Planetary Nebulae: A Universal Toolbox in the Era of Precision Astrophysics
Proceedings IAU Symposium No. 384, 2025
O. De Marco, A. Zijlstra & R. Szczerba, eds.
doi:10.1017/S1743921323005422

History of two mass loss processes in VY CMa.

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Abstract. Red Supergiant stars (RSGs) are known to eject large amounts of material during this evolutionary phase. However, the processes powering the mass ejection in low- and intermediate-mass stars do not work for RSGs and the mechanism that drives the ejection remains unknown. Different mechanisms have been proposed as responsible for this mass ejection including Alfvén waves, large convective cells, and magnetohydrodynamical (MHD) disturbances at the photosphere, but so far little is known about the actual processes taking place in these objects. Here we present high angular resolution interferometric ALMA maps of VY CMa continuum and molecular emission, which resolve the structure of the ejecta with unprecedented detail. We reconstructed the 3D structure of the gas traced by the different species. It allowed us to study the morphology and kinematics of the gas traced by the different species surrounding VY CMa. Two types of ejecta are clearly observed: extended, irregular, and vast ejecta surrounding the star that are carved by localized fast outflows. The structure of the outflows is found to be particularly flat. We present a 3D reconstruction of these outflows and proof of the carving. This indicates that two different mass loss processes take place in this massive star. We tentatively propose the physical cause for the formation of both types of structures. These results provide essential information on the mass loss processes of RSGs and thus of their further evolution.

Keywords. supergiants, radio lines: stars, stars: mass-loss, stars: individual: VY CMa, circumstellar matter

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1. Introduction

The processes driving the mass loss ejections in Asymptotic Giant Branch stars (AGBs) is more or less well established due to the effect of the radiation pressure pushing the dust grains formed in the stars' outer photosphere, and the dust's drift on the gas, generating an effective mass ejection (Höfner and Olofsson 2018). However, while we know Red Supergiant stars (RSGs) lose mass, regarding the detection of extended circumstellar material, the mechanism driving such ejections remains mostly unknown.

The amplitude and the irregular period of the pulsation observed in RSGs rule out the mechanism observed in AGB stars (Josselin and Plez 2007). Certain mechanisms have been proposed to be those responsible for the mass ejections in RSGs as the presence of giant convective cells that generate an extended photosphere where dust can be massively formed, as reported to be present in Betelgeuse (Lim et al. 1998). This type of mechanism would generate an inhomogeneous circumstellar envelope, with no preferential directions for the ejection events. However, certain objects as VY CMa or NML Cyg, present well-localized outflows. Due to this, some works have suggested that such ejections are compatible with events of magnetic origin such as the presence of cold spots on the stellar photosphere (O'Gorman et al. 2015). Such cold spots would trigger a

