The fundamentals of outflows from evolved stars

An Astro2020 Science White Paper

Stars and Stellar Evolution

Resolved Stellar Populations and their Environments

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<u>Abstract</u>: Models of the chemical evolution of the interstellar medium, galaxies, and the Universe rely on our understanding of the amounts and chemical composition of the material returned by stars and supernovae. Stellar yields are obtained from stellar-evolution models, which currently lack predictive prescriptions of stellar mass loss, although it significantly affects stellar lifetimes, nucleosynthesis, and chemical ejecta.

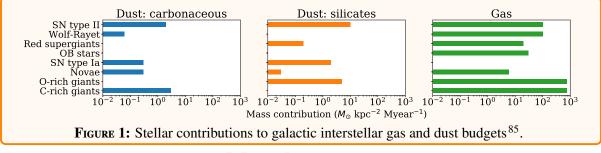
Galaxy properties are derived from observations of the integrated light of bright member stars. Stars in the late stages of their evolution are among the infrared-brightest objects in galaxies. An unrealistic treatment of the mass-loss process introduces significant uncertainties in galaxy properties derived from their integrated light.

We describe current efforts and future needs and opportunities to characterize AGB outflows: driving mechanisms, outflow rates, underlying fundamental physical and chemical processes such as dust grain formation, and dependency of these on metallicity.

Background: stellar outflows

The large majority of stars experience mass loss via surface outflows over a sizeable fraction of their lives. Low-to-intermediate mass stars ($0.8M_{\odot} \leq M_{ZAMS} \leq 8M_{\odot}$) develop increasingly strong outflows during their late evolutionary stages on the asymptotic giant branch (AGB), possibly with episodic modulations. Mass-loss rates are so high ($10^{-8} - 10^{-4}M_{\odot}/yr$) that these stars are eventually stripped of the entire envelopes, leaving white dwarfs as compact remnants. Massive stars ($M_{ZAMS} \geq 8M_{\odot}$) develop strong winds during most of their evolution. Mass loss is expected to significantly affect the structure and evolution at $M_{ZAMS} > 15M_{\odot}$, as well as the subsequent supernova explosion. Additionally, since the circumstellar environment of a progenitor will be swept up and reprocessed during and after the supernova event⁷⁴ or possibly even survive^{26,75}, we need to understand the physics and chemistry of these outflows. While the driving mechanisms of mass loss in hot, luminous stars (e.g. blue supergiants, luminous blue variables) are fairly well known, we still lack a comprehensive understanding of the stellar outflows in bright and cool evolved stars (red supergiants and AGB stars), where various complex processes are simultaneously at work: dust formation, stellar pulsation, and convection.

Figure 1 summarizes contributions of stellar outflows and supernovae to the galactic insterstellar medium⁸⁵. In this paper we address the challenges to characterize outflows from AGB stars in particular. The circumstellar chemistry of AGB stars is set by the atmospheric C/O abundance ratio. The O-rich and C-rich giants listed in Fig. 1 are AGB stars with C/O < 1 and C/O > 1, respectively. Although the underlying driving mechanisms are different, the outflows from red supergiants and yellow hypergiants, two types of evolved massive stars, are remarkably similar to those of O-rich AGB stars in terms of their gas and dust chemistry.



Mass-loss rates

We need to quantify stellar mass-loss rates to constrain the effect of outflows on stellar evolution. By deriving mass-loss rates for both the gas and dust in the outflows (\dot{M}_{gas} , \dot{M}_{dust}) we can obtain a dust-to-gas mass ratio, a proxy for dust-production efficiency. We review the methods used, the uncertainties surrounding these, and the observations needed to advance the field.

Gas-mass-loss rates of AGB stars can be derived from observations of CO rotational transitions. Whereas CO (J = 1 - 0) emission, at 3 mm wavelength, traces the outermost, coldest molecular gas (3 – 10 K), higher-excitation transitions (J > 7 - 6) – not observable from the ground – trace the dense, warm (500–2000 K) gas close to the star. A multi-transition approach, covering both the low- and high-excitation emission provides the most reliable outflow models by constraining the temperature and density of the entire circumstellar environment, and with that the mass-loss history of the star. Several studies have derived sample statistics or have performed detailed case studies for Galactic sources using ground- and space-based facilities 9,17,18,20,64,71,72 . In contrast, CO emission has been observed for only 4 extragalactic AGB stars 33 , although it is essential that we understand the effect of metallicity on mass loss. For these four stars, only the J = 2 - 1 emission was measured using the Atacama Large Millimetre/Submillimetre Array (ALMA). This emission is not the best outflow tracer since it probes mainly the outermost regions of the outflow, which are most affected by external factors such as dissociation by interstellar UV irradiation¹⁸. In addition, this approach can realistically provide \dot{M}_{gas} for only a limited fraction of the AGB populations in the Small and Large Magellanic Clouds (SMC, LMC), since all CO transitions have to be measured individually.

