Probing the Effects of Stellar Evolution: The Dust and Gas in Detached Shells around AGB Stars

Matthias Maercker[1]
Sofia Ramstedt[2]
Marcelo L. Leal-Ferreira[3]
Göran Olofsson[4]
Hans-Gustav Floren[4]

[1] Onsala Space Observatory, Dept. of Radio and Space Science, Chalmers University of Technology, Onsala, Sweden
[2] Department of Physics and Astronomy, Uppsala University, Sweden
[3] Argelander Institut für Astronomie, University of Bonn, Germany
[4] Department of Astronomy, Stockholm University, AlbaNova University Center, Sweden

In the last stages of their lives, Sun-like stars evolve along the asymptotic giant branch (AGB), and contribute a significant fraction of heavy elements to the interstellar medium, driving the chemical evolution of galaxies and providing the building material for new stars and planets. We observed the detached shells of dust around the evolved carbon AGB star R Scl in polarised, dust-scattered stellar light with the PolCor instrument on the ESO 3.6-metre telescope. The observations show the distribution of the dust in the shell with unprecedented detail. Comparison with high angular resolution observations of the molecular gas with ALMA show that dust and CO emission coincide almost exactly, implying a common evolution of the dust and gas since the creation of the shell. The results give unique insights into thermal pulses — the mechanism responsible for the chemical evolution of the star — and the way evolved stars lose their mass.

The thermally pulsing AGB

During its AGB evolution, a star periodically undergoes rapid helium burning in a shell around the core. This phenomenon is known as a thermal pulse (TP), and lasts for only a few hundred years every 10 000–100 000 years (Karakas & Lattanzio, 2007). The release of the extra energy into the stellar envelope causes the star to restructure, leading to the formation of elements inside the star (mainly carbon and s-process elements). The new elements are mixed to the stellar surface and incorporated into the stellar wind, leading to the chemical evolution of the circumstellar envelope (CSE). In particular, the mixing of extra carbon leads to the evolution from oxygen-rich (or M-type) AGB stars (with an atmospheric abundance ratio C/O < 1) to carbon-rich AGB stars (with C/O > 1). Owing to their short duration, and the long timescales between pulses, it is extremely unlikely that an AGB star will be observed during a TP directly. As a consequence, models of TPs have been essentially independent of observations (e.g., Karakas & Lattanzio, 2007).

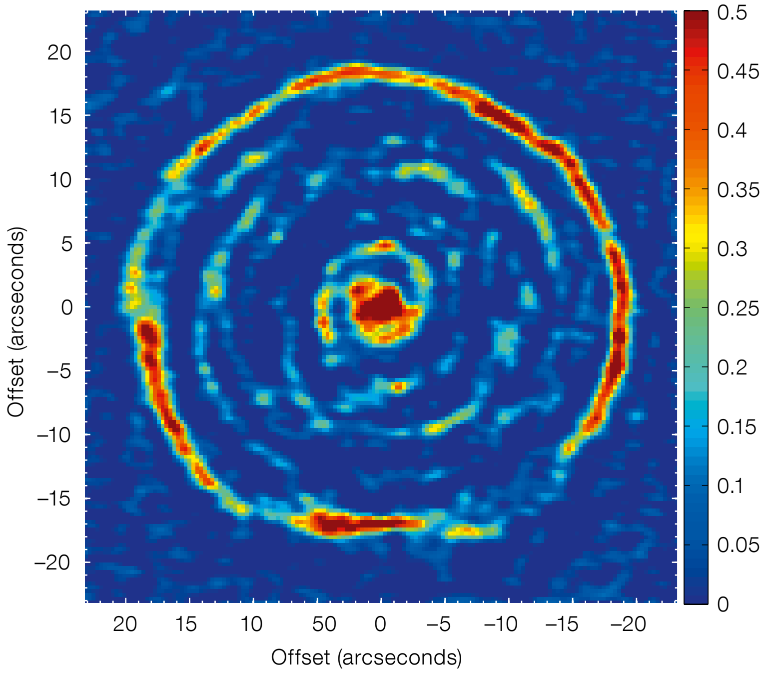
The increase in mass-loss rate and wind velocity during a TP cycle leads to the creation of a shell that may sweep up previously ejected material, leading to the appearance of a detached shell (Steffen & Schönberner, 2000; Schöier et al., 2005; Mattsson et al., 2007). One of the few ways to study the TP phenomenon is from the observations of detached shells that have been found around approximately ten carbon stars in molecular line emission, as well as in stellar dust-scattered light at optical wavelengths (e.g., Olofsson et al., 1996; 2010; Maercker et al., 2010; 2012; 2014).

