THE AXISYMMETRIC ENVELOPES OF RS CNC AND EP AQR

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Abstract. We report on observations obtained at IRAM on two semi-regular variable Asymptotic Giant Branch (AGB) stars, RS Cnc and EP Aqr, undergoing mass loss at an intermediate rate of $\sim 10^{-7}$ $M_\odot\,yr^{-1}$. Interferometric data obtained with the Plateau-de-Bure interferometer (NOEMA) have been combined with On-The-Fly maps obtained with the 30-m telescope in the CO(1-0) and (2-1) rotational lines. The spectral maps of spatially resolved sources reveal an axisymmetric morphology in which matter is flowing out at a low velocity ($\sim 2\,km\,s^{-1}$) in the equatorial planes, and at a larger velocity ($\sim 8\,km\,s^{-1}$) along the polar axes. There are indications that this kind of morpho-kinematics is relatively frequent among stars at the beginning of their evolution on the Thermally-Pulsing AGB, in particular among those that show composite CO line profiles, and that it might be caused by the presence of a companion. We discuss the progress that could be expected for our understanding of the mass loss mechanisms in this kind of sources by increasing the spatial resolution of the observations with ALMA or NOEMA.

Keywords: Stars: AGB and post-AGB – *(Stars:)* circumstellar matter – Stars: individual: RS Cnc, EP Aqr – Stars: mass-loss – radio lines: stars.

1 Introduction

Stars on the Asymtotic Giant Branch (AGB) are in a short phase of their life (from 1 to a few 10^6 years). They evolve rapidly owing to their large luminosity (few 10^3 $L_\odot$), and to the ejection of their stellar envelopes. The mechanism by which stars expel their envelopes is essential to the understanding of the terminal phases of stellar evolution, and to a proper description of their contribution to the replenishment of the interstellar medium.

Carbon monoxide (CO) is one of the best tracers of the winds from AGB stars. It originates in the stellar atmospheres and survives up to a few 10^{16-17} cm where it is distroyed by UV photons from the interstellar radiation field (Mamon et al. 1988). It thus can be used to probe the region where the winds are shaped and accelerated. The first rotational lines of CO (1-0 and 2-1) are easily accessible from the Plateau-de-Bure (NOEMA), and higher degree lines can be observed from the Atacama desert (ALMA). Modelling of the CO line profiles has provided the best mass loss rate estimates (e.g. Schöier & Olofsson 2001; Teyssier et al. 2006).

In the process of an investigation on the mass loss mechanisms (Winters et al. 2000, 2003), we became interested in sources that exhibit composite CO line profiles, with a narrow component (FWHM $\sim$ 2-3 $km\,s^{-1}$) overimposed on a broader (FWHM $\sim$ 8-10 $km\,s^{-1}$) one. These sources were first pointed out by Knapp et al. (1998) who suggested that the peculiar line profiles reveal two different successive winds. We report on our recent work on two such cases, EP Aqr and RS Cnc. We selected these two stars for which a wealth of ancillary data is available, and allows us to characterize their stages of evolution. Although our first investigation on EP Aqr (Winters et al. 2007) tended to support the Knapp et al. interpretation, our study of RS Cnc (Libert et al. 2010) showed that a composite CO line profile might also result from an axi-symmetrical structure, with a slow equatorial wind, and a rapid bipolar outflow. This encouraged us to revisit both sources with a new modelling approach based on the fitting of CO(1-0) and (2-1) spectral maps (Hoai 2015).

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2 Observations

2.1 RS Cnc

RS Cnc is an oxygen-rich S-type star (M6III), with an excess of s-process elements, a $^{12}C/^{13}C$ abundance ratio of 35 (Smith & Lambert 1986), and Tc lines in its optical spectrum (Lebzelter & Hron 1999). It is clearly in the thermally pulsing phase of the AGB (TP-AGB) with dredge-up events. The Hipparcos parallaxe places it at a distance of 143^{+12}_{-10} pc (van Leeuwen 2007). The associations with a far-infrared extended source, detected by IRAS and imaged by Spitzer (Geise 2011), and with an H I emission detected with the Nançay Radiotelescope (Gérard & Le Bertre 2003) and imaged with the VLA (Matthews & Reid 2007), show that the central star has been undergoing mass loss for at least 6×10^4 years (Hoai et al. 2014).

