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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 ~ 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 $\sim 10^{-8} M_{\odot} \text{yr}^{-1}$. The increase in luminosity while ascending the AGB induces an increase in mass-loss rate, of up to $\sim 10^{-4} M_{\odot} \text{yr}^{-1}$ (3). For stars with mass-loss rate greater than $10^{-7} M_{\odot} \text{yr}^{-1}$, 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 $\sim 80\%$ 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 $P_{\text{orb}} \lesssim 10$ 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 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 $\sim 0.24''$ and $\sim 1''$ using the rotational lines of $^{12}\text{CO } J=2\rightarrow 1$, $^{28}\text{SiO } J=5\rightarrow 4$, and $^{28}\text{SiO } J=6\rightarrow 5$ 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 ($P_{\text{orb}} \gtrsim 1$ 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 $10^{-7} M_{\odot} \text{ yr}^{-1}$ - including all those in the ATOMIUM sample - have masses above $\sim 1.5 M_{\odot}$. 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 ($P_{\text{orb}} \gtrsim 1$ yr) not undergoing a common-envelope evolution (18).

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

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

5 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_{\star} 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 $^{12}\text{CO } J=2\rightarrow 1$ 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_{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 $^{12}\text{CO } J=2\rightarrow 1$ 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 (\mathbf{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	Lumi- nosity (L_{\odot})	Mass-loss rate ($M_{\odot} \text{ yr}^{-1}$)	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 \mathbf{v} -field	Class 1
T Mic	4654	8.0×10^{-8}	14	x	Skewed rotating \mathbf{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 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 $< 180^\circ$, 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 $> 270^\circ$, 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 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’).

References and Notes:

1. K. P. Schröder, R. C. Smith, Distant future of the Sun and Earth revisited. *MNRAS* **386**, 155–163 (2008).
2. A. I. Karakas. Helium enrichment and carbon-star production in metal-rich populations, *MNRAS* **445**, 347–358 (2014).
3. H. J. Habing, H. Olofsson, Eds., *Asymptotic Giant Branch Stars* (Springer-Verlag New York, Inc., 2004).
4. I. McDonald, E. De Beck, A. A. Zijlstra, E. Lagadec, Pulsation-triggered dust production by asymptotic giant branch stars. *MNRAS* **481**, 4984–4999 (2018).
5. M. M. Miller Bertolami, New models for the evolution of post-asymptotic giant branch stars and central stars of planetary nebulae. *Astron. Astrophys.* **588**, A25 (2016).
6. K. Gesicki, A. A. Zijlstra, M. M. Miller Bertolami, The mysterious age invariance of the planetary nebula luminosity function bright cut-off. *Nature Astron.* **2**, 580–584 (2018).
7. R. Sahai, J. T. Trauger, Multipolar Bubbles and Jets in Low-Excitation Planetary Nebulae: Toward a New Understanding of the Formation and Shaping of Planetary Nebulae. *Astron. J.* **116**, 1357–1366 (1998).
8. R. Neri, C. Kahane, R. Lucas, V. Bujarrabal, C. Loup, A ^{12}CO ($J=1-0$) and ($J=2-1$) atlas of circumstellar envelopes of AGB and post-AGB stars. *Astron. Astrophys. Suppl. Ser.* **130**, 1–64 (1998).
9. R. Sahai, M. R. Morris, G. G. Villar, Young Planetary Nebulae: Hubble Space Telescope Imaging and a New Morphological Classification System. *Astron. J.* **141**, 134 (2011).
10. Q. A. Parker, A. Acker, D. J. Frew, M. Hartley, A. E. J. Peyaud, F. Ochsenbein *et al.*, The Macquarie/AAO/Strasbourg $\text{H}\alpha$ Planetary Nebula Catalogue: MASH. *MNRAS* **373**, 79–94 (2006).
11. G. García-Segura, N. Langer, M. Różyczka, J. Franco, Shaping Bipolar and Elliptical Planetary Nebulae: Effects of Stellar Rotation, Photoionization Heating, and Magnetic Fields. *Astrophys. J.* **517**, 767–781 (1999).
12. J. Nordhaus, E. G. Blackman, A. Frank, Isolated versus common envelope dynamo in planetary nebula progenitors. *MNRAS*. **376**, 599–608 (2007).
13. B. Miszalski, A. Acker, A. F. J. Moffat, Q. A. Parker, A. Udalski, Binary planetary nebulae nuclei towards the Galactic bulge. I. Sample discovery, period distribution, and binary fraction. *Astron. Astrophys.* **496**, 813–825 (2009).
14. B. Balick, A. Frank, Shapes and Shaping of Planetary Nebulae. *Ann. Rev. Astron. Astrophys.* **40**, 439–486 (2002).
15. H. van Winckel, Post-AGB Stars. *Ann. Rev. Astron. Astrophys.* **41**, 391–427 (2003).
16. N. Mauron, P. J. Huggins, Imaging the circumstellar envelopes of AGB stars. *Astron. Astrophys.* **452**, 257–268 (2006).