Extensive studies in recent decades have shown the importance of AGB stars for the cosmic cycle of matter. However, central questions still remain to be answered. Although it is well established that these stars lose a large fraction of their mass in stellar winds, the wind-driving mechanism and geometry, and the molecular and dust content of the CSE, are not well known. In the prevailing theory, the stars lose their mass through radiation pressure on dust grains in the inner CSE. Collisions with the molecular gas drag the gas along, driving the mass loss. The interaction of the dust and gas is hence an integral part of the mass-loss mechanism. Detached shells offer a unique opportunity to study the evolution of the dust and gas and their role in the mass loss on the AGB.

The detached shell around R Sculptoris

The carbon AGB star R Scl is surrounded by a large (approx 20 arcseconds radius), geometrically thin (approximately 2 arc-

Figure 1. ALMA observations of the detached shell around R Scl in CO(3-2) emission. The image shows the detached shell and spiral structure at the stellar velocity. The colour scale is in Jy/beam (Maercker et al., 2012).



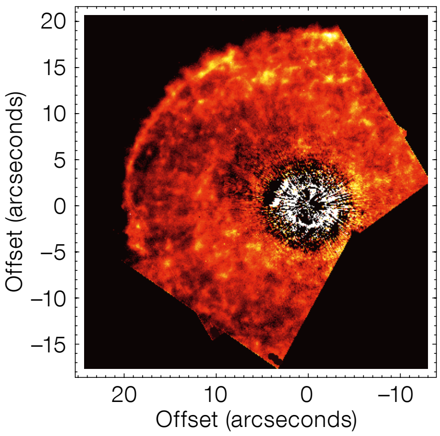


Figure 2. HST observations of the detached shell around R Scl in dust-scattered stellar light in the F814 filter observed with the Advanced Camera for Surveys (ACS) High Resolution Camera on HST. Due to the limited field of view of the ACS, only one third of the shell is covered in the image (from Olofsson et al., 2010).

seconds) shell of gas and dust. R Scl has been observed extensively with single-dish submillimetre observations (e.g., Olofsson et al., 1993). However, those low-resolution observations barely managed to resolve the shell of gas. High spatial resolution images of the detached gas shell in CO line emission were observed in the first cycle (Cycle 0) of science observations with the Atacama Large Millimeter/submillimeter Array (ALMA; see Figure 1 and Maercker et al., 2012). The data clearly show the detached shell, as well as a binary-induced spiral structure extending from the shell, providing evidence of the present-day mass loss. Although overall spherically symmetric, the CO observations show a clearly clumpy structure, and deviations from a perfect sphere along the perimeter of the shell.

Observations of dust-scattered stellar light showed the detached dust shell at high spatial resolution using the EFOSC2 instrument on the ESO 3.6-metre telescope (González Delgado et al., 2001; 2003). A small-scale clumpy structure in the dust shell was revealed in fine images with the Hubble Space Telescope (HST) and is shown in Figure 2 (see Olofsson et al., 2010), albeit covering only approximately one third of the shell. The most complete observations of the dust shell were recently obtained with the PolCor instrument on the ESO 3.6-metre telescope. PolCor observed the CSE around R Scl in polarised, dust-scattered stellar light, imaging the entire detached shell in unprecedented detail (see Figure 3 and Maercker et al., 2014).