2.2 EP Aqr

EP Aqr is an oxygen-rich M-type star (M8III). The Hipparcos parallaxe places it at a distance of 114^{+8}_{-8} pc (van Leeuwen 2007). Its luminosity (3450 $L_\odot$) and the low value of its $^{12}C/^{13}C$ abundance ratio ($\sim$ 10, Cami et al. 2000) show that it is at the beginning of its evolution on the TP-AGB. Also, the absence of clear Tc lines in its spectrum (Lebzelter & Hron 1999) suggests that it has not undergone any dredge-up event. It is associated with a far-infrared extended source, detected by IRAS and imaged by Herschel (Cox et al. 2012), which shows that it has been undergoing mass loss for more than a few 10^4 years.

2.3 Observational results and interpretation

We have obtained spectral maps in the (1-0) and (2-1) rotational lines of CO by combining interferometric data from the Plateau-de-Bure Interferometer with short spacing data from the Pico Veleta 30-m telescope. The data for RS Cnc have been presented by Libert et al. (2010) and Hoai et al. (2014). Those for EP Aqr have been presented by Winters et al. (2007), and reanalysed with a new processing by Nhung et al. (2015a).

On the basis of characteristically shaped PV diagrams, the RS Cnc data were interpreted by Libert et al. (2010) as showing evidence for a bipolar geometry. Furthermore, the CO(1-0) channel maps around the central velocity (6.6 km s^{-1}), which have been obtained with the extended configurations (A and B) at high angular resolution, reveal a companion at 1$''$ north-west of the AGB star (Hoai et al. 2014). As it is not seen in the continuum, it is presently not clear whether this companion is a compact (sub-)stellar object or a cloud in the circumstellar shell.

The EP Aqr data exhibit a rather circular symmetry with enhancements of the emission at some distance from the central star that led Winters et al. (2007) to assume, as first suggested by Knapp et al. (1998), that the mass loss has been variable within the last few 10^3 years. However, the reanalysis by Nhung et al. (2015a) showed that a morphology similar to that invoked for RS Cnc is also possible, and in fact provides an even better account of the available data.

3 Discussion

The spatio-kinematic structure of RS Cnc has been reconstructed by using a model of CO emission adapted to an arbitrary geometry (Hoai et al. 2014; Hoai 2015). We use an axi-symmetric model in which the wind velocity and the flux of matter are smooth functions of the latitude, θ. The wind is assumed to be stationary. The excitation temperature is parametrized as a power of r, the distance to the central star.

The parameters of the model and its orientation in space are obtained by minimizing the sum of the square of the deviations (modelled minus observed intensities in the two spectral maps). We obtained a good fit to the data with a model in which the velocity increases smoothly from the equatorial plane to the polar direction (Fig. 1, left), whereas the density is almost independent of the latitude (Fig. 1, right). Another important implication of our study is that matter might still be accelerated at large distances (a few hundred AU, Fig. 2, left).

It is interesting to note that, in this model, the bipolarity is essentially apparent in the kinematics. It illustrates the importance of spectrally resolving emission lines.

There are some slight deviations in the fits as compared to the observations that can be further reduced by introducing a slight asymmetry in the polar flows of the model, with, south, a denser and faster flow than north (Nhung et al. 2015b).

