.722	201.0	2.79	Worley (1978)
1989.86	200.4	2.45	Sahai (1992)
2003.47	203.1	2.82	HST (PI: Sahai)

has been derived by applying the catalogue proper motion to the listed J2000 epoch position. Care has been exercised to ensure consistency between the equinox of the proper motion and the position. Our own estimate for the proper motion is obtained from a linear fit on all these positions, weighted by the inverse square of the uncertainty on the position.

The resulting space velocity v_{LSR} (corrected for the solar motion vector $(U, V, W)_\odot = (8.50 \pm 0.29, 13.38 \pm 0.43, 6.49 \pm 0.26)$; Coşkunoğlu et al. 2011) based on these proper motions and the radial velocity derived by Van Eck et al. (2000) is listed in Table 2. Since the long-term Tycho-2 proper motion appears slightly more precise than the one we derived from the positions displayed in Fig. A.1, the Tycho-2 proper motion is adopted in the remainder of this paper.

A.2. G0V companion

Table A.2 shows the separations and position angles of the G0V companion. The observations do not show significant changes of the companion's position over a timespan of more than 100 years. However, in 1989.86, the system was observed by Sahai (1992), who reported the position of the companion with a projected separation of $2''.45$ at $\text{PA} = 200.4^\circ$, clearly different from previous observations. The author remarks that such a fast motion for an object located at least 460 au away from the primary would imply unrealistically large stellar masses. Moreover, given the large uncertainties induced by the $0''.9$ seeing that prevailed during the observations, no reliable conclusions regarding the orbital period could be drawn by Sahai (1992).

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2.4. Publications as co-author

2.4.1. A far-infrared survey of bow shocks and detached shells around AGB stars and red supergiants

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Abstract

Aims. Our goal is to study the different morphologies associated to the interaction of the stellar winds of AGB stars and red super-giants with the interstellar medium (ISM) to follow the fate of the circumstellar matter injected into the interstellar medium.

Methods. Far-infrared Herschel/PACS images at 70 and 160 μm of a sample of 78 Galactic evolved stars are used to study the (dust) emission structures developing out of stellar wind-ISM interaction. In addition, two-fluid hydrodynamical simulations of the coupled gas and dust in wind-ISM interactions are used for comparison with the observations.

Results. Four distinct classes of wind-ISM interaction (i.e. fermate, eyes, irregular, and rings) are identified, and basic parameters affecting the morphology are discussed. We detect bow shocks for $\approx 40\%$ of the sample and detached rings for $\approx 20\%$. The total dust and gas mass inferred from the observed infrared emission is similar to the stellar mass loss over a period of a few thousand years, while in most cases it is less than the total ISM mass potentially swept-up by the wind-ISM interaction. De-projected stand-off distances (R_0) defined as the distance between the central star and the nearest point of the interaction region of the detected bowshocks (fermata and eyes) are derived from the PACS images and compared to previous results, model predictions, and the simulations. All observed bow shocks have stand-off distances smaller than 1 pc. Observed and theoretical stand-off distances are used together to independently derive the local ISM density.

Conclusions. Both theoretical (analytical) models and hydrodynamical simulations give stand-off distances for adopted stellar properties that are in good agreement with the measured de-projected stand-off distance of wind-ISM bow shocks. The possible detection of a bow shock for the distance-limited sample appears to be governed by its physical size as set roughly by the stand-off distance. In particular the stars peculiar space velocity and the density of the ISM appear decisive in detecting emission from bow shocks or detached rings. In most cases the derived ISM densities concur with those typical of the warm neutral and ionised gas in the Galaxy, though some cases point towards the presence of cold diffuse clouds. Tentatively, the eyes class objects are associated to (visual) binaries, while the rings generally do not appear to occur for M-type stars, only for C or S-type objects that have experienced a thermal pulse.

2.4.2. Dusty shells surrounding the carbon variables S Scuti and RT Capricorni

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Abstract

For the Mass-loss of Evolved StarS (MESS) programme, the unprecedented spatial resolution of the PACS photometer on board the Herschel Space Observatory was employed to map the dusty environments of asymptotic giant branch (AGB) and red supergiant (RSG) stars. Among the morphologically heterogeneous sample, a small fraction of targets is enclosed by spherically symmetric detached envelopes. Based on observations in the $70\,\mu\text{m}$ and $160\,\mu\text{m}$ wavelength bands, we investigated the surroundings of the two carbon semiregular variables S Sct and RT Cap, which both show evidence for a history of highly variable mass-loss. S Sct exhibits a bright, spherically symmetric detached shell, $138''$ in diameter and co-spatial with an already known CO structure. Moreover, weak emission is detected at the outskirts, where the morphology seems indicative of a mild shaping by interaction of the wind with the interstellar medium, which is also supported by the stellar space motion. Two shells are found around RT Cap that were not known so far in either dust emission or from molecular line observations. The inner shell with a diameter of $188''$ shows an almost immaculate spherical symmetry, while the outer $\approx 5'$ structure is more irregularly shaped. *MoD*, a modification of the DUSTY radiative transfer code, was used to model the detached shells. Dust temperatures, shell dust masses, and mass-loss rates are derived for both targets.

2.4.3. Improving Herschel imaging datasets

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Abstract

The Herschel Space Observatory enabled a deep and detailed look into the far-infrared universe and even though the mission ended in May 2013, the rich archive is full of data to be analysed. The Herschel data reduction pipelines have progressed to give good results for most types of observations, but for other, more specialized programs, improved image reconstruction tools and methods need to be applied to fully exploit the telescope's unique sensitivity and spatial resolution. This is the case for post-main-sequence objects observed with Herschel/PACS as part of the MESS sample. Here, the standard pipeline as well as most map-makers cannot handle the bright central source surrounded by faint dust emission well. We compare the six standard map-making tools for Herschel observations and show how an improved astrometry can produce better maps. Our data processing steps can be applied to the standard pipeline as well as to external mappers based on inverse techniques.

2.4.4. The wonderful complexity of the Mira AB system

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Abstract

We have mapped the $^{12}\text{CO}(3-2)$ line emission around the Mira AB system at $0.5''$ resolution using the Atacama Large Millimeter/submillimeter Array (ALMA). The CO map shows amazing complexity. The circumstellar gas has been shaped by different dynamical actors during the evolution of the system and several morphological components can be identified. The companion is marginally resolved in continuum emission and is currently at $0.487'' \pm 0.006''$

separation. In the main line component, centered on the stellar velocity, spiral arcs around Mira A are found. The spiral appears to be relatively flat and oriented in the orbital plane. An accretion wake behind the companion is clearly visible and the projected arc separation is of order $5''$. In the blue wing of the line emission, offset from the main line, several large ($\approx 5 - 10''$), opposing arcs are found. We tentatively suggest that this structure is created by the wind of Mira B blowing a bubble in the expanding envelope of Mira A.

2.4.5. Dissecting the AGB star L₂ Puppis: a torus in the making

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Astronomy & Astrophysics, in press

Abstract

Aims. The circumstellar environment of L₂ Pup, an oxygen-rich semiregular variable, was observed in order to understand the evolution of mass loss and the shaping of ejecta in the late stages of stellar evolution.

Methods. High-angular resolution observations from a single 8 m telescope were obtained with the use of aperture masking in the near-infrared (1.64, 2.30 and 3.74 μm) on the NACO/VLT, both in imaging and polarimetric modes.

Results. The aperture-masking images of L₂ Pup at 2.30 μm show a resolved structure which resembles a toroidal structure, with a major axis of ≈ 140 milliarcseconds (mas) and an east-west orientation. Two clumps can be seen on either side of the star, ≈ 65 mas from the star, beyond the edge of the circumstellar envelope (estimated diameter is ≈ 27 mas), while a faint, hooklike structure appear towards the north-east. The patterns are visible both in the imaging and polarimetric mode (Stokes I). The overall shape of the structure is similar at the 3.74 μm pseudo-continuum (dust emission), where the clumps appear to be embedded within a dark, dusty lane. The faint, hook-like patterns are also seen at this wavelength, extending north-east and south-west with the central, dark lane being an apparent axis of symmetry. We interpret the structure as circumstellar torus with inner radius of 4.2 au. With a rotation velocity of 10 km,s⁻¹ as suggested by the SiO maser profile, we estimate a stellar mass of 0.7 $M_{\odot}$.

Conclusion & Outlook

The previous chapter demonstrated that far-IR observations of binary induced wind morphologies are possible when high sensitivity and resolution are provided. The *Herschel* observations proved that this phenomenon is common among binary AGB stars. Nevertheless, there is still a lack of observations in this field, especially for close binary systems, which evolve through a CE phase and are thought to be the progenitors for asymmetric PNe. These systems are extremely difficult to observe and so far this undertaking was unsuccessful. The wide binaries most likely do not cause any asymmetries in subsequent phases, since the ejection of the envelope at the end of the AGB phase decrease the angular momentum of these systems. To connect the PNe with the AGB phase one has to look at those close binaries.

However, even for wide systems the identification of binary interaction features is not easy as shown for R Aqr, W Aql, and π^1 Gru since the resulting wind morphology can be very diverse, depending on the separation of the system and stellar type of the companion (Mayer et al. 2011, 2013, 2014). It also seems that the AGB wind is often shaped by other interactions, too. Examples are R Scl, that additionally shows a detached shell from a TP and ISM interaction (Maercker et al. 2012), or Mira and CIT 6 which have a spiral embedded in a bow shock (Martin et al. 2007; Mayer et al. 2011; Dinh-V.-Trung & Lim 2009; Sahai & Mack-Crane 2014).

The general view of an AGB wind bubble that expands spherically for all times is antiquated: single stars interact with the ISM or show TP related detached shells and in multiple systems the interaction with a companion adds to the afore mentioned. The diverse wind shapes are one of the important legacies of the *Herschel* mission in the AGB research field.

However, with the end of the *Herschel* mission in 2013 the far-IR regime will not be explored further in the coming decade (with a small exception, namely the Stratospheric Observatory for Infrared Astronomy (SOFIA)). A possible successor for *Herschel* is the SPace Infrared telescope for Cosmology

and Astrophysics (SPICA), a candidate mission of ESA’s Cosmic Vision plan led by the Japanese Aerospace Exploration Agency (JAXA). SPICA possesses three imaging instruments covering $0.7\text{--}210\ \mu\text{m}$ and might be launched around 2025.

Until then, the future of this research field belongs to ground based observations at other wavelengths. Maercker et al. (2012), Ramstedt et al. (2014), Decin et al. (2015), Cernicharo et al. (2014), and Claussen et al. (2011) have shown that ALMA, IRAM, and VLA are capable to detect the spiral imprints of a companion in the sub-mm molecular emission of AGB winds. Especially the performance of ALMA is auspicious for future studies considering that the remarkable observation of R Scl by Maercker et al. (2012) was done with a restricted instrument setup of only 16 out of 66 antennas which are now available. One of the big advantages of tracing the molecular emission is that it provides kinematic information which is missing when observing thermal dust emission. This fact even boosts the importance to use ALMA, IRAM, and VLA for future studies.

Another facility to study large-scale structures is the VLT Spectro-Polarimetric High-contrast Exoplanet REsearch (SPHERE) mounted at UT3, which just has finished the science verification phase. Operating at $0.95 - 2.32\ \mu\text{m}$, the instrument offers classical imaging, polarization imaging, and spectroscopy (low and medium resolution). As a benchmark, R Scl was observed during the science verification and results of this project are eagerly awaited (Maercker et al., in prep.).

IR interferometric observations of the primary star are another important way for future studies. The Precision Integrated-Optics Near-infrared Imaging Experiment (PIONIER) instrument mounted at the VLTI, observing in the H band and open to the community since P93 offers is able to detect a companion within 30 mas from the primary or study the tidal deformation of the AGB star. This task will be taken over by VLTI/Gravity in the near future, which will provide high accuracy astrometry of order 10 microarcsecond in the K band. With such a precision it will be possible to study the motions in binary system. Further ahead, the successor of the VLTI instrument AMBER, the Multi-AperTure mid-Infrared SpectroScopic Experiment (MATISSE, estimated 2017), working in the L , M , and N band, will bring image reconstruction to a new level. These facilities will probably start to dissolve the barrier to study also closer binary systems. Maybe not yet building the bridge between AGB and PNe but approaching the cliff.

During this PhD project, two observing proposals as principal investigator (PI) using ALMA were submitted for further ground-based observations of θ Aps, EP Aqr, and RZ Sgr during the PhD. The *Herschel*/PACS images of

θ Aps and EP Aqr reveal bow shocks with possible embedded bipolar outflows which seem to push against the ISM border (see Section 3.1.1 and 3.1.2). This would imply an interaction of two shock fronts for which ALMA observations could provide important kinematic data. Even more mysterious is the CSE of RZ Sgr which is dominated by a ring with a surrounding bipolar structure. This morphology is an indication for binary interaction but both structures have an immense size. Interestingly, none of the three objects has a known companion. The proposals were ranked in the 40–70 % band of all submitted proposals and the observations were therefore not carried out.

Another proposal was more successful and two nights were granted with VLTI/PIONIER in September 2014 (PI: A. Mayer, see Appendix A.6). These observations are a follow-up study of π^1 Gru to image the (probably distorted) AGB star. The aim is to provide the first map of the circumstellar environment of π^1 Gru within 50 mas from the target. In combination with VLT/AMBER and the Hipparcos IAD, the obtained data will hopefully set limits to the orbital parameters of the close companion. A publication on the results of the VLTI/PIONIER observations is in preparation (Mayer et al., in prep.).

However, also the *Herschel* observations and especially the MESS sample are not fully exploited. As shown in Section 2.2, the MESS sample contains 18 known binary systems of which only α Cet, R Aqr, W Aql, π^1 Gru, and IRC +10 216 have been studied in detail. The remaining binary systems need further attention in the future. Especially θ Aps and EP Aqr, the two most nearby systems, show CSEs that are very unusual in certain aspects and thus are predestined for a future investigation. However, kinematic information are needed to proceed with this study, which means that the *Herschel* data ought to be combined with observations at other wavelengths.

In the following section the remaining binary objects of the MESS sample are briefly introduced together with a discussion of their far-IR morphologies.

3.1. Remaining binary objects of the MESS sample

3.1.1. θ Apodis

θ Aps is an SRb variable star of spectral type M6.5III (Houk & Cowley 1975) with periods of 100.9 and 111.0 days (Tabur et al. 2009), and a longer period of ≈ 1200 d (Moon 2008). With the star's location of only 113 pc away from the sun ($\varpi = 8.84 \pm 0.49$ mas, van Leeuwen 2007) it is one of the closest AGB stars in the MESS sample. An effective temperature $T_{\text{eff}} = 2800$ K was obtained from SED fitting by Heras & Honý (2005) who also determined a MLR $\dot{M} = 2.9 \times 10^{-7} M_{\odot} \text{yr}^{-1}$. Olofsson et al. (2002) modelled the circumstellar CO radio line emission of θ Aps and found it to fit best with slightly lower values of $T_{\text{eff}} = 2620$ K and $\dot{M} = 4 \times 10^{-8} M_{\odot} \text{yr}^{-1}$. In addition, the authors derived a wind velocity $v_w = 4.5 \text{ km s}^{-1}$. Recently, Ohnaka (2014) modelled the high resolution spectrum obtained with the VLT Imager and Spectrometer for mid Infrared (VISIR) and obtained $T_{\text{eff}} = 2850 \pm 160$ K, $\log g = -0.3 \pm 0.1$, $L = 3050 \pm 460 L_{\odot}$, and $M = 1.0 \pm 0.3 M_{\odot}$.

Dumm & Schild (1998) determined the radius $R = 196 R_{\odot}$ and mass $M = 1.9 M_{\odot}$ of θ Aps from the relation between the visual surface brightness parameter and the Cousins ($V - I$) colour index. However, the star's evolutionary stage on the AGB is not known since the stellar photosphere shows no signs of the s-process element technetium (Lebzelter & Hron 1999).

An Hipparcos and Tycho-2 proper motion analysis reveals that θ Aps is most probably part of a binary system (Pourbaix et al. 2003; Makarov & Kaplan 2005; Eggleton & Tokovinin 2008). Other indications for the binarity (e.g., composite spectrum, CO line profile, UV excess) are not found so far.

Herschel far-IR observations

The *Herschel* far-IR images (see Fig. 3.1) suggest that the surroundings of θ Aps are strongly dominated by the interaction of the stellar wind with the ISM. A bow shock is visible at $70 \mu\text{m}$ with a stand-off distance $R_0 \approx 65''$ at P.A. = 300° . At $160 \mu\text{m}$ the bow shock suffers from the lower resolution but remains recognizable. The object was therefore described as a bow shock object by Cox et al. (2012).

