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 nonspherical planetary nebula (PN) could be due to binary interactions. We observed a sample of AGB stars with the Atacama Large Millimeter/submillimeter Array (ALMA) and found that their winds exhibit distinct nonspherical geometries with morphological similarities to planetary nebulae (PNe). We infer that the same physics shapes both AGB winds and PNe; additionally, 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 that is consistent with observed phenomena in AGB stars and PNe.

At the end of their lives, stars with low and intermediate masses [0.8 to 8 solar masses ($M_{\odot}$)] evolve into luminous cool red giant stars along the asymptotic giant branch (AGB). The Sun will reach that phase ~7.7 billion years from now ($t_1$). During the AGB phase, a star’s radius may become as large as 1 astronomical unit (au), and its luminosity may reach thousands of times the current solar luminosity. The AGB phase lasts between ~0.1 and 20 million years, with the most massive stars being shorter-lived (2). At the start of the AGB phase, stars are oxygen rich with a carbon-to-oxygen (C/O) ratio <1 and have spectra classified as M-type. During the AGB phase, carbon fusion occurs in the stellar core, and the product elements are brought to the surface by convection. Eventually, the C/O ratio rises above 1, producing a carbon star. The AGB phase is characterized by a stellar wind with a mass-loss rate greater than ~10^{-4} $M_{\odot}$ year^{-1}. The increase in luminosity while a star evolves along the AGB induces an increase in the mass-loss rate of up to ~10^{-2} $M_{\odot}$ year^{-1} (3). For stars with mass-loss rates greater than ~10^{-7} $M_{\odot}$ year^{-1}, the mass-loss rate exceeds the hydrogen nuclear burning rate in the star’s interior, so mass loss determines the further stellar evolution (4). The wind then strips away the star’s outer envelope. When the remaining envelope constitutes less than ~1% of the stellar mass, the star becomes a post-AGB star (5). During this short evolutionary phase, which takes a few thousand years, the temperature of the star increases at constant luminosity and it becomes a planetary nebula (PN), characterized by a hot central star that ionizes the gas ejected during the previous red giant phase. The lifetime of a PN is roughly 20,000 years. The PN then disperses quickly, leaving an inert white dwarf, which slowly cools (6).

Planetary nebulae (PNe) have a wide range of morphologies, including elliptical, bipolar, and butterfly-shaped geometries; the mechanism that produces these diverse shapes is unknown (7). Whereas ~80% of the AGB stars have a wind with overall spherical symmetry (8), <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 these ideas have been questioned because strong asymmetries are not efficiently (12). Short-period (orbital period $P_{\text{orb}} \lesssim 10$ 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 phase or during the early post-AGB phase (14). Identification of the shaping mechanism and its time of occurrence is observationally challenging, owing to the short lifetime of the post-AGB and PN stages; the strong observational bias toward 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 that obscures the inner workings.

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)—embodied 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 DUs-tforming oxygen-rich M-type stars) program (18), we observed a sample of oxygen-rich AGB stars spanning a range of (circum)stellar parameters and AGB evolutionary stages (table S1). We studied the wind morphology at spatial resolutions of ~0.24" and ~1" using the rotational lines of $^{12}$CO $J = 2\rightarrow 1$, $^{32}$SiO $J = 5\rightarrow 4$, and $^{28}$SiO $J = 6\rightarrow 5$ in the ground vibrational state, where J is the rotational angular momentum quantum number. These two molecules (CO and SiO) have large fractional abundances with respect to that of molecular hydrogen and yield complementary information on the density (CO) and 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 (EDEs) 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 wind-shaping mechanism, while it is in operation, in a sample of stars with a range of AGB properties—i.e., the data cover the moment in time when
AGB morphologies are being transformed into aspherical geometries.