The way forward: Instantaneous observations of CO transition ladders, covering a large range in excitation properties, can provide an enormous improvement to \dot{M}_{gas} -quantifications. The SAFARI instrument for ESA's proposed SPICA mission and the OSS instrument for the proposed ORIGINS Space Telescope, broadband direct detectors in the far-infrared (FIR), would provide instantaneous coverage of a large number of CO lines at sensitivities better by over two orders of magnitude than the Herschel Space Observatory/PACS instrument⁸. The enormous gain in detector sensitivity opens the possibility to measure \dot{M}_{gas} also for AGB stars in the SMC/LMC, i.e. at significantly lower-than-solar metallicity. Additionally, ORIGINS/OSS would outperform SPICA in these studies with a broader wavelength coverage, a higher spectral resolution (needed to unblend molecular spectra), and a higher spatial resolution (needed to isolate individual extragalactic outflows). Based on Herschel/PACS+SPIRE fluxes for the prototypical source IRC +10 216⁶⁴, we could detect CO emission at $\leq 300 \,\mu$ m for on the order 100 evolved stars in the LMC with S/N = 3 - 10 in 1-hour integrations with ORIGINS/OSS. This would be limited to stars with $\dot{M}_{\rm gas} \gtrsim 10^{-6} M_{\odot}/{\rm yr}$, meaning that it covers a significant fraction of the AGB population, but misses stars with mass-loss rates $\dot{M}_{gas} = 10^{-8} - 10^{-6} M_{\odot}/yr$. As we currently do for galactic AGB stars, we could constrain the gas kinetic temperature and density structure of the outflows, and with that possibly the mass-loss history of these extragalactic stars, through radiative-transfer modelling of the CO emission.

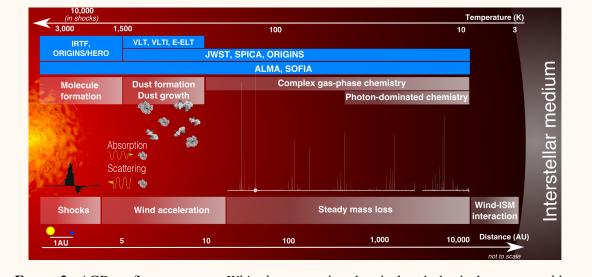


FIGURE 2: AGB outflow structure. *White boxes:* major chemical and physical processes, *blue boxes:* contribution of existing, planned, and proposed facilities.

Dust-mass-loss rates and the bulk properties of circumstellar dust (size distribution, chemical composition, temperature structure) are used alongside CO emission to set up empirical outflow models^{20,45,46,51,68}. There is a known dichotomy in the chemical properties of the dusty outflows. Amorphous carbon dust and silicon carbide appear together in the outflows of Cenriched stars, whereas silicates, alumina, and water ice dominate the dust emission of stars with C/O<1. The broad spectral features in the mid-infrared (MIR) of these solids have been studied for Galactic sources and in the Local Group, including the Magellanic Clouds, using e.g. UKIRT, IRAS, ISO, Spitzer, and Herschel, over a range of wavelengths and spectral resolving power^{5,7,15,16,53,54,61,63,73,77,78,79,80,81,82,83}. Surprisingly, it is found that the Fe-content of AGB dust is extremely low, although iron is significantly depleted from the gas phase in both circumstellar and interstellar environments, and ~90% of iron produced by stars should be in dust grains⁵². Fe-bearing minerals are likely on mineralogical grounds but have not yet been found^{38,52}.

