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(Sub-)stellar companions shape the winds of evolved stars

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Abstract: Binary interactions dominate the evolution of massive stars, but their role is less clear for low and intermediate mass stars. The evolution of a spherical wind from an Asymptotic Giant Branch (AGB) star into a non-spherical planetary nebula (PN) could be due to binary interactions. We observe a sample of AGB stars with the Atacama Large Millimeter/submillimeter Array (ALMA), finding that their winds exhibit distinct non-spherical geometries with morphological similarities to PNe. We infer that the same physics shapes both AGB winds and PNe. The morphology and AGB mass-loss rate are correlated. These characteristics can be explained by binary interaction. We propose an evolutionary scenario for AGB morphologies which is consistent with observed phenomena in AGB stars and PNe.

Main Text:

At the end of their life, low and intermediate mass (0.8 to 8 solar masses, $M_\odot$) stars turn into luminous cool red giant stars when ascending the AGB. Our Sun will reach that phase in $\sim$7.7 Gyr from now *(1)*. During the AGB phase, the star's radius may become as large as one astronomical unit (au) and its luminosity may reach thousands of times that of the Sun. The AGB phase lasts between ~0.1-20 Myr, the more massive stars are short-lived *(2)*. At the start of the AGB phase, stars are oxygen-rich with a carbon-to-oxygen (C/O) ratio lower than 1, and are referred to as M-type stars. During the AGB phase, carbon is fused in the stellar core and brought to the surface by convection. Eventually, the C/O ratio gets larger than 1, leading to a carbon star. The AGB phase is characterized by a stellar wind with mass-loss rate greater than $\sim 10^{-8}\ M_\odot\,yr^{-1}$. The increase in luminosity while ascending the AGB induces an increase in mass-loss rate, of up to $\sim 10^{-4}\ M_\odot\ yr^{-1}$ *(3)*. For stars with mass-loss rate greater than $10^{-7}\ M_\odot yr^{-1}$, the mass-loss rate exceeds the envelope's hydrogen nuclear burning rate, and mass loss determines the further stellar evolution *(4)*. The wind strips away the star's outer envelope. At the moment that the envelope is less than about 1% of the stellar mass, the star becomes a post-AGB star *(5)*. During this short evolutionary phase which takes a few 1000 yr, the temperature of the star increases at constant luminosity and it becomes a planetary nebula (PN), characterized by a hot central star which ionizes the gas ejected during the previous red giant phase. The lifetime of PNe is roughly 20 000 yr. The PN nebula then disperses quickly, leaving an inert white dwarf which slowly cools *(6)*.

One puzzling aspect about PNe formation concerns the mechanism that shapes the nebulae into a wide range of morphologies, including elliptical, bipolar, and `butterfly'-shaped geometries *(7)*. While ~80% of the AGB stars have a wind with overall spherical symmetry *(8)*, less than 20% of PNe are circularly symmetric *(9,10)*. Various hypotheses - including rapidly spinning or strongly magnetic single stars *(11)* - have been proposed to explain this morphological metamorphosis, but they have been questioned because strong asymmetries are not formed efficiently (*12)*. More recently, short-period (orbital period $P_{orb} \lesssim 10$ days) binary systems (orbital separation $a \lesssim 0.2$ au) surrounded by a common gaseous envelope - referred to as the common-envelope phase - have become the favored hypothesis (*13*). The proposed PN shaping mechanisms operate over a short time, either during the final few hundred years of the AGB or during the early post-AGB phase *(14)*. Identifying the shaping mechanism and its time of occurrence are observationally challenging owing to the short lifetime of the post-AGB and PN stages; the strong observational bias towards detecting binary post-AGB stars and PNe with short orbital periods *(15)*; and the high mass-loss rates at the end of the AGB phase, which surrounds the star with high optical depth material and obscures the inner workings.

During the last few years, observations at high spatial resolution have shown that AGB winds may exhibit small-scale structural complexity - including arcs, shells, bipolar structures, clumps, spirals, tori, and rotating disks *(16, 17)* - embedded in a smooth, radially outflowing wind. Only about a dozen AGB winds have been studied in detail *(18)*. It has not been possible to determine any systematic morphological change during the AGB evolution, and the transition from the smaller scale structures observed during the AGB to the PN morphologies is not understood.