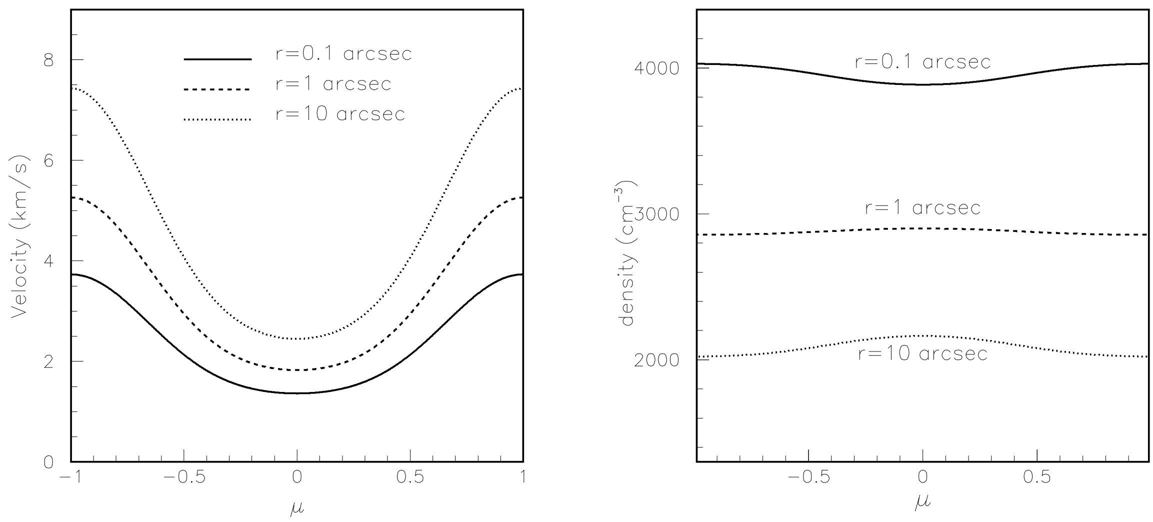

Fig. 1. RS Cnc morpho-kinematics (from Hoai et al. 2014). **Left:** velocity as a function of latitude ($\mu = cos\theta$). **Right:** density (in number of hydrogen atoms) as a function of latitude.

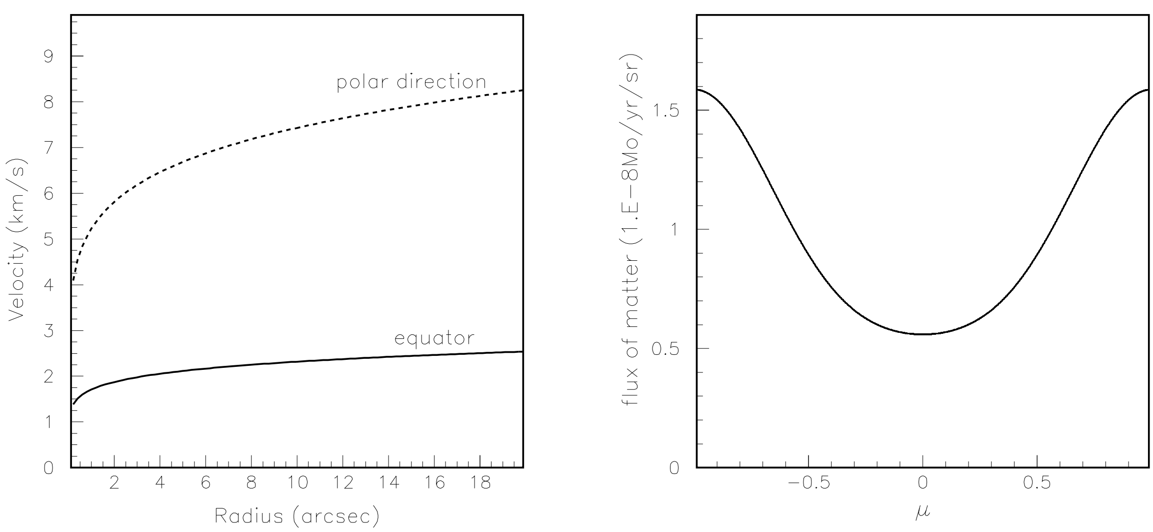

Fig. 2. RS Cnc (from Hoai et al. 2014). **Left:** velocity as a function of distance to the central star. **Right:** flux of matter as a function of latitude ($\mu = cos\theta$).

The successful modelling of RS Cnc with an axi-symmetrical geometry called for a reconsideration of our initial interpretation of a variable mass loss for EP Aqr. Indeed, an axi-symmetrical geometry with a polar axis pointing towards the observer could as well be considered for accounting for the symmetry of the images projected on the plane of the sky. In Nhung et al. (2015a) we studied this second option, and concluded that it is more likely than the first one. Interestingly, in the best model, the density does not deviate significantly from spherical symmetry, and, as for RS Cnc, the axi-symmetry shows up only in the velocity field.