Silicates show multiple emission features in the range $20 - 100 \,\mu$ m, which depend critically on their temperature and composition, and more specifically, on their relative content of Mg and Fe^{22,62,84}. In contrast, metallic iron and amorphous carbon have rather featureless dust continua. Other C-rich dust, like graphite, SiC, and especially polycyclic aromatic hydrocarbons (PAHs) do show emission features at $3 - 30 \,\mu$ m and the carriers of the 21 μ m and 30 μ m features in the outflows of C-rich stars are currently still debated. The feature observed around 30 micron in the outflows of C-stars is often attributed to MgS but its formation is unclear⁷⁶.

We know very little about the dust composition at low metallicity. Recent studies suggest that carbon dust may form independent of metallicity^{1,4,6,32}, whereas silicate dust composition likely has a strong metallicity dependence³⁹. Moreover, current studies^{58,59} suggest that the fraction of C-rich AGB stars is higher at lower metallicity, and, conversely, that the fraction of O-rich AGB stars decreases with lower metallicity. However, there is a possibility that the current surveys miss higher- \dot{M}_{gas} O-rich AGB stars that could significantly contribute to the interstellar enrichment. Additionally, the balance between AGB stars and supernovae as sources of dust input to the interstellar medium remains heavily debated and it is thus crucial to characterize AGB populations and quantify their dust-mass loss at different metallicities.

The way forward: The dust composition and \dot{M}_{dust} of outflows in the Galactic Bulge and throughout the Local Group (at much lower-than-solar metallicities) will be investigated with the MIRI and NIRCam instruments on board the James Webb Space Telescope (JWST), but ORIGINS and SPICA will provide further details on the chemical composition with their much broader wavelength coverage. These missions could observe the outflows of additional Galactic AGB stars which are not feasible with JWST because of saturation, and of AGB stars in the Local Group that can be spatially isolated. SOFIA/FORCAST can be used for Galactic sources.

Dust-production efficiency can be derived for a large part of the Galactic AGB population as we have estimates of both \dot{M}_{gas} and \dot{M}_{dust} . We do not have reliable dust-to-gas ratios for extragalactic AGB stars since we have virtually no \dot{M}_{gas} -estimates³³ (see above) and we instead have to rely on indirect \dot{M}_{gas} -measurements⁸⁶. To genuinely translate dust-mass-loss rates into a degree of chemical enrichment of the host galaxies, we need to understand how efficiently the dust is produced. Constraints on the dust-production efficiency in environments of substantially different metallicity are especially important in light of the discovery of extreme AGB stars producing about 65% of the total dust budget in the Magellanic Clouds and M32, but accounting for only 3% of the AGB population^{7,40,73,80}. Are these objects also extreme in their gas-mass-loss rates or is their dust-production efficiency substantially higher? How does this relate to the metallicity? The proposed measurements of \dot{M}_{gas} and \dot{M}_{dust} , outlined above, will directly serve to answer these questions.

Outflow drivers

Shocks Large-scale convective motions inside an AGB star replenish the outer stellar layers with newly processed elements and cause granulation at the surface^{29,69}. In combination with long-period (100-1000 days) pulsations, these motions cause shocks in the star's upper atmosphere, which can manifest themselves as a low-filling factor chromosphere with temperatures up to a few 10^4 K^{87} . For reference, the effective temperature of an AGB star is typically in the range $2000 - 3000 \text{ K}^{18}$. The high temperatures and densities in the shocked material cause an out-of-equilibrium chemistry^{13,14,30,56}. The main questions surrounding shocks and their role

in outflow driving are the following: How large is the region affected by shocks? Which densities and temperatures are reached in the shocked material? How do the shocks relate to the pulsation of the star, both in periodicity and strength?

The way forward: Observations of the stellar continuum and of molecular tracers, such as SiO or vibrationally excited CO, can reveal the size of the pockets of shocked material 50,87,88 and provide constraints on the temperature and density of the shocked gas. Near-infrared observations with e.g. IRTF/iSHELL of molecular bands of species that are highly abundant in the upper stellar atmosphere – such as C₂H₂, HCN, SiO, or H₂O – could trace the chemical effect of shocks; IRTF/TEXES and SOFIA/EXES could do this for matter at a few to a few tens of stellar radii; whereas SOFIA/GREAT and ORIGINS/HERO could do this in the far-infrared.

