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ALMA observations of the not-so detached shell around the carbon AGB star R Sculptoris

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Abstract. I present our ALMA observations of the CO emission around the carbon AGB star R Sculptoris. The data reveal the known detached shell and a previously unknown, binary induced, spiral shape. The observations confirm a formation of the shell during a thermal pulse about 2300 years ago. The full analysis of the ALMA data shows that the shell around R Scl in fact is entirely filled with molecular gas, and hence not as detached as previously thought. This has implications for the mass-loss rate evolution immediately after the pulse, indicating a much higher mass-loss rate than previously assumed. Comparing the ALMA images to our optical observations of polarised, dust scattered light, we further show that the distributions of the dust and gas coincide almost perfectly, implying a common evolution of the dust and gas, and constraining the wind-driving mechanism. The mass-loss process and amount of mass lost during the thermal pulse cycle affect the chemical evolution of the star, its lifetime on the AGB, and the return of heavy elements to the ISM. New high-resolution ALMA observations constrain the parameters of the binary system and the inner spiral, and will allow for a detailed hydrodynamical modelling of the gas and dust during and after the last thermal pulse. Our results present the only direct measurements of the thermal pulse evolution currently available. They greatly increase our understanding of this fundamental period of stellar evolution, and the implications it has for the chemical evolution of evolved stars, the ISM, and galaxies.

1. Introduction

All stars with a mass between $\approx 0.5 - 8\,\mathrm{M}_\odot$ evolve along the asymptotic giant branch (AGB). AGB stars are effective producers of heavy elements that are returned to the ISM through mass loss from the stellar surface. The photosphere and expanding CSE show a rich molecular chemistry, and are the formation sites of microscopic dust particles. AGB stars contribute to the chemical enrichment of galaxies and provide up to 70% of all interstellar dust particles [1]. The expelled dust and gas are incorporated into molecular clouds, where new stars and planets form. Understanding the chemistry in AGB stars, the mass loss, and the mixing of material into the ISM is therefore crucial to understanding early star formation and the evolution of galaxies.

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 $10^4 - 10^5$ years. 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). Most of the stellar mass is lost between pulses. The new elements are mixed to the stellar surface and incorporated into the stellar wind, leading to the chemical evolution of the CSE [2]. In particular, the mixing-up of extra carbon leads to the evolution

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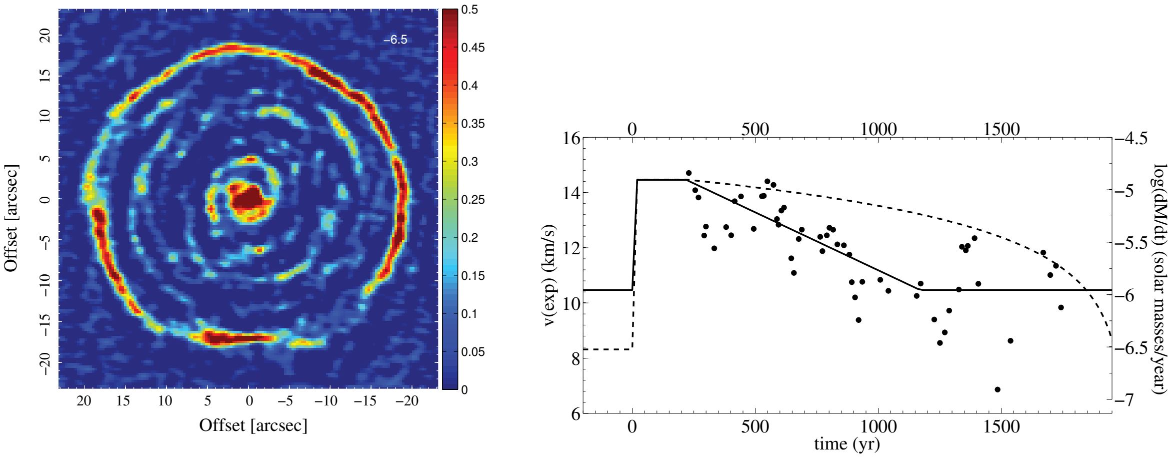

Figure 1. *Left:* ALMA Cycle 0 observations in ^{12}CO($J = 3 - 2$) of the detached shell around R Scl at the systemic velocity. The detached shell can be seen at 18.5", as well as the spiral structure due the shaping of the wind by a binary companion. The flux scale is given in Jy/beam. *Right:* The evolution of the mass-loss rate and expansion velocity as derived from hydrodynamical models [10].

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).