The combination of 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 $\tau_b$ of 0.79 (figs. S3 and 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”), and the winds of high mass-loss rate stars preferentially exhibit a spiral-like structure (“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 ($P_{\text{orb}} \geq 1$ year, $a \geq 2$ au) (19–21), can explain both the morphologies and the correlation with mass-loss rate (18). Stellar evolution models (22) show that most AGB stars with a mass-loss rate above $10^{-7} M_\odot$ year$^{-1}$—including all of those in the ATOMIUM sample—have masses above $1.5 M_\odot$. Stellar and substellar (including brown dwarfs and planets) binary population statistics (23, 24) indicate that stars with these masses have, on average, $\geq 1$ companion(s) with masses above $5$ Jupiter masses (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 most AGB stars with a mass-loss rate that exceeds the nuclear burning rate. Our conjecture is supported by the growing number of detected aspherical PNe whose binary central stars have a long-period orbit ($P_{\text{orb}} \geq 1$ year), not undergoing a common-envelope evolution (18).

On the assumption that binary interaction dominates, we derive (18) an analytical relation that estimates the probability of a binary system forming a (possibly rotating) EDE structure (large value of $Q^2$) or being dominated by a spiral-like structure (low value of $Q^2$) (18)

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

where $e$ is the eccentricity of the orbit, $f_w$ is the fraction of the stellar wind mass present at a radial distance $r = a$, and $M$ and $m_{\text{comp}}$ 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 it can be 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 up to tens of astronomical units, produce a spiral-like structure (19).

The observed transition of the wind morphology during the AGB phase applies to oxygen-rich AGB stars, whereas carbon-rich winds most often display a (broken) spiral-like structure.

**Fig. 1. Gallery of AGB winds.** Emission maps of 12 AGB stars are shown, derived from the ATOMIUM $^{12}$CO $J = 2 \rightarrow 1$ data. For each star, emission that is redshifted with respect to the local standard of rest velocity is shown in red, blueshifted emission is in blue, and rest velocity is in white. The scale bars have an angular extent of 1°. Full channel maps and position-velocity diagrams for each source are shown in fig. S8 to S65. (A) S Pav, (B) T Mic, (C) U Del, (D) V PsA, (E) R Hya, (F) U Her, (G) π Gru, (H) R Aql, (I) W Aql, (J) GY Aql, (K) IRC –10529, and (L) IRC +10011. For the two other AGB stars that we observed (RW Sco and SV Aqr), the signal-to-noise ratio was too low to produce three-color maps, but the individual channels show asymmetry (figs. S20 and S28).
Close-by companions wide companions

- **EDE/disk**
  - M low
  - Orbit widens ($a_{ini} > 20$ au)

- **Bipolar**
  - M medium

- **Spiral**
  - M high

Fig. 2. Schematic illustration of our inferred evolution of wind morphology during the AGB phase. Most (sub)stellar companions have initial orbits ($a_{ini}$) greater than 20 au (24). These orbits widen during AGB evolution because the stellar mass decreases. Binary systems with close-orbiting companions often have a high-density EDE and accretion disk (orange) and complex inner wind dynamics. For increasingly wider orbits and higher mass-loss rates, the prevailing outflow morphology initially transitions to a bipolar structure (blue shading) and then to a regularly spaced spiral structure. 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.** The first six columns contain the source name, luminosity (in units of solar luminosity, $L_\odot$), mass-loss rate, wind velocity based on the $^{12}$CO $J = 2 \rightarrow 1$ line ($v_{wind}$), the identification of arc morphologies in the CO $J = 2 \rightarrow 1$ channel map, and the SiO wind dynamics characterizing the velocity field ($v$) in the vicinity of the AGB star as derived from our ALMA data (figs. S8 to S65 and 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 EDE. Class 2 indicates a bipolar structure, sometimes with additional hourglass morphology in the CO channel maps. Class 3 denotes large density arc(s), often with a recognizable spiral-like structure.