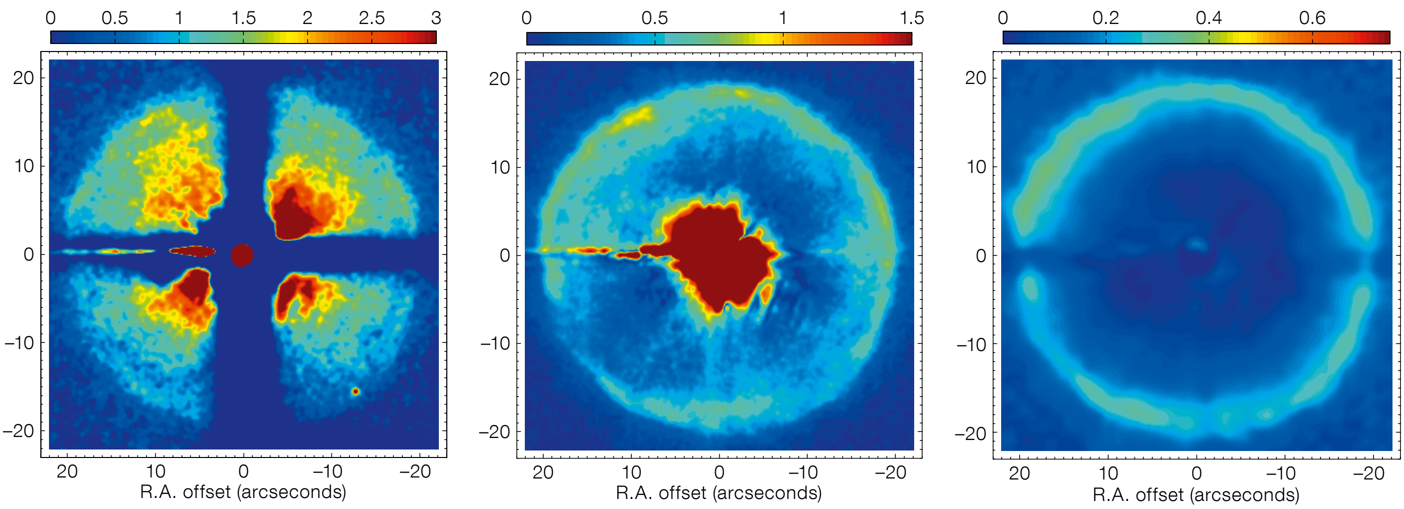
In addition to the detached shell around R Scl, the PolCor observations imaged the detached shell around the carbon AGB star V644 Sco (Figure 4). The shell around this star had been deduced from single-dish CO emission line observations, and estimated to have a radius of approximately 10 arcseconds. However, no direct image had ever been made before the PolCor observations, which, for the first time, directly constrain the size and width of the detached shell around V644 Sco.

PolCor and dust-scattered light

We imaged the detached shells around R Scl and V644 Sco in polarised, dust-scattered, stellar light using the PolCor instrument on the ESO 3.6-metre telescope. PolCor is a user instrument developed by the Department of Astronomy at Stockholm University (Ramstedt et al., 2011). It is a combined polariser and coronagraph, allowing the detection of faint, scattered light emission close to bright stars. A large number of short exposures allows the lucky imaging technique to be utilised, effectively resulting in high-quality images. The effective seeing in the observations of R Scl was typically reduced from 1.3 arcseconds during the observations to 0.9 arcseconds in the final shifted-and-added images. The pixel scale of the PolCor images was 0.114 arcseconds/pixel.

The images of the CSE of the detached shells were taken in *V*-band (0.55 μm) and *R*-band (0.64 μm). The light from the star is scattered by the dust grains in the CSE. The total amount of scattered light depends on the scattering efficiency and direction per grain, and on the total number of grains. The scattering efficiency mainly varies with grain size

Figure 3. PolCor observations of the CSE of R Scl in the *R*-band: total intensity (left), polarised intensity (middle), and degree of polarisation (right). The images are smoothed by a Gaussian kernel with a full width half maximum of two pixels (0.23 arcseconds). The total and polarised intensities are given in counts s^{-1} (from Maercker et al., 2014).



