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Mass-loss and silicate production in oxygen-rich AGB stars: current understanding and open questions

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AGB stars play a crucial role in the chemical enrichment of the Universe, polluting their host galaxies with gas and dust that reflect the nucleosynthesis processes active during their evolution. Among the dust species formed in the AGB phase, oxygen-rich dust is produced in significant quantities in sources with masses above 4 solar masses, influencing wind dynamics and, consequently, the total dust budget of such stars. In this regard, this manuscript aims to update the reader on some key open questions that still limit the estimation of the role of oxygen-rich AGB stars in the silicate budget of the interstellar medium in galaxies. This is achieved by reviewing previous studies and focusing on the limitations in the description of mass-loss rates and dust yields.

KEYWORDS

AGB -stars, silicates, mass-loss -stars, dust production, stellar evolution, IR observations

1 Introduction

The Asymptotic Giant Branch (AGB) represents a crucial phase in the evolution of low- and intermediate-mass stars (~0.8–8 $M_{\odot}$), characterized by complex nucleosynthesis processes, intense mass-loss, and significant dust production. During this phase, stars experience substantial structural and internal changes, developing a degenerate CO core surrounded by alternating burning shells of hydrogen and helium (Herwig, 2005), while their extended convective envelope undergoes significant mass-loss through powerful stellar winds. The stellar winds, composed of gas and dust, are responsible for a substantial portion of the material returned to the interstellar medium (ISM), contributing to the formation of new stars and planetary systems (Tielens et al., 2005; Karakas, 2010). The chemical composition of the circumstellar envelope, particularly the surface carbon-to-oxygen (C/O) ratio, determines the type of dust produced. Carbon-rich AGB stars (C/O $>$ 1) produce carbonaceous dust (CRD), while oxygen-rich AGB stars (C/O $<$ 1) produce oxygen-rich dust (ORD), mainly composed of silicates such as olivine, pyroxene, and quartz. Both species are recognized as among the most efficient dust manufacturers in the Universe (Ferrarotti and Gail, 2006).

This manuscript focuses on oxygen-rich AGB stars and the silicates they produce, which play a crucial role in various astrophysical contexts. In fact, silicates have been observed in diverse environments, from nearby protoplanetary disks (Maaskant et al., 2015) to the surroundings of active galactic nuclei (Xie et al., 2017) and even in distant quasars (Pennock et al., 2022). For this reason, a deeper understanding of these environments requires a more detailed characterization of oxygen-rich sources, particularly in metal-rich systems where they dominate the stellar population (Li et al., 2023). Moreover, the impact of silicates on the cosmic cycle of matter is significant (Henning, 2010). They influence the thermal balance of dense and cold regions within interstellar and circumstellar dust populations, contribute to interstellar extinction, and emit thermally in the infrared and millimeter wavelengths. Additionally, studying this dust species provides a unique opportunity to probe AGB wind structures, as its formation depends on specific thermodynamic conditions that are highly sensitive to stellar outflow properties (Gail and Sedlmayr, 2013). Silicate grains play a key role in wind acceleration but require sufficient growth to interact effectively with stellar radiation. If they remain too small, the radiative pressure is insufficient to drive a wind; however, when their sizes approach the wavelengths where stellar flux peaks (0.1–1 μm), they can efficiently scatter radiation, enhancing their contribution to the wind-driving process (Höfner, 2008).

Nonetheless, modeling the formation and growth of silicate grains in AGB winds remains challenging, given the delicate interplay between dust condensation, mass-loss, radiation pressure, and local thermodynamic conditions (Mattsson et al., 2010; Gail and Sedlmayr, 2013). Metallicity further modifies these processes, as illustrated by observations of oxygen-rich AGB stars that show a nearly linear decrease in gas-to-dust ratios (Marshall et al., 2004). Accurately quantifying how oxygen-rich AGB stars shape the dust content of galaxies and how the production of silicates regulates the mass-loss process is thus a pivotal goal for both stellar evolution and cosmic dust research.

We note that this mini-review does not aim to provide a comprehensive overview of AGB mass-loss and dust production, but rather seeks to highlight some limitations that still hinder our ability to robustly assess the importance of oxygen-rich AGB stars for the silicate enrichment of the interstellar medium in galaxies and, more broadly, in the Universe.

2 Dust formation in oxygen-rich AGB stars: The role of the C/O ratio and progenitor mass

As anticipated in the Introduction, the mineralogy of the dust formed in AGB winds depends primarily on the C/O ratio. This is due to the extreme stability of the CO molecule, which entirely locks the less abundant element between carbon and oxygen, making it unavailable for dust formation. The abundances of these elements are significantly influenced by the Third Dredge-Up (TDU) (Herwig, 2005) and Hot Bottom Burning (HBB) (Sackmann and Boothroyd, 1991). The TDU is a mixing process that enhances the surface carbon abundance, and repeated TDU episodes can lead to C/O > 1, consequently favoring the formation of CRD. Conversely, ORD is favored when the number of TDU episodes is too low to achieve C/O > 1 or when HBB is active. In fact, HBB is a nucleosynthetic process that lowers the surface carbon abundance, operating at temperatures above 40 MK and thus occurring in stars with masses exceeding approximately 4 $M_\odot$. Stars in this mass range, known as intermediate-mass stars, are predicted to be the most efficient silicate producers in their stellar winds (Ventura et al., 2014; 2018).

