



Dust in the Very Metal-poor Galaxy Sextans A with JWST. I. Characterizing the Evolved Stellar Population of Sextans A Based on JWST Observations and Stellar Evolution Models

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Abstract

The nearby star-forming dwarf galaxy Sextans A offers a unique window into galaxy evolution in the early Universe, owing to its extremely low metallicity ($\sim 0.01\text{--}0.07 Z_{\odot}$). Recent JWST imaging of Sextans A spanning $1\text{--}21 \mu\text{m}$ enables a detailed characterization of its dusty stellar populations and interstellar medium. In this work, we compare the observed JWST color–magnitude distributions of evolved stars with stellar evolution and dust-formation models to characterize the properties of the asymptotic giant branch (AGB) population, including progenitor mass, formation epoch, metallicity, and dust production. Evolutionary tracks for $0.8\text{--}7 M_{\odot}$ stars with metallicity $Z = 10^{-3}$ provide good agreement with the overall distribution of AGB stars in Sextans A. More than 90% of the AGB population occupies a nearly vertical sequence in the color–magnitude diagrams, corresponding to stars spanning a wide range of masses and ages but exhibiting little or no circumstellar dust. This sequence appears to be dominated by oxygen-rich (M-type) AGB stars and reveals that the F444W flux is a robust luminosity diagnostic. A small subset of sources displays strong IR excesses and is dominated by carbon stars descending from 1.25 to $1.5 M_{\odot}$ progenitors that formed $\sim 2\text{--}3$ Gyr ago and are currently in the final AGB phases. Their MIRI colors imply very low metallicities, consistent with estimates from the red giant branch morphology ($\sim 0.01\text{--}0.02 Z_{\odot}$). Finally, we show that the JWST/NIRCam F277W–F444W color serves as an effective proxy for the dust production rate, with models predicting rates up to $\sim 10^{-7} M_{\odot} \text{yr}^{-1}$ for the reddest sources in Sextans A.

Unified Astronomy Thesaurus concepts: James Webb Space Telescope (2291); Asymptotic giant branch (108); Carbon stars (199); Circumstellar dust (236); Dwarf galaxies (416)

1. Introduction

The asymptotic giant branch (AGB) is an evolutionary phase experienced by all the stars of mass below $\sim 8 M_{\odot}$,

which follows core helium burning and precedes the white dwarf cooling. During the AGB phase the stars are supported by a CNO-burning shell, with periodic ignitions of a helium layer lying above the degenerate core, which are commonly referred to as thermal pulses, because helium burning occurs in thermally unstable conditions (M. Schwarzschild & R. Härm 1965). The surface chemical composition of AGB stars can be altered by two physical mechanisms, namely third dredge-up and hot bottom burning. The former consists of the



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inward penetration of surface convection to regions of the star touched by helium-burning nucleosynthesis, thus significantly enriched in carbon (I. Iben 1974); a series of third dredge-up events causes the surface carbon abundance to exceed that of oxygen, and hence the formation of carbon stars. Hot bottom burning consists of the activation of advanced proton-capture nucleosynthesis at the base of the convective envelope, once the temperatures in those regions reach and exceed 3×10^7 K (I.-J. Sackmann & A. I. Boothroyd 1992); following the ignition of hot bottom burning the surface chemistry is altered on the basis of the equilibria of the proton-capture nucleosynthesis experienced, which is to be extremely sensitive to the metallicity of the stars (F. Dell’Agli et al. 2018).

Several studies over the past decades have convincingly shown that stars evolving through the AGB are highly efficient dust manufacturers. This efficiency arises from the physical conditions in their extended circumstellar envelopes, which are particularly favorable for the condensation of gaseous molecules into solid particles (H.-P. Gail & E. Sedlmayr 1985, 1999; S. Höfner & H. Olofsson 2018). What remains unclear is the relative contribution of AGB stars with respect to supernovae (SNe) to the overall dust budget of the Universe (R. Schneider & R. Maiolino 2024), an issue further complicated by the uncertainties affecting the description of dust production during the SN explosion (P. Todini & A. Ferrara 2001; S. Bianchi & R. Schneider 2007; M. Bocchio et al. 2016). Assessing the relative importance of AGB stars and SNe as sources of dust and mass in different environments and cosmic epochs is a complex task, considering that a significant, though largely unknown, fraction of the dust formed in SNe may be destroyed by the reverse shock (M. Lakićević et al. 2015), and that the dust produced by either class of stars is exposed to destruction through subsequent interstellar medium processes.