Although the shape of the far-IR emission is doubtless dominated by the ISM interaction, the star comes up with some surprises. For instance, the direction of the space motion does not fit to the orientation of the bow shock cone. According to the new Hipparcos reduction (van Leeuwen 2007) the proper

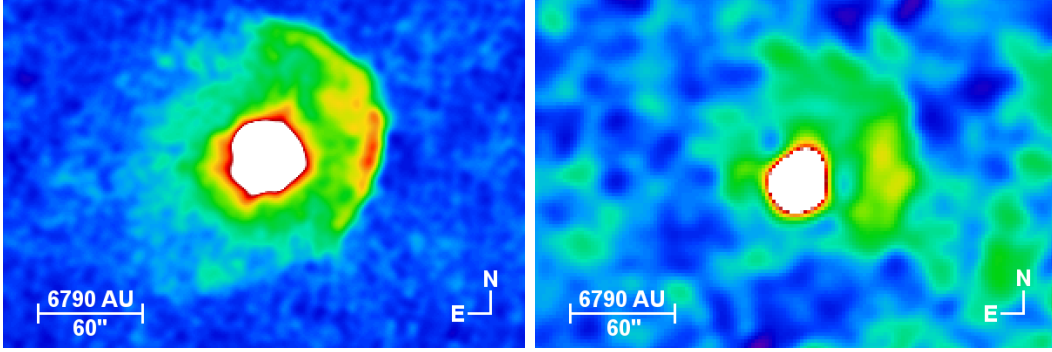


Figure 3.1.: Deconvolved PACS images of θ Aps at $70\mu\text{m}$ (left) and $160\mu\text{m}$ (right).

motion of θ Aps is $\mu_{\alpha*} = -87.54 \pm 0.43 \text{ mas yr}^{-1}$ and $\mu_{\delta} = -32.54 \pm 1.5 \text{ mas yr}^{-1}$ for right ascension (RA) and declination (DEC), respectively. Adopting $10.2 \pm 0.5 \text{ km s}^{-1}$ for the RV (Anderson & Francis 2012) and following the scheme of Johnson & Soderblom (1987), the space velocity is $35.4 \pm 1.9 \text{ km s}^{-1}$, inclined by $5.3 \pm 8.8^\circ$ along $\text{P.A.} = 256.3 \pm 0.4^\circ$. The direction of motion is thus offset from the bow shock orientation by more than 40° .

Therefore, the positions of the star were retrieved from various catalogues spanning observations over the last century, similar to the work done for W Aql and π^1 Gru. Table 3.1 gives the positions from these catalogues and Fig. 3.2 shows a weighted fit through the data points in RA and DEC. The fitted proper motion is $\mu_{\alpha*} = -89.2 \pm 3.8 \text{ mas yr}^{-1}$ and $\mu_{\delta} = -37.4 \pm 1.5 \text{ mas yr}^{-1}$ with a resulting space motion of $36.9 \pm 2.4 \text{ km s}^{-1}$ along a $\text{P.A.} = 252.7 \pm 1.2^\circ$. The direction of the motion is thus similar to the one inferred from the Hipparcos data and the offset between proper motion and bow shock cone seems not to be caused by a close companion which alters the proper motion on short time-scales. The origin of this discrepancy remains unknown.

Another feature that is easily overlooked by the strength of the bow shock on the $70\mu\text{m}$ image are two opposing lobes, SE and NW of the star, almost perpendicular to the direction of the space motion. Figure 3.3 depicts the different features on the PACS $70\mu\text{m}$ image. The southern lobe is well visible as a density enhancement and located about $73''$ away from the star at $\text{P.A.} \approx 155^\circ$. The most extended part of the lobe has the shape of a spade with an extension of about $25''$. The northern lobe is visible as a cavity in the emission of the bow shock, as if it is pushing against the shocked region. It extends towards $56''$ from the star at $\text{P.A.} \approx 340^\circ$ and thus considerably smaller than its southern counterpart.

A possible interpretation of the two lobes is that they represent a bipolar

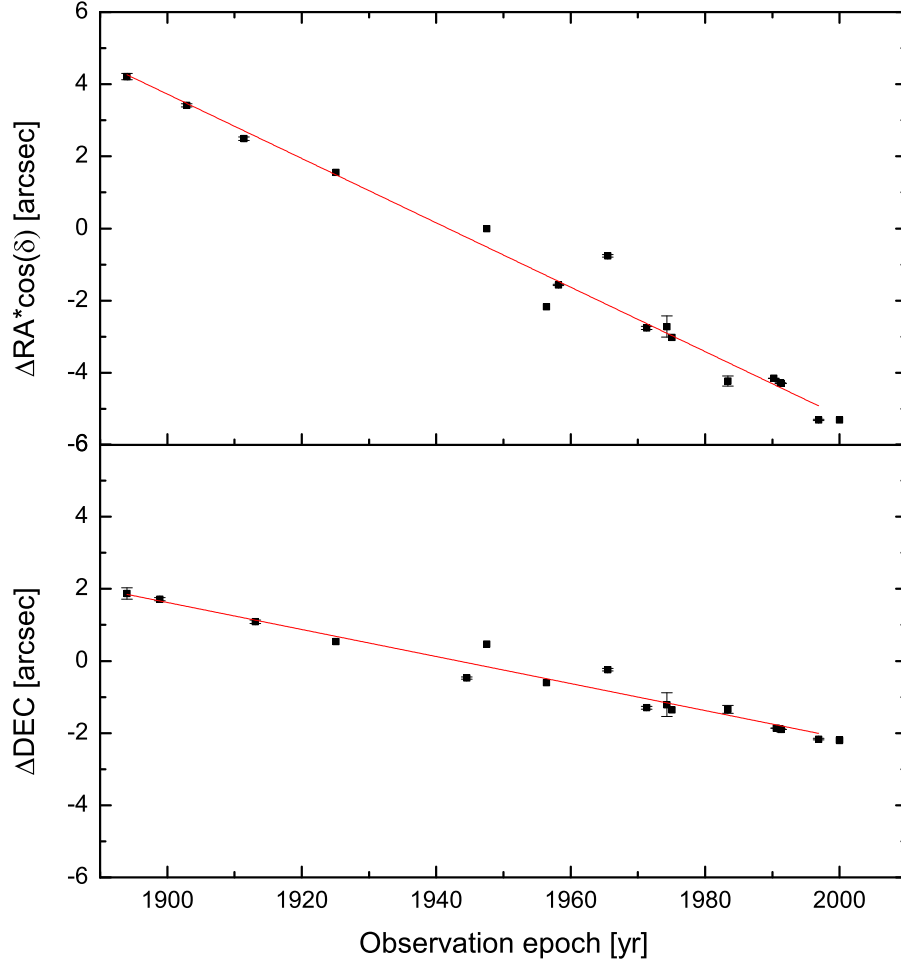


Figure 3.2.: Positional data of θ Aps from various catalogues over the last 100 years. The red line gives the weighted fit in RA (upper panel) and DEC (lower panel). The resulting proper motion is $\mu_{\alpha*} = -89.2 \pm 3.8 \text{ mas yr}^{-1}$ and $\mu_{\delta} = -37.4 \pm 1.5 \text{ mas yr}^{-1}$.

outflow that is triggered by the accretion disk of a close companion. While the southern part of the bipolar outflow can expand freely, the northern part is hindered by material piled up by the ISM. This explanation supports also the fact that the northern lobe is considerably closer to the star than the southern lobe.

Regarding the orthogonality of the bipolar outflow to the direction of the space motion of θ Aps, an interesting aspect arises. To investigate whether or not this is a coincidence, we compared the position angles for the proper motion

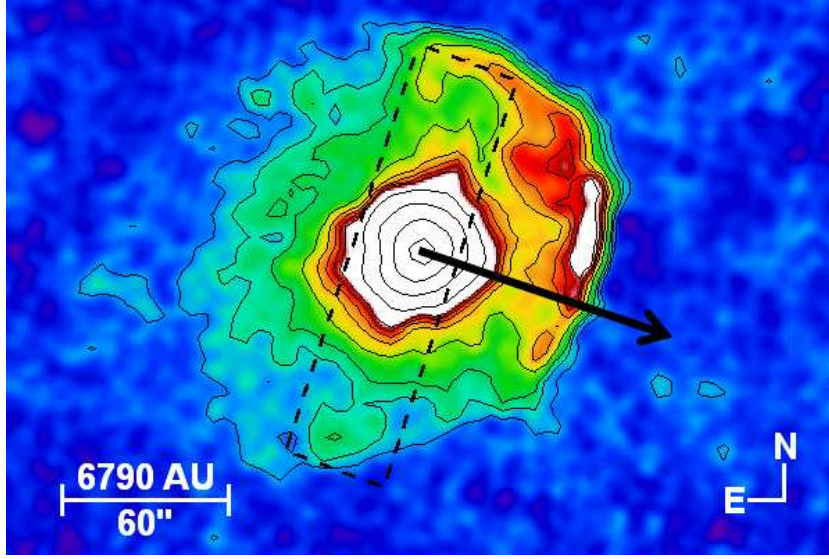


Figure 3.3.: *Herschel*/PACS 70 μm image overplotted with contours from the same image. The arrow gives the direction of the space motion and the dashed box covers the two opposing lobes.

and the bipolar outflow of eleven AGB stars with known bipolar outflows (see Table 3.2). We found five out of eleven objects (X Her, RX Boo, R Aqr, θ Aps, S Crt) to show a projected angle of $90^\circ \pm 15^\circ$ between the bipolar outflow and the direction of the space motion. Four out of the eleven objects (TX Psc, α Cet, V Hya, W Hya) have their bipolar outflow aligned with the space motion ($\Delta\text{P.A.} = 0^\circ \pm 15^\circ$). Only two objects (RS Cnc, π^1 Gru) show a random alignment with the two angles ($45^\circ \pm 30^\circ$).

The small number of objects in the sample prohibit any immovable conclusion, however, a correlation seems to be existent between the orientation of the bipolar outflow and the space motion. The distribution suggests a perpendicular or parallel alignment. Physically, this correlation is an odd fact since it is not known in which way the bipolar outflow could influence the space motion or vice versa. Therefore, the distribution might be coincidental. A further study of this connection is beyond the scope of this work but should be pursued in the future.

Table 3.1.: Positional data of θ Aps over the last century from various catalogues. All positions are given in the J2000.0 system.

	AC 2000.2	GC	SAO	N30	CPC	Yale	PPM
Mean epoch of RA [yr]	1894	1902.9	1911.4	1925.1	1947.5	1956.4	1958.2
Mean epoch of DEC [yr]	1894	1898.9	1913.1	1925.1	1947.5	1956.4	1944.6
$\mu_{\alpha*}$ [mas yr ⁻¹]	-	-82.6 ± 2.5	-85 ± 2	-82.2 ± 2.1	-80	-44	-93.9 ± 0.9
μ_{δ} [mas yr ⁻¹]	-	-42.0 ± 2.4	-35 ± 2	-45 ± 2	-27	-28	-32.0 ± 1.0
RA at obs. epoch [deg]	211.34440	211.34344	211.34231	211.34117	211.33928	211.33664	211.33738
Error in RA [10 ⁻⁵ deg]	2.427	1.222	1.388	-	-	-	0.555
DEC at obs. epoch [deg]	-76.79563	-76.79567	-76.79585	-76.79600	-76.79602	-76.79632	-76.79628
Error in DEC [10 ⁻⁵ deg]	4.305	1.166	1.388	-	-	-	0.833
	SPF2	CPC2	SHC	Perth 75	FOCAT-S	PPMXL	Tycho-2
Mean epoch of RA [yr]	1965.5	1971.3	1974.3	1975.1	1983.4	1990.6	1991.2
Mean epoch of DEC [yr]	1965.5	1971.3	1974.3	1975.1	1983.4	1990.6	1991.1
$\mu_{\alpha*}$ [mas yr ⁻¹]	-	-	-	-85.4	-98 ± 1	-88.9 ± 0.5	-87.7 ± 0.7
μ_{δ} [mas yr ⁻¹]	-	-	-	-35.1	-23 ± 4	-35.7 ± 0.5	-35.0 ± 0.7
RA at obs. epoch [deg]	211.33836	211.33593	211.33597	211.33561	211.33423	211.33414	211.33407
Error in RA [10 ⁻⁵ deg]	1	1.305	8.055	-	3.888	0.111	0.111
DEC at obs. epoch [deg]	-76.79622	-76.79651	-76.79649	-76.79653	-76.79667	-76.79652	-76.79667
Error in DEC [10 ⁻⁵ deg]	1	1.083	9.166	-	3.055	0.083	0.111
	UCAC4	SPM4	USNO-B	GSC2.3			
Mean epoch of RA [yr]	1991.3	1996.9	2000.0	2000.0			
Mean epoch of DEC [yr]	1991.3	1996.9	2000.0	2000.0			
$\mu_{\alpha*}$ [mas yr ⁻¹]	-87.5 ± 1.0	-85.74 ± 3.80	-	-			
μ_{δ} [mas yr ⁻¹]	-32.5 ± 1.0	-33.53 ± 3.42	-	-			
RA at obs. epoch [deg]	211.33406	211.33283	211.33283	211.33283			
Error in RA [10 ⁻⁵ deg]	0.056	0.547	-	-			
DEC at obs. epoch [deg]	-76.79668	-76.79675	-76.79676	-76.79676			
Error in DEC [10 ⁻⁵ deg]	0.056	0.547	-	-			

References: AC 2000.2: Urban et al. (2001), GC: Boss (1937), SAO: SAO Staff (1966), N30: Morgan (1952), CPC: Stoy (1968), Yale: Lü (1971), PPM: Bastian & Röser (1993), SPF2: Baturina et al. (1986), CPC2: Zacharias et al. (1999), SHC: Rousseau et al. (1996), Perth 75: Nikoloff et al. (1982), FOCAT-S: Bystrov et al. (1994), PPMXL: Roesser et al. (2010), Tycho-2: Høg et al. (2000), UCAC4: Zacharias et al. (2012), SPM4: Girard et al. (2011), USNO-B: Monet et al. (2003), GSC2.3: Lasker et al. (2008)

Table 3.2.: Comparison between the P.A. of the bipolar outflow (bo) and of the proper motion (pm) of AGB stars. The proper motions are taken from Hipparcos (van Leeuwen 2007) and corrected from solar motion, except for π^1 Gru and V Hya, for which the proper motion values of the Tycho-2 catalogue (Høg et al. 2000) are adopted since they differ significantly from the Hipparcos values and are more reliable. The heliocentric RV used in the computation is listed in the first column.

Name	RV [km s ⁻¹]	v_{LSR} [km s ⁻¹]	P.A. (pm) [°]	P.A. (bo) [°]	Δ P.A. [°]	Reference
X Her	-88.95 ± 0.40	91.3 ± 2.1	316 ± 1	45	89	Castro-Carrizo et al. (2010)
TX Psc	11.5 ± 1.5	64.4 ± 4.4	248 ± 1	240 or 115	8 or 133	Heske et al. (1989)
RX Boo	-9.42 ± 1.73	50.6 ± 3.9	141 ± 1	50	91	Castro-Carrizo et al. (2010)
RS Cnc	-13.72 ± 0.42	14.1 ± 1.5	163 ± 1	10	153	Libert et al. (2010)
R Aqr	-22 ± 0.9	36.0 ± 4.8	139 ± 1	46 & 211	93 & 72	Kellogg et al. (2007)
θ Aps	10.2 ± 0.5	35.4 ± 1.9	256 ± 1	155 & 340	101 & 84	this work
π^1 Gru	-5.7 ± 1.5	15.0 ± 2.8	103 ± 4	210 & 355	107 & 108	Chiu et al. (2006)
α Cet	63.8 ± 0.9	110.0 ± 6.8	185 ± 1	173	12	Meaburn et al. (2009)
V Hya	-14.8 ± 1.7	32.1 ± 23.2	275 ± 12	110	165	Sahai et al. (2003)
S Crt	32.0 ± 4.6	31.4 ± 9.7	167 ± 4	255	88	Nakagawa et al. (2008)
W Hya	42.3 ± 3.0	48.8 ± 3.1	211 ± 1	200	11	Zhao-Geisler et al. (in prep.)

3.1.2. EP Aquarii

EP Aqr is a well-studied M8III SRb star with periods of 81.8, 117.9, and 125.8 days (Tabur et al. 2009) located at a distance of 114 ± 8 pc (van Leeuwen 2007). Dumm & Schild (1998) determined the mass of the AGB star with $M = 1.7 M_{\odot}$ and its effective temperature $T_{\text{eff}} = 3236$ K while De Beck et al. (2010) find a moderate MLR of $3.1 \times 10^{-6} M_{\odot} \text{ yr}^{-1}$.

EP Aqr has a rich mid-IR spectrum, as revealed by ISO (Posch et al. 1999, 2006). It does not only exhibit 9.7 and $18 \mu\text{m}$ amorphous silicate features, but also a broad $11 \mu\text{m}$ emission shoulder (probably due to amorphous Al_2O_3), a narrow $13 \mu\text{m}$ dust feature (either due to crystalline $\alpha\text{-Al}_2\text{O}_3$ or due to crystalline MgAl_2O_4), a $19.5 \mu\text{m}$ band (assigned to an Mg-Fe-oxide with a composition close to FeO) as well as unidentified bands beyond $25 \mu\text{m}$. Additionally, it shows strong molecular lines from CO_2 in the $15 \mu\text{m}$ region.

CO observations of the star revealed the presence of a double-component profile with a narrow component superimposed on a broader feature (Knapp et al. 1998; Kerschbaum & Olofsson 1999; Winters et al. 2003; Nakashima 2006). This line profile can either be interpreted as two winds with different velocities that interact with each other (Knapp et al. 1998), as a slow spherical wind that interacts with a bipolar outflow (Kahane & Jura 1996), or as an orbiting molecular gas reservoir in Keplerian rotation around the binary system (Jura & Kahane 1999). Winters et al. (2007) modelled the emission and were able to exclude a simple two-wind solution. In SiO, the narrow component was not detected, suggesting that this component has a different origin than the broader one (González Delgado et al. 2003).

The large-scale environment was observed by many authors. In the IRAS $60 \mu\text{m}$ band, Young et al. (1993a,b) found that EP Aqr is surrounded by a detached dust shell with $r_{\text{inner}} = 1.5'$ (0.06 pc) and $r_{\text{outer}} = 5.9'$ (0.23 pc). An asymmetric extended emission was detected in HI (Le Bertre & Gérard 2001, 2004; Gérard & Le Bertre 2006). Matthews & Reid (2007) observed arcminute-scale HI features at velocities consistent with the circumstellar envelope but spatially offset from the stellar position.