In the ALMA ATOMIUM - ALMA Tracing the Origins of Molecules In dUst-forming oxygen-rich M-type stars - Program *(18)*, we have observed a sample of oxygen-rich AGB stars spanning a range of (circum)stellar parameters and AGB evolutionary stages (Table S1). We study the wind morphology at a spatial resolution of ~0.24″ and ~1″ using the rotational lines of ^{12}CO J=2→1, ^{28}SiO J=5→4, and ^{28}SiO J=6→5 in the ground vibrational state, with J the rotational angular momentum quantum number. These two molecules have large fractional abundances with respect to molecular hydrogen and yield complementary information on the density (CO) and on the morphological and dynamical properties close to the stellar surface (SiO).

Figure 1 shows a gallery of the CO observations. None of the sources has a smooth, spherical geometry. The images exhibit various structures in common with post-AGB stars and PNe: bipolar morphologies with a central waist, equatorial density enhancements (EDE) and disk-like geometries, eye-like shapes, spiral-like structures, and arcs at regularly spaced intervals *(18)*. We infer from these images that the same physical mechanism shapes both AGB winds and PNe. These data constrain the mechanism shaping the winds while it is in operation in a sample of stars with a range of AGB properties, i.e. cover the moment in time when AGB morphologies are being transformed into aspherical geometries.

Combining the CO and SiO data provides an observational criterion (Fig. S2) for classifying the prevailing wind morphologies (Table S2). We find a correlation between the AGB mass-loss rate ($\dot{M}$) and the prevailing geometry (Table 1), with a Kendall's rank correlation coefficient τ_b of 0.79 (Fig. S3-S4, *(18)*). A dynamically complex EDE is often observed for oxygen-rich AGB stars with low mass-loss rates (which we refer to as 'Class 1'), a bipolar structure tends to be dominant for stars with medium mass-loss rates ('Class 2'), while the winds of high mass-loss rate stars preferentially exhibit a spiral-like structures ('Class 3'). Other oxygen-rich AGB stars whose geometry was deduced from previous observations follow this same schematic order (Table S3). This correlation suggests that a common mechanism controls the wind morphology throughout the AGB phase, and that it depends on the mass-loss rate.

Among the mechanisms proposed to explain asphericity, binary models including long-period systems ($P_{\rm orb} \gtrsim 1$ yr, a $\gtrsim$ 2 au) *(19-21)* can explain both the morphologies and the correlation with mass-loss rate *(18)*. Stellar evolution models *(22)* show that the majority of AGB stars with a mass-loss rate above 10^{-7} M$_\odot$ yr^{-1} - including all those in the ATOMIUM sample - have masses above ~1.5 M$_\odot$. Planet and stellar binary population statistics *(23,24)* indicate that stars with these masses have an average number of companions (with mass above ~5 Jupiter mass) $\gtrsim$ 1 *(18)*. Binary interaction is known to dominate the evolution of more massive stars *(25)*. We conjecture that (sub-)stellar binary interaction is the dominant wind shaping agent for the majority of AGB stars with mass-loss rate exceeding the nuclear burning rate. Our conjecture is supported by the growing number of aspherical PNe detected whose binary central stars have a long-period orbit ($P_{\rm orb} \gtrsim 1$ yr) not undergoing a common-envelope evolution *(18)*.

On the assumption that binary interaction dominates, we derive *(18)* an analytical relation

$$Q^1 = 10^{-6}\, Q^p = 8.32\, \frac{1}{(1\text{-}e)^2}\, \frac{1}{f_w} \left(\frac{m_{comp}}{M_\odot}\right)^{1/3} \left(\frac{M_*}{M_\odot}\right)^{7/6} \left(\frac{a}{1\ \mathrm{au}}\right)^{-3/2} \left(\frac{\dot{M}}{10^{-6} M_\odot\ \mathrm{yr}^{-1}}\right)^{-1}$$