17. P. Kervella, W. Homan, A. M. S. Richards, L. Decin, I. McDonald, M. Montargès *et al.*, ALMA observations of the nearby AGB star L2 Puppis. I. Mass of the central star and detection of a candidate planet. *Astron. Astrophys.* **596**, A92 (2016).
18. Materials and Methods are available as supplementary materials.
- 5 19. H. Kim, R. E. Taam, Wide Binary Effects on Asymmetries in Asymptotic Giant Branch Circumstellar Envelopes. *Astrophys. J.* **759**, 59 (2012).
20. Z. Chen, A. Frank, E. G. Blackman, J. Nordhaus, J. Carroll-Nellenback, Mass transfer and disc formation in AGB binary systems. *MNRAS* **468**, 4465–4477 (2017).
- 10 21. M. I. Saladino, O. R. Pols, E. van der Helm, I. Pelupessy, S. Portegies Zwart, Gone with the wind: the impact of wind mass transfer on the orbital evolution of AGB binary systems. *Astron. Astrophys.* **618**, A50 (2018).
22. P. Marigo, A. Bressan, A. Nanni, L. Girardi, M. L. Pumo, Evolution of thermally pulsing asymptotic giant branch stars - I. The COLIBRI code. *MNRAS* **434**, 488–526 (2013).
- 15 23. M. Moe, R. Di Stefano, Mind Your Ps and Qs: The Interrelation between Period (P) and Mass-ratio (Q) Distributions of Binary Stars. *Astrophys. J. Suppl. Ser.* **230**, 15 (2017).
24. B. J. Fulton, E. A. Petigura, The California-Kepler Survey. VII. Precise Planet Radii Leveraging Gaia DR2 Reveal the Stellar Mass Dependence of the Planet Radius Gap. *Astron. J.* **156**, 264 (2018).
- 20 25. H. Sana, S. E. de Mink, A. de Koter, N. Langer, C. J. Evans, M. Gieles *et al.*, Binary Interaction Dominates the Evolution of Massive Stars. *Science* **337**, 444 (2012).
26. H. Olofsson, U. Carlstrom, K. Eriksson, B. Gustafsson, L. A. Willson, Bright carbon stars with detached circumstellar envelopes - A natural consequence of helium shell flashes *Astron. Astrophys.* **230**, L13–L16 (1990).
- 25 27. F. J. Molster, I. Yamamura, L. B. F. Waters, L. Å. Nyman, H. U. Kaüfl, T. de Jong, C. Loup, IRAS 09425-6040: A carbon star surrounded by highly crystalline silicate dust. *Astron. Astrophys.* **366**, 923–929 (2001).
28. L. Guzman-Ramirez, A. A. Zijlstra, R. Níchuimín, K. Gesicki, E. Lagadec, T. J. Millar *et al.*, Carbon chemistry in Galactic bulge planetary nebulae. *MNRAS* **414**, 1667–1678 (2011).
- 30 29. T. Ueta, M. Meixner, M. Bobrowsky, A Hubble Space Telescope Snapshot Survey of Proto-Planetary Nebula Candidates: Two Types of Axisymmetric Reflection Nebulosities. *Astrophys. J.* **528**, 861–884 (2000).
- 30 30. G.-M. Oomen, H. Van Winckel, O. Pols, G. Nelemans, A. Escorza, R. Manick *et al.*, Orbital properties of binary post-AGB stars. *Astron. Astrophys.* **620**, A85 (2018).
- 35 31. J. L. Beuzit, A. Vigan, D. Mouillet, K. Dohlen, R. Gratton, A. Boccaletti *et al.*, SPHERE: the exoplanet imager for the Very Large Telescope. *Astron. Astrophys.* **631**, A155 (2019).
32. B. Lopez, S. Lagarde, W. Jaffe, R. Petrov, M. Scholler, P. Antonelli *et al.*, An Overview of the MATISSE Instrument — Science, Concept and Current Status. *The Messenger* **157**, 5–12 (2014).
- 40 33. I. McDonald, M. Trabucchi, The onset of the AGB wind tied to a transition between sequences in the period-luminosity diagram. *MNRAS* **484**, 4678–4682 (2019).