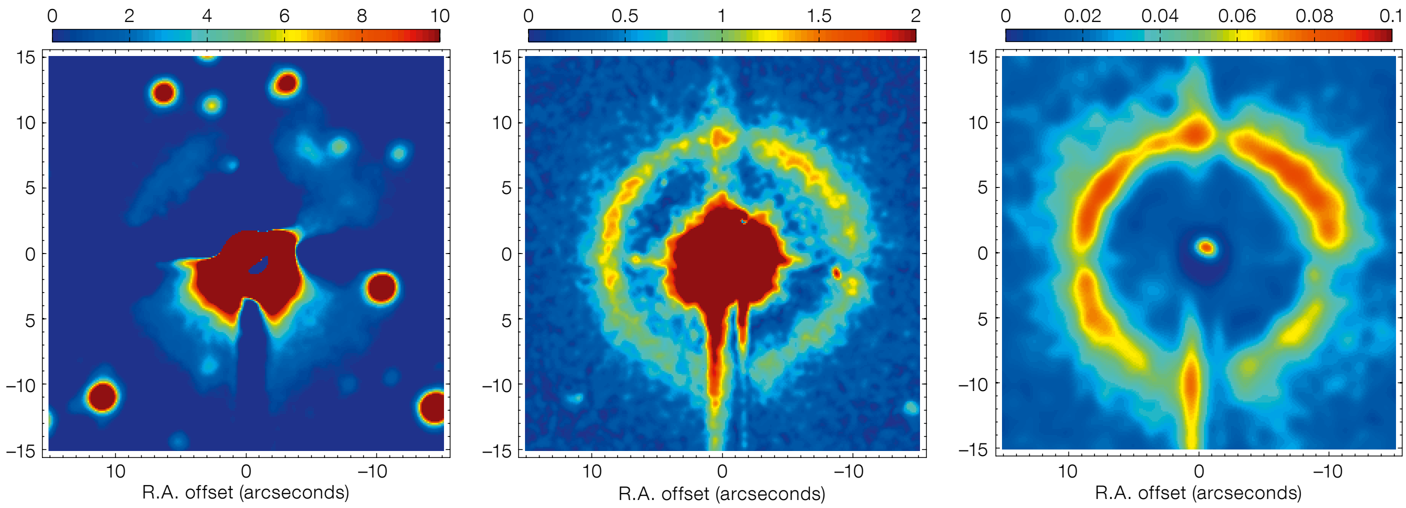


Figure 4. PolCor observations of the CSE of V644 Sco in the *R*-band: total intensity (left), polarised intensity (middle), and polarisation degree (right). The images are Gaussian smoothed (full width half maximum 0.23 arcseconds) and the total and polarised intensities are in counts s^{-1}. The observations present the first direct images of the detached shell around V644 Sco (from Maercker et al., 2014).

(Olofsson et al., 2010) and observations of dust-scattered light effectively probe the distribution of dust grains in the CSE, independent of radiative transfer effects for low optical depths (as for thermal dust emission). Additionally, while the stellar light is essentially unpolarised, the scattering by the grains introduces a linear polarisation in scattered light. The degree of polarisation is highest when the angle between the incoming light and the direction of the scattered light is around 90 degrees. As a consequence, images of polarised, dust-scattered stellar light probe the distribution of the dust predominantly in the plane of the sky.

The PolCor observations were taken as part of a pilot project to test the instrument on the ESO 3.6-metre telescope and the feasibility of observing the dusty CSEs around AGB stars. A total of 14 evolved stars were observed, with varying stellar properties (e.g., mass-loss rates and binarity) and circumstellar morphologies. Due to their clearly extended nature and geometry, detached shell sources are readily analysed and interpreted by polarised light observations in the optical.

The detached dust shell with PolCor

The PolCor observations of the CSE around R Scl give the first complete view of the detached dust shell around this star at high angular resolution. The shell is clearly detected in the total intensity and polarised images in both filters. Small-scale structure can also be seen along the shell in polarised light. The measured degree of polarisation is strongly affected by the subtraction of the stellar point spread function in the total intensity images (see Maercker et al. [2014] for details). We derive a lower limit for the degree of linear polarisation of 30 %, indicating that a large amount of the dust mass is indeed confined to the shell.

The high image quality allows us to measure the radius and observed width of the shell to high accuracy, giving an average shell radius of 19.5 arcseconds and a width of 3.2 arcseconds. This measurement is confirmed by model profiles of stellar light scattered by dust particles in a homogeneous, thin, detached shell. The determined shell radius and width agrees well with previous estimates. However, the PolCor data is of such quality that it allows for direct comparison with the HST data for dust-scattered light (Figure 2). The Hubble field only covers part of the shell, but for the overlapping regions it is obvious that the PolCor data detects the same small-scale structure, indicative of a clumpy detached shell (Figure 5, upper). In contrast to the HST data however, the PolCor data shows that the clumpy structure is not evenly distributed throughout the shell. In particular there appears to be less clumpy structure and limb brightening in the southwest quadrant of the shell.

Synergy between optical and submillimetre observations

The ALMA observations of R Scl provide the highest spatial resolution images of the detached shell in molecular gas to date. The resolution of the CO(3-2) observations in Band 7 is approx. 1.4 arcseconds (Maercker et al., 2012). It is hence possible to directly compare the distribution of the dust with the distribution of the gas in the detached shell. The ALMA observations at the stellar velocity and the polarised observations with PolCor both show the distribution of the gas and the dust in the plane of the sky, respectively (Figure 5, lower). The contours of the ALMA observations closely trace the emission seen in polarised intensity. In particular, the deviations from a perfect spherical shape are identical in both observations (most prominently the flattening of the shell in the south). The gas and dust hence have a nearly identical distribution, indicating that they have evolved together since the detached shell was created. This is in contrast to other detached shell sources, in particular the carbon AGB star U Ant. Here a clear separation of the dust and gas was observed (Maercker et al., 2010). The shell around U Ant is about twice as old as the shell around R Scl. It is not clear whether the difference between the two objects is an evolutionary effect, or whether the dust and gas interaction differs.