that estimates the probability of a binary system forming a (possibly rotating) EDE structure (large value of Q^1) or being dominated by a spiral-like structure (low value of Q^1) *(18)*. Here e denotes the eccentricity of the orbit, f_w the fraction of the stellar wind mass present at a distance $r = a$, and M_* and m_{comp} are the mass of the primary star and companion, respectively. This relation holds for a wind velocity at $r = a$ that is lower than the orbital velocity, and can be easily reformulated for the case of a high wind velocity *(18)*. Our analytical relation supports the correlation observed in the ATOMIUM data. Higher mass-loss rate or orbital separation leads to lower injection of angular momentum into the initially spherical AGB wind by interactions with the orbiting companion, and weaker shaping of the material along the orbital plane into an EDE, a circumbinary disk or an accretion disk *(18)*. Wide binaries, with a separation of up to several tens of astronomical units, produce a spiral-like structure *(19)*.

The transition of the wind morphology during the AGB phase we observe applies to oxygen-rich AGB stars, whereas carbon-rich winds most often display a (broken) spiral/arc-like structure *(18)*. We attribute this differentiation to stronger wind acceleration for carbon-rich than oxygen-rich stars, due to the different dust composition (Fig. S5). Stronger acceleration results in a smaller geometrical region in which the velocity field is non-radial, in a lower probability of forming an EDE, and in a smaller radius beyond which the wind shows a self-similar morphology *(18)*. This implies that carbon-rich AGB stars are more commonly surrounded by an expanding, self-similar, spiral structure, which is consistent with past observations *(18)*. Although EDEs may form in carbon-rich winds, EDEs will be most commonly found around low mass-loss rate oxygen-rich AGB stars with slowly accelerating winds *(18)*.

Observations of binary companions around AGB progenitor stars indicate the highest fraction of binary companions are at an orbital distance greater than ~20 au *(23)*. We calculate *(18)* that those orbits will widen during the AGB evolution as the mass-loss rate increases (Fig. S6-S7). This implies that early-type low mass-loss rate AGB stars will often have an EDE, with complex flow patterns, and the wind of late-type high mass-loss rate AGB stars are mainly shaped by spiral structures (Fig. 2). Our results also imply that the effects of planets around evolved stars are more easily detected in early-type oxygen-rich AGB stars *(18)*.

Our proposed evolutionary and chemical scheme for AGB wind morphologies can explain multiple AGB, post-AGB and PN phenomena *(18),* including why (i) circular detached shells are only detected around carbon-rich AGB stars *(26)*; (ii) disks are mainly found around oxygen-rich post-AGB and PN binaries (*15*); (iii) carbon-rich stars can be surrounded by silicate dust (*27*); (iv) PNe in the bulge of the Milky Way can have a mixed carbon/oxygen chemistry (*28*); (v) post-AGB envelopes can be classified according to two distinct morphological types (*29*); (vi) post-AGB binaries can have non-zero eccentricities with values as high as 0.3 (*30*); and (vii) the low fraction of round PNe (*9,10*).

Fig. 1. Gallery of AGB winds. Emission maps of twelve stars are shown, derived from the ATOMIUM ^{12}CO J=2→1 data. For each star, the emission which is red-shifted with respect to the local standard of rest velocity is shown in red, blue-shifted in blue, and rest velocity in white. The white scale bars are of length 1″. Full channel maps and position-velocity diagrams for each source are shown in Figures S8-S65. Fig. 1A: S Pav, Fig. 1B: T Mic, Fig. 1C: U Del, Fig 1D: V PsA, Fig. 1E: R Hya, Fig. 1F: U Her, Fig. 1G: π^1 Gru, Fig. 1H: R Aql, Fig 1I: W Aql, Fig. 1J: GY Aql, Fig. 1K: IRC -10529, and Fig. 1L: IRC +10011. For two stars (RW Sco and SV Aqr) the signal-to-noise of the data was too low to produce a three-colour map, although the individual channels show clear signs of asymmetry (Fig. S20, Fig. S28 *(18)*).