In oxygen-rich winds, various dust species can form, including silicates, alumina (Al_2O_3), and solid iron (Ferrarotti and Gail, 2002; 2006; Gail and Sedlmayr, 1999). Among these, alumina dust is the most stable, forming at high temperatures of around ~1500 K, corresponding to a distance of ~1–2 R_* from the star's photosphere. However, due to its high optical transparency, alumina dust does not contribute significantly to wind acceleration and therefore does not hinder the formation of other dust species. In contrast, silicate dust forms in a more distant region, approximately ~10 R_* from the star, where temperatures range from 1000 to 1100 K (Gail and Sedlmayr, 2013; Höfner, 2008). Once silicates form in sufficient quantities and reach adequate size, they become the primary drivers of radiative pressure, playing a crucial role in accelerating the AGB wind (Dell'Agli et al., 2014).

Before silicates and other dust species can condense, initial seed nuclei (known as nucleation) must form; however, this remains a major open question in oxygen-rich AGB winds (Jeong et al., 2003; Woitke, 2006; Gail and Sedlmayr, 2013). Al_2O_3, the most stable dust species, is a leading candidate due to its high condensation temperature and proximity to the star. (Karovicova et al., 2013; Höfner et al., 2016). Titanium dioxide (TiO_2) and iron oxides (FeO, Fe_2O_3) have also been proposed as potential condensates (Jeong et al., 2003; Gail and Sedlmayr, 2013), although evidence suggests that they are not primary nucleation seeds. Stellar metallicity, which dictates the abundance of key metals like Al and Ti, may act as a bottleneck, affecting both nucleation and subsequent dust condensation (Nanni et al., 2013; Ventura et al., 2018). While a detailed discussion is beyond the scope of this review, nucleation remains a key factor in dust formation efficiency across different stellar environments.

In AGB stars, silicates can be observed in both amorphous and crystalline forms (Waters et al., 1996; Molster et al., 2002). These two forms exhibit distinct features in infrared spectroscopic observations: amorphous silicates produce broad, smooth bands at 9.7 and 18 μm, while crystalline silicates display sharper resonance peaks. The exact positions and shapes of these peaks are highly sensitive to factors such as composition, lattice structure, grain size, and morphology (Molster et al., 2002; Koike et al., 2003). This is evident in Figure 1, which shows the spectra of an AGB (SSID165, panel A) and a post-AGB (HD 179821, panel B), where the location of the aforementioned silicate species is highlighted. Temperature plays a key role in determining whether silicates condense into a crystalline or amorphous lattice: formation above the glass transition favors the more energetically stable crystalline arrangement (e.g., olivine, pyroxene, quartz), whereas lower temperatures typically result in amorphous grains.

Concerning the amount of dust produced, the progenitor mass of a star generally plays a pivotal role in this aspect. For instance, in the work of Ventura et al. (2018), different evolutionary models agree that higher-mass stars produce larger amounts of silicates, as they are characterized by higher luminosities and mass-loss rates (Gail and Sedlmayr, 2013). This is illustrated in Figure 21 of that study.

3 Mass-loss and silicate formation in oxygen-rich AGB stars: challenges and advances

In recent years, significant efforts have been made to develop accurate models of AGB stars that couple stellar evolution with the processes of dust formation and its influence on wind dynamics

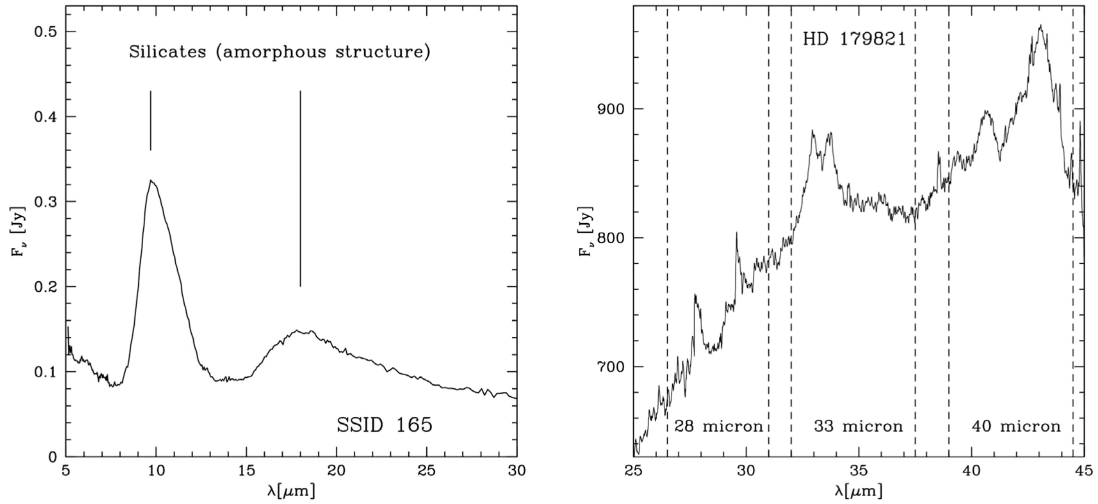

FIGURE 1
(A) Spitzer spectra from the sample studied both by Jones et al. (2012) and Marini et al. (2020) of SSID165, an oxygen-rich AGB star, showing the characteristics features of the silicates in the amorphous structure at 9.7 and 18μm **(B)** ISO spectrum (Sloan et al., 2003) of the Galactic post-AGB star HD 179821, where we indicated with dashed lines the range of some crystalline silicates complexes.