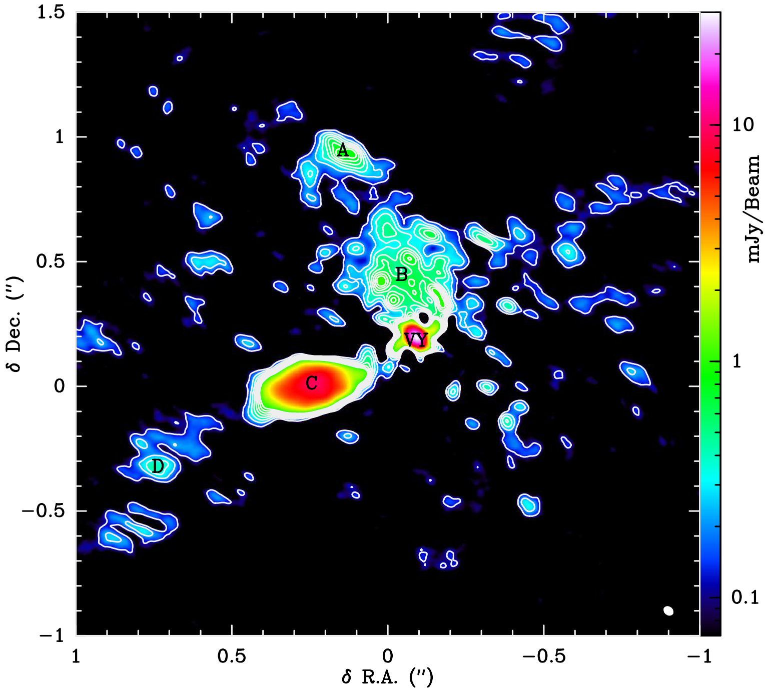

Figure 1. Continuum emission obtained from the ALMA data at $\lambda = 1\,mm$. The Half power beam-width (HPBW) is $0.''04 \times 0.''03$ with a position angle (P.A.) of 29° (see bottom-right corner). The contours correspond to steps of 5σ ($\sigma = 0.023$ mJy/beam). The labels of the different regions follow Kamiński (2019).

localized dust formation and thus a localized gas drifting and mass ejection. In any case, the source powering both types of mass ejections would be radiation pressure on dust, as in AGB objects.

In this work, we focused on VY CMa. The structure of the ejecta observed towards this object is complex, showing clumps, arcs, and other asymmetries (see e.g. Humphreys et al. 2007). Here we present ALMA high-angular resolution maps of a series of molecular species towards VY CMa, and explore the implications to the structures observed.

2. Results

The continuum emission observed toward VY CMa in our maps at 1 mm (Fig. 1) shows three main structures: VY, which is the central compact sources corresponding to the star, a northern elongation and a clump to the East of VY, which is called Clump C in literature.

When comparing these structures with the emission traced by different species (see Fig. 2) we observed that some of these transitions follow relatively well the structure observed in the continuum (e.g. H_2S, or NaCl) while the structures inferred in other molecular lines is very different (e.g. SiO, SO_2,..).

In order to understand the characteristics of the ejecta, we first focused on the H_2S emission, which very accurately traces the emission from the continuum. We obtained a position-velocity diagram along the line connecting VY with clump C, and found that the velocity field is compatible with a Hubble-like velocity field ($v \propto r$).

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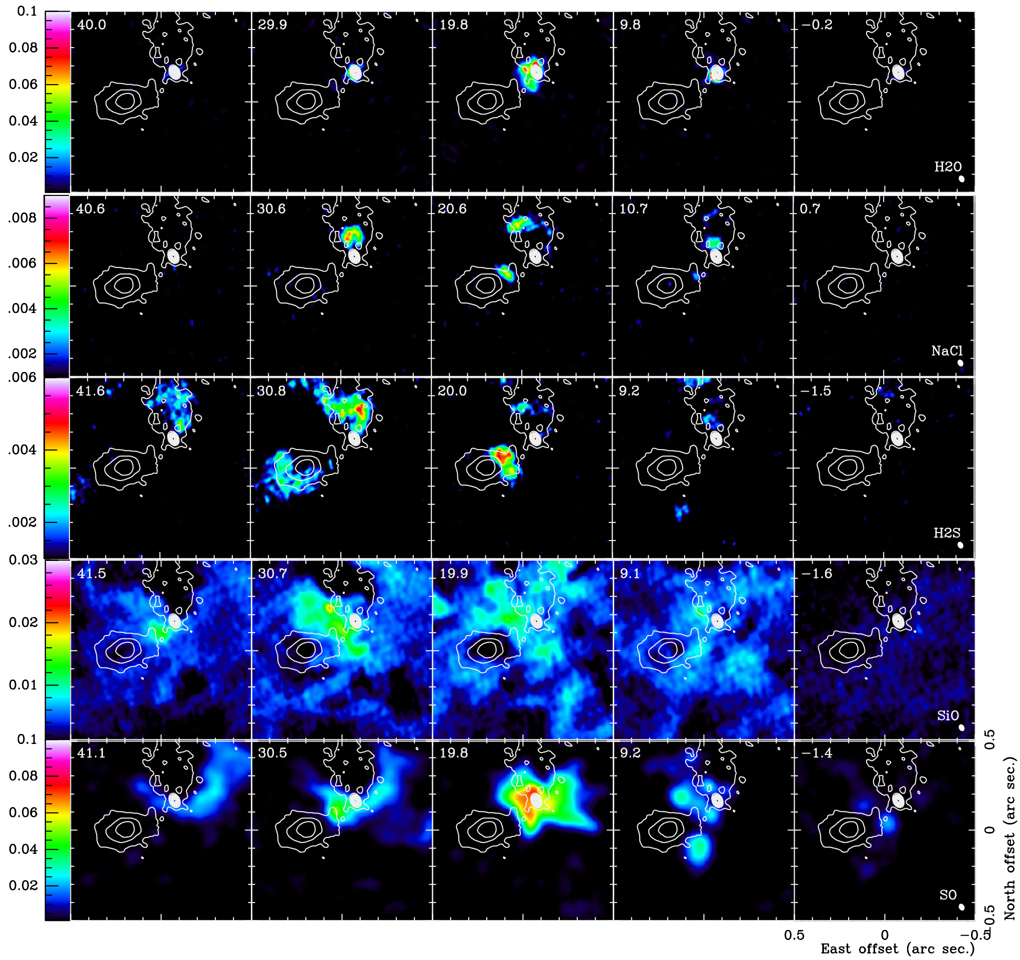