It is worth noting that the bipolarity which has been evidenced in RS Cnc and EP Aqr corresponds to an excess of flux of matter along the polar directions (Fig. 2, right), and not to evacuated regions. Magnetic fields and binarity are commonly invoked to explain the bipolarity observed in circumstellar shells. Matt et al. (2010) have shown that a magnetic field should enhance the mass loss towards the equatorial plane. However we observe the opposite (Fig. 2, right), and thus we tend to prefer the second option (i.e. the effect of a companion).

Theuns & Jorissen (1993) and Mastrodemos & Morris (1999) have studied the hydrodynamics of stellar flows in binary systems. They find that for some configurations a three-dimensional shock wave propagates through the circumstellar shell and that it supports a spiral pattern. In the carbon star AFGL 3068, Mauron & Huggins (2006) have found in dust-scattered galactic light a spiral pattern that fits well with the predictions of Mastrodemos & Morris (1999). A spiral structure has also been detected in the CO(3-2) line emission of R Scl by ALMA (Maercker et al. 2015). The model predictions agree with a nearly spherical wind structure in the equatorial plane on which the spiral pattern is imprinted. There are indications in the EP Aqr channel maps of arcs, that may originate through such a mechanism.

Hoai (2015) has also applied the RS Cnc modelling approach to X Her, another AGB star that shows composite CO line-profiles (Knapp et al. 1998). The same kind of model fits satisfactorily well the data obtained at IRAM by Castro-Carrizo et al. (2010) on this source.

4 Prospects

To understand better the flow of matter from RS Cnc, we need to investigate the nature of the component (cloud ?, companion ?) located north-west of RS Cnc. Broad-band observations would help to identify the presence of a compact stellar object We need also to investigate the possibility of the presence of a rotating disk, such as those found in some post-AGB stars (Castro-Carrizo et al. 2012). However, presently, there is no evidence of such a kinematic structure in the data.

For EP Aqr, we need also imaging at high spatial resolution ($\sim 0.2''$, or better) to probe the acceleration region of the polar flows, as well as the structures in the equatorial plane (spiral ?), that in principle we should detect from a priviledged almost-polar line of sight.

Although they do not bring the highest spatial resolution, the low-J lines allow to probe matter at large distances from the central star. They are also less affected by deviations from local thermal equilibrium and, especially in the inner regions of circumstellar envelopes, by optical depth effects, than the high-J lines.

5 Concluding remarks

Axisymmetry seems to be a common feature in stellar winds, even in the early phases of the TP-AGB. For instance, for EP Aqr the likely absence of Tc in the atmosphere suggests that dredge-up events are still not operating. It shows that non-spherical shapes observed often in planetary nebulae may arise from phenomena that are already active during the AGB phase, although with effects which are less dramatic.

In sources like RS Cnc or EP Aqr, the axi-symmetry becomes apparent only if the kinematical information is available. The two important conclusions for these objects are that (i) the flux of matter is larger along the polar axis than in the equatorial plane, (ii) the stellar winds might still be accelerated at a few hundred AU.

We stress the importance of the high spectral resolution for studying the relatively slow winds from AGB stars. Indeed, we need to resolve spectrally the emission for detecting the axi-symmetry of the source, but also this axi-symmetry may appear only as a kinematic effect (i.e. not as a density effect).

The origin of bipolarity still needs to be identified. The fact that we find sources with a flux of matter larger along the polar axis than in the equatorial plane does not favor magnetic fields. The presence of a companion should produce sub-structures, such as spirals that can be detected in CO lines. It may affect the rate of mass loss, and may play an important role in the ultimate phases of evolution of its primary. The presence of a rotating disk may have a considerable meaning for the mass loss mechanism, that up to now has not been well explored in the models.

High spatial resolution imaging at high spectral resolution of the central parts of these sources where the winds are launched and accelerated with ALMA and NOEMA is clearly essential.

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