(Ventura et al., 2012; 2014; Nanni et al., 2013; 2014). This is essential for evaluating how wind dynamics shape stellar evolution and determine the properties of the material ejected into the ISM. In this context, the framework proposed by the Heidelberg group (Ferrarotti and Gail, 2002; 2006) has played a pivotal role, providing valuable insights into dust production, particularly regarding the formation of silicate grains in oxygen-rich AGB stars. However, several uncertainties still affect the accuracy of these theoretical results, particularly regarding the luminosities and mass-loss rates reached by intermediate-mass AGB stars (Karakas and Lattanzio, 2014) and the likelihood of these stars evolving into the C-star phase during the final stages of their AGB evolution (Ventura et al., 2018).

Since the mass-loss process directly influences the amount and composition of dust expelled into the interstellar medium, a detailed understanding of this mechanism is essential for quantifying silicate production. However, accurately modeling mass-loss rates, which are critical for dust formation, has been a long-standing challenge. Early mass-loss prescriptions, such as the Reimers (1975) formula, provided a simple parameterization based on stellar luminosity, radius, and mass. However, since it was derived from observations of red giants and does not account for the effects of dust formation, it fails to describe the intense mass-loss rates of late AGB stars. Consequently, it is most commonly used to model mass-loss during the early AGB phases. Bloecker (1995) proposed a more advanced prescription based on the dynamical calculations for Mira-like star atmospheres by Bowen (1988), which introduced a stronger dependence on luminosity, capturing the rapid mass-loss rates observed in intermediate-mass stars. Vassiliadis and Wood (1993), hereafter VW93 further improved these models by linking mass-loss rates to stellar pulsation periods, allowing for a more realistic description of the increasing mass-loss toward the end of the AGB phase, particularly during the so-called super-wind phase. Recent work by Goldman et al. (2017) introduced an empirical mass-loss prescription that accounts for both luminosity and metallicity effects, revealing a strong correlation between mass-loss rates and luminosity. Their findings suggest that AGB mass-loss is nearly independent of metallicity within a range of half to twice the solar value. Each model provides valuable insights but faces to fully capture the complexities of stellar atmospheres and interactions, particularly in the final AGB phases. Additionally, the calibration of parameters, such as the scaling factor in Bloecker (1995) prescription, remains debated, and it is likely that no single prescription can fully account for the diversity of all OH/IR stars (Goldman et al., 2017). In this regard, a comprehensive overview of the various mass-loss prescriptions can be found in Rosenfield et al. (2014). This underscores the need for more refined models that better incorporate diverse stellar conditions and observational constraints, which are crucial for improving our understanding of mass-loss and dust formation in AGB stars.

The parameterization of AGB star winds and the connection between mass-loss rates and the conditions required for dust condensation depend on the assumptions made in wind dynamics models. These models, which typically assume spherically symmetric flows to simplify computations, fall into two categories. Steady wind models have been instrumental in studying the driving mechanism of winds, predicting dust yields, and are commonly applied in stellar population studies (e.g., Nanni et al., 2013; Nanni et al., 2014; Dell'Agli et al., 2014). While they are well-suited for coupling with stellar evolution models, their limitation is that mass-loss rates are treated as input parameters rather than being derived as a result. Time-dependent models, on the other hand, simulate the formation of dust and its role in driving mass-loss (Höfner et al., 2016). While these models can provide mass-loss rates as an output, their complexity makes it challenging to couple them directly with stellar evolution models. Thus, despite these advances, critical challenges remain, including the complex interplay between pulsations, dust formation, and wind acceleration.

These challenges are particularly relevant for oxygen-rich AGB stars, as the production of silicate grains depends sensitively on the local physical conditions in the stellar atmosphere. Recent observational studies have confirmed the complexity of mass-loss dynamics in deeply embedded AGB stars, revealing intricate circumstellar structures and extreme dust production rates. These findings highlight the limitations of simplified theoretical models and underscore the need for more advanced prescriptions that can accurately reproduce the observed properties of these stars. For example, studies such as Bladh et al. (2019) show that mass-loss rates do not exhibit a straightforward correlation with pulsation properties, suggesting that additional factors, such as non-LTE effects or time-dependent chemistry, may play a role. Furthermore, high-resolution imaging has revealed non-spherical morphologies in the circumstellar envelopes of AGB stars, indicating the potential influence of mechanisms such as binary interactions, magnetic fields, or stellar rotation (Decin et al., 2020). These complexities emphasize the need for models that account for asymmetries and non-linear processes to accurately capture the conditions under which silicate dust forms and is ejected.