Fig. 2. Schematic illustration of our inferred evolution of wind morphology during the AGB phase. Most (sub-)stellar companions have initial orbits ($a_{\rm ini}$) greater than 20 au *(24)*. These orbits widen during AGB evolution because the stellar mass decreases. Binary systems with close-by companions often have a high-density EDE and accretion disk (shown in orange) and complex inner wind dynamics. For increasingly wider orbits and higher mass-loss rates, the prevailing outflow morphology first transitions to a bipolar structure (in blue) and then to a regularly spaced spiral structure (in black). EDEs or accretion disks can be present at these later stages, but at lower density.

Table 1. Wind characteristics of the AGB stars in the ATOMIUM sample. Columns 1-6 contain the source name, luminosity in units of solar luminosity $L_{\odot}$, mass-loss rate, wind velocity based on the ^{12}CO J=2→1 line ($v_{\rm wind}$), the identification of arc morphologies in the CO J=2→1 channel map, and the SiO wind dynamics characterizing the velocity field ($\boldsymbol{v}$) in the vicinity of the AGB star as derived from our ALMA data (Fig. S8-S65, Table S2 *(18)*). The stars are ordered by increasing mass-loss rate. The last column indicates objects with similar wind characteristics. Class 1 designates sources with multiple density arcs and dynamically complex inner wind structures, with signs of a biconical outflow and/or rotation, shaping the wind in an equatorial density enhancement (EDE). Class 2 indicates a bipolar structure, some with additional hourglass morphology in the CO channel maps. Class 3 has large density arc(s) often with a recognizable spiral-like structure.

Name	Luminosity ($L_{\odot}$)	Mass-loss rate ($M_{\odot}$ yr^{-1})	v_{wind} (km s^{-1})	CO morphology arcs$^{(a)}$	SiO inner wind dynamics$^{(b)}$	ATOMIUM classification
S Pav	4859	8.0×10^{-8}	14	(x)	Skewed rotating $\boldsymbol{v}$-field	Class 1
T Mic	4654	8.0×10^{-8}	14	x	Skewed rotating $\boldsymbol{v}$-field	Class 1
U Del	4092	1.5×10^{-7}	17	c-xx	Bipolar/rotating flow	Class 2
RW Sco	7714	2.1×10^{-7}	19	c-xx	- (low S/N)	Class 2

V PsA	4092	3.0×10^{-7}	20	c-xx	Bipolar flow	Class 2
SV Aqr	4000	3.0×10^{-7}	16	c-xx	- (low S/N)	Class 2
R Hya	7375	4.0×10^{-7}	22	o-xx	Skewed rotating $\boldsymbol{v}$-field	Class 2
U Her	8026	5.9×10^{-7}	20	a-xx	Complex dynamics	Class 3
π^1 Gru	4683	7.7×10^{-7}	65	o-xx	Bipolar/rotating flow	Class 2
R Aql	4937	1.1×10^{-6}	16	xxx	-	Class 3
W Aql	9742	3.0×10^{-6}	25	xxx	Complex dynamics	Class 3
GY Aql	9637	4.1×10^{-6}	18	xxx	Complex dynamics	Class 3
IRC -10529	14421	4.5×10^{-6}	20	xxx	Bipolar/rotating flow	Class 3
IRC +10011	13914	1.9×10^{-5}	23	xxx	Complex dynamics	Class 3

(a) (x): faint arc, x: several arcs with extent $< 180°$, c-xx: circular/elliptical arc centered around the star, o-xx: arcs symmetrically offset from the central star, a-xx: pronounced asymmetric arcs, xxx: more than 1 arc with extent $> 270°$, linked to a (complex) spiral structure.

(b) ‘Bipolar/rotating flow’ indicates a directed bipolar flow or an EDE/disk-like structure, sometimes with Keplerian rotation; ‘skewed rotating $\boldsymbol{v}$-field’ denotes systematic, but complex, signs of rotation and the $v = 0$ signature in the map of the intensity weighted velocity field (moment1-map) is skewed; ‘complex dynamics’ refers to a clear blue-shifted and red-shifted velocity structure in the moment1-map, but no obvious systematic rotation can be deduced; ‘-’ denotes that no conclusion could be drawn, sometimes owing to too low a signal-to-noise ratio of the SiO data (‘low S/N’).

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Supplementary Materials:

Materials and Methods

Supplementary Text

Figures S1-S65

Tables S1-S7

Data S1-S2

References (*31*-*168*)