34. E. Vassiliadis, P. R. Wood, Evolution of Low- and Intermediate-Mass Stars to the End of the Asymptotic Giant Branch with Mass Loss. *Astrophys. J.* **413**, 641 (1993).
35. E. De Beck, L. Decin, A. de Koter, K. Justtanont, T. Verhoelst, F. Kemper, K. M. Menten, Probing the mass-loss history of AGB and red supergiant stars from CO rotational line profiles. II. CO line survey of evolved stars: derivation of mass-loss rate formulae. *Astron. Astrophys.* **523**, A18 (2010).
36. I. McDonald, A. A. Zijlstra, Pulsation-triggered Mass Loss from AGB Stars: The 60 Day Critical Period. *Astrophys. J.* **823**, L38 (2016).
37. Gaia Collaboration, A. G. A. Brown, A. Vallenari, T. Prusti, J. H. J. de Bruijne, C. Babusiaux *et al.*, Gaia Data Release 2. Summary of the contents and survey properties. *Astron. Astrophys.* **616**, A1 (2018).
38. M. A. C. Perryman, L. Lindegren, J. Kovalevsky, E. Hog, U. Bastian, P. L. Bernacca *et al.*, The Hipparcos Catalogue. *Astron. Astrophys.* **500**, 501–504 (1997).
39. H. Olofsson, D. Gonzalez Delgado, F. Kerschbaum, F. L. Schöier, Mass loss rates of a sample of irregular and semiregular M-type AGB-variables. *Astron. Astrophys.* **391**, 1053–1067 (2002).
40. P. Marigo, L. Girardi, A. Bressan, M. A. T. Groenewegen, L. Silva, G. L. Granato, Evolution of asymptotic giant branch stars. II. Optical to far-infrared isochrones with improved TP-AGB models. *Astron. Astrophys.* **482**, 883–905 (2008).
41. I. L. Andronov, L. L. Chinarova, Two-Component Variability of the Semi-Regular Pulsating Star U Delphini. *Odessa Astronomical Publications* **25**, 148 (2012).
42. A. Richichi, I. Percheron, M. Khristoforova, CHARM2: An updated Catalog of High Angular Resolution Measurements. *Astron. Astrophys.* **431**, 773–777 (2005).
43. M. A. T. Groenewegen, F. Baas, J. A. D. L. Blommaert, R. Stehle, E. Josselin, R. P. J. Tilanus, Millimeter and some near infra-red observations of short-period Miras and other AGB stars. *Astron. Astrophys. Suppl. Ser.* **140**, 197–224 (1999).
44. N. Vogt, A. Contreras-Quijada, I. Fuentes-Morales, S. Vogt-Geisse, C. Arcos, C. Abarca *et al.*, Determination of Pulsation Periods and Other Parameters of 2875 Stars Classified as MIRA in the All Sky Automated Survey (ASAS). *Astrophys. J. Suppl. Ser.* **227**, 6 (2016).
45. A. A. Zijlstra, T. R. Bedding, J. A. Mattei, The evolution of the Mira variable R Hydrae. *MNRAS* **334**, 498–510 (2002).
46. W. H. T. Vlemmings, H. J. van Langevelde, Improved VLBI astrometry of OH maser stars. *Astron. Astrophys.* **472**, 547–553 (2007).
47. K. Young. A CO(3–2) Survey of Nearby Mira Variables. *Astrophys. J.* **445**, 872 (1995).
48. C. Paladini, F. Baron, A. Jorissen, J. B. Le Bouquin, B. Freytag, S. van Eck *et al.*, Large granulation cells on the surface of the giant star π_1 Gruis. *Nature* **553**, 310–312 (2018).

49. L. Doan, S. Ramstedt, W. H. T. Vlemmings, S. Hofner, E. De Beck, F. Kerschbaum *et al.*, The extended molecular envelope of the asymptotic giant branch star π_1 Gruis as seen by ALMA. I. Large-scale kinematic structure and CO excitation properties. *Astron. Astrophys.* **605**, A28 (2017).
- 5 50. S. Ramstedt, S. Mohamed, W. H. T. Vlemmings, T. Danilovich, M. Brunner, E. De Beck *et al.*, The circumstellar envelope around the S-type AGB star W Aql. Effects of an eccentric binary orbit. *Astron. Astrophys.* **605**, A126 (2017).
51. C. Loup, T. Forveille, A. Omont, J. F. Paul, CO and HCN observations of circumstellar envelopes. A catalogue - mass loss rates and distributions. *Astron. Astrophys. Suppl. Ser.* **99**, 291–377 (1993).
- 10 52. E. A. Olivier, P. Whitelock, F. Marang, Dust-enshrouded asymptotic giant branch stars in the solar neighbourhood. *MNRAS* **326**, 490–514 (2001).
53. P. A. Whitelock, M. W. Feast, F. Van Leeuwen, AGB variables and the Mira period-luminosity relation. *MNRAS* **386**, 313–323 (2008).
- 15 54. W. Homan, L. Decin, A. de Koter, A. J. van Marle, R. Lombaert, W. Vlemmings, Simplified models of stellar wind anatomy for interpreting high-resolution data. Analytical approach to embedded spiral geometries. *Astron. Astrophys.* **579**, A118 (2015).
55. L. Decin, W. Homan, T. Danilovich, A. de Koter, D. Engels, L. B. F. M. Waters *et al.*, Reduction of the maximum mass-loss rate of OH/IR stars due to unnoticed binary interaction. *Nature Astron.* **3**, 408–415 (2019).
- 20 56. S. Ramstedt, F. L. Schöier, H. Olofsson, A. A. Lundgren, On the reliability of mass-loss-rate estimates for AGB stars. *Astron. Astrophys.* **487**, 645–657 (2008).
57. F. van Leeuwen, Validation of the new Hipparcos reduction. *Astron. Astrophys.* **474**, 653–664 (2007).
- 25 58. E. Humphreys, R. Miura, C. L. Brogan, J. Hibbard, T. R. Hunter, R. Indebetouw, The ALMA Science Pipeline: Current Status. In *Proceedings of the 2016 ALMA Conference, “Half a Decade of ALMA: Cosmic Dawn Transformed”*, Sept. 20–23, 2016, Indian Wells, CA, USA, *id.1*, 1 (2016).
59. A. Avison, Lumberjack. <https://github.com/adam-avison/LumberJack> (2019).
- 30 60. K. Willacy, T. J. Millar, Chemistry in oxygen-rich circumstellar envelopes. *Astron. Astrophys.* **324**, 237–248 (1997).
61. G. Winnewisser, S. P. Belov, T. Klaus, R. Schieder, Sub-Doppler Measurements on the Rotational Transitions of Carbon Monoxide. *Journal of Molecular Spectroscopy* **184**, 468–472 (1997).
- 35 62. F. L. Schöier, F. F. S. van der Tak, E. F. van Dishoeck, J. H. Black, An atomic and molecular database for analysis of submillimetre line observations. *Astron. Astrophys.* **432**, 369–379 (2005).
63. C. P. Endres, S. Schlemmer, P. Schilke, J. Stutzki, H. S. P. Müller, The Cologne Database for Molecular Spectroscopy, CDMS, in the Virtual Atomic and Molecular Data Centre, VAMDC. *J. Mol. Spectrosc.* **327**, 95–104 (2016).
- 40