To disentangle the complex velocity field at the base of the outflow with infall and outflow, we require a resolution better than 1 km/s, since the contributions of molecular absorption and emission otherwise become indistinguishable or undetectable. Moreover, the variability in the emitted light over time can only be characterized using multi-epoch observations. Multiepoch, multi-frequency observations with ALMA can already now trace shock waves as they propagate through the atmosphere in submm/mm tracers^{42,48}. The in-depth treatment of the molecular excitation using detailed, non-LTE radiative transfer models will be an essential step in the analysis to characterize the effect of the variations in the stellar radiation field on the line emission^{11,70}, as opposed to changes in the molecular abundance caused by shocks.

Dust forms in the warm regions (1000-1500 K) close to the AGB star, although observations suggest that the smallest dust grains could form at even higher temperatures⁴⁹. The grains experience radiation pressure through absorption or scattering of incident stellar light and are pushed radially outward. Momentum transfer to the gas leads to steady outflows that build large circumstellar envelopes of gas and dust³⁷. Since the opacities of different dust species cause significantly different responses to radiation pressure from the incident stellar light, wind-driving models depend critically on the dust properties. Grain size, density, and opacity (absorption/emission cross-section) need to be well-constrained, especially at the base of the outflows³⁴. The observed outflow rates in the case of C-rich AGB stars can be reproduced, given optical properties of the carbonaceous dust. For O-rich AGB stars, however, a number of open questions remain. Alumina form closest to the star, at $\sim 2R_{\star}^{44,49,51,89}$ but cannot drive the wind³⁵. Iron-bearing silicates seem to represent a larger mass fraction of the total dust in the outflow (e.g. ~65% in the case of W Hya⁵¹), but are found only beyond $5R_{\star}^{89}$ which rules them out as drivers at the base of the outflow. In order for radiation pressure to be sufficient, scattering of stellar light on large Fe-free silicate grains close to the star has been suggested³⁴. The presence of large grains has been corroborated^{65,66,67}, but the micro-physics of their formation processes remains unclear. Which seed particles do the grains grow on? How efficient is the gradual Fe-enrichment of silicates in the wind?

The way forward: Observations at high-angular resolution using e.g. VLT/SPHERE, VLTI/MATISSE and the future E-ELT/METIS can provide the spatial information, size, and density of dust close to the star^{47,49,66,67} in the case of Galactic sources. If ORIGINS/MISC carries a coronagraph, it could trace the emission from solid-state bands at distances of a few to a few tens of stellar radii in these outflows, where the dust grains grow to their final size and composition. Improved knowledge of the bulk dust properties (see above) will set strong constraints on the possible dust-condensation sequences.

Dust formation

Large uncertainties in the current wind-driving paradigm relate to the path of dust formation and growth. Which molecules form the first clusters that serve as seeds for solid-grain growth? Which are the relevant condensation sequences? What are the properties (size, shape, opacity) of the grains close enough to the star to drive a wind? Do these vary over the stellar pulsation cycle? If so, how does this affect the outflow? Do these properties vary with metallicity?

Gas depletion and the chemical processes involved in the transition between the gas and solid phases around AGB stars of all chemical types are currently only poorly characterized. Several theoretical efforts have recently been made to understand this critical part of circumstellar chemistry^{3,30,31}. Empirical constraints have to come from observations of both the dusty and gaseous components in the upper atmosphere and at the base of the outflow of all chemical types of AGB stars^{10,19,21,24,28,41,43,47,49,57}. Additionally, there is a lack of characterization (both observationally and theoretically) of the effect of dust grains on the gas chemistry. What is the role of grain-surface reactions, evaporation, sputtering, etc.?

The way forward: Current efforts to measure the depletion of gas-phase species in the dust-formation and growth processes lack access to sensitive, high-spectral resolution observations in the far-infrared. Whereas ALMA can observe at high-angular resolution and extremely high sensitivity, a high-spectral resolution instrument on board a space-based facility like ORI-GINS/HERO is needed to access transitions of H₂O and hydrides, as well as high-excitation lines of numerous other molecules considered critical in the dust formation and growth (e.g. Ti-, Al-, Fe- bearing molecules)^{42,43}. No other planned facility will be able to address this aspect of the fundamental question of how dust is formed. High-spatial resolution observations with e.g. ALMA are additionally needed to study the effect of dust grains on gas chemistry²³.

<u>The first solids</u> to appear in the outflows have not yet been characterized. In the case of O-rich stars, large gas-phase clusters such as $(Al_2O_3)_n$ are likely candidates to form the first dust grains. For C-rich stars, PAHs, have been suggested ^{12,14}.