Herschel far-IR observations

The far-IR emission of the CSE has the shape of a jellyfish with the head pointing northward and the tentacles southward. The symmetry axis agrees with the direction of the space motion at P.A. = $(4 \pm 1)^{\circ}$ inclined by $(-56 \pm 7)^{\circ}$. The jellyfish structure is without doubt the result of the interaction between the stellar wind and the ISM forming a bow shock in direction of the space motion. The tentacles are likely made out of material stripped off from the

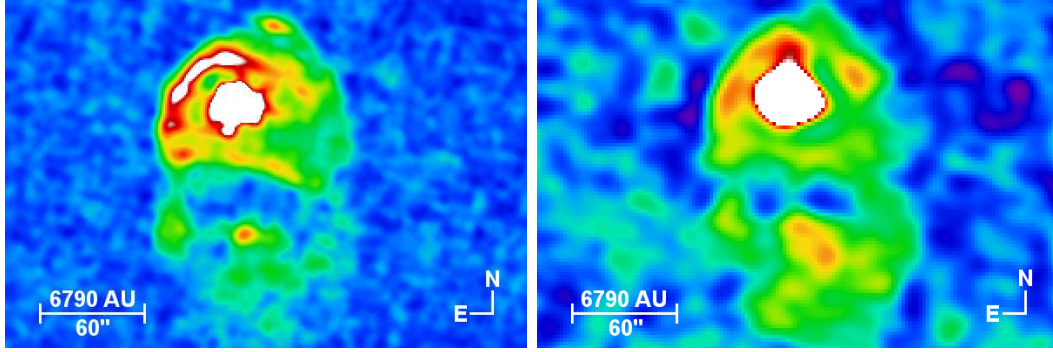


Figure 3.4.: Deconvolved PACS images of EP Aqr at $70\mu\text{m}$ (left) and $160\mu\text{m}$ (right).

bow shock head moving downstream (Wareing et al. 2007; Villaver et al. 2012). The star was therefore categorised as a bow shock object by Cox et al. (2012).

However, a line symmetry along the space motion which is expected for a bow shock cone is not seen. The motion through the ISM is almost due north (P.A. = 4°) but the eastern side shows a bright arc from P.A. 340° – 115° which has no counterpart in the west. This weakens the argument that the bright arc represents ISM interaction but favours the possibility that it reflects the orbital motion of a companion. The arc is then brightened by the inner shock front of the wind–ISM interface, the termination shock. This was observed in a similar way for *o* Cet (see Section 2.1).

At the southern edge of the bow shock cone, a bright arc oriented EW is visible, stretching from P.A. = 115° to 250° . In addition to the arcs, two clumps are visible in the $70\mu\text{m}$ image. One is north of the star at P.A. = 335° and the other to the south, at P.A. = 183° . The northern clump is clearly located outside of the bow shock cone at a distance of $49''$ from the star. In contrast, the southern clump is embedded in the jellyfish tentacle at a distance of $75''$. A cavity is clearly visible just north of this clump, with no IR emission at all, but with HI emission detected by Matthews & Reid (2007).

The upper and lower panels of Fig. 3.5 show intensity cuts through the northern and southern clumps, respectively. The intensity profile across the southern clump (located $75''$ away from the star) shows how sharp the edge of the EW arc $32''$ away from the star is, leading to the cavity with no far IR emission.

The profiles through the northern clump reveal that it is only visible in the $70\mu\text{m}$ image as a peak at $49''$. At this position, the $160\mu\text{m}$ profile starts a steeper decline but shows no signs of a peak. The innermost bump, $25''$ from the star, behaves similarly and is only visible in the blue band – in contrast to

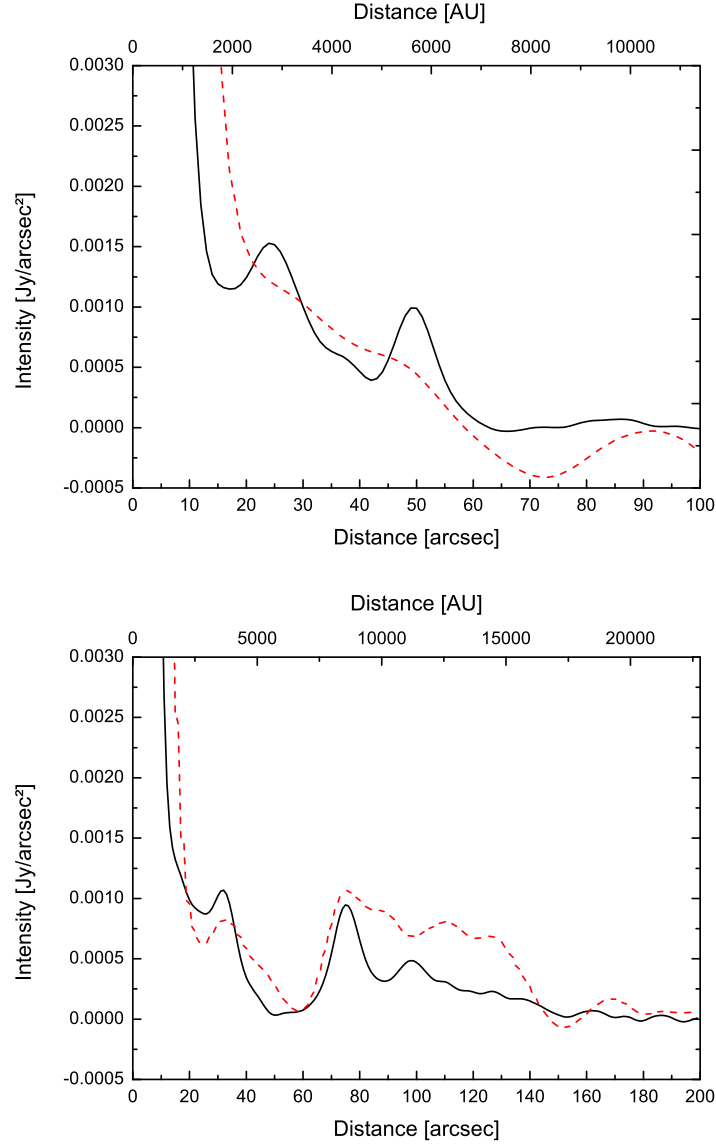


Figure 3.5.: Intensity cut of EP Aqr. *Upper panel*: intensity integrated in a wedge in direction of the northern clump ($325^\circ \leq \text{P.A.} \leq 345^\circ$). *Lower panel*: same as the upper panel, but for the southern clump integrated in a wedge $175^\circ \leq \text{P.A.} \leq 190^\circ$. In both panels, the black continuous curve corresponds to the $70\,\mu\text{m}$ image and the red dashed curve to the $160\,\mu\text{m}$ image.

the southern clump which is well visible in both bands.

To investigate the nature of the clumps, aperture photometry was performed for both bands. For the northern clump, a radius of $12''$ was chosen to fully cover the emission. A background emission of $5 \times 10^{-6} \text{ Jy pix}^{-1}$ at $70 \mu\text{m}$ and $1 \times 10^{-5} \text{ Jy pix}^{-1}$ at $160 \mu\text{m}$ was measured at the periphery. Subtracting the background, a flux ratio of $F_{\nu,70}/F_{\nu,160} = 6.05$ is obtained for the northern clump. Assuming that the light emitted by the clump is due to amorphous silicate dust emission results in a dust temperature of 45 K (for an outline of the method see Jorissen et al. 2011). The same calculations for the southern clump yield a dust temperature of 33 K from a flux ratio $F_{\nu,70}/F_{\nu,160} = 2.45$ found in an aperture of $16''$ radius around the clump.

At least two explanations may be proposed for the origin of these clumps. Clumps occur when instabilities disturb the bow shock, leading to material stripped off the bow shock and flowing downstream, as hydrodynamical simulations have shown (Blondin & Koerwer 1998; Comeron & Kaper 1998). Such features have been observed for TX Psc and X Her (Jorissen et al. 2011). Moreover, a bright clump lying exactly upstream, like the northern clump of EP Aqr (and the one observed in TX Psc), has been found in the Mach 10 simulation of Blondin & Koerwer (1998). The southern clump then represents a very turbulent part of the collimated wake.

Another possible explanation is that the clumps correspond to the end points of a bipolar outflow. However, the CO emission map of Nakashima (2006) does not show any evidence neither for a bipolar outflow nor for a Keplerian disc, since all emission components (narrow, broad red-shifted and broad blue-shifted) are exactly centred on the star.

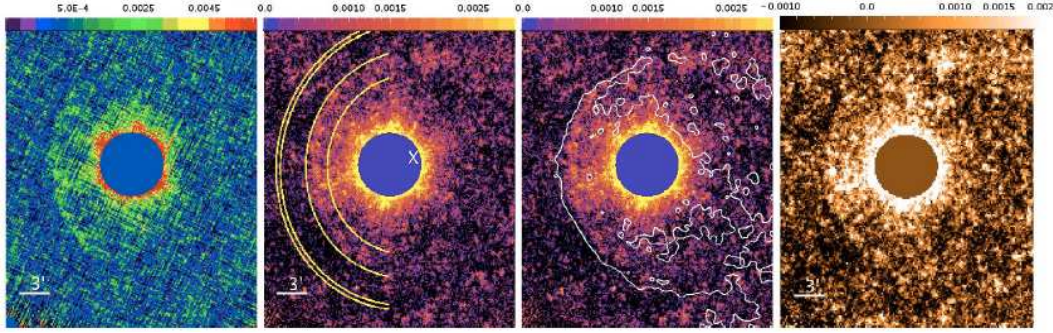


Figure 3.6.: *Herschel* PACS & SPIRE images of IRC +10 216 by Ladjal et al. (2010). From left to right: PACS 160 μm , SPIRE 250 μm , SPIRE 250 μm overplotted with GALEX FUV contours, SPIRE 350 μm .

3.1.3. IRC +10 216 (CW Leonis)

IRC +10 216 is the nearest C-type AGB star (123 ± 14 pc; Groenewegen et al. 2012) and, although it was not discovered until the late 1960s (Becklin et al. 1969), it became the best studied AGB star to date. De Beck et al. (2012) derived a high gas-MLR of $1.5 \times 10^{-5} M_{\odot} \text{yr}^{-1}$ for the last 1000 years and a wind velocity of 14.5 km s^{-1} from CO line modelling. The same authors also determined a stellar luminosity of $11\,300 L_{\odot}$ which varies between 6250 and $15\,800 L_{\odot}$ during the star’s pulsation cycle of 629 days (Samus et al. 2004), a gas-to-dust-mass ratio of 375, and an effective temperature of 2330 K.

The environment of the star was studied intensively in the past years. Close to the star (in the milli-arcsecond range) dust clumps have been found that move along with the expanding wind (e.g., Tuthill et al. 2000). Farther away from the star (in the arcsecond range), the material around IRC +10 216 appears bipolar in north-south direction in the optical (Mauron & Huggins 2000). Even farther outside, multiple almost concentric shells with a typical width of $1.6''$ separated by $3\text{--}20''$ are visible up to a distance of $320''$ in the optical and IR (e.g., Mauron & Huggins 2000; Decin et al. 2011).

The binarity of the star was deduced recently from ALMA and IRAM observations by Decin et al. (2015) and Cernicharo et al. (2014), respectively. In the ALMA $^{13}\text{CO}(6\text{--}5)$ channel maps spiral arc can be seen $1.5''$ north and $2''$ south of IRC +10 216 at -17.5 km s^{-1} and -37.4 km s^{-1} , respectively. Decin et al. (2015) modelled the position-velocity diagram following Kim et al. (2013) and found the orbital axis at P.A. = $10\text{--}20^{\circ}$. The spiral spacing is about $1.12''$, leading to an orbital period of about 55 yr and a separation of $20\text{--}25$ au for $M_1 = 4 M_{\odot}$ and $M_2 \approx 0.6 M_{\odot}$. Decin et al. (2015) suggest that the companion

is most likely a low mass main sequence star. Cernicharo et al. (2014) were able to map the corresponding spiral pattern in $^{12}\text{CO}(2-1)$ and $^{13}\text{CO}(2-1)$ with the IRAM 30 m telescope. The spiral spacing point to an orbital period of ≈ 800 yr. The discovery of the companion can explain the bipolar structure and the concentric shells observed earlier by Mauron & Huggins (2000). Recently, Kim et al. (2014) claimed to have found the companion of IRC +10 216 on archival HST images, however, separated by 65 au which agrees with the spiral spacing observed by Cernicharo et al. (2014).

Herschel far-IR observations

IRC +10 216 was categorised as a bow shock object by Cox et al. (2012) given the huge arcs in direction of the space motion seen in the PACS $160\ \mu\text{m}$ band. Ladjal et al. (2010) provide an in-depth study of the *Herschel* observations. The main feature of the observations is an arc visible in the PACS $160\ \mu\text{m}$ as well as in the SPIRE 250 and $350\ \mu\text{m}$ band (see Fig. 3.6). The arc is similar to the one found on GALEX images with a spatial scale as large as $450''$ (Sahai & Chronopoulos 2010; Ladjal et al. 2010). It is almost concentric and reflects a bow shock although the space velocity is only about $25\ \text{km s}^{-1}$. Ladjal et al. (2010) determine a dust temperature of 25 K within the bow/termination shock.

Inside the bow shock various dust shells are visible in the blue, green, and red PACS bands (Decin et al. 2011). The outermost arc is located $320''$ from the star and was ejected about 16 000 years ago while the innermost arc is detected at $24''$. These dust shells have a typical thickness of $5\text{--}8''$ and are significantly warmer than the bow shock, with temperatures between 108 K at $20''$ and 40 K at $180''$ (Decin et al. 2011).

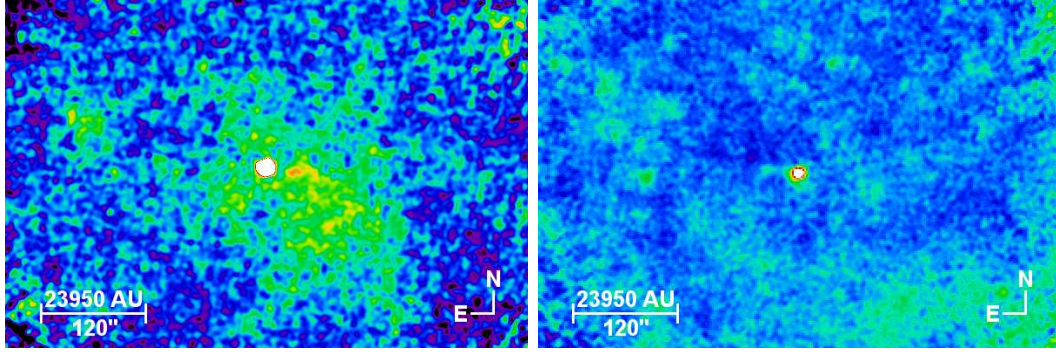


Figure 3.7.: PACS images of o^1 Ori at $70\mu\text{m}$ (left) and $160\mu\text{m}$ (right).

3.1.4. o^1 Orionis

o^1 Ori is a well studied SRb star of spectral type MS3.5 with periods of 30.8 and 70.7 days (Keenan & Boeshaar 1980; Tabur et al. 2009), located at a distance of 200 ± 28 pc away from the sun (van Leeuwen 2007). The star is in an evolved state on the AGB given its detection of technetium (Smith & Lambert 1988; Lebzelter & Hron 1999) and a C/O ratio of 1.20 (Wylie-de Boer & Cottrell 2009). However, the MLR of $\dot{M} \leq 4 \times 10^{-8} M_{\odot} \text{yr}^{-1}$ is quite low for this evolutionary phase (Groenewegen & de Jong 1998). An effective temperature of 3600 ± 200 K was derived from Fe I and Fe II lines (Wylie-de Boer & Cottrell 2009). The same authors also obtained $\log g = 1.0 \pm 0.2$ while the apparent stellar diameter was found to be 9.78 mas (1.96 au) from VLTI/AMBER observations (Cruzalèbes et al. 2013).

A white dwarf companion with $T_{\text{eff}} = 22\,000$ K was found for o^1 Ori by Ake & Johnson (1988). The WD is of spectral type DA3, showing only hydrogen absorption lines in its spectrum. The primary's variability is seen weakly in the obtained UV spectrum while the contribution of the WD companion is constant. Measurements of the Mg II and C II emission lines suggest that there is no interaction between the two components. Despite this clear detection of a companion, Pourbaix et al. (2003) found that a single star solution fits best the Hipparcos VIM data, meaning that the gravitational influence of the WD companion on the astrometric data of o^1 Ori was not detected.

Herschel far-IR observations

o^1 Ori was categorised as an irregular object by Cox et al. (2012) from the far-IR emission seen on the *Herschel*/PACS images (see Fig. 3.7). The $70\mu\text{m}$ image shows a clear asymmetry west of the star that extends to about $160''$

(32 000 au). The emission is patchy and shows no signs of being formed by the interaction with a companion or the surrounding medium, viz. there is no evidence for an arc or a bow shock. The direction of the space motion inferred from the proper motion data by van Leeuwen (2007) ($\mu_{\alpha*} = -0.05 \pm 0.84 \text{ mas yr}^{-1}$ and $\mu_{\delta} = -54.81 \pm 0.53 \text{ mas yr}^{-1}$) and the RV ($-8.40 \pm 0.23 \text{ km s}^{-1}$, Famaey et al. 2005) is at P.A. = 187° , thus not aligned with the emission at $70 \mu\text{m}$. The velocity of the space motion, however, is quite high ($45 \pm 4 \text{ km s}^{-1}$) and an interaction with the ISM is expected for this velocity (Cox et al. 2012). A reason for the absence of a bow shock might be the low MLR ($\dot{M} < 4 \times 10^{-8} M_{\odot} \text{ yr}^{-1}$; Groenewegen & de Jong 1998) or a low density environment. Furthermore, the image at $160 \mu\text{m}$ shows no foreground emission at all which may suggest that the irregular structure seen at $70 \mu\text{m}$ does not originate from the star and might be part of the background.