Figure 2. Channel maps of some lines showing the complexity of VY CMa ejecta (continuum shown in contours). From top to bottom in color: H_2O $v = 2$ $5_{5,0} - 6_{4,3}$; NaCl 18–17; H_2S $2_{2,0}$–$2_{1,1}$ SiO 5–4; SO $5_6 - 4_5$. The value of V_{LSR} of each panel is shown in their upper-left corner. The HPBW is 0.″04 × 0.″03 with a P.A. of 29° (see the bottom-right corner of the last panel). The continuum emission is shown in white contours.

Using this velocity field we were able to reconstruct the 3D structure of the H_2S emission. For this purpose, we made use of the `Astructures` program†. This 3D structure revealed that the elongation observed towards the North in the continuum and in H_2S emission is actually composed of a series of outflows. It is worth noting that the velocity these outflows reach in their outermost regions reaches values above ∼100km s^{-1}.

The velocity field and the structure of the SO $5_6 - 4_5$ is relatively complex for an accurate 3D reconstruction. However, we observed a series of shell-like structures coincident with those regions where the fast outflows traced by H_2S are located (see Fig. 3).

This suggests that the VY CMa ejecta consists of two different types of ejections. First, a slow and inhomogeneous, yet not-localized, mass ejection. Second, fast high-collimated outflows carving the formerly ejected slow gas.

Another particular feature observed in the outflows of H_2S is the relative flatness of these structures.

† https://github.com/GQuintanaL/Astructures

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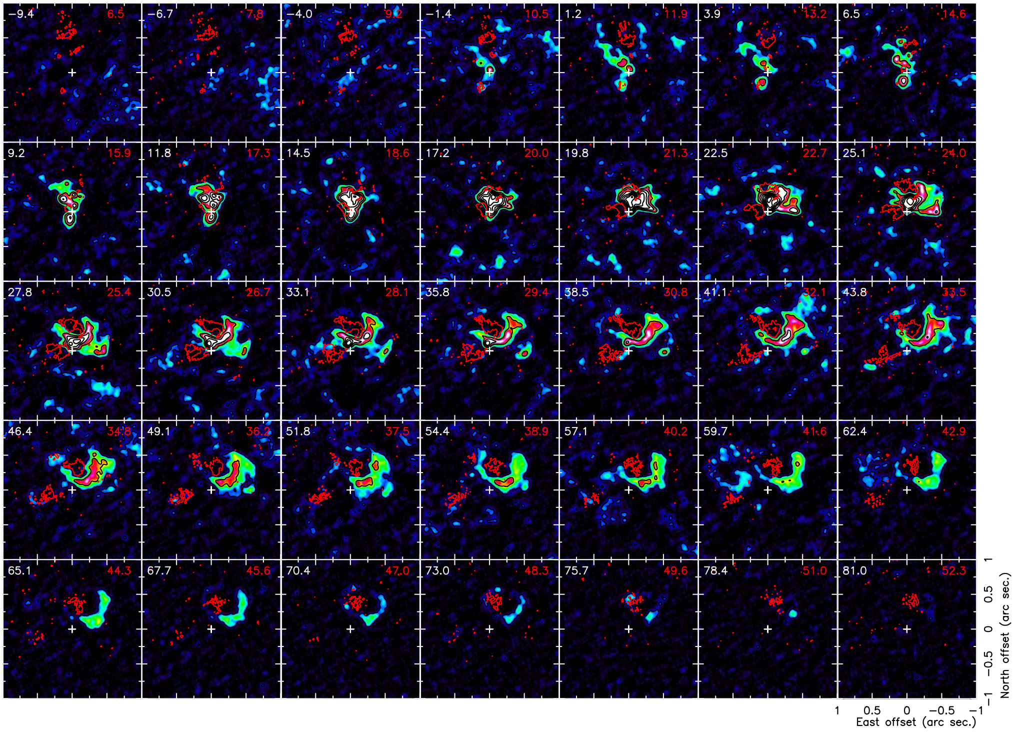