| Name   | Luminosity ($L_\odot$) | Mass-loss rate ($M_\odot$ year$^{-1}$) | $v_{wind}$ (km s$^{-1}$) | CO morphology arcs | SiO inner wind dynamics† | ATOMIUM classification |
|--------|------------------------|----------------------------------------|--------------------------|---------------------|--------------------------|------------------------|
| S Pav  | 4895                   | $8.0 \times 10^{-8}$                   | 14                       | (x)                 | Skewed rotating $v$-field | Class 1                |
| T Mic  | 4654                   | $8.0 \times 10^{-8}$                   | 14                       | x                   | Skewed rotating $v$-field | Class 1                |
| U Del  | 4092                   | $1.5 \times 10^{-7}$                   | 17                       | c-xx                | Bipolar/rotating flow    | Class 2                |
| RW Sco | 7714                   | $2.1 \times 10^{-7}$                   | 19                       | c-xx                | – (low S/N)              | Class 2                |
| V PsA  | 4092                   | $3.0 \times 10^{-7}$                   | 20                       | c-xx                | Bipolar flow             | Class 2                |
| SV Aqr | 4000                   | $3.0 \times 10^{-7}$                   | 16                       | c-xx                | – (low S/N)              | Class 2                |
| R Hya  | 7375                   | $4.0 \times 10^{-7}$                   | 22                       | o-xx                | Skewed rotating $v$-field | Class 2                |
| U Her  | 8026                   | $5.9 \times 10^{-7}$                   | 20                       | a-xx                | Complex dynamics         | Class 3                |
| π Gru  | 4683                   | $7.7 \times 10^{-7}$                   | 65                       | o-xx                | Bipolar/rotating flow    | Class 2                |
| R Aql  | 4937                   | $1.1 \times 10^{-6}$                   | 16                       | xxx                 | –                        | Class 3                |
| W Aql  | 9742                   | $3.0 \times 10^{-6}$                   | 25                       | xxx                 | Complex dynamics         | Class 3                |
| IRC -10529 | 14421                  | $4.5 \times 10^{-6}$                   | 20                       | xxx                 | Bipolar/rotating flow    | Class 3                |
| IRC +10011 | 13914                  | $1.9 \times 10^{-5}$                   | 23                       | xxx                 | Complex dynamics         | Class 3                |

*†(x): faint arc; x: several arcs with extent <180°; c-xx: circular or elliptical arc centered on the star; o-xx: arcs symmetrically offset from the central star; a-xx: pronounced asymmetric arcs; xxx: more than one arc with extent >270° linked to a (complex) spiral structure. †Skewed rotating $v$-field: systematic but complex signs of rotation; the $v = 0$ signature in the map of the intensity-weighted velocity field (moment1 map) is skewed. Bipolar/rotating flow: a directed bipolar flow or an EDE/disk-like structure, sometimes with Keplerian rotation. Dash: no conclusion could be drawn, sometimes because the signal-to-noise ratio of the SiO data was too low (low S/N). Complex dynamics: a clear blueshifted and redshifted velocity structure in the moment1 map, but no obvious systematic rotation can be deduced.
We attribute this difference to stronger wind acceleration for carbon-rich stars than for oxygen-rich stars, owing to the different dust compositions (fig. S3). Stronger acceleration results in a smaller geometrical region in which the velocity field is nonradial, a lower probability of forming an EDE, and 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 silicate dust (i) PNe in the Milky Way have two distinct morphological types (ii) disks are mainly found around oxygen-rich AGB stars (iii) most exclusively around carbon-rich AGB stars (iv) PNe in the bulge of the Milky Way can have a mixed carbon-and-oxygen chemistry (v) PNe in the Milky Way have a self-similar morphology of forming an EDE, and a smaller radius beyond which the wind shows a self-similar morphology (vi) PNe in the Milky Way have a self-similar morphology of forming an EDE, and a smaller radius beyond which the wind shows a self-similar morphology (vii) PNe in the Milky Way have a self-similar morphology of forming an EDE, and a smaller radius beyond which the wind shows a self-similar morphology.

Observations of binary companions around AGB progenitor stars indicate that the highest fraction of binary companions occurs 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 (figs. S6 and S7). This implies that early-type AGB stars with low rates of mass loss will often have an EDE, with complex flow patterns, and the wind of late-type AGB stars with high rates of mass loss is 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 scheme for AGB wind morphologies can explain multiple AGB, post-AGB, and PN phenomena (18), including why (i) circular detached shells are detected almost exclusively 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-and-oxygen chemistry (28); (v) post-AGB envelopes can be classified according to two distinct morphological types (29); (vi) post-AGB binaries can have nonzero eccentricities with values as high as 0.3 (30); and (vii) there is a low fraction of round PNe (9, 10).

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