Understanding mass-loss mechanisms is vital to resolving the debate on whether intermediate-mass AGB stars contribute significantly to silicate production in galaxies. While their role is likely negligible in metal-poor environments, silicate yields at sub-solar, solar, and super-solar metallicities remain unclear due to conflicting studies (Schneider et al., 2014; Ventura et al., 2014; Ventura et al., 2020). Models that integrate hydrodynamical simulations and observational constraints will be crucial for refining our understanding of silicate production and the role of oxygen-rich AGB stars in the chemical evolution of galaxies.

4 Deeply obscured AGB stars as drivers of silicate production

While all oxygen-rich AGB stars contribute to the silicate budget, deeply embedded sources with extreme mass-loss rates appear to be the primary contributors. These objects, characterized by thick circumstellar dust shells, provide key insights into the terminal AGB phases and the peak of silicate dust production.

In this section, we first review the observational evidence supporting the role of high-mass-loss oxygen-rich AGB stars as major silicate dust producers, focusing on studies that have identified and characterized these sources. We then discuss the theoretical advances that have shaped our understanding of their dust formation processes, including recent modeling efforts that highlight the connection between mass-loss, dust production, and stellar evolution.

4.1 Observational evidence

Oxygen-rich AGB stars with high mass-loss rates have been widely recognized by the scientific community as key contributors to the silicate enrichment of the ISM, often appearing heavily obscured by their dusty envelopes. As a result, they have been extensively studied and are considered ideal laboratories for exploring the interplay between stellar evolution, mass-loss processes, and dust production. Indeed, Olivier et al. (2001) conducted a comprehensive study of 58 dust-enshrouded AGB stars within approximately one kpc of the Sun, using infrared photometry from various surveys (Two Micron Sky Survey, IRAS, and AFGL). Their analysis revealed that the majority of these sources are cool variable stars experiencing moderate to high mass-loss, confirming the importance of local dust-enshrouded AGB stars in the galactic dust budget. van Loon et al. (2005) analyzed obscured AGB stars in nearby galaxies, contributing to the understanding of their properties through the analysis of infrared emissions. Jones et al. (2012) demonstrated their crucial role in the production of large amounts of silicates, particularly in metal-rich environments. Groenewegen and Sloan (2018) further expanded this work by studying a sample of both carbon-rich and oxygen-rich AGB stars in the Magellanic Clouds, combining Spitzer IRS spectra with optical and infrared photometry to model their spectral energy distributions and derive mass-loss rates and luminosities. Their results confirmed the existence of a population of extremely dusty oxygen-rich AGB stars with significant contributions to the overall dust budget. High-resolution observations have revealed unexpected complexities in the circumstellar environments of these stars. Most notably, Decin et al. (2020) identified spiral structures around extreme OH/IR stars, revealing them to be wide binary systems and showing a correlation between the morphology of AGB ejecta and the current mean mass-loss rate in these systems. Additional insights have come from AKARI/IRC observations of extremely red IRAS sources, as reported by Bunzel et al. (2009), showing that OH/IR variables exhibit strong silicate absorption features at 10 μm, indicative of their substantial dust production.

4.2 Theoretical understanding and advances

The theoretical framework for understanding the observations outlined in Section 4.1 has evolved significantly through various modeling efforts since the early studies. Early work by Ferrarotti and Gail (2006) established foundational models for dust production in AGB stars across different chemical phases (M, S, and C), incorporating complex radiation-dust interactions in circumstellar shells. Their models, while comprehensive in treating various dust species, including olivine, pyroxene, and quartz, suggested lower silicate condensation temperatures than later experimental measurements would indicate. Nanni et al. (2013) advanced this understanding by developing detailed models of dust formation in circumstellar envelopes using the COLIBRI code. Their work particularly emphasized the importance of condensation temperature in silicate formation, comparing low condensation temperature (LCT) and high condensation temperature (HCT) models. They identified the significant role of chemo-sputtering in silicate destruction at temperatures above 1100 K and demonstrated how dust production varies with stellar mass and metallicity. Ventura et al. (2018) further contributed by providing a detailed comparison of two different evolutionary codes (ATON and MONASH) for modeling solar-metallicity AGB stars. Their work underscored the crucial importance of considering dust formation processes and metallicity in AGB evolution, particularly in the final phases where dust production peaks. More recently, Marini et al.