Figure 3. Comparison of the SO $5_6 - 4_5$ emission (colors & black contours) and H_2S $2_{2,0}$–$2_{1,1}$(red contours). $V_{\rm LSR}$ for SO is shown in the upper-left corner, while that of H_2S if shown in red in the upper-right corner. Video available as supplementary material.

In order to explain this flatness we explore if it would be due to the effect of the stellar rotation on the ejection arising from a single point of the photosphere, i.e. a mass ejection arising from a single point in the photosphere would create an emission contained to the angle given by a given angle w.r.t the rotation axis. In the first place, we inspected the 3D structure to see if all the ejections and their flatness could be constrained to different "latitudes". We found that assuming that the rotation axis is in an angle of ∼95° w.r.t the plane of the sky, all the ejections would lay within a single latitude.

Furthermore, we created a simple expansion model to recreate those ejections. This model had as inputs the latitude of the emitting spot, the duration of the ejection, the velocity field provided by the H_2S maps, and the rotation velocity. We were able to reconstruct the 5 fast outflows observed (Fig. 4).

It is worth noting that, while for RSGs 1 km s^{-1} is a standard value for the rotation velocity, velocities as high as 15 km s^{-1} have been observed and related to processes such as planet engulfment and strong dynamos (Wheeler et al. 2017). The ejection time derived, t_e, in general would be $t_e = 120/V_{rot}[\rm months\,s\,km^{-1}]$ (for a $V_{rot} = 15$km s^{-1} the value of t_e would be 8 months.)

Finally, we estimated the total linear momentum associated with clump C, in order to explore if an event of magnetic origin could power such an ejection. We found a value for the momentum of 9.3×10^{38} $\rm gr\,cm\,s^{-1}$. If we estimate the strength needed for a magnetic field to power such momentum, scaling what we know from the Solar coronal mass ejections (Welsch 2018), we found that this value should be of at least 5 kG.

Such high values for the magnetic field have indeed been derived for VY CMa. In particular Shinnaga et al. (2017) found values up to 20 kG. As mentioned above, these

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Table 1. Parameters of the Sprinkler model outflows. The rotation velocity of the star is 1 km s^{-1}. V_{16} is the value for a Hubble-like expansion velocity at 10^{16} cm.

Outflow	θ_i (°)	ϕ_i (°)	V_{16} (km s^{-1})	t_e (yr)
1	100	190	94.44	10
2	85	287	94.44	10
3	140	320	85.86	10
4	100	260	85.86	10
5	120	300	85.86	10