The amount of new elements created depends critically on the physical parameters of the star during subsequent TPs. Owing to their short duration, and the long timescales between pulses, it is extremely unlikely to observe an AGB star during a TP directly. As a consequence models of TPs have been essentially independent of observations [3].

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 [4, 5, 6]. One of the few ways to study the thermal-pulse phenomenon are the observations of detached shells that have been found around ≈10 carbon stars in molecular line emission, as well as in stellar dust-scattered light at optical wavelengths [7, 8, 9, 10, 11].

2. The shell around R Sculptoris

We observed the circumstellar environment around the carbon AGB star R Scl using the compact configuration of ALMA in cycle 0. R Scl was already known to have a detached shell, observed in highest detail in dust scattered, stellar light with the Hubble Space Telescope [8]. The ALMA observations provided the highest-spatial resolution images in ^{12}CO of the CSE around R Scl, and clearly show the detached shell and a previously undetected spiral structure, shaped through interaction of the wind with a so far unknown binary companion (Fig. 1, left; [10]). Hydrodynamical and radiative transfer models of the observed ^{12}CO(3–2) emission from the spiral shape and shell, allowed us to constrain the evolution of the mass-loss rate and expansion velocity during and after the thermal pulse. The shell has an age of 2300 years. We can model the observed structure by assuming a thermal-pulse mass-loss rate of $\approx 2 \times 10^{-5}\,M_\odot\,yr^{-1}$, followed by a slow decline of the mass-loss rate to the present-day value of $3 \times 10^{-7}\,M_\odot\,yr^{-1}$ (Fig. 1, right; [10]). Theoretical models predict a much faster decline in mass-loss rate.

A full analysis of the ALMA Cycle 0 data, including the ^{12}CO(1–0) and ^{12}CO(2–1) lines, allowed us to model the CO emission from the shell and the extended CSE *separately* [12]. Radiative transfer models of the three CO line emissions from the shell constrain the shell mass and temperature. We derive a shell mass of $4.5 \times 10^{-3}\,M_\odot$ and a temperature of 50 K. For typical

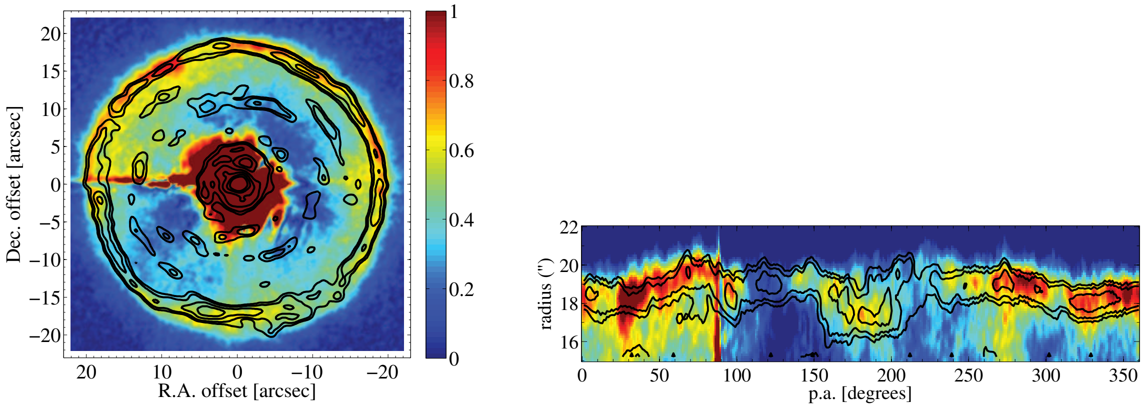

Figure 2. *Left:* Comparison of the PolCor polarised intensity image for R Scl (color scale) with the ALMA Cycle 0 ^{12}CO(3–2) data at the systemic velocity. *Right:* Position angle vs. radius for the same image, but of the detached shell only, showing the close correlation between the dust and gas shells [11].

thermal pulse timescales this implies a thermal pulse mass-loss rate of $2.3 \times 10^{-5}\,M_\odot\,yr^{-1}$. We then use the model of the shell and subtract the emission from single-dish observations, providing us with spectral lines from the extended CSE inside the shell. The analysis of the *overall* density distribution inside the shell (i.e. not modelling the spiral explicitly) shows that the mass-loss rate remains high even after the pulse (on average $1.6 \times 10^{-5}\,M_\odot\,yr^{-1}$ during the last 2100 years), confirming our results from the hydrodynamical models. As a consequence of the slow decline in mass-loss rate, the shell around R Scl does not appear detached, but is instead filled by the extended CSE [12]. The high post-pulse mass-loss rate causes the star to lose significantly more mass throughout the cycle ($0.03\,M_\odot$ vs. $0.007\,M_\odot$; [12]) than previously predicted [6, 3].