To quantify the dust produced by low- and intermediate-mass stars during the AGB phase, some research teams combined models of AGB evolution with those of dust formation in the circumstellar envelope (P. Ventura et al. 2012, 2014; A. Nanni et al. 2013, 2014). These models are based on the description of a static wind expanding from the stellar surface, as proposed by A. S. Ferrarotti & H.-P. Gail (2002, 2006). These developments made it possible to determine the mineralogy and the quantity of dust produced by the stars during different evolutionary phases, to predict the time evolution of the spectral energy distribution (SED) and to estimate the dust yields for the different species.

The modeling described above can be applied to single stars only, which is the focus of the present investigation. We believe it is important to stress that binary interactions may also influence the dust properties of evolved low- and intermediate-mass stars (L. Decin 2021). Indeed, episodes of envelope stripping or common-envelope evolution can significantly modify the mass-loss history and the chemical composition of the material expelled (F. Dell’Agli et al. 2021), potentially producing sources with dust characteristics that deviate from those expected from isolated AGB evolution. Examples of the effects of binary interaction include some post-red giant branch (post-RGB) and post-AGB objects, which are known to display substantial mid-IR excess and dusty circumstellar structures (R. Sahai et al. 2007; G. Sarkar & R. Sahai 2022). While a detailed treatment of binary channels lies beyond the scope of this work, their possible

contribution should be kept in mind when interpreting the dust-rich component of evolved stellar populations.

A valuable opportunity to validate and improve the theoretical description of the dust production mechanism in the wind of AGB stars is offered by the study of the evolved stellar populations of galaxies. The formation of dust grains modifies the SED of the stars, thus affecting the morphology of the evolutionary tracks in the various observational color–magnitude diagrams. This can be compared with the observed distribution of the stars in the same diagrams. Early attempts to interpret the AGB population of galaxies by means of results from stellar evolution modeling in which the formation of dust in the circumstellar envelope is considered, mostly based on data collected from the Hubble Space Telescope (HST), Spitzer Space Telescope (Spitzer), and the Two Micron All Sky Survey, were first applied to the Magellanic Clouds (F. Dell’Agli et al. 2014, 2015a, 2015b; A. Nanni et al. 2018, 2019), to a few Local Group galaxies (F. Dell’Agli et al. 2016, 2018), and more recently to M31 (C. Gavetti et al. 2025). In these studies part of the effort was devoted to relating the distribution of the sources in the various regions of the observational diagrams by considering the star formation history (SFH) and the age–metallicity relation of the galaxies investigated.

The advent of the James Webb Space Telescope (JWST; J. P. Gardner et al. 2023) provides substantial support to this line of research, because it opens the way to investigating the evolved stellar populations of all the Local Group galaxies, and possibly beyond (C. Nally et al. 2024). JWST data hold promise to improve upon previous state-of-the-art programs such as DUSTiNGS (M. L. Boyer et al. 2015a, 2015b, 2017; S. R. Goldman et al. 2019), the Sagittarius dSph (I. McDonald et al. 2013, 2014), and M32 (O. C. Jones et al. 2015, 2023). The interpretation of the incoming JWST observations will therefore be crucial for making a decisive step toward a comprehensive understanding of dust formation mechanisms in the circumstellar envelopes of evolved stars and, more generally, for assessing their contribution to the dust budget of their host systems and of the Universe as a whole.

We compare state-of-the-art dust formation and stellar evolutionary models to new JWST observations of the dwarf galaxy Sextans A. This galaxy is particularly interesting for studying the process of dust formation, because it harbors a metal-poor population of stars with metallicity between 1% and 7% of solar (S. Sakai et al. 1996; A. Y. Kniazev et al. 2005; A. W. McConnachie 2012). Consequently, it can provide important insights into the metallicity dependence of dust production, a topic for which no general consensus has yet been reached (J. T. van Loon et al. 2008; G. C. Sloan et al. 2012, 2016). The data were observed as part of program ID 1619 (PI: M. Boyer; M. L. Boyer et al. 2025; E. Tarantino et al. 2026, in preparation), and the combination of NIRCам (M. J. Rieke et al. 2023) and MIRI (G. S. Wright et al. 2023) data enables an exhaustive analysis of the entire sample of AGB stars. E. Tarantino et al. (2026, in preparation) present a JWST stellar catalog, including the classification of the dusty stellar populations and color-based estimates of the dust production for individual stars. T. Henry et al. (2026, in preparation) present full SED fitting of the evolved stars from 1 to 21 μm . In this paper, we focus on characterizing the evolved star population of Sextans A by comparing the data to stellar evolution models to constrain progenitor masses,

formation epochs, metallicities, and dust production. Particular attention is given to the six stars for which MIRI (5–12 μm) low-resolution spectroscopy (LRS) is available (M. L. Boyer et al. 2025). We also aim to improve the theoretical framework for dust formation.