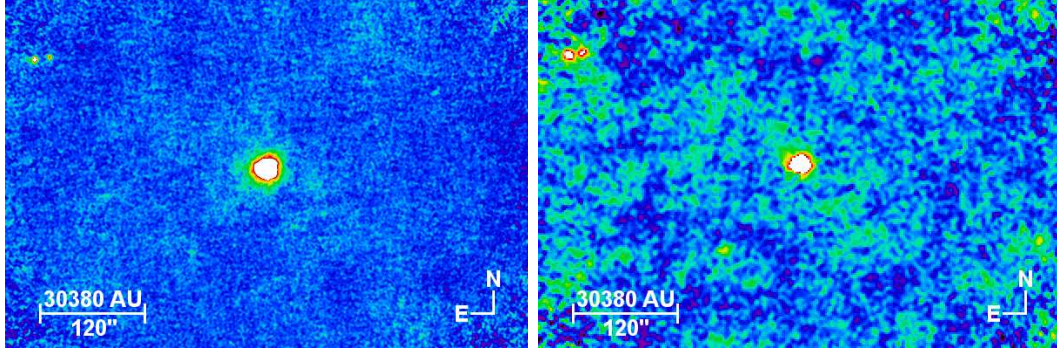


Figure 3.8.: PACS images of Y Lyn at $70\mu\text{m}$ (left) and $160\mu\text{m}$ (right).

3.1.5. Y Lyncis

Y Lyn is an M6SIb-II SR variable star with a period of 110 days (Samus et al. 2004) and a long secondary period of approximately 1240 days (Percy & Sato 2009). Given the bolometric magnitude ($M_{\text{bol}} = -4.43$) and colour $((V - K)_0 = 7.63)$ the star is quite evolved on the AGB (Van Eck et al. 1998). This is also supported by the detection of Tc (Smith & Lambert 1988; Jorissen et al. 1993). Modelling of the SED, using a distance of 253 ± 63 pc (van Leeuwen 2007), was done by Ramstedt & Olofsson (2014) and resulted in an effective temperature of 2700 K and luminosity $L = 4000 L_{\odot}$. The same authors also obtained a wind velocity $v_w = 7.5 \text{ km s}^{-1}$, and a MLR $\dot{M} = 1.8 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$ of the star from CO line modelling (Schöier et al. 2013). Young et al. (1993a) studied the stellar environment with IRAS and found it to be extended with an outer and inner radius of 0.41 pc and 0.13 pc, respectively (equivalent to $330''$ and $105''$).

The binarity of Y Lyn is supposed from the Hipparcos VIM data which is fitted by a non single-star solution (Pourbaix et al. 2003).

Herschel far-IR observations

The *Herschel*/PACS images of Y Lyn (Fig. 3.8) are absent of an extended structure in both photometric bands and the object was therefore marked as a point-source by Cox et al. (2012).

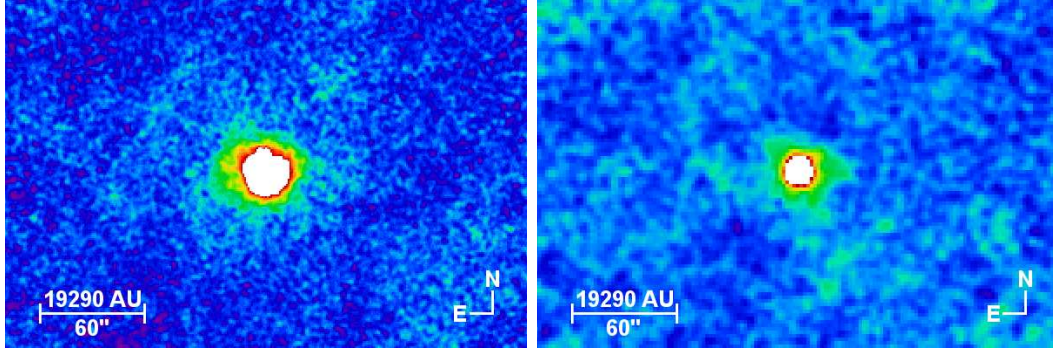


Figure 3.9.: PACS images of TW Hor at $70\mu\text{m}$ (left) and $160\mu\text{m}$ (right).

3.1.6. TW Horologii

TW Hor is a Tc rich (Lebzelter & Hron 2003) SRb carbon star [C7,2(N0)] with a parallax of 3.11 ± 0.37 mas (322 ± 38 pc; van Leeuwen 2007). According to the GCVS, the period of the star is 158 days (Samus et al. 2004) while Tabur et al. (2009) find one with 270.3 days. The MLR $\dot{M} = 8.3 \times 10^{-7} M_{\odot} \text{yr}^{-1}$ and wind velocity $v_w = 5.3 \text{ km s}^{-1}$ were determined from millimetre CO observations by Groenewegen et al. (2002); however, assuming a distance of 1.89 kpc. Bergeat & Chevallerier (2005) found an effective temperature $T_{\text{eff}} = 2950$ K of the star.

A variable far-UV flux was detected in the spectrum of TW Hor by Sahai et al. (2008), Querci & Querci (1985), and Johnson & Luttermoser (1987). Querci & Querci (1985) explained this by a variable chromospheric-type line emission of the AGB star. Sahai et al. (2011) proposed a different scenario for the AGB star Y Gem, which also shows a highly variable UV emission and a similar FUV to NUV flux ratio. According to the authors the UV emission is most likely related to the presence of a nearby companion and caused by episodic accretion of the mass lost by the AGB star onto a disc, or from the inner part of a disc, onto the companion.

Herschel far-IR observations

Figure 3.9 depicts the observations of TW Hor with *Herschel*/PACS at $70\mu\text{m}$ and $160\mu\text{m}$. No extended far-IR emission is visible around the star and it was therefore marked as a point source by Cox et al. (2012).

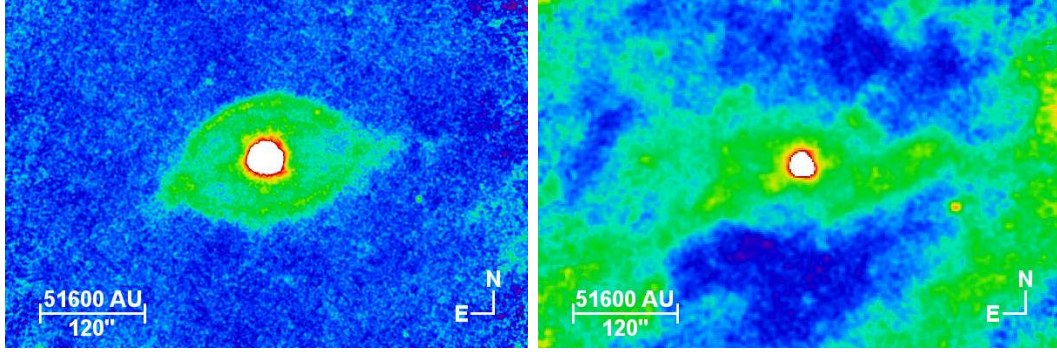


Figure 3.10.: PACS images of U Cam at $70\mu\text{m}$ (left) and $160\mu\text{m}$ (right).

3.1.7. U Camelopardis

U Cam is a C6 SRb star at a distance of 340 pc from the sun (Schöier et al. 2007; Samus et al. 2004). A luminosity $L = 7000 L_{\odot}$, wind velocity $v_w = 11.5 \text{ km s}^{-1}$, temperature $T_{\text{eff}} = 2700 \text{ K}$, and MLR $\dot{M} = 2.0 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$ was derived from SED and CO line modelling (Schöier et al. 2007). Slightly higher values for all of the parameters were found by Guandalini et al. (2006).

The surroundings of U Cam were studied in CO and HCN lines where Lindqvist et al. (1996, 1999) and Schöier et al. (2005) found a young detached shell around the star with a diameter of $15''$ and a width of the shell of $\approx 1.5''$. Hony & Bouwman (2004) found that the shell contains MgS and demonstrated its C-rich chemistry.

The binary nature of U Cam is undermined by the Hipparcos Double and Multiple Systems Annex (DMSA; Perryman & ESA 1997). A component solution was found to fit the astrometry (DMSA/C) and the companion was resolved separated by $a = 0.17''$ (58 au) at P.A. = 79° .

Herschel far-IR observations

Together with VY UMa, U Cam is the only binary system with an eye-shaped CSE in the MESS sample (Cox et al. 2012). Fig 3.10 depicts the *Herschel*/PACS observations in the blue and red band. The total extent of the eye is about $250''$ (85 000 au) in EW direction and about $150''$ (51 000 au) NS. This is more than twice as large as the CSE around VY UMa but similar to this star the eye around U Cam is also displaced from the star. The edges of the eye are at P.A. = 110° and P.A. = 273° and are not aligned with the space motion which is along P.A. = $341 \pm 2^\circ$. Moreover, the space velocity is only $9 \pm 3 \text{ km s}^{-1}$ and therefore too low to have a strong impact on the CSE.

Recently, van Marle et al. (2014) demonstrated that an interstellar magnetic field can be responsible for shaping the eye. Perpendicular to the magnetic field, the wind bubble remains spherical while the elongation is always along the field lines. The strength of this effect is favoured for stars with low proper motion and a weak wind situated in a low density ISM (van Marle et al. 2014).

In the red PACS band, the emission is distorted by bright emission that is most likely part of the background, since it extends far out to the edges of the frame. The emission of the dust shell at $160\,\mu\text{m}$ is weaker than the background emission and thus not well visible. Interestingly, Stanek et al. (1995) found an elongation of the CO emission in east-west direction along approximately 120° with a size of $\approx 50''$ (see their Fig. 4).

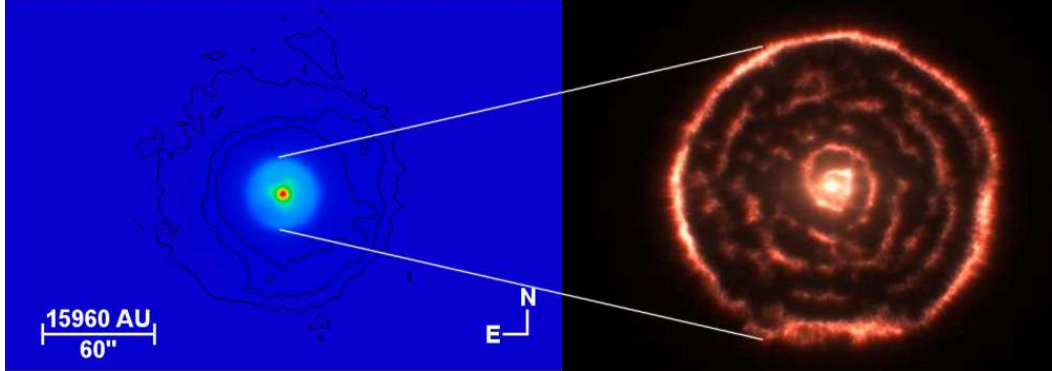


Figure 3.11.: Illustration of the environment of R Scl. The left part of the image shows the *Herschel*/PACS observation at $70\,\mu\text{m}$ overplotted with contours from the same image with different cuts (see Fig. 3.12). The right part depicts the ALMA observations revealing a spiral structure in the close environment of the star (Maercker et al. 2012).

3.1.8. R Sculptoris

R Scl is a very well studied carbon star at a distance of 370 pc from the sun (Whitelock et al. 2008). The star is a SRb variable with a period of 374 days and a long secondary period of 1304 days (Whitelock et al. 1997). De Beck et al. (2010) found a MLR of $1.6 \times 10^{-6} M_{\odot} \text{yr}^{-1}$ and wind velocity $v_w = 17.0 \text{ km s}^{-1}$, while the luminosity $L = 7000 L_{\odot}$, effective temperature $T_{\text{eff}} = 2700 \text{ K}$, and C/O=1.40 was determined by Sacuto et al. (2011) from SED modelling. The same authors also derived a stellar diameter of 10.2 mas (and $\log g = -0.7$.

The environment of the star was extensively studied in the past, as a result of the detached shell detected in CO lines by Olofsson et al. (1990) and Olofsson (1996). These CO shells are most likely a product of a wind-wind interaction, when a faster wind expelled during a thermal pulse piles up and pushes away the older and slower stellar AGB wind (Olofsson et al. 1990; Mattsson et al. 2007; Maercker et al. 2010). A shock front forms at the interface of the two winds and it appears as a projected ring. The formation time of the shell around R Scl is less than 100 years and the amount of ejected mass about $10^{-3} M_{\odot}$ (Olofsson et al. 2010).

Scattered light images of the detached shell were presented by González Delgado et al. (2001, 2003) and Olofsson et al. (2010). The authors found a clumpy shell of $\approx 20''$ radius with an overall spherically symmetric geometry but offset by $0.7''$ at P.A.= 160° . Olofsson et al. (2010) attributes this to a

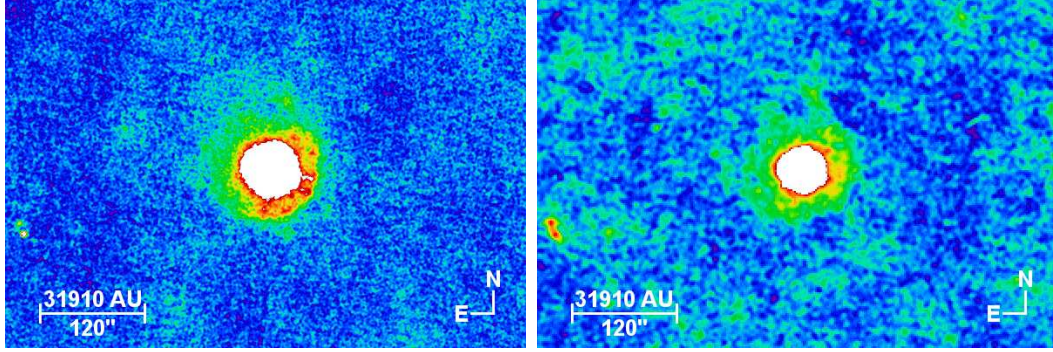


Figure 3.12.: PACS images of R Scl at $70\mu\text{m}$ (left) and $160\mu\text{m}$ (right).

possible binary companion. The Hipparcos VIM data was revised to trace such a possible companion but no indication was found (Pourbaix et al. 2003). Another recent attempt to image the closer surroundings of the star with VLTI/VISIR was undertaken by Lagadec et al. (2011) who were not able to resolve it due to saturation.

Maercker et al. (2012) used the resolution and sensitivity of ALMA to map the CO emission around R Scl and confirmed the clumpy shell with a radius of $18.5''$ (see right part of Fig. 3.11). The observations, however, revealed unexpectedly a spiral structure inside the detached shell ranging from the star to the edge of the shell – a clear indication for an ongoing binary interaction. The full-fledged spiral covers five windings whereof the inner half shows a constant spacing of $2.6''$ and an increasing spacing towards the detached shell. The wind velocity was found to be 14.3 km s^{-1} and combined with the (inner) spiral spacing an orbital period of 350 years was deduced (Maercker et al. 2012). The increased spiral spacing can be explained by the sweep-up of the older ejecta or by an increase of the MLR which is equivalent to an increase of the wind velocity. In the case of R Scl the wind velocity has to increase by $\approx 4\text{ km s}^{-1}$ to fit the slope of the spiral spacing (see Fig. 3 of Maercker et al. 2012).

Subsequently, Vlemmings et al. (2013) studied with ALMA the $^{12}\text{CO}/^{13}\text{CO}$ ratio in the circumstellar environment of R Scl and found it to be different in the detached shell from the recent mass loss. The authors related this to isotope fractionation and photo-dissociation from chromospheric activity or the hidden companion.

Herschel far-IR observations

The *Herschel*/PACS images of R Scl add another interesting feature to the complex environment seen in the CO. Figure 3.12 depicts the PACS observations with the cuts set to see the most extended parts of the dusty environment. At this scaling, a bow shock is visible with $R_0 = 56''$ at P.A.= 218° . This is in rough accordance with the space motion at P.A.= 208° . The velocity of the star with respect to the LSR is $59.9 \pm 10.0 \text{ km s}^{-1}$ and it is therefore not unexpected that a bow shock forms around R Scl. The far-IR dust emission of the object was studied with IRAS by Young et al. (1993a) who found an extended shell with an inner and outer radius of 0.76 pc (6.5') and 0.13 pc (1.1'), respectively. This is much larger than the bow shock found on the PACS images.

Setting the cuts suitable to see the wind structure inside the bow shock, the PACS 70 μm image shows a disc with a radius of $19''$ which represents the disc of the same size seen in the CO observations (see Fig. 3.11).

To make a conclusive note, the wind of the star is shaped by all known forms of interaction: the presence of a companion imprints a spiral structure surrounding the binary system, visible in the ALMA CO maps (Maercker et al. 2012). The spiral itself is surrounded by a detached shell formed during a thermal pulse when the faster ejecta swept up the older and slower wind (Olofsson et al. 1990). The outermost part of the wind interacts with the ISM due to the fast motion of the star through its surrounding medium forming a bow shock interface seen in the far-IR with *Herschel* (Cox et al. 2012).

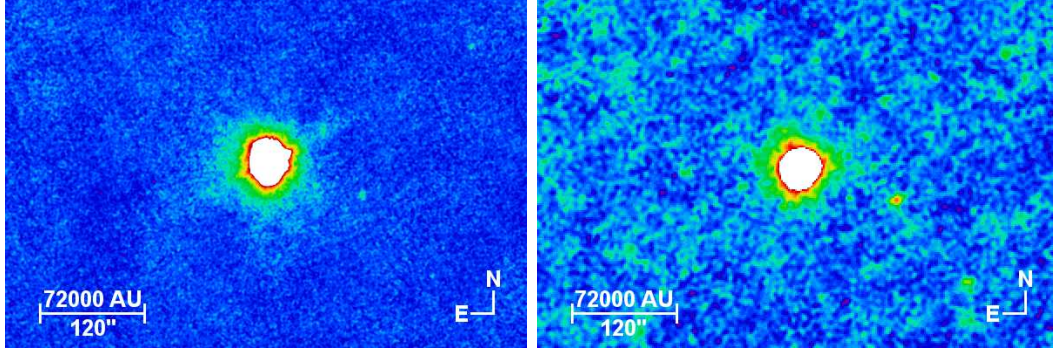


Figure 3.13.: PACS images of V Hya at 70μm (left) and 160μm (right).