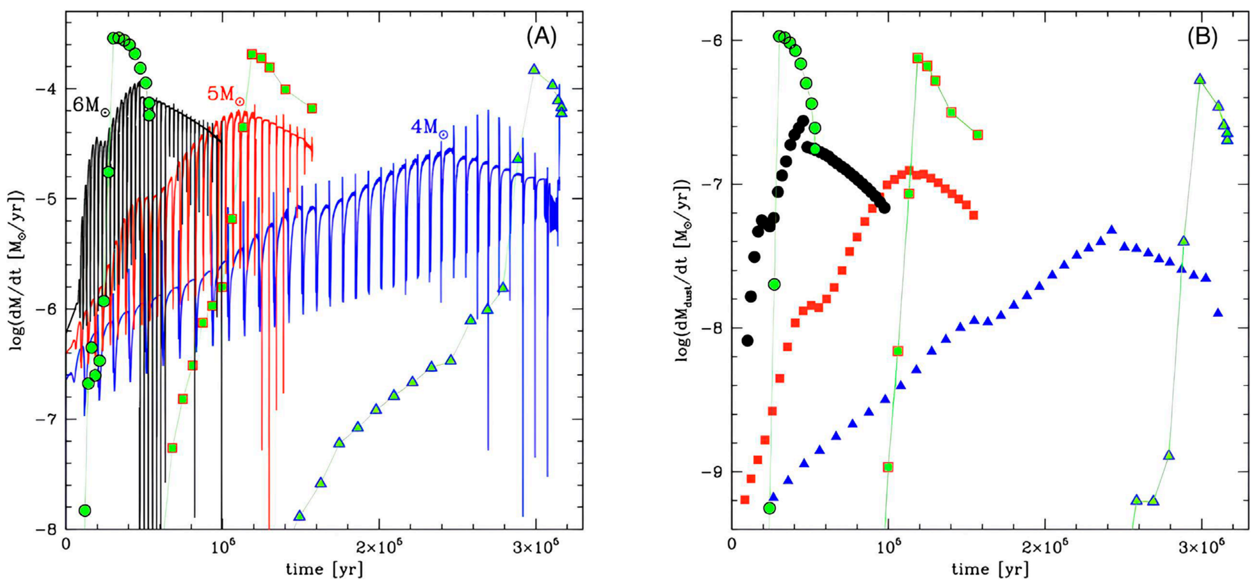

FIGURE 2
Theoretical models from the work by Marini et al. (2023). Time variation of the mass-loss rate **(A)** and dust production rate **(B)** of model stars of initial mass 4 $M_\odot$ (black lines and circles) 5 $M_\odot$ (red lines and squares) and 6 $M_\odot$ (blue lines and triangles), calculated with the mass-loss prescription by Bloecker (1995). Green points refer to the inter-pulse phases, and indicate results from modelling based on the VW93 description of mass-loss.

(2023) explored silicate dust production in a group of deeply obscured intermediate-mass AGB stars in the Galaxy, testing different mass-loss rate prescriptions to better reproduce the observational data. The best agreement was achieved using the VW93 formula, leading the authors to show that intermediate-mass stars undergo a dramatic increase in silicate dust production during their terminal AGB phases. This enhanced production remains highly efficient until the very final stages, just before contraction into the post-AGB phase. The process is characterized by extremely high mass-loss rates (10^{-4} $M_\odot$/yr) and is evidenced by deep absorption features at 9.7 and 18 μm. Such features confirm that these stars represent the most significant contributors to silicate production across the Universe, as suggested by earlier studies (Riebel et al., 2012). A comparison of some of the results obtained by Marini et al. (2023) using different mass-loss descriptions (Bloecker, 1995, and VW93) is shown in Figure 2, where the time variation of the mass-loss rate and silicate production rate of intermediate-mass AGB stars are displayed. Significant differences are found in the mass-loss rates experienced, especially during the final phases, with the VW93 models producing values approximately three times higher than those calculated using the Bloecker (1995) prescription.

The implications of these extreme mass-loss rates are substantial and directly impact the dust production rate of the stars, as seen in the panel (B) of Figure 2. Marini et al. (2023) showed that the total amount of silicate dust expelled into the interstellar medium during the final stages of intermediate-mass AGB stars is approximately three times larger than previously estimated by earlier studies, including Dell'Agli et al. (2017), Nanni et al. (2018), and Ferrarotti and Gail (2006), which had calculated lower silicate yields for intermediate-mass stars at similar metallicities (see Table 2 in Marini et al., 2023).

This comprehensive body of observational and theoretical work underscores that, to accurately assess the contribution of AGB stars to the silicate enrichment of the interstellar medium in galaxies and the Universe, it is crucial to focus particularly on the most extreme cases of mass-loss in oxygen-rich AGB stars. These heavily obscured stars, despite their relatively small numbers, appear to dominate the overall silicate dust production, especially in metal-rich environments. The findings highlight the critical importance of accurately modeling mass-loss processes and dust formation mechanisms in these stars, with particular attention to the terminal AGB phase, to precisely quantify their role in the cosmic dust cycle.

5 Conclusion

Heavily obscured oxygen-rich AGB stars in the intermediate-mass regime ($M \geq 4$ $M_\odot$) have emerged as pivotal contributors to cosmic dust enrichment, particularly through the production of silicates. Although comparatively rare, these deeply embedded sources, distinguished by extreme mass-loss rates, can dominate the dust budget in metal-rich environments. Their optically thick envelopes not only obscure the central star from direct view but also offer a unique window into the final and most dust-productive stages of AGB evolution.

While significant progress has been made in characterizing these objects, fundamental gaps remain in our understanding of the mechanisms governing their mass-loss and dust formation. Although current one-dimensional models and empirical frameworks capture key features of AGB winds, they still produce divergent estimates of the total dust budget, reflecting uncertainties in how pulsations, dust condensation, and nucleosynthesis processes interact to shape the circumstellar envelope chemistry.