Comparison to our observations in dust-scattered optical light with PolCor additionally show an essentially identical distribution of the dust and gas in the detached shell around the star (Fig. 2), implying a common evolution [11]. This is in contrast to the detached shells observed around the carbon AGB star U Ant, where the dust and gas are clearly separated [9]. Detailed observations of the dust and gas in detached-shell sources hence describe the evolution of the mass loss, and the interaction between the dust and gas.

3. New high-spatial resolution ALMA observations

In ALMA Cycle 1 we observed the inner part of the spiral around R Scl at a spatial resolution of 0.12" (Fig. 3). The images resolve the beginning of the spiral, clearly revealing the effects of binary interaction on the wind, and indicating the binary separation. By measuring the deviations from a perfect spiral in the Cycle 1 observations, as well as the contrast between the spiral windings and the inter-winding material [13], we will be able to determine the eccentricity, inclination, and period of the orbit, as well as the companion mass. By constraining these parameters we will be able to fully exploit the Cycle 0 observations to understand the evolution of the mass-loss rate and wind expansion velocity during, and after, the last thermal pulse. Resolving the binary pair will additionally allow us to determine the present-day mass of R Scl.

4. Conclusions

Thermal pulses dominate the chemical evolution of the most numerous stars in the Galaxy. Determining the evolution of the mass-loss rate during this critical phase of stellar evolution is essential in understanding the chemical enrichment of the ISM and galaxies. Our observations combine images of dust and gas at multiple wavelengths and at high-angular resolution to

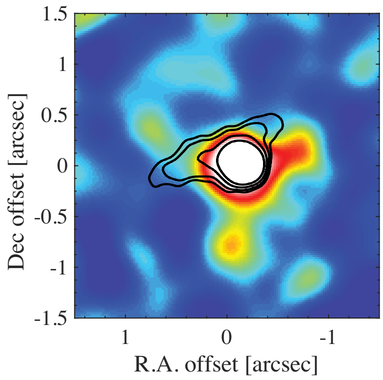

Figure 3. ALMA cycle 1 observations in ^{12}CO(3–2) of the inner part of the CSE around R Scl at the systemic velocity. The images show the beginning of the spiral (color scale), and an extension of the continuum emission (black contours). The observed structure show clear signs of the interaction of the binary companion with the AGB wind, and indicate the location of the companion.

describe the circumstellar structure. We set constraints on the thermal pulse cycle, one of the main drivers of AGB evolution. We find that the mass-loss rate remains significantly higher immediately after the pulse than predicted by stellar evolution models. As a consequence, much more mass may be lost during the thermal pulse cycle than previously expected, and hence limit the life-time of the star on the TP-AGB. This effects the amount of new material returned to the ISM, and hence the contribution of AGB stars to the chemical evolution of galaxies.

References

[1] Schneider R, Valiante R, Ventura P, dell'Agli F, Di Criscienzo M, Hirashita H and Kemper F 2014 *Mon. Not. R. Astron. Soc.* **442** 1440–1450
[2] Busso M, Gallino R and Wasserburg G J 1999 *Annu. Rev. Astron. Astrophys.* **37** 239–309
[3] Karakas A and Lattanzio J C 2007 *Publ. Astron. Soc. Australia* **24** 103–117
[4] Steffen M and Schönberner D 2000 *Astron. Astrophys.* **357** 180–196
[5] Schöier F L, Lindqvist M and Olofsson H 2005 *Astron. Astrophys.* **436** 633–646
[6] Mattsson L, Höfner S and Herwig F 2007 *Astron. Astrophys.* **470** 339–352
[7] Olofsson H, Bergman P, Eriksson K and Gustafsson B 1996 *Astron. Astrophys.* **311** 587–615
[8] Olofsson H, Maercker M, Eriksson K, Gustafsson B and Schöier F 2010 *Astron. Astrophys.* **515** A27
[9] Maercker M, Olofsson H, Eriksson K, Gustafsson B and Schöier F L 2010 *Astron. Astrophys.* **511** A37+
[10] Maercker M *et al* 2012 *Nature* **490** 232–234
[11] Maercker M, Ramstedt S, Leal-Ferreira M L, Olofsson G and Floren H G 2014 *Astron. Astrophys.* **570** A101
[12] Maercker M, Vlemmings W H T, Brunner M, De Beck E, Humphreys E M, Kerschbaum F, Lindqvist M, Olofsson H and Ramstedt S 2016 *Astron. Astrophys.* **586** A5
[13] Kim H and Taam R E 2012 *Astrophys. J.* **744** 136