3.1.9. V Hydræ

According to the GCVS, V Hya is a C6,5e SRa variable star with a period of 530.7 days and long secondary period of 6500 days (Samus et al. 2004). It is believed that the star has left the AGB and is now in the early post-AGB phase (Kahane & Jura 1996). Its distance to the sun was determined by Whitelock et al. (2008) with 370 ± 60 pc from the PL-relation. De Beck et al. (2010) modelled the CO line profile and found $T_{\text{eff}} = 2007$ K, $L = 5414 L_{\odot}$, $\dot{M} = 6.1 \times 10^{-5} M_{\odot} \text{ yr}^{-1}$, and $R_{*} = 609 R_{\odot}$ fitting the observations.

Sahai et al. (2003) observed a very fast ($\approx 250 \text{ km s}^{-1}$) and highly collimated outflow emerging from V Hya with HST-STIS. It is under discussion whether this kind of fast collimated outflows in the proto-planetary nebula (PPN) phase are caused by the magnetic field of a single star, the angular momentum of a binary system or both (e.g., Blackman et al. 2001; Soker 1994; Balick & Frank 2002). In addition to the high velocity outflow, an extended dusty torus and a hot inner disk were detected (Sahai et al. 2003). Hirano et al. (2004) noted that the jet is perpendicular to the major axis of the disk-like feature while a medium-velocity wind moves along the disk plane.

Although a single star solution was found for the Hipparcos astrometry data (Pourbaix et al. 2003), Barnbaum et al. (1995) measured the photospheric velocity and spectral broadening over 10 phases and noted that the rotation spin-up is most likely caused by a companion.

Herschel far-IR observations

The PACS observations are shown in Fig. 3.13, where an extended CSE is not visible and the source was categorised as a point source (Cox et al. 2012).

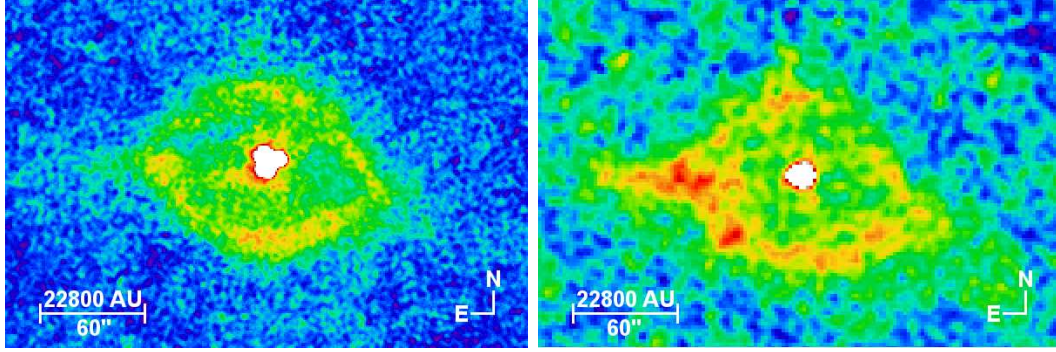


Figure 3.14.: PACS images of VY UMa at $70\mu\text{m}$ (left) and $160\mu\text{m}$ (right).

3.1.10. VY Ursæ Majoris

VY UMa is a slow irregular variable (Lb) AGB star with not well constraint periods of 125 and 190 days (Percy et al. 2001). The star is of spectral type C5II and shows Tc lines in its spectrum (Samus et al. 2004; Little-Marenin & Little 1979). The distance of VY UMa from the sun was measured to be 380 ± 59 pc (van Leeuwen 2007). Bergeat et al. (2001) derived an effective temperature $T_{\text{eff}} = 2930$ K and Loup et al. (1993) give 8.4 km s^{-1} for the wind velocity. According to the authors, the star is located in region VI of the IRAS colour-colour diagram, which means that it shows a $60 \mu\text{m}$ excess, most likely dust emission far away from the central star. Stencel & Backman (1991) and Young et al. (1993a) observed the star with IRAS and found the shell to be extended up to 0.46 pc.

Similar to TW Hor (see Section 3.1.6) a UV excess was also detected for VY UMa (Sahai et al. 2008). In both cases the UV emission appears most likely to be a product of accretion on a binary companion directly from the AGB star or from the inner part of a surrounding disk (Sahai et al. 2008).

Herschel far-IR observations

The *Herschel*/PACS images of VY UMa (Fig. 3.14) show dust emission shaped as an eyelid and was classified as such by Cox et al. (2012). This shape is found seven times in the MESS sample and the shaping mechanisms are not fully understood to date but most likely caused by an interstellar magnetic field (van Marle et al. 2014). The proper motion of the star can be ruled out as a trigger since VY UMa moves with $26.6 \pm 1.5 \text{ km s}^{-1}$ along P.A. = $66 \pm 1^\circ$ and the elongation of the structure is along P.A. = 89° .

Another interesting feature is the displacement of the eye-shell from the

CHAPTER 3. CONCLUSION & OUTLOOK

central star. It extends about $60''$ to the south but only $45''$ north. Also both edges of the eyelid are not perfectly opposing. While the eastern edge is located at P.A.= 89° the western edge is at P.A.= 252° .

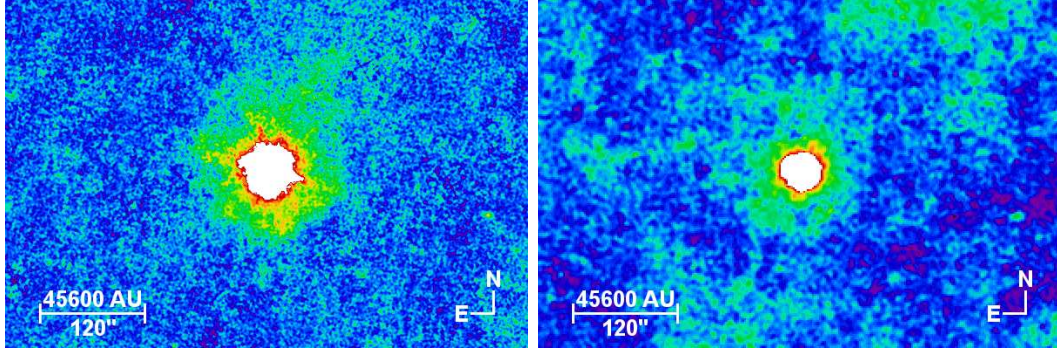


Figure 3.15.: PACS images of TX Cam at $70\mu\text{m}$ (left) and $160\mu\text{m}$ (right).

3.1.11. TX Camelopardis

The well studied M8.5 star TX Cam is a Mira variable with a period of 557 days (Samus et al. 2004). In a study of De Beck et al. (2010), the authors derived the distance from the sun $d = 380$ pc, the effective temperature $T_{\text{eff}} = 2779$ K, the stellar radius $R = 460 R_{\odot}$, the wind velocity $v_w = 21.2 \text{ km s}^{-1}$, and the MLR $\dot{M} = 6.5 \times 10^{-6} M_{\odot} \text{ yr}^{-1}$. In contrast, Ramstedt & Olofsson (2014) derived quite deviating values of $L_* = 8600 L_{\odot}$, $T_{\text{eff}} = 2400$ K, $\dot{M} = 5.5 \times 10^{-6} M_{\odot} \text{ yr}^{-1}$, and $v_w = 18.5 \text{ km s}^{-1}$ from SED and CO modelling.

The first indications of binarity were found in the CO maps of the star (Castro-Carrizo et al. 2010). The outermost component is spherically symmetric while the inner part shows a conspicuous hook-like structure in the J=2-1 line with a diameter of $\approx 20''$ (7600 au; Castro-Carrizo et al. 2010).

TX Cam has a very rich history of SiO maser observations and among others, Diamond & Kemball (2003), Kemball et al. (2009), Gonidakis et al. (2013), and Desmurs et al. (2014) studied the emission zone around the star and found it to follow the pulsation period of the star. In addition, the authors notice that the SE and NW maser spots are significantly brighter and the ring shows gaps in perpendicular direction. The authors conclude from this behaviour that a bipolar outflow penetrates the maser emission zone.

Herschel far-IR observations

Figure 3.15 shows the *Herschel*/PACS observations at $70 \mu\text{m}$ and $160 \mu\text{m}$. Despite the star's interesting detections in SiO and CO, no extended dust emission is visible on the far-IR images, and the object was therefore classified as point source (Cox et al. 2012).

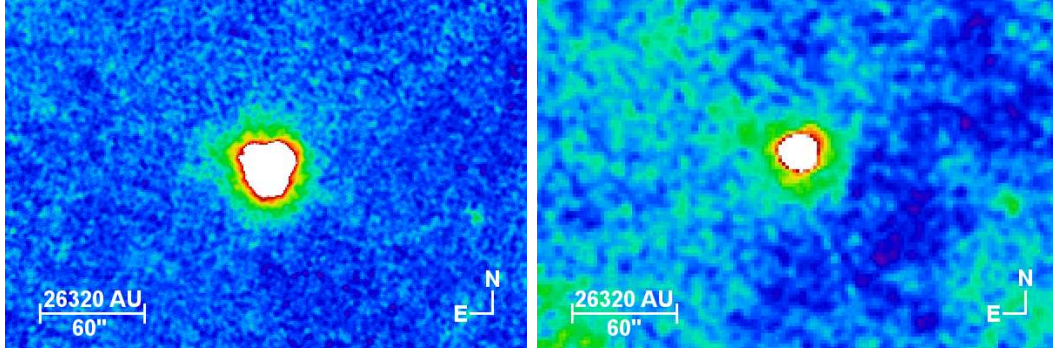


Figure 3.16.: PACS images of V Eri at $70\mu\text{m}$ (left) and $160\mu\text{m}$ (right).

3.1.12. V Eridani

V Eri is an M6II SRc variable star with a period of 97 days (Samus et al. 2004), located 439 ± 133 pc away from the sun (van Leeuwen 2007). A MLR of $1.5 \times 10^{-7} M_{\odot} \text{yr}^{-1}$ and a wind velocity $v_w = 13 \text{ km s}^{-1}$ were derived by Loup et al. (1993).

V Eri is a $\Delta\mu$ binary which means that its long term proper motion recorded by Tycho-2 differs from the short term Hipparcos proper motion, caused by a probable disturbance of a companion (Makarov & Kaplan 2005; Frankowski et al. 2007). The binary nature of V Eri is supported by observations with GALEX, which show a UV excess (Sahai et al. 2008), as it was seen also for other stars in the MESS sample (V Hya, VY UMa, TW Hor). This UV excess is most likely a sign for ongoing accretion of material from the primary or a disk onto a stellar companion. Sahai et al. (2008) was able to determine the effective temperature $T_{\text{eff}} = 10\,000 \text{ K}$ and luminosity $L = 6.2 L_{\odot}$ of the companion from SED modelling.

Herschel far-IR observations

Figure 3.16 shows the *Herschel*/PACS observations of V Eri. Based on these observations and the lack of extended emission in both bands, the star was declared a point source by Cox et al. (2012).

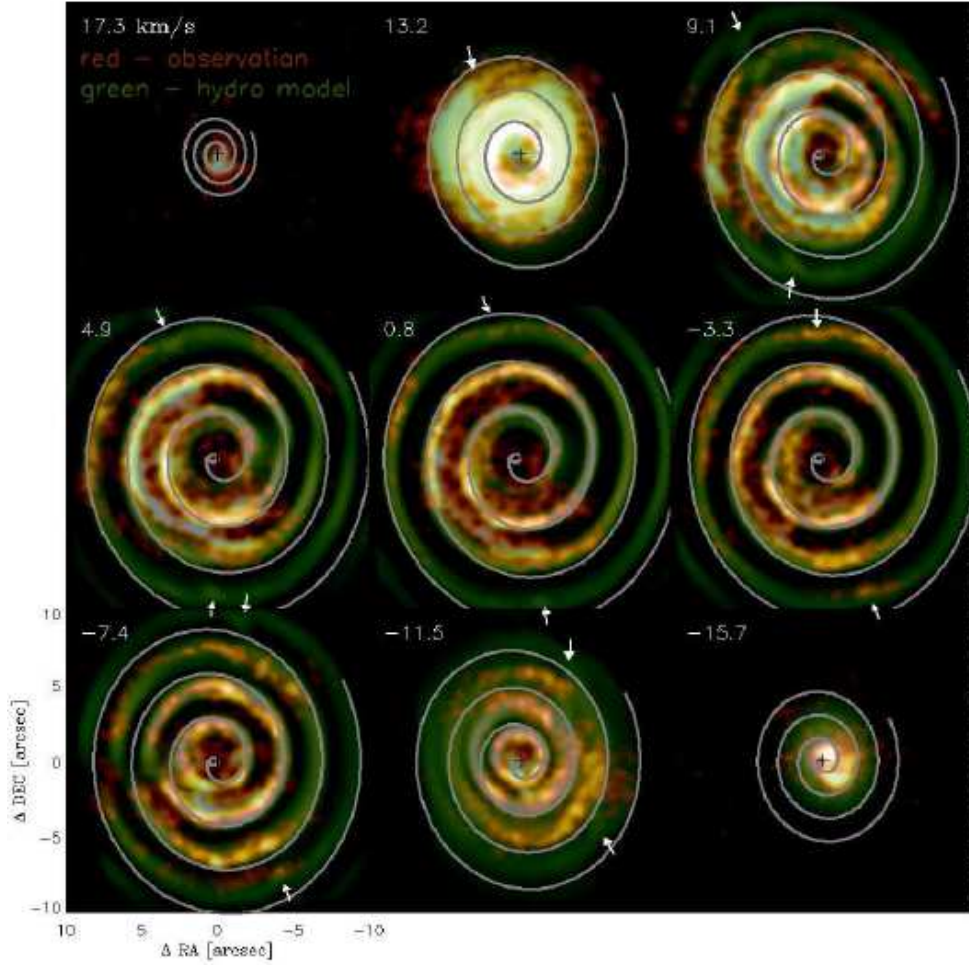


Figure 3.17.: Image of CIT 6 by Kim et al. (2013) showing the velocity channel maps from the VLA $\text{HC}_3\text{N}(J=4-3)$ observations by Claussen et al. (2011) in red together with the binary interaction model (green).

3.1.13. CIT 6 (RW Leonis Minoris)

The extreme carbon star CIT 6 is a well studied object located 440 pc away from the sun (Woods et al. 2003) and is, after IRC +10 216 (CW Leo), the second brightest C-star (Chau et al. 2012). Both stars share similar stellar properties and are believed to be in a transition phase from AGB to post-AGB (Kim et al. 2013). Johnson & Jones (1991) remark that the star might be already in the PPN phase. According to the GCVS, CIT 6 is a SRa variable C4,3eV star with a period of 640 days (Samus et al. 2004). Woods et al.

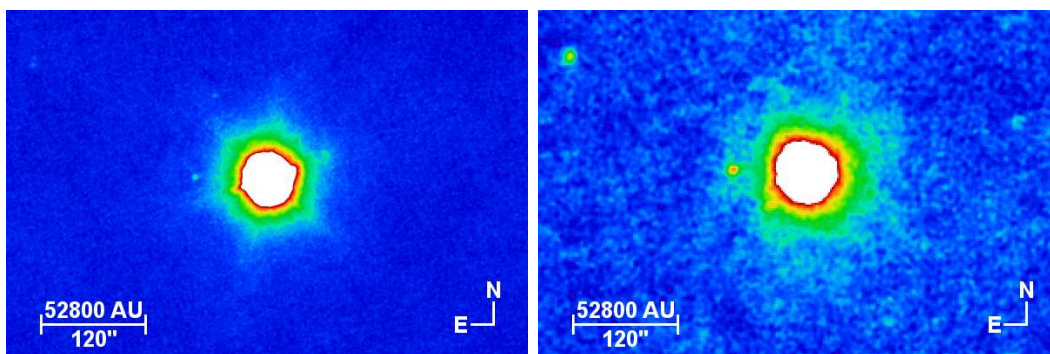


Figure 3.18.: PACS images of CIT 6 at $70\mu\text{m}$ (left) and $160\mu\text{m}$ (right).

(2003) studied the properties of the star and found a (variable) MLR $\dot{M} = 5 \times 10^{-6} M_{\odot} \text{yr}^{-1}$ and wind velocity $v_w = 17.0 \text{ km s}^{-1}$ from CO line modelling. A luminosity of $5912 L_{\odot}$ and a huge stellar radius of $641 R_{\odot}$ was derived by De Beck et al. (2010) while Ramstedt & Olofsson (2014) found $L = 10\,000 L_{\odot}$ together with $T_{\text{eff}} = 1800 \text{ K}$, $\dot{M} = 6.0 \times 10^{-6} M_{\odot} \text{yr}^{-1}$, and $v_w = 17.0 \text{ km s}^{-1}$ from SED and CO line modelling.