The most detailed view of R Scl and thermal pulses

The PolCor images of R Scl give the most detailed view of the detached dust shell to date. Combined with the observations of the molecular gas with ALMA, this provides the strongest constraints on the thermal pulse cycle ever obtained observationally. The images of the dust-scattered light and CO line emission show a strong coupling between the dust and gas, constraining both the mass-loss mechanism during creation of the shell, as well as the interaction with a surrounding medium. The spiral shape observed in the ALMA data further constrains the evolution of the mass loss and expansion velocity since the shell was formed. Together this gives the most complete description of the thermal pulse cycle, and effectively constrains theoretical models observationally for the first time.

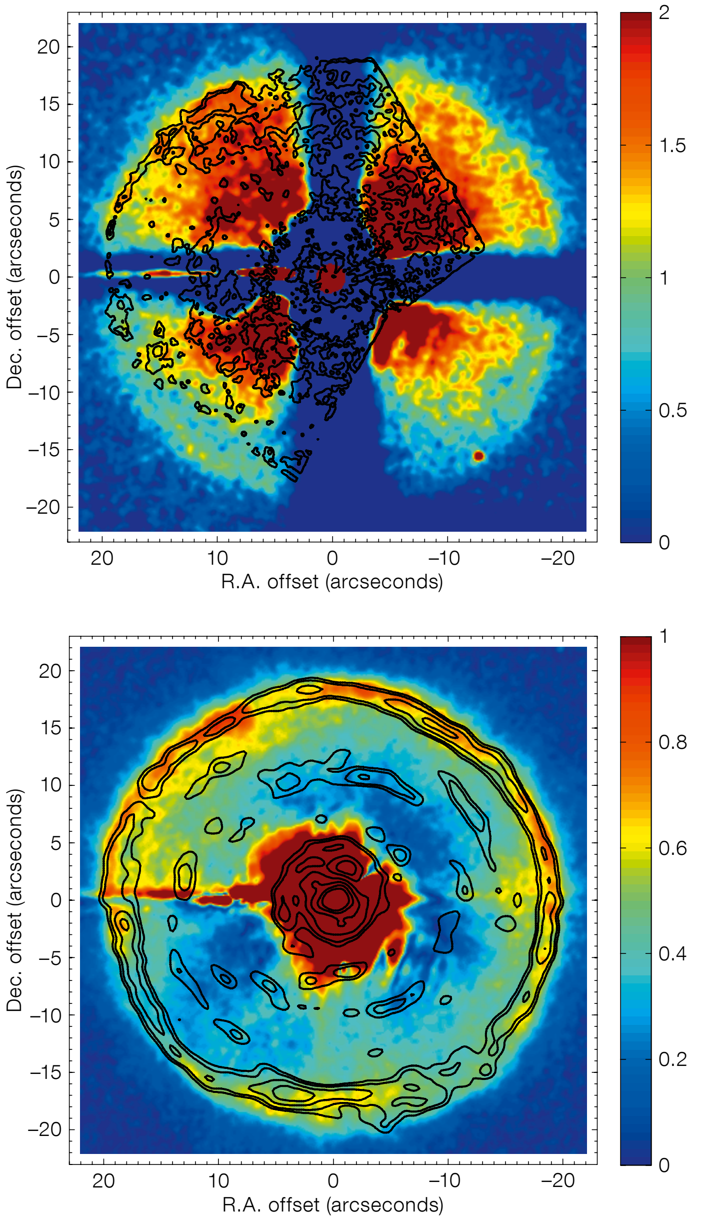


Figure 5. PolCor observations in *R*-band compared to HST and ALMA data. Top: PolCor total intensity image (colour) overlaid by the ACS F814 image (contours). Bottom: PolCor polarised intensity image (colour) overlaid by the ALMA CO(3-2) map at the stellar velocity, shown as contours (from Maercker et al., 2014).

References

González Delgado, D. et al. 2001, A&A, 372, 885
González Delgado, D. et al. 2003, A&A, 399, 1021
Karakas, A. & Lattanzio, J. C. 2007, PASA, 24, 103
Maercker, M. et al. 2010, A&A, 511, A37
Maercker, M. et al. 2012, Nature, 490, 232
Maercker, M. et al. 2014, A&A, 570, A101
Mattsson, L., Höfner, S. & Herwig, F. 2007, A&A, 470, 339
Olofsson, H. et al. 1993, ApJS, 87, 267
Ramstedt, S. et al. 2011, A&A, 531, A148
Schöier, F. L., Lindqvist, M. & Olofsson, H. 2005, A&A, 436, 633