The advent of next-generation observational facilities promises to revolutionize our understanding of these stars. The James Webb Space Telescope (JWST) and forthcoming extremely large telescopes will enable high-angular-resolution infrared observations, allowing us to map the distribution of silicate grains with unprecedented detail and probe the thermal and chemical conditions under which dust condenses. Systematic spectroscopic surveys across different metallicity regimes will further clarify how local environments influence mass-loss rates, dust composition, and ultimate dust yields.

On the theoretical front, there is a pressing need for more advanced, multidimensional models that incorporate stellar pulsations, dust-driven winds, magnetic fields, rotation, and binary interactions-phenomena known to influence circumstellar outflows. Such models must not only reproduce the global dust budget but also account for the complex morphologies and episodic mass-loss patterns inferred from high-resolution imaging and spectral data.

Ultimately, the study of heavily obscured oxygen-rich AGB stars extends beyond stellar astrophysics. These objects play a central role in the galactic dust cycle, supplying essential raw materials for the formation of new stars and planets. By refining our models of their final evolutionary phases and leveraging increasingly sophisticated observational capabilities, we can gain deeper insights into how intermediate-mass AGB stars influence the chemical evolution of galaxies and, by extension, the broader cosmic ecosystem.

Author contributions

EM: Conceptualization, Funding acquisition, Methodology, Writing–original draft, Writing–review and editing. ST: Data curation, Writing–review and editing.

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References

Bladh, S., Liljegren, S., Höfner, S., Aringer, B., and Marigo, P. (2019). An extensive grid of DARWIN models for M-type AGB stars. I. Mass-loss rates and other properties of dust-driven winds. *Astron. Astrophys.* 626, A100. doi:10.1051/0004-6361/201935366

Bloecker, T. (1995). Stellar evolution of low and intermediate-mass stars. I. Mass loss on the AGB and its consequences for stellar evolution. *Astron. Astrophys.* 297, 727

Bowen, G. H. (1988). Dynamical modeling of long-period variable star atmospheres. *Astrophys. J.* 329, 299. doi:10.1086/166378

Bunzel, F., García-Hernández, D. A., Engels, D., Perea-Calderón, J. V., and García-Lario, P. (2009). "AKARI/IRC observations of heavily obscured oxygen-rich AGB and post-AGB stars," in *AKARI, a light to illuminate the misty Universe*. Editors T. Onaka, G. J. White, T. Nakagawa, and I. Yamamura doi:10.48550/arXiv.0904.4134

Decin, L., Montargès, M., Richards, A. M. S., Gottlieb, C. A., Homan, W., McDonald, I., et al. (2020). (Sub) stellar companions shape the winds of evolved stars. *Science* 369, 1497–1500. doi:10.1126/science.abb1229

Dell'Agli, F., García-Hernández, D. A., Schneider, R., Ventura, P., La Franca, F., Valiante, R., et al. (2017). Asymptotic giant branch and super-asymptotic giant branch stars: modelling dust production at solar metallicity. *Mon. Not. R. Astron. Soc.* 467, 4431–4440. doi:10.1093/mnras/stx387

Dell'Agli, F., Ventura, P., Garcia Hernandez, D. A., Schneider, R., di Criscienzo, M., Brocato, E., et al. (2014). Dissecting the Spitzer colour-magnitude diagrams of extreme Large Magellanic Cloud asymptotic giant branch stars. *Mon. Not. R. Astron. Soc.* 442, L38–L42. doi:10.1093/mnrasl/slu051

Ferrarotti, A. S., and Gail, H. P. (2002). Mineral formation in stellar winds: III. Dust formation in S stars. *Dust Form. S stars* 382, 256–281. doi:10.1051/0004-6361:20011580

Ferrarotti, A. S., and Gail, H. P. (2006). Composition and quantities of dust produced by AGB-stars and returned to the interstellar medium. *Astron. Astrophys.* 447, 553–576. doi:10.1051/0004-6361:20041198

Gail, H. P., and Sedlmayr, E. (1999). Mineral formation in stellar winds. I. Condensation sequence of silicate and iron grains in stationary oxygen rich outflows. *Astron. Astrophys.* 347, 594–616.

Gail, H.-P., and Sedlmayr, E. (2013). *Physics and chemistry of circumstellar dust shells*. Cambridge University Press.

Goldman, S. R., van Loon, J. T., Zijlstra, A. A., Green, J. A., Wood, P. R., Nanni, A., et al. (2017). The wind speeds, dust content, and mass-loss rates of evolved AGB and RSG stars at varying metallicity. *Mon. Not. R. Astron. Soc.* 465, 403–433. doi:10.1093/mnras/stw2708

Groenewegen, M. A. T., and Sloan, G. C. (2018). Luminosities and mass-loss rates of Local Group AGB stars and red supergiants. *Astron. Astrophys.* 609, A114. doi:10.1051/0004-6361/201731089

Henning, T. (2010). Cosmic silicates. *Cosm. Silic.* 48, 21–46. doi:10.1146/annurev-astro-081309-130815

Herwig, F. (2005). Evolution of asymptotic giant branch stars. *Annu. Rev. Astron. Astrophys.* 43, 435–479. doi:10.1146/annurev.astro.43.072103.150600