64. H. S. P. Müller, S. Spezzano, L. Bizzocchi, C. A. Gottlieb, C. Degli Esposti, M. C. McCarthy, Rotational Spectroscopy of Isotopologues of Silicon Monoxide, SiO, and Spectroscopic Parameters from a Combined Fit of Rotational and Rovibrational Data. *J. Phys. Chem. A* **117**, 13843–13854 (2013).
- 5 65. A. G. G. M. Tielens, L. B. F. M. Waters, F. J. Molster, K. Justtanont, Circumstellar Silicate Mineralogy. *Astrophys. Space Sci.* **255**, 415–426 (1998).
66. R. Lucas, V. Bujarrabal, S. Guilloteau, R. Bachiller, A. Baudry, J. Cernicharo *et al.*, Interferometric observations of SiO $v=0$ thermal emission from evolved stars. *Astron. Astrophys.* **262**, 491–500 (1992).
- 10 67. R. Sahai, J. H. Bieging, Interferometric Observations of Non-Maser SiO Emission From Circumstellar Envelopes of AGB Stars: Acceleration Regions and SiO Depletion. *Astron. J.* **105**, 595 (1993).
68. J. L. Verbena, V. Bujarrabal, J. Alcolea, M. Gómez-Garrido, A. Castro-Carrizo, Interferometric observations of SiO thermal emission in the inner wind of M-type AGB stars IK Tauri and IRC+10011. *Astron. Astrophys.* **624**, A107 (2019).
- 15 69. M. Van de Sande, C. Walsh, T. P. Mangan, L. Decin, Chemical modelling of dust-gas chemistry within AGB outflows - I. Effect on the gas-phase chemistry. *MNRAS* **490**, 2023–2041 (2019).
70. C. R. O’Dell, B. Balick, A. R. Hajian, W. J. Henney, A. Burkert, Knots in Nearby Planetary Nebulae. *Astron. J.* **123**, 3329–3347 (2002).
- 20 71. C. R. O’Dell, P. R. McCullough, M. Meixner, Unraveling the Helix Nebula: Its Structure and Knots. *Astron. J.* **128**, 2339–2356 (2004).
72. K. Y. L. Su, Y. H. Chu, G. H. Rieke, P. J. Huggins, R. Gruendl, R. Napiwotzki *et al.*, A Debris Disk around the Central Star of the Helix Nebula? *Astrophys. J.* **657**, L41–L45 (2007).
- 25 73. T. Ueta, K. Murakawa, M. Meixner, Hubble Space Telescope NICMOS Imaging Polarimetry of Proto-Planetary Nebulae. II. Macromorphology of the Dust Shell Structure via Polarized Light. *Astron. J.* **133**, 1345–1360 (2007).
74. M. A. Guerrero, Y.-H. Chu, A. Manchado, K. B. Kwitter, Physical Structure of Planetary Nebulae. I. The Owl Nebula. *Astron. J.* **125**, 3213–3221 (2003).
- 30 75. M. Cohen, H. Van Winckel, H. E. Bond, T. R. Gull, Hubble Space Telescope Imaging of HD 44179, The Red Rectangle. *Astron. J.* **127**, 2362–2377 (2004).
76. R. Wesson, X. W. Liu, Physical conditions in the planetary nebula NGC 6543. *MNRAS* **351**, 1026–1042 (2004).
77. S. Ertel, D. Kamath, M. Hillen, H. van Winckel, J. Okumura, R. Manick *et al.*, Resolved Imaging of the AR Puppis Circumbinary Disk. *Astron. J.* **157**, 110 (2019).
- 35 78. V. Bujarrabal, A. Castro-Carrizo, J. Alcolea, M. Santander-García, H. van Winckel, C. Sanchez Contreras, Further ALMA observations and detailed modeling of the Red’ Rectangle. *Astron. Astrophys.* **593**, A92 (2016).