The binary nature of CIT 6 was suspected from HST observations by Monnier et al. (2000) who found a second compact source at P.A. = 10° separated by $0.17''$ (75 au at 440 pc) from the primary AGB star. This detection is supported by observations carried out with the VLA in the HC_3N (J=5-4) by Dinh-V.-Trung & Lim (2009) which revealed a full fledged one-arm spiral with two windings covering approximately $15''$. CIT 6 was, after AFGL 3068 (see 3.1.14), the second AGB star for which a spiral pattern was observed. Given a distance of 440 au and the observed spiral spacing, the authors derived a separation of the binary system of ≈ 70 au with an orbital period of about 600 years (Dinh-V.-Trung & Lim 2009). The derived separation is similar to the HST detection and supports the binary hypothesis. Claussen et al. (2011), however, argued that the observed structures reflect multiple incomplete shells rather than a spiral pattern. Recently, Sahai & Mack-Crane (2014) discovered two extended half-rings with diameters of $15'$ and $18'$ in the far-UV with GALEX. The authors suggest that these rings are caused by interaction with the local ISM. The GALEX near-UV band does not show any emission (Sahai & Mack-Crane 2014).

Kim et al. (2013) modelled the VLA observations and included also the inclination of the viewing angle with respect to the orbital plane in order to explain knots and disrupted parts of the CSE which are visible on position-velocity plots of the VLA HC_3N (J=4-3) observations (Claussen et al. 2011). Figure 3.17 shows the observations and models by Kim et al. (2013). The

authors conclude that a configuration consisting of a $0.8 M_{\odot}$ primary and a $2.2 M_{\odot}$ companion separated by 68 au fits nicely the spiral pattern when observing it from an angle of 60° with respect to the orbital plane. An average wind velocity of 15.7 km s^{-1} at a distance of 400 pc was also determined from the model (Kim et al. 2013).

Herschel far-IR observations

In contrast to the molecular line observations, the far-IR PACS observations do not show extended dust emission around CIT 6 (see Fig. 3.18). This might be due to the fact that the spiral observed with VLA is too small ($15''$), thus covering a region where the PACS image is still dominated by the PSF. Therefore, Cox et al. (2012) described the star as a point source.

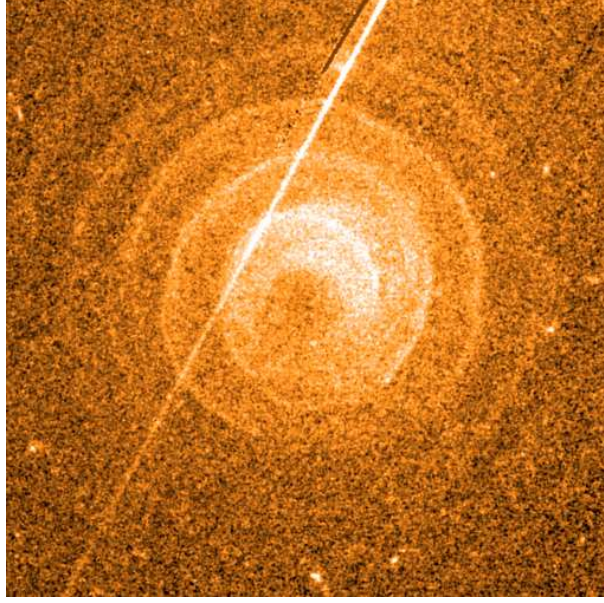


Figure 3.19.: HST/ACS image of AFGL 3068 at 606 nm (Mauron & Huggins 2006). The star itself is not visible at this wavelength but the CSE shaped as an Archimedean spiral.

3.1.14. AFGL 3068 (LL Pegasi)

AFGL 3068 (LL Peg) is an extreme carbon star with a high MLR of $3.1 \times 10^{-5} M_{\odot} \text{ yr}^{-1}$ and wind velocity of 16 km s^{-1} (De Beck et al. 2010). From SED and CO modelling Schöier et al. (2013) found $L = 7800 L_{\odot}$, $T_{\text{eff}} = 2000 \text{ K}$, $\dot{M} = 1.0 \times 10^{-5} M_{\odot} \text{ yr}^{-1}$, and $v_w = 13.5 \text{ km s}^{-1}$. It is the most distant physically related binary system in the MESS sample, located approximately 980 pc from the sun. Despite its distance, AFGL 3068 is a cornerstone object in the field of binary interaction with the stellar AGB wind.

Observations done with the HST-ACS in the F606W filter by Mauron & Huggins (2006) revealed a true Archimedean spiral around the star – the first observed indication of a binary-wind interaction on the AGB more than 10 years after these spirals were predicted in hydrodynamical simulations by Theuns & Jorissen (1993). The HST/ACS image shows a single-armed spiral pattern with five constant windings in dust-scattered galactic light. The spiral can be traced out to a distance of $12''$ from the star ($\approx 12000 \text{ au}$). The individual spiral arms are separated by $2.29''$ and show the density profile of thin shells with widths smaller than $0.5''$ (Mauron & Huggins 2006). From the arm separation ($\rho = 2.29''$), the wind velocity ($v_w = 16 \text{ km s}^{-1}$), and the

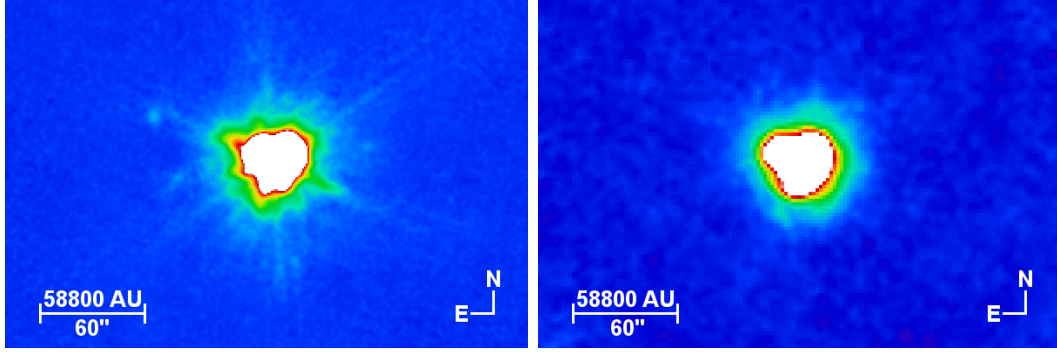


Figure 3.20.: PACS images of AFGL 3068 (LL Peg) at $70\mu\text{m}$ (left) and $160\mu\text{m}$ (right).

masses of the system ($M_1 = 2 M_\odot$ and $M_2 = 0.5 M_\odot$) the authors derive a separation of the binary system of 120 au at 1 kpc with an orbital period of 830 yr. AFGL 3068 was until then not known to have a companion. This was confirmed later by Morris et al. (2006) who were able to resolve the companion separated by 109 au on H and K -band images from Keck II/NIRC2.

Herschel far-IR observations

Figure 3.20 pictures the Herschel/PACS observations at 70 and $160\mu\text{m}$. Due to the lack of extended emission, the star was classified as point source by Cox et al. (2012).

3.1.15. VY Canis Majoris

VY CMa is an outstanding object in the solar vicinity given its diameter which is 1400 times bigger than the sun (13 au; Wittkowski et al. 2012). It is an extensively studied star of spectral type M2.5-M5eIa (Wallerstein 1958) and the only (suspected) binary Red Supergiant in the MESS sample. Compared to an AGB star, the stellar properties of VY CMa are enormous. Wittkowski et al. (2012) derived the luminosity with $L = 2.7 \times 10^5 L_{\odot}$, which exceeds that of an average AGB star by a factor of 50. The same authors also pinned down an effective temperature of 3500 K and the initial mass of the star with $25 \pm 10 M_{\odot}$ of which $17 \pm 8 M_{\odot}$ are left, which means that VY CMa might be a Supernova type II progenitor. Currently, the star loses $1.85 \times 10^{-4} M_{\odot} \text{ yr}^{-1}$ which leave the star with a velocity $v_w = 46.5 \text{ km s}^{-1}$ (Danchi et al. 1994; Matsuura et al. 2014). The distance to the star was determined to be $\approx 1.2 \text{ kpc}$ (Choi et al. 2008; Zhang et al. 2012).

Observations in the 1920s already suggested that VY CMa is embedded in a complex nebula (Perrine 1923). In more recent observations, Monnier et al. (1999), Smith et al. (2001), Humphreys et al. (2007), and Jones et al. (2007) studied the kinematics of the stellar wind in the optical and showed that it is highly asymmetric including several arcs, fingers and loops all within a few arcseconds from the star. Interestingly, the CSE is mostly extended to the west and south of the star, and only a small part of the emission and smaller structures are found east. Smith et al. (2001) suggests that this is caused by a higher extinction north and east to the star, possibly obscured by the dark cloud Lynds 1667, at whose western edge VY CMa is situated (Humphreys et al. 2007). In the IR, the star was studied by e.g., Monnier et al. (1999, 2004) who found similar structures to the optical but the overall shape of the nebula is much more symmetric.

The binary nature of VY CMa is under discussion for many years because the knots seen in the optical nebula were in early observations often mistaken as a companion. Throughout the 1970s, VY CMa was regarded as a single star (e.g., Worley 1972), but Humphreys et al. (2007) pointed out that a close low mass companion could produce the perturbations. Altogether, the evidence for binarity is weak and most of the authors that studied the nebula relate the asymmetric features to strong magnetic fields or mass ejecta from active regions on the star but an investigation of the interaction of the ejecta with a companion could be an interesting topic for future studies.

Herschel far-IR observations

Cox et al. (2012) categorized VY CMa as a point source based on the *Herschel*

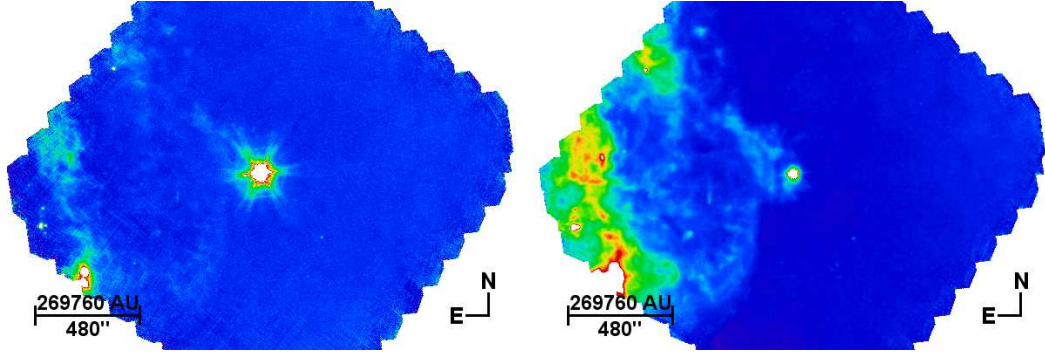


Figure 3.21.: PACS images of VY CMa at $70\mu\text{m}$ (left) and $160\mu\text{m}$ (right).

far-IR images (see Fig. 3.21). However, at the edges of the frames a large-scale structure is visible in both bands, best at $160\mu\text{m}$. Unfortunately, it seems that most of the emission is cut off at the edge, which complicates to distinguish the origin of the structure. The structure itself is huge, located approximately $14'$ east of VY CMa, clumpy and filamentary with bright areas and connected to the star via a filamentary arm. The emission appears curved in the SE which suggests a bow shock shape. However, the proper motion of VY CMa is not very well determined. The values obtained from Hipparcos (van Leeuwen 2007) are significantly different from maser spot measurement of Zhang et al. (2012) who propose a motion that differs from the Hipparcos by approx. 180° , thus no statement can be done concerning the orientation of the structure seen at $160\mu\text{m}$ and the direction of the space motion.

Most likely, the structure reflects a part of the dark cloud Lynds 1667, which is located east of the star and a tail of the cloud reaches VY CMa (Humphreys et al. 2007). In this case, the categorisation as a point source by Cox et al. (2012) would be correct, since the emission is not part of the CSE.

The star was also studied with *Herschel*/HIFI to probe the molecular line inventory of the envelope. Alcolea et al. (2013) found that VY CMa is very rich in molecular lines and a strong emitter of less abundant molecules (other than ^{12}CO and H_2O). However, a new molecular species was not identified in these observations. A similar study using PACS and SPIRE was performed by Matsuura et al. (2014) who found more than 260 emission lines in the far-IR data.

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A.1. Kurzfassung

Diese Dissertation handelt von den Wechselwirkungen zwischen dem Wind eines Sterns auf dem asymptotischen Riesenast (AGB) und einem Begleitstern. Wenn Helium im Kern eines Sterns aufgebraucht ist, endet das Leben von Sternen geringer und mittlerer Masse und sie steigen den AGB des Hertzsprung-Russell Diagramms hinauf. In dieser letzten Phase des Sternlebens wird ein Großteil der Masse in Form eines staubreichen Sternwindes abgegeben, bis nur noch der Kern übrig bleibt. Im einfachsten Fall expandiert der Wind in das umgebende interstellare Medium und formt eine sphärische Windblase. Beobachtungen des *Herschel Weltraumteleskops* zeigen jedoch, dass die zirkumstellaren Hüllen vieler AGB Sterne keineswegs sphärisch symmetrisch sind.

Einer der Gründe hierfür kann ein Begleitstern sein. In einem gewissen Abstandsbereich zum AGB Stern kann der Begleiter einen Teil des Windes akkretieren, und ein Schweif entsteht, der sich um das Doppelsternsystem wickelt. Darüber hinaus wird der AGB Stern auf einen Orbit um das gemeinsame Massenzentrum gezwungen, was dem ausgestoßenen Sternwind eine zusätzliche Geschwindigkeitskomponente gibt. Beides führt zu einer Windblase, die nicht mehr länger rund sondern die Form einer Archimedischen Spirale hat. Abhängig vom Abstand der beiden Sterne sind aber auch andere Windmorphologien möglich.

Diese Doktorarbeit zeigt zum ersten Mal, dass diese Interaktionen auch im fernen Infrarot erforscht werden können. *Herschel* Beobachtungen von 18 AGB-Doppelsternsystemen werden vorgestellt, die alle Teil des *Mass loss of Evolved StarS* Samples sind. Die Beobachtungen führten zu drei Veröffentlichungen als Erstautor, die detailliert die deformierten Sternhüllen von vier bekannten AGB Sternen behandeln: *o* Ceti, R Aquarii, W Aquilæ und π^1 Gruis. Sie alle zeigen deutliche Hinweise auf eine Wechselwirkung mit einem Begleitstern. Die Staubemission um *o* Cet und W Aql ist spiralförmig, während R Aqr so viel

Masse auf seinen Begleitstern, einen Weißen Zwerg, transferiert, dass sich eine symbiotische Nova bildet. π^1 Gru wird sogar von zwei Begleitern beeinflusst, was sich aus seiner Windmorphologie ablesen lässt.

Diese Dissertation stellt eine der detailliertesten Beobachtungsstudien von Interaktionen in einem AGB-Doppelsternsystem dar.

A.2. Abstract

This dissertation deals with the interaction of the stellar wind of an asymptotic giant branch (AGB) star with a companion. When helium in the stellar core is depleted, the lifetime of low and intermediate mass stars come to an end and the ascent on the AGB of the Hertzsprung-Russell diagram begins. In this terminal phase of stellar life most of the mass is lost by a dusty stellar wind until only the stellar core, a white dwarf remains. In the simplest scenario, the stellar AGB wind expands freely into the surrounding interstellar medium forming a spherical wind bubble. Observations with the *Herschel Space Observatory*, however, reveal that the circumstellar envelopes of a large number of AGB stars deviate massively from spherically symmetric.

One of the reasons can be the presence of a companion. At certain separations of the components the companion can attract part of the wind which forms an accretion wake behind the companion as it moves around the AGB star. In addition, the AGB star itself is forced to perform an orbital motion around the centre of mass which adds an additional velocity component to the wind. Both alter the wind morphology, which no longer appears spherical but shaped as an Archimedean spiral. Depending on the orbital separation, also other wind morphologies are encountered in binary systems.

The thesis at hand shows for the first time that these binary interaction features can be observed and studied in the far-infrared wavelength regime. *Herschel* observations of 18 AGB stars in binary systems as part of the Mass loss of Evolved StarS sample are studied of which many show asymmetric wind shapes. Three first-author publications are presented which give an in-depth study of the astonishing surroundings of the well known AGB stars *o* Ceti, R Aquarii, W Aquilæ, and π^1 Gruis. All of them show clear indications of an interaction with a companion, each object in its own way: *o* Cet and W Aql reveal a detailed spiral around the binary system, while R Aqr transfers so much mass to its white dwarf companion that a dusty symbiotic nova is observed. The wind of π^1 Gru is even shaped by two companions.

So far, this work constitutes one of the most extensive observational studies of the binary-wind interaction on the AGB.