The way forward: Clusters and PAHs show broad spectral features in the mid-/far-infrared much like most dust species^{24,25} and there is a need for spectroscopic predictions. The enormous wavelength coverage of SPICA and ORIGINS/OSS would be ideal to search for these. E-ELT/METIS observations will be essential to test the presence of these very small clusters.

Variability: Ideally, future observations of gas depletion and dust formation will sample the gas and dust (quasi-)simultaneously, to mitigate effects of variability on the analysis, and at multiple epochs in time⁴⁹, to characterize the chemical variability in the material throughout the pulsation cycles of the stars (periods of a few hundred days) and provide empirical constraints for true time-domain astrochemistry. The transit channel of ORIGINS/MISC could measure the temporal variations in the dust emission in the outflow (see also above). Although it is optimized for high-cadence time series (5s-1min), we could get low-spectral resolution variability measures on timescales of tens of days.

Prospects and needs

Observations from current and upcoming facilities need to provide strong constraints on dust formation and growth. This includes ground- and space-based facilities covering an enormous wavelength range and covering a large variety of observational techniques.

Theory: The spectroscopy of molecules and clusters needs to be expanded in order to successfully search for and identify the relevant spectral features. More theoretical efforts are also needed to describe the chemical processes involved in the dust-gas chemistry, such as molecular-cluster formation, grain-surface chemistry, and evaporation of gas from the grain surfaces. To consider the effects of large-scale convective flows on the wind driving, 3D radiation-hydrodynamical models of dust-driven winds need to be developed ³⁶, to complement the spherically symmetric models used at present ^{1,2,27,60}. In addition, there will be a need for hydrodynamical models that study the influence of the interaction between the stellar outflows and the ISM on the properties of the dust grains that are deposited into the ISM. Finally, results

from wind models and observations (mass-loss rates, molecular abundances, dust-to-gas ratios) may be included in stellar evolution calculations for evolved stars^{55,56} to test their impact as a function of stellar mass and metallicity.

References

- Bladh, S., Eriksson, K., Marigo, P., Liljegren, S., & Aringer, B. 2019, arXiv e-prints [arXiv:1902.05352]
- [2] Bladh, S., Höfner, S., Aringer, B., & Eriksson, K. 2015, A&A, 575, A105
- [3] Boulangier, J., Clementel, N., van Marle, A. J., Decin, L., & de Koter, A. 2019, MN-RAS, 482, 5052
- [4] Boyer, M. L., McQuinn, K. B. W., Barmby, P., et al. 2015, ApJ, 800, 51
- [5] Boyer, M. L., McQuinn, K. B. W., Barmby, P., et al. 2015, ApJS, 216, 10
- [6] Boyer, M. L., McQuinn, K. B. W., Groenewegen, M. A. T., et al. 2017, ApJ, 851, 152
- [7] Boyer, M. L., Srinivasan, S., Riebel, D., et al. 2012, ApJ, 748, 40
- [8] Bradford, C. M., Cameron, B., Moore, B., et al. 2018, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 10698, Space Telescopes and Instrumentation 2018: Optical, Infrared, and Millimeter Wave, 1069818
- [9] Bujarrabal, V., Hifistars, & Success Teams. 2011, in Astronomical Society of the Pacific Conference Series, Vol. 445, Why Galaxies Care about AGB Stars II: Shining Examples and Common Inhabitants, ed. F. Kerschbaum, T. Lebzelter, & R. F. Wing, 577
- [10] Cernicharo, J., McCarthy, M. C., Gottlieb, C. A., et al. 2015, ApJL, 806, L3
- [11] Cernicharo, J., Teyssier, D., Quintana-Lacaci, G., et al. 2014, ApJL, 796, L21
- [12] Cherchneff, I. 2000, in IAU Symposium, Vol. 177, The Carbon Star Phenomenon, ed. R. F. Wing, 331
- [13] Cherchneff, I. 2006, A&A, 456, 1001
- [14] Cherchneff, I. 2012, A&A, 545, A12
- [15] Clément, D., Mutschke, H., Klein, R., & Henning, T. 2003, ApJ, 594, 642
- [16] Clément, D., Mutschke, H., Klein, R., et al. 2005, ApJ, 621, 985
- [17] Danilovich, T., Teyssier, D., Justtanont, K., et al. 2015, A&A, 581, A60
- [18] De Beck, E., Decin, L., de Koter, A., et al. 2010, A&A, 523, A18
- [19] De Beck, E., Decin, L., Ramstedt, S., et al. 2017, A&A, 598, A53
- [20] De Beck, E., Lombaert, R., Agúndez, M., et al. 2012, A&A, 539, A108