The paper is structured as follows: Section 2 describes the set of evolutionary tracks adopted in the present work and the schematization adopted to model dust formation in the wind and the evolution of the SED; the path of the evolutionary tracks of stars of different mass on the color–magnitude diagrams built with the NIRCcam filters, and a gross distinction between dust-free objects of Sextans A and red, dusty stars, is discussed in Section 3; Section 4 is focused on the interpretation of the MIRI photometry; the discussion on the dust produced by the individual sources is presented in Section 5; finally, the conclusions are given in Section 6.

2. Physical Input and Data

To study the evolved stellar population of Sextans A, we use observations from the JWST-GO-1619 program, where imaging of most of Sextans A’s star-forming disk was obtained. Both NIRCcam and MIRI instruments were used to map the galaxy in the F090W, F140M, F150W, F200W, F277W, F300M, F335M, F444W, F770W, F1000W, F1130W, and F1280W bands. Preliminary Vega-based magnitudes from NIRCcam and MIRI²⁴ were measured using DOLPHOT, the point-spread function photometry package developed by A. E. Dolphin (2000, 2016) and adapted for JWST by the JWST Stellar Populations Early Release Science team (D. R. Weisz et al. 2023, 2024). Here we briefly describe the procedure followed, while the detailed description of the imaging and photometry of the galaxy will be discussed in a forthcoming paper (E. Tarantino et al. 2026, in preparation). We followed the photometric quality cuts recommended by D. R. Weisz et al. (2023) and J. T. Warfield et al. (2023), which are designed to separate stars and unresolved background galaxies, minimizing background contaminants. The field of view consists of a 2×1 MIRI mosaic, covering the bulk of the disk of Sextans A, and is 2.5 by 3.75 in size. The photometric catalog is complete up to 25 mag in all NIRCcam filters, much fainter than the magnitudes of the bright AGB stars studied in this work. We adopt photometric uncertainties that include the photon-noise characteristics reported by DOLPHOT, of <0.005 mag for NIRCcam bands and <0.05 mag for MIRI bands in the magnitude regime analyzed. The final uncertainties tend to be 3 – $10\times$ higher in HST data with a similar depth and crowding (B. F. Williams et al. 2014). The JWST data presented in this article were obtained from the Mikulski Archive for Space Telescopes at the Space Telescope Science Institute. The specific observations analyzed can be accessed via DOI:10.17909/edr6-ny09.

We interpret the distribution of the stars on the observational color–magnitude diagrams using evolutionary tracks for different stellar masses at metallicity $Z=0.001$ and α enhancement $[\alpha/\text{Fe}] = +0.4$ (corresponding to $[\text{Fe}/\text{H}] \sim -1.4$), which are appropriate for the low-metallicity stellar population of Sextans A (S. Sakai et al. 1996; A. W. McConnachie 2012). We adopt the evolutionary sequences at $Z=0.001$ from P. Ventura et al. (2014), further

refined and extended to the post-AGB and planetary nebula phases by D. Kamath et al. (2023).

Starting from the results of stellar evolution modeling, the calculation of the evolutionary tracks was based on a three-step process, consisting of (a) the modeling of the dust formation process from the start of the core helium-burning phase to the beginning of the post-AGB evolution; (b) the determination of the synthetic SED; and (c) the calculation of the magnitudes in the various NIRCcam and MIRI filters. This procedure follows the methodology introduced by F. Dell’Agli et al. (2014, 2015a), and which was applied to Spitzer photometric observations of the Magellanic Clouds, in order to interpret their evolved stellar population.

For some specific points along the AGB phase (typically 10 points equally spaced in time during each interpulse phase), we simulated the dust formation process in the circumstellar envelope based on the values of the luminosity, effective temperature, mass-loss rate, and surface chemical composition of the star, predicted by the stellar evolution modeling. This step allows the determination of the quantity and the mineralogy of the dust formed in the stellar wind, the dust production rate (DPR) and the optical depth, which we define at the wavelength of $10 \mu\text{m}$ (τ_{10}). A side result of this computation is the grain size distribution of the various dust species formed.