A.3. A&A reprint permission

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A.4. Abbreviations

Abbreviation	Meaning	Page
2MASS	Two Micron All Sky Survey	73
AAVSO	American Association of Variable Star Observers	77
ACS	Advanced Camera for Surveys	55
AGB	asymptotic giant branch	9
ALMA	Atacama Large Millimetre/submillimetre Array	55
AMBER	Astronomical Multi-BEam combineR	82
ASAS	All Sky Automated Survey	77
BHL	Bondi-Hoyle-Lyttleton	38
CE	common envelope	36
COBE	Cosmic Background Explorer	10
CoM	centre of mass	35
COMARCS	Copenhagen Opacities of Model Atmospheres in Radiative and Convective Scheme	74
CSE	circumstellar envelope	30
DEC	declination	109
DMSA	Double and Multiple System Annex	71
EMMI	ESO Multi Mode Instrument	75
ESA	European Space Agency	9
ESO	European Southern Observatory	75
ESTEC	European Space Research and Technology Centre	11
FIRST	Far-Infrared and Submillimetre Telescope	9
FITS	Flexible Image Transport System	16
FoV	field of view	12
FWHM	full width at half maximum	13
GALEX	Galaxy Evolution Explorer	41
GCVS	General Catalogue of Variable Stars	31
GTKP	guaranteed time key program	19
HIFI	Heterodyne Instrument for the Far-Infrared	12
HIPE	Herschel Interactive Processing Environment	14
HRD	Hertzsprung-Russell diagram	20
HSA	Herschel Science Archive	14
HST	Hubble Space Telescope	55
IDL	Interactive Data Language	15
IMF	initial mass function	23
IR	infrared	9
IRAS	Infrared Astronomical Satellite	10
ISM	interstellar medium	42
ISO	Infrared Space Observatory	9
JAXA	Japanese Aerospace Exploration Agency	106
LBV	luminous blue variable	19
LMC	large magellanic cloud	31
LWS	long wave spectrometer	73
MATISSE	Multi-AperTure mid-Infrared SpectroScopic Experiment	106
MEM	maximum entropy method	16
MESS	Mass loss of Evolved StarS	19
MLR	mass loss rate	19
MS	main sequence	22
NIRC2	near-infrared camera 2	138
NTSI	non-linear thin shell instability	51
P.A.	position angle	57
PACS	Photodetecting Array Camera and Spectrometer	10
PI	principal investigator	95
PIONIER	Precision Integrated-Optics Near-infrared Imaging ExpeRiment	94
PLM	payload module	10
PN	planetary nebula	19
PPN	proto-planetary nebula	129

APPENDIX A. APPENDIX

PSF	point spread function	15
RA	right ascension	94
RGB	red giant branch	20
RLOF	Roche-lobe overflow	36
RSG	red supergiant	19
RV	radial velocity	39
SAO	Smithsonian Astrophysical Observatory	74
SED	spectral energy distribution	67
SNR	Supernova remnant	19
SOFIA	Stratospheric Observatory for Infrared Astronomy	105
SPH	smoothed-particle hydrodynamics	61
SPICA	SPace Infrared telescope for Cosmology and Astrophysics	106
SPIRE	Spectral and Photometric Imaging Receiver	12
SR	semi-regular	31
STIS	Space Telescope Imaging Spectrograph	129
SVM	service module	10
SWS	short wave spectrometer	73
TAI	transverse acceleration instability	51
TP	thermal pulse	19
USNO	US Navel Observatory	74
UV	ultraviolet	30
VIM	variability-induced mover	39
VISIR	VLT spectrometer and imager for the mid-infrared	108
VLA	Very Large Array	56
VLT	Very Large Telescope Interferometer	60
WD	white dwarf	23
WFPC	Wide Field and Planetary Camera	77
WMAP	Wilkinson Microwave Anisotropy Probe	10
WR	Wolf-Rayet	19
ZAMS	zero-age main sequence	19

A.5. Constants

Constant	Meaning	Value
m_{H}	atomic mass unit	$1.661 \times 10^{-27} \text{ kg}$
G	gravitational constant	$6.673 \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}$
c	speed of light	$2.998 \times 10^8 \text{ m s}^{-1}$
k	Boltzmann constant	$1.381 \times 10^{-23} \text{ J K}^{-1}$
h	Planck constant	$6.626 \times 10^{-34} \text{ J s}$
σ	Stefan-Boltzmann constant	$5.670 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$
$M_{\odot}$	solar mass	$1.989 \times 10^{30} \text{ kg}$
$L_{\odot}$	solar luminosity	$3.839 \times 10^{26} \text{ J s}^{-1}$
$R_{\odot}$	solar radius	$6.955 \times 10^8 \text{ m}$
pc	parallax second	$3.086 \times 10^{16} \text{ m}$
au	astronomic unit	$1.496 \times 10^{11} \text{ m}$
eV	electron volt	$1.602 \times 10^{-19} \text{ J}$
Jy	Jansky	$10^{-26} \text{ J s}^{-1} \text{ m}^{-2} \text{ Hz}^{-1}$

A.6. Observing proposal for ESO P93A

The following paragraph includes the successful ESO proposal to observe the close surroundings of π^1 Gruis with VLTI/PIONIER in period 93A. Two nights were granted and the observing run was executed in September 2014. The results of this study are not included in this thesis and will be part of a forthcoming publication.

APPENDIX A. APPENDIX



European Organisation for Astronomical Research in the Southern Hemisphere

OBSERVING PROGRAMMES OFFICE • Karl-Schwarzschild-Straße 2 • D-85748 Garching bei München • e-mail: opo@eso.org • Tel.: +49 89 320 06473

APPLICATION FOR OBSERVING TIME

PERIOD: **93A**

Important Notice:

By submitting this proposal, the PI takes full responsibility for the content of the proposal, in particular with regard to the names of CoIs and the agreement to act according to the ESO policy and regulations, should observing time be granted.

1. Title					Category: D-2					
Hunting out the close companion of π^1 Gruis										
2. Abstract / Total Time Requested Total Amount of Time: 2 nights VM, 0 hours SM A companion interacting with the circumstellar environment (CSE) is the most accepted explanation for the presence of asymmetric planetary nebulae (PN). In the previous phase of stellar evolution, on the asymptotic giant branch (AGB), evidence for this interaction was observed only in the CSEs of a handful of objects. To close the gap between the AGB and the PN phase we propose to image with VLTI/PIONIER the environment of π^1 Gru which is close to the tip of the AGB. <i>Herschel</i> far infra-red images reveal an asymmetric wind morphology, while an analysis of the Hipparcos Intermediate Astrometric Data (IAD) supports the presence of a close companion. The proposed observations will allow to determine the position of the companion and the precise separation from the AGB star, which is needed to model the binary interaction.										
3.	Run	Period	Instrument	Time	Month	Moon	Seeing	Sky	Mode	Type
A		93	SpecialVLTI	1n	aug	n	1.2	THN	v	
B		93	SpecialVLTI	1n	aug	n	1.2	THN	v	
4. Number of nights/hours Telescope(s) Amount of time a) already awarded to this project: b) still required to complete this project:										
5. Special remarks: Data important for the PhD thesis of A. Mayer (mid-course).										
6. Principal Investigator: Andreas Mayer, a.mayer@univie.ac.at, AT, Universitaet Wien, Institut fuer Astrophysik										
6a. Co-investigators: C. Paladini Institut d'Astronomie et d'Astrophysique, Universite libre de Bruxelles, B JB. Le Bouquin Laboratoire d'astrophysique de Grenoble, Observatoire de Grenoble, F A. Jorissen Institut d'Astronomie et d'Astrophysique, Universite libre de Bruxelles, B J. Kluska Laboratoire d'astrophysique de Grenoble, Observatoire de Grenoble, F <i>Following CoIs moved to the end of the document ...</i>										

7. Description of the proposed programme

A – Scientific Rationale: **Shaping asymmetric winds during the AGB phase and beyond.**

Mass loss is one of the most important factor in the post main sequence evolution, making low- and intermediate-mass stars crucial contributors to the chemical enrichment of the Universe. Although the mass loss process on the AGB has been studied for over 40 years, many basic aspects are still not understood. This is especially the case for the geometry of the process and how it influences the following phase of stellar evolution when the star expels its envelope as a planetary nebula (PN). Although $\approx 70\%$ of the observed PNe are not spherically symmetric (e.g. Miszalski et al. 2009), and neither are the winds of post-AGB objects (e.g. Bujarrabal et al. 2013), the AGB wind morphology is widely regarded as such. So far, the most accepted explanation that accounts for the asymmetries observed in the PN phase is the presence of a nearby companion in the environment of the (once) mass-losing star. Observations of an interaction between a companion and stellar wind on the AGB were only successful for a handful of objects (Mauron & Huggins 2006, Dinh-V.-Trung & Lim 2008, Mayer et al. 2011, Maercker et al. 2012, Mayer et al. 2013). All of the objects show a spiral pattern caused by the orbital motion of a companion. This feature occurs when the mass of the companion forces the primary to move around the center of mass while ejecting the dusty wind. The companion itself accretes the material via wind-Roche-lobe overflow (WRLOF) or Bondi-Hoyle accretion and an accretion wake forms opposite to the direction of the orbital motion. The resulting spiral pattern was already proposed by hydrodynamic simulations of Theuns & Jorissen (1993) and later refined by Mastrodemos & Morris (1998,1999), and Kim & Taam (2012a,b,c). These simulations suggest that binary systems separated by five to a few hundred AU form spirals. However, due to resolution constraints, all objects that exhibit spirals are separated by more than 50 AU. The closer, and for shaping PNe more important systems are thus lacking.

We therefore propose the observations of π^1 Gru, which will help the scientific field in two ways: i) there is strong evidence that the system consists of three objects, thus π^1 Gru is the only known triple system with an asymmetric wind. ii) The detection of the close companion will make π^1 Gru a prototype for the shaping of pre-PNe because the star is near the edge of the AGB, and the close companion has a major impact on the very extended atmosphere of the star. Thus it will build a bridge from the AGB to the PN, and help to understand the evolution of asymmetric winds.

B – Immediate Objective:

We propose to image the environment of the AGB star π^1 Gru with VLTI/PIONIER. π^1 Gru is an S5,7 SRb variable with a period of 150 days and due to its proximity ($D=163$ pc; van Leeuwen 2007), a well-studied object. According to van Eck et al. (2000), the star appears to be very evolved and close to the tip of the asymptotic giant branch given its bolometric magnitude and $(V-K)_0$ colour. This assumption is supported by the presence of spectral lines from the element Tc (Jorissen et al. 1993). The star is known to have a G0V companion located $\approx 2.7''$ (≈ 450 AU) away from the primary. Frankowski et al. (2007) and Makarov & Kaplan (2005) found that the long-term Tycho-2 proper motion differs significantly from the short-term Hipparcos motion, indicating that π^1 Gru is influenced by the orbital motion of a companion. However, such variations require that the companion orbits with a period of 1500 to 30 000 days, much shorter than the 2×10^6 days that are expected for the G0V companion. A study of the Hipparcos IAD performed along a method described by Pourbaix & Jorissen (2000) revealed that the photocenter of the system shows an orbital motion with a period of 5–11 years (see Fig. 1: left) pointing towards a companion separated by 20–50 mas (3–8 AU) given a mass range of $0.5\text{--}1.5 M_{\odot}$ (spectral type K5V to F5V). This object is in the field of view of the PIONIER interferometer.

Strong evidence for the presence of a close companion is given by observations of the material around the system. π^1 Gru has a rich history of CO and SiO line observations in the past 20 years (e.g. Sahai 1992, Knapp et al. 1999, Chiu et al. 2006). In all of the observations, the CO(2–1) profile shows an asymmetric, double-peaked structure and extended emission wings which are interpreted as an expanding disk and a fast bipolar outflow oriented perpendicular to the disk. As observed with *Herschel*/PACS, the environment of π^1 Gru is dominated by an elliptical emission and a hook east of the star at a distance of $38''$ (see Fig. 1: center). This kind of hooks or arcs are most probably part of an Archimedean spiral formed by the interaction with a companion (cf. α Ceti; Mayer et al. 2011). The extent of the hook clarifies that it is caused by the wide companion. However, the appearance as a hook and not a full-fledged spiral implies that something is disturbing the accretion of material on the companion, or that the wind geometry is not isotropic. Our target was already observed with VLTI/AMBER in low resolution mode, and the observations showed the presence of a strong asymmetry (Mayer et al. in prep.). Unfortunately the poor (u,v) coverage, and the poor data quality make the interpretation of this signature ambiguous. To dispel all doubts of the origin of this signature, imaging is needed to determine the position and separation of the close companion.

Observation and data reduction strategy

PIONIER is currently the best instrument in terms of efficiency, dynamic range, and precision (few %) to carry on imaging program at VLTI (see Fig. 1: right for an example of uv-coverage we will obtain with the requested observations). Data acquired will be reduced by the PIONIER Team (Le Bouquin) and we will use

7. Description of the proposed programme and attachments

Description of the proposed programme (continued)

two independent methods for the interpretation: imaging, and comparison of the visibilities with proper 2D models. The images will be reconstructed with different algorithms: BSMEM (Lykou; Buscher 1994) and MiRA (Le Bouquin, Kluska; Thiebaut 2008) to ensure the reliability of the result. If the primary star is too bright we will subtract the main source from the image, and study the pattern of the residual using the algorithm developed by Kluska et al. (2013, subm.). At this point the image will show the presence of the companion that will appear with the typical signature of the onset of a spiral. To confirm the result the visibilities and closure phases will be also interpreted (Mayer, Paladini, Siopis, Sadowski) with dedicated 2D models developed by Siopis & Sadowski (2012). The models are generated through software that simulates binary systems in a realistic way, using a Roche representation of the stellar surfaces and the MARCS stellar atmosphere models. The synthetic visibilities are obtained using custom model-fitting tools for optical-IR interferometry (Paladini; Li Causi). The PIONIER observations will complement the results from Herschel (Mayer, Jorissen, Kerschbaum), AMBER and MIDI (Paladini, Jorissen), and upcoming ALMA data (Ramstedt). **This program will secure the first image of the circumstellar environment of π^1 Gru within 50 mas from the target, and it will unveil the position and separation of the second companion which is up to now unknown. Together with the Hipparcos IAD and the other archive observations, it will be possible to define an orbit of the close companion.**

Attachments (Figures)

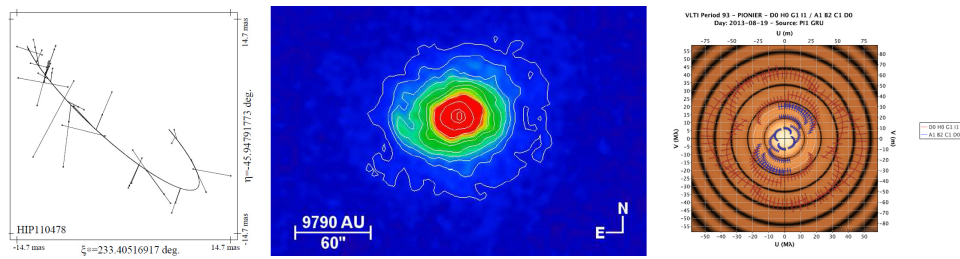


Fig. 1. *Left*: an orbital motion of the photocenter of π^1 Gru was found in the Hipparcos Intermediate Astrometric Data. Analysis of these data suggests an orbital period of 5–11 years. *Centre*: deconvolved $70\mu\text{m}$ Herschel/PACS image of π^1 Gru. The far-IR emission reveals an arc east of the star that is most likely part of a spiral pattern. *Right*: uv-coverage expected for the PIONIER observations.

8. Justification of requested observing time and observing conditions

Lunar Phase Justification: **PIONIER: No constraints of lunar phase for VLTI observations.**

Time Justification: (including seeing overhead) The goal of this proposal is to obtain an image of π^1 Gru. For this purpose we need to gather the best possible (u,v) coverage within a short amount of time as the star is a variable. We cannot also recombine the different spectral channels into a single image because of the strong spectral behaviour of the atmosphere. We should rather compute one independent image per spectral channel. Consequently, the uv-plane coverage per image does not benefit from the spectral-supersynthesis effect, used in image reconstruction. This is why we really need to gather 2 full nights of observations with the small and intermediate quadruplets. The star is observable the full night in the end of August 2014.

8a. Telescope Justification:

VLTI is the only telescope in the world that can properly image the extended atmosphere of AGB stars (as already demonstrated by Le Bouquin et al. 2009; Chiavassa et al. 2010). Its main competitor - the CHARA array - does not provide the short baselines essential to image these complex objects. π^1 Gru is perfect target for the ATs because of its brightness. PIONIER is ideally suited for spectro-imaging campaign because it combines 4 telescopes (instead of 3 like in AMBER) with high angular precision.

8b. Observing Mode Justification (visitor or service):

PIONIER: the instrument is operated in visitor mode only, but this program is suitable for delegated-visitor mode.

8c. Calibration Request:

Standard Calibration

APPENDIX A. APPENDIX

9. Report on the use of ESO facilities during the last 2 years 187.D-0924 (PI Paladini): VISIR data not acquired due to technical problems, MIDI paper will be submitted in Fall 2013. One conference proceeding. 088.D-0340 and 091.D-0382 (PI Paladini): only 1/3 of the first program was observed and had good quality. We are waiting for model calculations. The data will be merged with the one of the program 091.D-0382 in one single paper. 090.D-0410 + 092.D-0665 (PI Paladini): 5 of 8.3h observed, data reduced but only half of them have good quality. We are waiting for data of program 092.D-0665 to submit a regular paper, otherwise this will be a research note. 090.D-0333 (PI Paladini): data reduced, image reconstructed, interpretation ongoing, letter will be submitted in Fall 2013. Twelve referee publications based on PIONIER data to date (http://ipag.osug.fr/pionier), work in progress for at least five additional publications. Three ESO announcements or press-release <i>ann1081</i> (Nov. 2010), <i>ann11021</i> (March 2011) and <i>eso1148</i> (December 2011).
9a. ESO Archive - Are the data requested by this proposal in the ESO Archive (http://archive.eso.org)? If so, explain the need for new data. This star has already been observed by AMBER, however definite conclusions require a rich, precise and homogeneous dataset in order to perform image reconstruction which is best done with a four telescope operation. The AMBER data are part of the paper Mayer et al. (2013, prep.).
9b. GTO/Public Survey Duplications: The star is not part of GTO programs for the current period.
10. Applicant's publications related to the subject of this application during the last 2 years van Belle G., Paladini, C., et al. 2013, ApJ: The PTI Carbon Star Angular Size Survey: Effective Temperatures and Non-Sphericity. Mayer A., Jorissen A., Kerschbaum F. et al., 2013, A&A, 549, A69: Large-scale environments of binary AGB stars probed by Herschel. I. Morphology statistics and case studies of R Aquarii and W Aquilae Mayer A., Jorissen A., Kerschbaum F. et al., 2011, A&A, 531, L4: Herschel's view into Mira's head Klotz D., Sacuto S., Kerschbaum F. et al., 2012, A&A, 541, A164: The geometry of the close environment of SV Piscium as probed by VLTI/MIDI Jorissen A., Mayer A. et al., 2011, A&A, 532, A135: X Herculis and TX Piscium: two cases of ISM interaction with stellar winds observed by Herschel Paladini C., Sacuto S., Klotz D. et al., 2012, A&A, 544, L5: Detection of an asymmetry in the envelope of the carbon Mira R Fornacis using VLTI/MIDI Cox N., Kerschbaum F., van Marle A.-J., Decin L., Ladjal D., Mayer A., Groenewegen M.A.T., Van Eck S., Royer P., Ottensamer R., Ueta T., Jorissen A., Mecina M., et al., 2012, A&A, 537, A35: A far-infrared survey of bow shocks and detached shells around AGB stars and red supergiants De Becker, M., et al, 2012, MNRAS 423, 2711D: The particle accelerator HD 167971 revealed by long baseline interferometry Defrere, D. et al. 2012, A&A 546L, 9D: Hot circumstellar material resolved around beta Pic with VLTI/PIONIER Le Bouquin J-B, Berger J-P, et al. 2011, A&A 535A, 67L: PIONIER: a 4-telescope instrument for VLTI Absil O., Le Bouquin J-B, et al., 2011, A&A, 535A, 68A: Searching for faint companions with PIONIER Blind N., Boffin H., Berger J-P. et al., 2011, A&A, 536A, 55B: The symbiotic star SS Leporis: Milli-arcsecond imaging with PIONIER

A.6. Observing proposal for ESO P93A

11. List of targets proposed in this programme

Run	Target/Field	α (J2000)	δ (J2000)	ToT	Mag.	Diam.	Additional info	Reference star
A	pi1 Gru	22 22 44	-45 56 52	10	6.14	20		
B	pi1 Gru	22 22 44	-45 56 52	10	6.14	20		

Target Notes: The photospheric diameter of π^1 Gru is derived by fitting AMBER low resolution data with uniform disc. The AMBER data had poor uv coverage, and baseline length limited to < 50 m. Already at 40 m we had differential and closure phase signature.