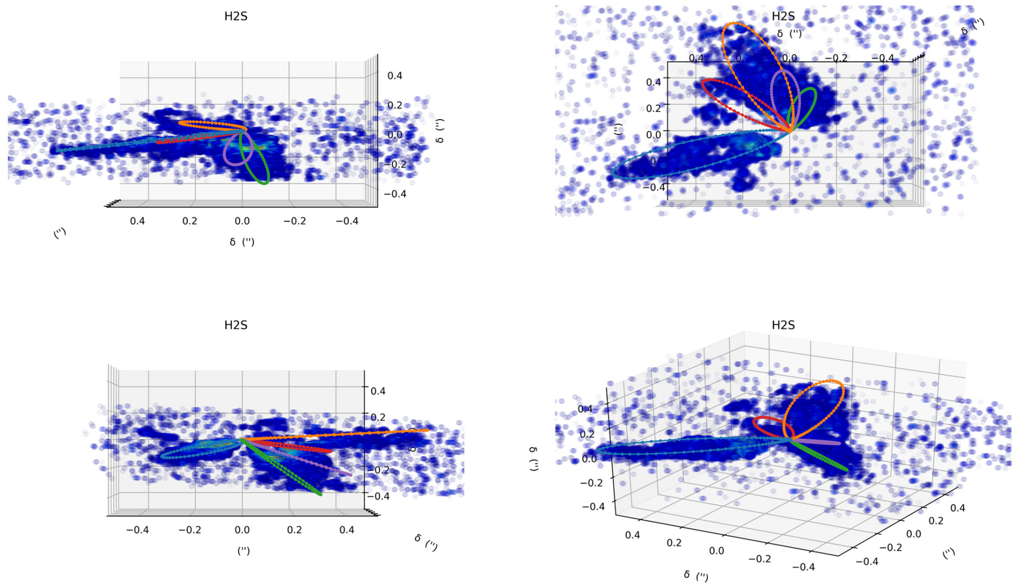

Figure 4. H_2S emission rotated so that the rotation axis corresponds to the Z axis, overplotted to the result of the sprinkler model applied to 5 ejections.

high values can be related to a strong dynamo and a fast rotation. This latter phenomenon can be associated with events such as planets' engulfment (Wheeler et al. 2017).

3. Conclusions

Our analysis reveals that, in the case of the RSG VY CMa, the formation of its circumstellar envelope is formed by two different and independent processes:

• A slow wind. A mass ejection that forms somehow ubiquitous and inhomogeneous ejecta, expanding at relatively low velocities ($30 - 40$km s^{-1}). These values are compatible with a mass ejection driven by radiation pressures on dust. The mechanism driving this ejection might be the formation of giant convective cells, as those proposed by Lim et al. (1998).

• A fast wind. A fast, collimated and well-localized mass ejection. Its velocity field is similar to the fast collimated outflows observed in proto-planetary nebulae (e.g. Alcolea et al. 2007), i.e. $V_{exp} \propto r$. These fast outflows are compatible with a magnetic-driven event. The magnetic field needed for these outflows is compatible with the momentum derived from the observations. In addition, the structure of these outflows suggests that rotation might leave an imprint in these ejections. A fast rotation velocity would explain these structures as well as the high dynamo needed to power the magnetic field observed.

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The results presented here are essential in the context of massive star evolution and in particular in the evolutionary path of these objects shall follow during their final evolution. For the first time, we have shown that mass loss can take place in two completely different ways within this phase.

Future detailed studies of RSGs ejecta will help us to determine the characteristics favoring each type of mass event and the mechanism powering them.

Two of the questions to be addressed in the future regarding the paradigm suggested in by these findings are whether the slow expanding wind is the standard mass ejection process within this evolutionary phase, and if the jets are restricted only to those RSGs presenting higher rotation velocities and strong dynamos.

The research leading to these results has received funding from the European Research Council under the European Union's Seventh Framework Programme (FP/2007-2013) / ERC Grant Agreement n. 610256 (NANOCOSMOS). We would also like to thank the Spanish MINECO for funding support from grants CSD2009-00038, AYA2012-32032. M.A. also thanks for funding support from the Ramón y Cajal programme of Spanish MINECO (RyC-2014-16277). This publication is part of the "I+D+i" (research, development, and innovation) projects PID2019-107115GB-C21, and PID2019-106110GB-I00, and PID2020-117034RJ-I00, supported by the Spanish "Ministerio de Ciencia e Innovación" MCIN/AEI/10.13039/501100011033.

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