- [21] De Beck, E., Vlemmings, W., Muller, S., et al. 2015, A&A, 580, A36
- [22] de Vries, B. L., Acke, B., Blommaert, J. A. D. L., et al. 2012, Nature, 490, 74
- [23] Decin, L., Richards, A. M. S., Millar, T. J., et al. 2016, A&A, 592, A76
- [24] Decin, L., Richards, A. M. S., Waters, L. B. F. M., et al. 2017, A&A, 608, A55
- [25] Draine, B. T. 2011, in EAS Publications Series, Vol. 46, EAS Publications Series, ed. C. Joblin & A. G. G. M. Tielens, 29–42
- [26] Edmunds, M. G. & Morgan, H. L. 2005, in Astronomical Society of the Pacific Conference Series, Vol. 332, The Fate of the Most Massive Stars, ed. R. Humphreys & K. Stanek, 331
- [27] Eriksson, K., Nowotny, W., Höfner, S., Aringer, B., & Wachter, A. 2014, A&A, 566, A95
- [28] Fonfría, J. P., Cernicharo, J., Richter, M. J., & Lacy, J. H. 2008, ApJ, 673, 445
- [29] Freytag, B., Liljegren, S., & Höfner, S. 2017, A&A, 600, A137
- [30] Gobrecht, D., Cherchneff, I., Sarangi, A., Plane, J. M. C., & Bromley, S. T. 2016, A&A, 585, A6
- [31] Gobrecht, D., Cristallo, S., Piersanti, L., & Bromley, S. T. 2017, ApJ, 840, 117
- [32] Goldman, S. R., Boyer, M. L., Mc-Quinn, K. B., et al. 2019, arXiv e-prints [arXiv:1902.07362]
- [33] Groenewegen, M. A. T., Vlemmings,
 W. H. T., Marigo, P., et al. 2016, A&A, 596,
 A50
- [34] Höfner, S. 2008, A&A, 491, L1
- [35] Höfner, S., Bladh, S., Aringer, B., & Ahuja, R. 2016, A&A, 594, A108
- [36] Höfner, S. & Freytag, B. 2019, arXiv e-prints [arXiv:1902.04074]
- [37] Höfner, S. & Olofsson, H. 2018, AARv, 26, 1
- [38] Jones, A. P. 1990, MNRAS, 245, 331
- [39] Jones, O. C., Kemper, F., Sargent, B. A., et al. 2012, MNRAS, 427, 3209
- [40] Jones, O. C., McDonald, I., Rich, R. M., et al. 2015, MNRAS, 446, 1584
- [41] Kamiński, T., Gottlieb, C. A., Menten, K. M., et al. 2013, A&A, 551, A113
- [42] Kamiński, T., Müller, H. S. P., Schmidt, M. R., et al. 2017, A&A, 599, A59
- [43] Kamiński, T., Wong, K. T., Schmidt, M. R.,