12. Scheduling requirements

A.6. Observing proposal for ESO P93A

13. Instrument configuration

Period	Instrument	Run ID	Parameter	Value or list
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APPENDIX A. APPENDIX

14. List of interferometry targets proposed in this programme

Run	Name	Vmag	mag(λ)	λ_{obs}	size(λ)	Baseline	Vis.	mag_c	Tot
A	pi1 Gru	6.14	-1.88	1.6	20	A1-B2-C1-D0	0.55	-1.23	10
B	pi1 Gru	6.14	-1.88	1.6	20	D0-H0-G1-I1	0.05	1.37	10

VLT Target Notes: The values for visibility and correlated magnitude are lower limits.

15. Visitor instrument

Description of the instrument and of its operation: PIONIER (Precision Integrated Optics Near-infrared Imaging Experiment) provides VLTI with an observational capability, unique in the world, that combines imaging, sensitivity and precision. By the mean of the integrated optics technology, PIONIER is able to combine all the four ATs (or four UTs) providing simultaneous measurements of 6 visibilities and 3 closure phases, with two low spectral resolutions, i.e., broadband and $R \sim 40$. PIONIER interferogram acquisition concept is an extension of VINCI's to four telescopes, which combines fast acquisition with simultaneous photometric calibration (between 100 to 5 times faster than AMBER), therefore increasing significantly the precision on the interferometric data. PIONIER reads a small number of pixels and its sensitivity with respect to AMBER is increased by about 1.5 mag. PIONIER has been conceived to be a "point and shoot" instrument with limited request on the infrastructure except for the need to operate four telescopes simultaneously. Following the go-ahead from ESO and STC in 2009, the PIONIER team has interacted with the VLTI Paranal team in order to define all the proper instrumental interfaces. PIONIER is located on the VLTI laboratory and has its own combiner, detector, control and acquisition module. Once the VLTI presetted, PIONIER takes care of fringe acquisition, centering and data recording to its own archive. PIONIER is funded by Université Joseph Fourier (Grenoble) and french Programme National de Physique Stellaire. It has been developed by IPAG in collaboration with R. Millan-Gabet (Caltech) and W. Traub (JPL).

PIONIER is designed to carry out science objectives that could not be done with AMBER, requiring either imaging capability, sensitivity, or precision. The PIONIER science team regroups researchers from IPAG, Université de Liège, Caltech, JPL, CRAL (Lyon), LESIA (Paris), ESO (Santiago and Garching), Arcetri, Exeter. The proposals make use of PIONIER/VLTI imaging capability covering different topics related to the observation with milli-arcsecond resolution of various types of compact circumstellar environments, faint companions, and stellar surfaces. **The majority of these programs can be carried out with the ATs but few of them require the UTs.** We stress that the VLTI is the only observatory on earth capable of combining four giant (8 m) telescopes interferometrically, which opens the case of faint objects at the highest angular resolution such as the Galactic Center. VLTI is also the only interferometer with relatively large (1.8 m) relocatable telescopes, which makes it an ideal place to image interesting complex targets such as Young Stellar Objects. In order to operate with the maximum efficiency we request, when possible, to group the PIONIER runs into consecutive nights.

On which telescope(s) has your instrument been commissioned and/or used (scientific publications): **PIONIER is installed at the Paranal observatory since october 2010. We successfully demonstrated that the four UTs can be combined together with PIONIER in 2011 (ESO press release ann11021). The instrument matches the expectation in terms of sensitivity and imaging capabilities, as demonstrated in the dedicated publication: Le Bouquin et al. 2011 A&A, 535A, 68A. PIONIER data are already at the heart of more than 10 published papers. Several other publications are in preparation.**

Total weight and value of equipment to be shipped: The total weight of the equipment is approximately 700kg.

Weight at the focus (including ancillary equipment): PIONIER is located inside VLTI laboratory.

Compatibility of attachment interface with required telescope focus: PIONIER intercepts incoming VLTI beams 1,3,5,7 and requires no attachment interface.

Back focal distance value: PIONIER uses the VLTI afocal beams.

Acquisition, focusing, and guiding procedure: Instrument description in document LAOG-TRE-PNR-23000-1103 provided independently to ESO.

Compatibility with ESO software standards (data handling): PIONIER has been designed to be as much as possible ESO compliant (see LAOG-TRE-PNR-23000-1103). This is always true for software at interfaces. As of today data handling are managed inside the instrument but we have requested access to ESO's archiving facility. PIONIER data product is described in LAOG-SPE-PNR-23100-1127.

Estimate of supplies and services expected from ESO (in person days): At the request of STC, services expected from ESO have been evaluated by P. Haguenauer head of VLTI engineering and have been approved by Paranal observatory director A. Kaufer.

APPENDIX A. APPENDIX

6b. Co-investigators:

...continued from Box 6a.

F.	Kerschbaum	Universitaet Wien,Institut fuer Astrophysik,AT
F.	Lykou	Universitaet Wien,Institut fuer Astrophysik,AT
M.	Wittkowski	ESO Office Santiago,ESO
J.-P.	Berger	ESO Office Santiago,ESO
C.	Siopis	Institut d'Astronomie et d'Astrophysique,Universite libre de Bruxelles,B
G.	Sadowski	Institut d'Astronomie et d'Astrophysique,Universite libre de Bruxelles,B
G.	Li Causi	INAF - IASF di Roma,I
M.	Mecina	Universitaet Wien,Institut fuer Astrophysik,AT
S.	Ramstedt	Uppsala University,Department of Physics and Astronomy,S
E.	Lazareff	Laboratoire d'astrophysique de Grenoble,Observatoire de Grenoble,F
R.	Millan-Gabet	California Institute of Technology,Michelson Science Center,US

Curriculum Vitæ

Andreas Mayer

Education

- 2011–** Doctorate’s program at University of Vienna, Austria. Supervisor: F. Kerschbaum
- 2008-2011** Master’s program at University of Vienna, Austria
Master degree in Astronomy with thesis: “*X Herculis and TX Piscium: The interaction of their stellar winds with the interstellar medium observed by Herschel*”. Supervisor: F. Kerschbaum
- 2004-2008** Undergraduate studies at University of Vienna, Austria
Bachelor degree in Astronomy with thesis: “*Nucleosynthesis: Chemical elements and their astrophysical origin*”. Supervisor: F. Kerschbaum
- 2003** University-entrance diploma from Friedrich-von-Alberti-Gymnasium, Bad Friedrichshall, Germany

Teaching experience

- 2011** Tutoring lectures on astronomical instruments

Positions, grants & awards

- 2014** University of Vienna Ph.D. thesis grant
- 2013-2014** ASAP Grant position on Mapmaking and Deconvolution Algorithms for space applications
- 2011-2013** National Science Fund Position in Herschel project *Dust guaranteed*

Conferences

- Aug. 2014** Why Galaxies Care About AGB Stars III, Vienna, Austria (**Talk**)
- Dec. 2013** Astrospheres workshop, Leiden, The Netherlands (**Invited talk**)
- Nov. 2013** Asymmetrical Planetary Nebulae VI, Playa del Carmen, Mexico (**Talk**)
- Aug. 2013** Workshop on symbiotic stars, binary post-AGB and related, Wierzba, Poland (**Talk**)
- Aug. 2012** XXVIII IAU General Assembly, Beijing, China (**Invited talk**)
- Aug. 2011** Physical and chemical aspects of late stages of stellar evolution, Warsaw, Poland (**Poster**)
- Aug. 2010** Why Galaxies Care About AGB Stars II, Vienna, Austria (**Poster**)

B.1. Publication list

Refereed articles

- 2015 Dissecting the AGB star L₂ Puppis: a torus in the making**
 F. Lykou, D. Klotz, C. Paladini, J. Hron, A. A. Zijlstra, J. Kluska, B. R. M. Norris, P. G. Tuthill, S. Ramstedt, E. Lagadec, M. Wittkowski, M. Maercker, J. Meisner, **A. Mayer**, *In Astronomy & Astrophysics*, in press.
- 2014 The wonderful complexity of the Mira AB system**
 S. Ramstedt, S. Mohamed, W. H. T. Vlemmings, M. Maercker, R. Montez, A. Baudry, E. De Beck, M. Lindqvist, H. Olofsson, E. M. L. Humphreys, A. Jorissen, F. Kerschbaum, **A. Mayer**, M. Wittkowski, N. L. J. Cox, E. Lagadec, M. L. Leal-Ferreira, C. Paladini, A. Pérez-Sánchez, S. Saccuto, *In Astronomy & Astrophysics*, volume 570, L14, 2014.
- 2014 Large-scale environments of binary AGB stars probed by Herschel. II. Two companions interacting with the wind of π^1 Gruis**
A. Mayer, A. Jorissen, C. Paladini, F. Kerschbaum, D. Pourbaix, C. Siopis, R. Ottensamer, M. Mećina, N. L. J. Cox, M. A. T. Groenewegen, D. Klotz, G. Sadowski, A. Spang, P. Cruzalèbes, C. Waelkens, *In Astronomy & Astrophysics*, volume 570, A113, 2014.
- 2014 Dusty shells surrounding the carbon variables S Scuti and RT Capricorni**
 M. Mećina, F. Kerschbaum, M. A. T. Groenewegen, R. Ottensamer, J. A. D. L. Blommaert, **A. Mayer**, L. Decin, A. Luntzer, B. Vandenbussche, T. Posch, C. Waelkens, *In Astronomy & Astrophysics*, volume 566, pp. A69, 2014.
- 2013 Large-scale environments of binary AGB stars probed by Herschel. I. Morphology statistics and case studies of R Aquarii and W Aquilae**
A. Mayer, A. Jorissen, F. Kerschbaum, R. Ottensamer, W. Nowotny, N. L. J. Cox, B. Aringer, J. A. D. L. Blommaert, L. Decin, S. van Eck, H.-P. Gail, M. A. T. Groenewegen, K. Kornfeld, M. Mećina, T. Posch, B. Vandenbussche, C. Waelkens, *In Astronomy & Astrophysics*, volume 549, pp. A69, 2013.

2012 A far-infrared survey of bow shocks and detached shells around AGB stars and red supergiants

N. L. J. Cox, F. Kerschbaum, A.-J. van Marle, L. Decin, D. Ladjal, **A. Mayer**, M. A. T. Groenewegen, S. van Eck, P. Royer, R. Ottensamer, T. Ueta, A. Jorissen, M. Mećina, Z. Meliani, A. Luntzer, J. A. D. L. Blommaert, T. Posch, B. Vandenbussche, C. Waelkens, *In Astronomy & Astrophysics*, volume 537, pp. A35, 2012.

2011 Herschel's view into Mira's head

A. Mayer, A. Jorissen, F. Kerschbaum, S. Mohamed, S. van Eck, R. Ottensamer, J. A. D. L. Blommaert, L. Decin, M. A. T. Groenewegen, T. Posch, B. Vandenbussche, C. Waelkens, *In Astronomy & Astrophysics*, volume 531, pp. L4, 2011.

2011 X Herculis and TX Piscium: two cases of ISM interaction with stellar winds observed by Herschel

A. Jorissen, **A. Mayer**, S. van Eck, R. Ottensamer, F. Kerschbaum, T. Ueta, P. Bergman, J. A. D. L. Blommaert, L. Decin, M. A. T. Groenewegen, J. Hron, W. Nowotny, H. Olofsson, T. Posch, L. O. Sjouwerman, B. Vandenbussche, C. Waelkens, *In Astronomy & Astrophysics*, volume 532, pp. A135, 2011.

Conference proceedings**2015 Winds of binary AGB stars as observed by Herschel**

A. Mayer, A. Jorissen, F. Kerschbaum, R. Ottensamer, M. Mećina, C. Paladini, N. L. J. Cox, W. Nowotny, B. Aringer, D. Pourbaix, S. Mohamed, C. Siopis, M. A. T. Groenewegen, *In Why Galaxies Care about AGB Stars III: A Closer Look in Space and Time* (F. Kerschbaum, T. Lebzelter, R. F. Wing, eds.), in press.

2015 A Spiral Goes Viral: Observations and modeling of the circumstellar envelope around R Sculptoris

M. Brunner, M. Maercker, W. H. T. Vlemmings, M. Mećina, F. Kerschbaum, **A. Mayer**, and E. Humphreys, *In Why Galaxies Care about AGB Stars III: A Closer Look in Space and Time* (F. Kerschbaum, T. Lebzelter, R. F. Wing, eds.), in press.

2015 Dust in Stellar Winds: A Micro- and Macroscopic View

M. Mećina, M. A. T. Groenewegen, F. Kerschbaum, B. Aringer, W. Nowotny, R. Ottensamer, **A. Mayer**, A. Luntzer, *In Why Galaxies Care about*

AGB Stars III: A Closer Look in Space and Time (F. Kerschbaum, T. Lebzelter, R. F. Wing, eds.), in press.

2015 Herschel/PACS Image Data Processing

M. Mečina, **A. Mayer**, R. Ottensamer, A. Luntzer, F. Kerschbaum, *In Why Galaxies Care about AGB Stars III: A Closer Look in Space and Time* (F. Kerschbaum, T. Lebzelter, R. F. Wing, eds.), in press.

2014 Improving Herschel imaging datasets

M. Mečina, **A. Mayer**, R. Ottensamer, A. Luntzer, F. Kerschbaum, *In Software and Cyberinfrastructure for Astronomy III* (G. Chiozzi, N. M. Radziwill, eds.), Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 9152, 2014.

2014 Large-scale asymmetries in the winds of (binary) AGB stars

A. Mayer, A. Jorissen, F. Kerschbaum, R. Ottensamer, W. Nowotny, B. Aringer, C. Paladini, M. Mečina, D. M. Pourbaix, M. Groenewegen, S. Mohamed, *In Asymmetrical Planetary Nebulae VI conference, Proceedings of the conference held 4-8 November, 2013*. Edited by C. Morisset, G. Delgado-Inglada and S. Torres-Peimbert. Online at <http://www.astroscu.unam.mx/apn6/PROCEEDINGS/>, id. #59, 2014.

2011 Headwind: The AGB-ISM Frontier

A. Mayer, A. Jorissen, F. Kerschbaum, S. van Eck, M. Mečina, R. Ottensamer, J. A. D. L. Blommaert, L. Decin, T. Posch, M. A. T. Groenewegen, B. Vandenbussche, C. Waelkens, *In Why Galaxies Care about AGB Stars II: Shining Examples and Common Inhabitants* (F. Kerschbaum, T. Lebzelter, R. F. Wing, eds.), volume 445, pp. 351, 2011.

2011 The Mass-Loss History of UX Dra and Other AGB Stars as Probed by Herschel

M. Mečina, F. Kerschbaum, D. Ladjal, R. Ottensamer, A. Luntzer, **A. Mayer**, M. A. T. Groenewegen, J. A. D. L. Blommaert, B. Baumann, L. Decin, D. Klotz, B. Vandenbussche, C. Waelkens, T. Posch, *In Why Galaxies Care about AGB Stars II: Shining Examples and Common Inhabitants* (F. Kerschbaum, T. Lebzelter, R. F. Wing, eds.), volume 445, pp. 353, 2011.

2011 TX Psc and X Her: Two Cases of Stellar Wind-ISM Interaction

A. Jorissen, **A. Mayer**, S. van Eck, R. Ottensamer, F. Kerschbaum, T. Ueta, J. A. D. L. Blommaert, M. A. T. Groenewegen, J. Hron, W.

Nowotny, H. Olofsson, T. Posch, C. Waelkens, *In Why Galaxies Care about AGB Stars II: Shining Examples and Common Inhabitants* (F. Kerschbaum, T. Lebzelter, R. F. Wing, eds.), volume 445, pp. 595, 2011.

Others

2011 Mira, die Wundersame

A. Mayer, F. Kerschbaum, *In Der Sternenbote*, volume 11, 2011.

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