Höfner, S. (2008). Winds of M-type AGB stars driven by micron-sized grains. *Astron. Astrophys.* 491, L1–L4. doi:10.1051/0004-6361:200810641

Höfner, S., Bladh, S., Aringer, B., and Ahuja, R. (2016). Dynamic atmospheres and winds of cool luminous giants. I. Al2O3 and silicate dust in the close vicinity of M-type AGB stars. *Astron. Astrophys.* 594, A108. doi:10.1051/0004-6361/201628424

Jeong, K. S., Winters, J. M., Le Bertre, T., and Sedlmayr, E. (2003). Self-consistent modeling of the outflow from the O-rich Mira IRC -20197. *Astron. Astrophys.* 407, 191–206. doi:10.1051/0004-6361:20030693

Jones, O. C., Kemper, F., Sargent, B. A., McDonald, I., Gielen, C., Woods, P. M., et al. (2012). On the metallicity dependence of crystalline silicates in oxygen-rich asymptotic giant branch stars and red supergiants. *Mon. Not. R. Astron. Soc.* 427, 3209–3229. doi:10.1111/j.1365-2966.2012.21978.x

Karakas, A. I. (2010). Updated stellar yields from asymptotic giant branch models. *Mon. Not. R. Astron. Soc.* 403, 1413–1425. doi:10.1111/j.1365-2966.2009.16198.x

Karakas, A. I., and Lattanzio, J. C. (2014). The dawes review 2: nucleosynthesis and stellar yields of low- and intermediate-mass single stars. *Publ. Astron. Soc. Aust.* 31, e030. doi:10.1017/pasa.2014.21

Karovicova, I., Wittkowski, M., Ohnaka, K., Boboltz, D. A., Fossat, E., and Scholz, M. (2013). New insights into the dust formation of oxygen-rich AGB stars. *Astron. Astrophys.* 560, A75. doi:10.1051/0004-6361/201322376

Koike, C., Chihara, H., Tsuchiyama, A., Suto, H., Sogawa, H., and Okuda, H. (2003). Compositional dependence of infrared absorption spectra of crystalline silicate: II. Natural and synthetic olivines. *Nat. synthetic olivines* 399, 1101–1107. doi:10.1051/0004-6361:20021831

Li, J., Liu, C., Zhang, Z.-Y., Tian, H., Fu, X., Li, J., et al. (2023). Stellar initial mass function varies with metallicity and time. *Nature* 613, 460–462. doi:10.1038/s41586-022-05488-1

Maaskant, K. M., de Vries, B. L., Min, M., Waters, L. B. F. M., Dominik, C., Molster, F., et al. (2015). Location and sizes of forsterite grains in protoplanetary disks. *Interpretation Herschel DIGIT programme* 574, A140. doi:10.1051/0004-6361/201423770

Marini, E., Dell'Agli, F., Di Criscienzo, M., García-Hernández, D. A., Ventura, P., Groenewegen, M. A. T., et al. (2020). Characterization of M-stars in the LMC in the JWST era. *Mon. Notices R. Astronomical Soc.* 493, 2996–3013. doi:10.1093/mnras/staa353

Marini, E., Dell'Agli, F., Kamath, D., Ventura, P., Mattsson, L., Marchetti, T., et al. (2023). The intense production of silicates during the final AGB phases of intermediate mass stars. *Astron. Astrophys.* 670, A97. doi:10.1051/0004-6361/202245501

Marshall, J. R., van Loon, J. T., Matsuura, M., Wood, P. R., Zijlstra, A. A., and Whitelock, P. A. (2004). Asymptotic giant branch superwind speed at low metallicity. *Mon. Not. R. Astron. Soc.* 355, 1348–1360. doi:10.1111/j.1365-2966.2004.08417.x

Mattsson, L., Wahlin, R., and Höfner, S. (2010). Dust driven mass loss from carbon stars as a function of stellar parameters. *I. A grid solar-metallicity wind models* 509, A14. doi:10.1051/0004-6361/200912084

Molster, F. J., Waters, L. B. F. M., Tielens, A. G. G. M., and Barlow, M. J. (2002). Crystalline silicate dust around evolved stars: I. The sample stars. *sample stars* 382, 184–221. doi:10.1051/0004-6361:20011550

Nanni, A., Bressan, A., Marigo, P., and Girardi, L. (2013). Evolution of thermally pulsing asymptotic giant branch stars - II. Dust production at varying metallicity. *Mon. Not. R. Astron. Soc.* 434, 2390–2417. doi:10.1093/mnras/stt1175

Nanni, A., Bressan, A., Marigo, P., and Girardi, L. (2014). Evolution of thermally pulsing asymptotic giant branch stars - III. Dust production at supersolar metallicities. *Mon. Not. R. Astron. Soc.* 438, 2328–2340. doi:10.1093/mnras/stt2348

Nanni, A., Marigo, P., Girardi, L., Rubele, S., Bressan, A., Groenewegen, M. A. T., et al. (2018). Estimating the dust production rate of carbon stars in the Small Magellanic Cloud. *Mon. Not. R. Astron. Soc.* 473, 5492–5513. doi:10.1093/mnras/stx2641