79. W. Homan, T. Danilovich, L. Decin, A. de Koter, J. Nuth, M. Van de Sande, ALMA detection of a tentative nearly edge-on rotating disk around the nearby AGB star R Doradus. *Astron. Astrophys.* **614**, A113 (2018).
- 5 80. V. Bujarrabal, A. Castro-Carrizo, J. Alcolea, H. Van Winckel, Detection of Keplerian dynamics in a disk around the post-AGB star AC Herculis. *Astron. Astrophys.* **575**, L7 (2015).
81. W. Homan, A. Richards, L. Decin, P. Kervella, A. de Koter, I. McDonald, K. Ohnaka, ALMA observations of the nearby AGB star L₂ Puppis. II. Gas disk properties derived from ¹²CO and ¹³CO J = 3-2 emission. *Astron. Astrophys.* **601**, A5 (2017).
- 10 82. I. S. Shklovsky, The nature of planetary nebulae and their nuclei. *Astronomicheskii Zhurnal* **33**, 315–329 (1956).
83. S. Höfner, H. Olofsson, Mass loss of stars on the asymptotic giant branch. Mechanisms, models and measurements. *Astron. Astrophys. Rev.* **26**, 1 (2018).
84. H. J. G. L. M. Lamers, J. P. Cassinelli, *Introduction to Stellar Winds* (Cambridge University Press, 1999).
- 15 85. W. Homan, J. Boulanger, L. Decin, A. de Koter, Simplified models of circumstellar morphologies for interpreting high-resolution data. Analytical approach to the equatorial density enhancement. *Astron. Astrophys.* **596**, A91 (2016).
86. A. Castro-Carrizo, R. Lucas, V. Bujarrabal, F. Colomer, J. Alcolea, SiO emission from a huge, detached shell in IRC +10420. *Astron. Astrophys.* **368**, L34–L37 (2001).
- 20 87. F. Hoyle, R. A. Lyttleton, The effect of interstellar matter on climatic variation. *Proceedings of the Cambridge Philosophical Society* **35**, 405 (1939).
88. H. Bondi, F. Hoyle, On the mechanism of accretion by stars. *MNRAS* **104**, 273 (1944).
89. L. Decin, A. M. S. Richards, T. Danilovich, W. Homan, J. A. Nuth, ALMA spectral line and imaging survey of a low and a high mass-loss rate AGB star between 335 and 362 GHz. *Astron. Astrophys.* **615**, A28 (2018).
- 25 90. Agresti, A, *Analysis of Ordinal Categorical Data* (New York: John Wiley & Son, 2010).
91. McFadden, D, Quantitative methods for analysing travel behavior of individuals: Some recent developments. In D. Hensher, P. Stopher (eds.) *Behavioural travel modelling*, 279–318 (1979).
- 30 92. N. Mastrodemos, M. Morris, Bipolar Pre-Planetary Nebulae: Hydrodynamics of Dusty Winds in Binary Systems. II. Morphology of the Circumstellar Envelopes. *Astrophys. J.* **523**, 357–380 (1999).
93. B. Paczyński, Evolutionary Processes in Close Binary Systems. *Ann. Rev. Astron. Astrophys.* **9**, 183 (1971).
- 35 94. S. Mohamed, P. Podsiadlowski, Mass Transfer in Mira-type Binaries. *Baltic Astronomy* **21**, 88–96 (2012).
95. T. Theuns, H. M. J. Boffin, A. Jorissen, Wind accretion in binary stars - II. Accretion rates. *MNRAS* **280**, 1264–1276 (1996).

96. I. El Mellah, J. O. Sundqvist, R. Keppens, Wind Roche lobe overflow in high-mass X-ray binaries. A possible mass-transfer mechanism for ultraluminous X-ray sources. *Astron. Astrophys.* **622**, L3 (2019).
97. Z. Chen, N. Ivanova, J. Carroll-Nellenback, A 3D Radiation Hydrodynamic AGB Binary Model. *Astrophys. J.* **892**, 110 (2020).
98. N. Maun, P. J. Huggins, Multiple shells in the circumstellar envelope of IRC +10216. *Astron. Astrophys.* **349**, 203–208 (1999).
99. S. Ramstedt, S. Mohamed, W. H. T. Vlemmings, M. Maercker, R. Montez, A. Baudry *et al.*, The wonderful complexity of the Mira AB system. *Astron. Astrophys.* **570**, L14 (2014).
100. K. T. Wong, T. Kamiński, K. M. Menten, F. Wyrowski, Resolving the extended atmosphere and the inner wind of Mira (o Ceti) with long ALMA baselines. *Astron. Astrophys.* **590**, A127 (2016).
101. W. Homan, A. Richards, L. Decin, A. de Koter, P. Kervella, An unusual face-on spiral in the wind of the M-type AGB star EP Aquarii. *Astron. Astrophys.* **616**, A34 (2018).
102. D. T. Hoai, P. T. Nhung, P. Tuan-Anh, P. Darriulat, P. N. Diep, T. Le Bertre *et al.*, The morpho-kinematics of the circumstellar envelope around the AGB star EP Aqr. *MNRAS* **484**, 1865–1888 (2019).
103. V. Bujarrabal, J. Alcolea, J. Mikołajewska, A. Castro-Carrizo, S. Ramstedt, High resolution observations of the symbiotic system R Aqr. Direct imaging of the gravitational effects of the secondary on the stellar wind. *Astron. Astrophys.* **616**, L3 (2018).
104. S. Ramstedt, S. Mohamed, T. Olander, W. H. T. Vlemmings, T. Khouri, S. Liljegren, CO envelope of the symbiotic star R Aquarii seen by ALMA. *Astron. Astrophys.* **616**, A61 (2018).
105. H. Kim, S.-Y. Liu, N. Hirano, R. Zhao-Geisler, A. Trejo, H.-W. Yen *et al.*, High-resolution CO Observation of the Carbon Star CIT 6 Revealing the Spiral Structure and a Nascent Bipolar Outflow. *Astrophys. J.* **814**, 61 (2015).
106. L. Decin, A. M. S. Richards, D. Neufeld, W. Steffen, G. Melnick, R. Lombaert, ALMA data suggest the presence of spiral structure in the inner wind of CW Leonis. *Astron. Astrophys.* **574**, A5 (2015).
107. M. Guélin, N. A. Patel, M. Bremer, J. Cernicharo, A. Castro-Carrizo, J. Pety *et al.*, IRC +10 216 in 3D: morphology of a TP-AGB star envelope. *Astron. Astrophys.* **610**, A4 (2018).
108. M. Maercker, S. Mohamed, W. H. T. Vlemmings, S. Ramstedt, M. A. T. Groenewegen, E. Humphreys *et al.*, Unexpectedly large mass loss during the thermal pulse cycle of the red giant star R Sculptoris. *Nature* **490**, 232–234 (2012).
109. M. Maercker, W. H. T. Vlemmings, M. Brunner, E. De Beck, E. M. Humphreys, F. Kerschbaum *et al.*, A detailed view of the gas shell around R Sculptoris with ALMA. *Astron. Astrophys.* **586**, A5 (2016).
110. H. Kim, A. Trejo, S.-Y. Liu, R. Sahai, R. E. Taam, M. R. Morris *et al.*, The large-scale nebular pattern of a superwind binary in an eccentric orbit. *Nature Astron.* **1**, 0060 (2017).