et al. 2016, A&A, 592, A42

- [44] Karovicova, I., Wittkowski, M., Ohnaka, K., et al. 2013, A&A, 560, A75
- [45] Khouri, T., de Koter, A., Decin, L., et al. 2014, A&A, 561, A5
- [46] Khouri, T., de Koter, A., Decin, L., et al. 2014, A&A, 570, A67
- [47] Khouri, T., Maercker, M., Waters, L. B. F. M., et al. 2016, A&A, 591, A70
- [48] Khouri, T., Velilla-Prieto, L., De Beck, E., et al. 2019, A&A, 623, L1
- [49] Khouri, T., Vlemmings, W. H. T., Olofsson, H., et al. 2018, A&A, 620, A75
- [50] Khouri, T., Vlemmings, W. H. T., Ramstedt, S., et al. 2016, MNRAS, 463, L74
- [51] Khouri, T., Waters, L. B. F. M., de Koter, A., et al. 2015, A&A, 577, A114
- [52] Kimura, Y., Tanaka, K. K., Nozawa, T., Takeuchi, S., & Inatomi, Y. 2017, Science Advances, 3, e1601992
- [53] Kraemer, K. E., Sloan, G. C., Price, S. D., & Walker, H. J. 2002, ApJS, 140, 389
- [54] Kwok, S., Volk, K., & Bidelman, W. P. 1997, ApJS, 112, 557
- [55] Marigo, P., Bressan, A., Nanni, A., Girardi, L., & Pumo, M. L. 2013, MNRAS, 434, 488
- [56] Marigo, P., Ripamonti, E., Nanni, A., Bressan, A., & Girardi, L. 2016, MNRAS, 456, 23
- [57] Massalkhi, S., Agúndez, M., Cernicharo, J., et al. 2018, A&A, 611, A29
- [58] Matsuura, M., Barlow, M. J., Zijlstra, A. A., et al. 2009, MNRAS, 396, 918
- [59] Matsuura, M., Woods, P. M., & Owen, P. J. 2013, MNRAS, 429, 2527
- [60] Mattsson, L., Wahlin, R., & Höfner, S. 2010, A&A, 509, A14
- [61] Messenger, S. J., Speck, A., & Volk, K. 2013, ApJ, 764, 142
- [62] Molster, F. J., Yamamura, I., Waters, L. B. F. M., et al. 1999, Nature, 401, 563
- [63] Mutschke, H., Begemann, B., Dorschner, J., et al. 1998, A&A, 333, 188
- [64] Nicolaes, D., Groenewegen, M. A. T., Royer, P., et al. 2018, A&A, 618, A143
- et al. 2012, Nature, 484, 220

- [66] Ohnaka, K., Weigelt, G., & Hofmann, K.-H. 2016, A&A, 589, A91
- [67] Ohnaka, K., Weigelt, G., & Hofmann, K.-H. 2017, A&A, 597, A20
- [68] Oudmaijer, R. D., Groenewegen, M. A. T., Matthews, H. E., Blommaert, J. A. D. L., & Sahu, K. C. 1996, MNRAS, 280, 1062
- [69] Paladini, C., Baron, F., Jorissen, A., et al. 2018, Nature, 553, 310
- [70] Pardo, J. R., Cernicharo, J., Velilla Prieto, L., et al. 2018, A&A, 615, L4
- [71] Ramos-Medina, J., Sánchez Contreras, C., García-Lario, P., & da Silva Santos, J. M. 2018, A&A, 618, A171
- [72] Ramstedt, S., Schöier, F. L., Olofsson, H., & Lundgren, A. A. 2008, A&A, 487, 645
- [73] Riebel, D., Srinivasan, S., Sargent, B., & Meixner, M. 2012, ApJ, 753, 71
- [74] Sarangi, A., Matsuura, M., & Micelotta, E. R. 2018, SSR, 214, 63
- [75] Scicluna, P., Siebenmorgen, R., Wesson, R., et al. 2015, A&A, 584, L10
- [76] Sloan, G. C., Lagadec, E., Zijlstra, A. A., et al. 2014, ApJ, 791, 28
- [77] Speck, A. K., Barlow, M. J., & Skinner, C. J. 1997, MNRAS, 288, 431
- [78] Speck, A. K., Barlow, M. J., Sylvester, R. J., & Hofmeister, A. M. 2000, A&AS, 146, 437
- [79] Speck, A. K., Corman, A. B., Wakeman, K., Wheeler, C. H., & Thompson, G. 2009, ApJ, 691, 1202
- [80] Srinivasan, S., Boyer, M. L., Kemper, F., et al. 2016, MNRAS, 457, 2814
- [81] Suh, K.-W. 1999, MNRAS, 304, 389
- [82] Suh, K.-W. 2000, MNRAS, 315, 740
- [83] Suh, K.-W. 2002, MNRAS, 332, 513
- [84] Sylvester, R. J., Kemper, F., Barlow, M. J., et al. 1999, A&A, 352, 587
- [85] Tielens, A. G. G. M. 2005, The Physics and Chemistry of the Interstellar Medium
- [86] van Loon, J. T. 2000, A&A, 354, 125
- [87] Vlemmings, W., Khouri, T., O'Gorman, E., et al. 2017, Nature Astronomy, 1, 848
- [88] Wong, K. T., Kamiński, T., Menten, K. M., & Wyrowski, F. 2016, A&A, 590, A127
- [65] Norris, B. R. M., Tuthill, P. G., Ireland, M. J., [89] Zhao-Geisler, R., Quirrenbach, A., Köhler, R., & Lopez, B. 2012, A&A, 545, A56