Olivier, E. A., Whitelock, P., and Marang, F. (2001). Dust-enshrouded asymptotic giant branch stars in the solar neighbourhood. *Mon. Not. R. Astron. Soc.* 326, 490–514. doi:10.1046/j.1365-8711.2001.04511.x

Pennock, C. M., van Loon, J. T., Anih, J. O., Maitra, C., Haberl, F., Sansom, A. E., et al. (2022). The VMC survey - XLIX. Discovery of a population of quasars dominated by nuclear dust emission behind the Magellanic Clouds. *Mon. Notices R. Astron. Soc.* 515, 6046–6065. doi:10.1093/mnras/stac2096

Reimers, D. (1975). "Circumstellar envelopes and mass loss of red giant stars," in *Problems in stellar atmospheres and envelopes*. Editors B. Baschek, W. H. Kegel, and G. Traving, 229–256.

Riebel, D., Srinivasan, S., Sargent, B., and Meixner, M. (2012). The mass-loss return from evolved stars to the large magellanic cloud. *VI. Luminosities Mass-loss Rates Popul. Scales* 753, 71. doi:10.1088/0004-637X/753/1/71

Rosenfield, P., Marigo, P., Girardi, L., Dalcanton, J. J., Bressan, A., Gullieuszik, M., et al. (2014). Evolution of thermally pulsing asymptotic giant branch stars. IV. Constraining mass loss and lifetimes of low mass. *Low. Met. AGB Stars* 790, 22. doi:10.1088/0004-637X/790/1/22

Sackmann, I. J., and Boothroyd, A. I. (1991). Mixing length and opacity effects: deep convective envelopes on the asymptotic giant branch. *Astrophys. J.* 366, 529. doi:10.1086/169587

Schneider, R., Valiante, R., Ventura, P., dell'Agli, F., Di Criscienzo, M., Hirashita, H., et al. (2014). Dust production rate of asymptotic giant branch stars in the Magellanic Clouds. *Mon. Not. R. Astron. Soc.* 442, 1440–1450. doi:10.1093/mnras/stu861

Sloan, G. C., Kraemer, K. E., Price, S. D., and Shipman, R. F. (2003). A Uniform Database of 2.4-45.4 Micron Spectra from the Infrared Space Observatory Short Wavelength Spectrometer. *Astrophys. J. Suppl. Ser.* 147, 379–401. doi:10.1086/375443

Tielens, A. G. G. M., Waters, L. B. F. M., and Bernatowicz, T. J. (2005). "Origin and evolution of dust in circumstellar and interstellar environments," in *Chondrites and the protoplanetary disk*. Editors A. N. Krot, E. R. D. Scott, and B. Reipurth 605.

van Loon, J. T., Cioni, M. R. L., Zijlstra, A. A., and Loup, C. (2005). An empirical formula for the mass-loss rates of dust-enshrouded red supergiants and oxygen-rich Asymptotic Giant Branch stars. *Astron. Asrophys.* 438, 273–289. doi:10.1051/0004-6361:20042555

Vassiliadis, E., and Wood, P. R. (1993). Evolution of low- and intermediate-mass stars to the end of the asymptotic giant branch with mass loss. *Astrophys. J.* 413, 641. doi:10.1086/173033

Ventura, P., Dell'Agli, F., Lugaro, M., Romano, D., Tailo, M., and Yagüe, A. (2020). Gas and dust from metal-rich AGB stars. *Astron. Asrophys.* 641, A103. doi:10.1051/0004-6361/202038289

Ventura, P., Dell'Agli, F., Schneider, R., Di Criscienzo, M., Rossi, C., La Franca, F., et al. (2014). Dust from asymptotic giant branch stars: relevant factors and modelling uncertainties. *Mon. Not. R. Astron. Soc.* 439, 977–989. doi:10.1093/mnras/stu028

Ventura, P., di Criscienzo, M., Schneider, R., Carini, R., Valiante, R., D'Antona, F., et al. (2012). The transition from carbon dust to silicate production in low-metallicity asymptotic giant branch and super-asymptotic giant branch stars. *Mon. Not. R. Astron. Soc.* 420, 1442–1456. doi:10.1111/j.1365-2966.2011.20129.x

Ventura, P., Karakas, A., Dell'Agli, F., García-Hernández, D. A., and Guzman-Ramirez, L. (2018). Gas and dust from solar metallicity AGB stars. *Mon. Notices R. Astron. Soc.* 475, 2282–2305. doi:10.1093/mnras/stx3338

Waters, L. B. F. M., Molster, F. J., de Jong, T., Beintema, D. A., Waelkens, C., Boogert, A. C. A., et al. (1996). Mineralogy of oxygen-rich dust shells. *Astron. Astrophys.* 315, L361–L364.

Woitke, P. (2006). Too little radiation pressure on dust in the winds of oxygen-rich AGB stars. *Astron. Astrophys.* 460, L9–L12. doi:10.1051/0004-6361:20066322

Xie, Y., Li, A., and Hao, L. (2017). Silicate dust in active galactic nuclei. *Astrophys. J. Suppl. Ser.* 228, 6. doi:10.3847/1538-4365/228/1/6