111. S. V. Jeffers, M. Min, L. B. F. M. Waters, H. Canovas, O. R. Pols, M. Rodenhuis *et al.*, Surprising detection of an equatorial dust lane on the AGB star IRC +10216. *Astron. Astrophys.* **572**, A3 (2014).
- 5 112. R. Sahai, M. Morris, G. R. Knapp, K. Young, C. Barnbaum, A collimated, high-speed outflow from the dying star V Hydrae. *Nature* **426**, 261–264 (2003).
113. L. Decin, K. Justtanont, E. De Beck, R. Lombaert, A. de Koter, L. B. F. M. Waters *et al.*, Water content and wind acceleration in the envelope around the oxygen-rich AGB star IK Tauri as seen by Herschel/HIFI. *Astron. Astrophys.* **521**, L4 (2010).
- 10 114. T. Khouri, A. de Koter, L. Decin, L. B. F. M. Waters, R. Lombaert, P. Royer *et al.*, The wind of W Hydrae as seen by Herschel. I. The CO envelope. *Astron. Astrophys.* **561**, A5 (2014).
115. M. Van de Sande, L. Decin, R. Lombaert, T. Khouri, A. de Koter, F. Wyrowski *et al.*, Chemical content of the circumstellar envelope of the oxygen-rich AGB star R Doradus. Non-LTE abundance analysis of CO, SiO, and HCN. *Astron. Astrophys.* **609**, A63 (2018).
- 15 116. I. El Mellah, J. Bolte, L. Decin, W. Homan, R. Keppens, Wind morphology around cool evolved stars in binaries. The case of slowly accelerating oxygen-rich outflows. *Astron. Astrophys.* **637**, A91 (2020).
117. A. F. Illarionov, R. A. Sunyaev, Why the Number of Galactic X-ray Stars Is so Small? *Astron. Astrophys.* **39**, 185 (1975).
- 20 118. P. P. Eggleton, Approximations to the radii of Roche lobes. *Astrophys. J.* **268**, 368–369 (1983).
119. D. P. Hamilton, J. A. Burns, Orbital stability zones about asteroids II. The destabilizing effects of eccentric orbits and of solar radiation. *Icarus* **96**, 43–64 (1992).
- 25 120. N. Soker, Planetary nebula progenitors that swallow binary systems. *MNRAS* **455**, 1584–1593 (2016).
121. A. J. Mustill, E. Villaver, Foretellings of Ragnarök: World-engulfing Asymptotic Giants and the Inheritance of White Dwarfs. *Astrophys. J.* **761**, 121 (2012).
122. Z. Chen, E. G. Blackman, J. Nordhaus, A. Frank, J. Carroll-Nellenback, Wind-accelerated orbital evolution in binary systems with giant stars. *MNRAS* **473**, 747–756 (2018).
- 30 123. M. Trabucchi, P. R. Wood, J. Montalbán, P. Marigo, G. Pastorelli, L. Girardi. Modelling long-period variables - I. A new grid of O-rich and C-rich pulsation models. *MNRAS* **482**, 929–949 (2019).
124. R. De Nutte, L. Decin, H. Olofsson, R. Lombaert, A. de Koter, A. Karakas *et al.*, Nucleosynthesis in AGB stars traced by oxygen isotopic ratios. I. Determining the stellar initial mass by means of the $^{17}\text{O}/^{18}\text{O}$ ratio. *Astron. Astrophys.* **600**, A71 (2017).
- 35 125. K. H. Hinkle, T. Lebzelter, O. Straniero, Carbon and Oxygen Isotopic Ratios for Nearby Miras. *Astrophys. J.* **825**, 38 (2016).
126. A. Weiss, J. W. Ferguson, New asymptotic giant branch models for a range of metallicities. *Astron. Astrophys.* **508**, 1343–1358 (2009).

127. M. A. T. Groenewegen, J. A. D. L. Blommaert, Mira variables in the OGLE bulge fields. *Astron. Astrophys.* **443**, 143–156 (2005).
128. E. L. Nielsen, R. J. De Rosa, B. Macintosh, J. J. Wang, J.-B. Ruffio, E. Chiang *et al.*, The Gemini Planet Imager Exoplanet Survey: Giant Planet and Brown Dwarf Demographics from 10 to 100 au. *Astron. J.* **158**, 13 (2019).
129. B. Fulton, Frequency of Gaseous Planets Beyond the Ice Line. Paper presented at the meeting of Extreme Solar Systems IV, August 19–23, 2019, Reykjavik, Iceland (2019).
130. N. Soker, Extrasolar planets and the rotation and axisymmetric mass-loss of evolved stars. *MNRAS* **324**, 699–704 (2001).
131. P. Mróz, A. Udalski, J. Skowron, R. Poleski, S. Kozłowski, M. K. Szymański *et al.*, No large population of unbound or wide-orbit Jupiter-mass planets. *Nature* **548**, 183–186 (2017).
132. B. T. Gänsicke, M. R. Schreiber, O. Toloza, N. P. G. Fusillo, D. Koester, C. J. Manser, Accretion of a giant planet onto a white dwarf star. *Nature* **576**, 61–64 (2019).
133. P. Kervella, F. Arenou, F. Mignard, F. Thévenin, Stellar and substellar companions of nearby stars from Gaia DR2. Binarity from proper motion anomaly. *Astron. Astrophys.* **623**, A72 (2019).
134. M. W. Feast, I. S. Glass, P. A. Whitelock, R. M. Catchpole, A period-luminosity-colour relation for Mira variables. *MNRAS* **241**, 375–392 (1989).
135. M. I. Saladino, O. R. Pols, C. Abate, Slowly, slowly in the wind. 3D hydrodynamical simulations of wind mass transfer and angular-momentum loss in AGB binary systems. *Astron. Astrophys.* **626**, A68 (2019).
136. J. D. Cummings, J. S. Kalirai, P. E. Tremblay, E. Ramirez-Ruiz, J. Choi, The White Dwarf Initial-Final Mass Relation for Progenitor Stars from 0.85 to 7.5 M_{\odot} . *Astrophys. J.* **866**, 21 (2018).
137. F. L. Schöier, M. Lindqvist, H. Olofsson, Properties of detached shells around carbon stars. Evidence of interacting winds. *Astron. Astrophys.* **436**, 633–646 (2005).
138. T. M. Gledhill, K. P. Forde, Imaging the transition between pre-planetary and planetary nebulae: integral field spectroscopy of hot post-AGB stars with NIFS. *MNRAS* **447**, 1080–1095 (2015).
139. H. van Winckel, Post-AGB binaries as tracers of stellar evolution. In X. Liu, L. Stanghellini, A. Karakas (eds.) *Planetary Nebulae: Multi-Wavelength Probes of Stellar and Galactic Evolution*, vol. 323 of *IAU Symposium*, 231–234 (2017).
140. M. Meixner, T. Ueta, M. Bobrowsky, A. Speck, Two Subclasses of Proto-Planetary Nebulae: Model Calculations. *Astrophys. J.* **571**, 936–946 (2002).
141. S. R. Pottasch, J. Bernard-Salas, Planetary nebulae abundances and stellar evolution II. *Astron. Astrophys.* **517**, A95 (2010).
142. C. Sánchez Contreras, A. Báez-Rubio, J. Alcolea, V. Bujarrabal, J. Martín-Pintado, A pilot search for mm-wavelength recombination lines from emerging ionized winds in pre-planetary nebulae candidates. *Astron. Astrophys.* **603**, A67 (2017).

143. T. Dermine, R. G. Izzard, A. Jorissen, H. Van Winckel, Eccentricity-pumping in postAGB stars with circumbinary discs. *Astron. Astrophys.* **551**, A50 (2013).
144. R. R. Rafikov, On the Eccentricity Excitation in Post-main-sequence Binaries. *Astrophys. J.* **830**, 8 (2016).
- 5 145. N. Soker, Binary Progenitor Models for Bipolar Planetary Nebulae. *Astrophys. J.* **496**, 833–841 (1998).
146. B. Paczynski, Common Envelope Binaries. In P. Eggleton, S. Mitton, J. Whelan (eds.) *Structure and Evolution of Close Binary Systems*, vol. 73 of *IAU Symposium*, 75 (1976).
- 10 147. H. M. J. Boffin, B. Miszalski, T. Rauch, D. Jones, R. L. M. Corradi, R. Napiwotzki *et al.*, An Interacting Binary System Powers Precessing Outflows of an Evolved Star. *Science* **338**, 773 (2012).
148. D. Jones, H. M. J. Boffin, Binary stars as the key to understanding planetary nebulae. *Nature Astron.* **1**, 0117 (2017).
- 15 149. H. M. J. Boffin, D. Jones, *The Importance of Binaries in the Formation and Evolution of Planetary Nebulae* (SpringerBriefs in Astronomy, 2019).
150. B. Miszalski, H. M. J. Boffin, D. J. Frew, A. Acker, J. Köppen, A. F. J. Moffat, Q. A. Parker, A barium central star binary in the Type I diamond ring planetary nebula Abell 70. *MNRAS* **419**, 39–49 (2012).
- 20 151. A. A. Tyndall, D. Jones, H. M. J. Boffin, B. Miszalski, F. Faedi, M. Lloyd *et al.*, Two rings but no fellowship: LoTr 1 and its relation to planetary nebulae possessing barium central stars. *MNRAS* **436**, 2082–2095 (2013).
- 25 152. H. Van Winckel, A. Jorissen, K. Exter, G. Raskin, S. Prins, J. Perez Padilla *et al.*, Binary central stars of planetary nebulae with long orbits: the radial velocity orbit of BD+33 2642 (PN G052.7+50.7) and the orbital motion of HD112313 (PN LoTr5). *Astron. Astrophys.* **563**, L10 (2014).
153. D. Jones, H. Van Winckel, A. Aller, K. Exter, O. De Marco, The long-period binary central stars of the planetary nebulae NGC 1514 and LoTr 5. *Astron. Astrophys.* **600**, L9 (2017).
154. M. Moe, O. De Marco, Do Most Planetary Nebulae Derive from Binaries? I. Population Synthesis Model of the Galactic Planetary Nebula Population Produced by Single Stars and Binaries. *Astrophys. J.* **650**, 916–932 (2006).
- 30 155. N. Soker, Why Magnetic Fields Cannot Be the Main Agent Shaping Planetary Nebulae. *Publ. Astron. Soc. Pac.* **118**, 260–269 (2006).
156. V. Bujarrabal, J. Alcolea, R. Sahai, J. Zamorano, A. A. Zijlstra, The shock structure in the protoplanetary nebula M1-92: imaging of atomic and H₂ line emission. *Astron. Astrophys.* **331**, 361–371 (1998).
- 35 157. N. Smith, B. Balick, R. D. Gehrz, Kinematic Structure of H₂ and [Fe II] in the Bipolar Planetary Nebula M2-9. *Astron. J.* **130**, 853–861 (2005).
158. R. Sahai, N. A. Patel, An Extreme High-velocity Bipolar Outflow in the Pre-planetary Nebula IRAS 08005-2356. *Astrophys. J.* **810**, L8 (2015).
- 40 159. N. Soker, M. Livio, Disks and jets in planetary nebulae. *Astrophys. J.* **421**, 219 (1994).

160. B. Balick, A. Frank, B. Liu, Models of the Mass-ejection Histories of Pre-planetary Nebulae. IV. Magnetized Winds and the Origins of Jets, Bullets, and FLIERs. *Astrophys. J.* **889**, 13 (2020).
161. P. Kervella, L. Decin, A. M. S. Richards, G. M. Harper, I. McDonald, E. O’Gorman *et al.*, The close circumstellar environment of Betelgeuse. V. Rotation velocity and molecular envelope properties from ALMA. *Astron. Astrophys.* **609**, A67 (2018).
162. H. Kim, S.-Y. Liu, R. E. Taam, Templates of Binary-induced Spiral-shell Patterns around Mass-losing Post-main-sequence Stars. *Astrophys. J. Suppl. Ser.* **243**, 35 (2019).
163. M. I. Saladino, O. R. Pols, The eccentric behaviour of windy binary stars. *Astron. Astrophys.* **629**, A103 (2019).
164. Z.-W. Liu, R. J. Stancliffe, C. Abate, E. Matrozis, Three-dimensional Hydrodynamical Simulations of Mass Transfer in Binary Systems by a Free Wind. *Astrophys. J.* **846**, 117 (2017).
165. T. Danilovich, G. Olofsson, J. H. Black, K. Justtanont, H. Olofsson, Classifying the secondary component of the binary star W Aquilae. *Astron. Astrophys.* **574**, A23 (2015).
166. M. W. Feast, The absolute magnitude and spectrum of the class S star π_1 Gruis. *MNRAS* **113**, 510 (1953).
167. A. Mayer, A. Jorissen, C. Paladini, F. Kerschbaum, D. Pourbaix, C. Siopis *et al.*, Large-scale environments of binary AGB stars probed by Herschel. II. Two companions interacting with the wind of π_1 Gruis. *Astron. Astrophys.* **570**, A113 (2014).
168. B. D. Mason, G. L. Wycoff, W. I. Hartkopf, G. G. Douglass, C. E. Worley, The 2001 US Naval Observatory Double Star CD-ROM. I. The Washington Double Star Catalog. *Astron. J.* **122**, 3466–3471 (2001).

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Supplementary Materials:

Materials and Methods

Supplementary Text

Figures S1-S65

Tables S1-S7

Data S1-S2

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