The chemo-dynamical description of the stellar wind, performed for all the selected points, is based on the schematization proposed by A. S. Ferrarotti & H.-P. Gail (2002, 2006), in which the wind is assumed to expand isotropically from the surface of the star, until it reaches the dust condensation region, typically at temperatures below ~ 1500 K, where the physical conditions are such that dust grains can form and grow. The relevant equations describing the dynamics of the wind and the growth rate of the size of the various dust species are extensively described and discussed in P. Ventura et al. (2012). The optical constants for the different dust species used in the present investigation are amorphous carbon (V. G. Zubko et al. 1996), silicon carbide (SiC; B. Pegourie 1988), solid iron (M. A. Ordal et al. 1983), silicates (V. Ossenkopf et al. 1992), and alumina dust (C. Koike et al. 1995).

These computations lead to the determination of the size reached by the grains of the various dust species, the asymptotic velocity of the wind, and the fraction of gaseous silicon, iron, and carbon condensed into dust (P. Ventura et al. 2012). These quantities, combined with the knowledge of the surface chemical composition and of the mass-loss rate of the star, allow the computation of the production rates of the different dust species and of the density stratification of the circumstellar envelope, according to the equations listed in Section 5.2 of A. S. Ferrarotti & H.-P. Gail (2006).

For the selected points along the evolutionary sequences, we also calculated the synthetic SED, using the radiative transfer code DUSTY (M. Nenkova et al. 1999). In the first step the dust-free atmosphere for each evolutionary stage considered is selected among the spectra available in the COMARCS (B. Aringer et al. 2009) and NEXTGEN (P. H. Hauschildt et al. 1999) libraries, for C and M stars, respectively. The final SED is obtained by including the effects of dust, based on the results from stellar evolution + dust formation modeling. This enables a description of the SED temporal evolution for stars with different progenitor masses during the AGB phase.

²⁴ Data were reduced using pipeline version 1.15.1 and the CRDS context jwst_1293.pmap.

Finally, to obtain the evolutionary tracks, the synthetic SEDs are convolved with the transmission curves of the NIRCcam and MIRI filters, which are used to derive the magnitudes in the various bands. We adopt a distance modulus $\mu_0 = 25.7$ mag (see Z. Yan et al. 2025, and references therein) in order to compare the various evolutionary tracks with the observational data in different color–magnitude diagrams. With the $E(B - V) = 0.0374$ mag from E. F. Schlafly & D. P. Finkbeiner (2011), and adopting a standard $R_V = 3.1$ reddening law, the models are reddened accordingly, and the extinction values in the JWST filters considered in this analysis are negligible.

3. Understanding the NIRCcam Data

As in other galaxies of the Local Group (M. L. Boyer et al. 2011, 2015a, 2015b), the AGB population of Sextans A is made up of a majority of stars with little or no dust in their surroundings, complemented by a minority of sources exhibiting a strong IR excess, indicating the ongoing formation of large quantities of dust. The fraction of dusty objects is small, since dust formation occurs under relatively rare conditions; indeed the physical conditions required for significant dust production are reached only after the star experiences several thermal pulses. Moreover, the onset of dust formation enhances the mass-loss rate, thereby shortening the AGB lifetime (F. Dell’Aglì et al. 2015a). In addition, metal-poor systems host relatively small stellar populations, which further reduces the probability of observing stars during these short-lived, dust-enshrouded evolutionary phases. As a consequence, the region of the parameter space associated with efficient dust formation is only sparsely populated in metal-poor galaxies such as Sextans A.

To study the dust-free objects, we use NIRCcam data, in particular the distribution of stars on the (F277W – F444W, F444W) diagram, while the investigation of the dusty sources is supported by the analysis of the MIRI fluxes. We adopted the (F277W – F444W, F444W) diagram because this filter combination provides a clear separation between dust-free and dust-enshrouded AGB stars, as it is highly sensitive to circumstellar dust emission at $4\mu\text{m}$ while still tracing the stellar photosphere at $2.8\mu\text{m}$. Other NIRCcam color combinations provide a smaller dynamic range, and thus a narrower color spread separating dust-free and dusty objects. These combinations suffer from stronger degeneracies between effective temperature and dust emission, making them less efficient for distinguishing the different AGB sequences.

The distribution of stars in Sextans A in the (F277W – F444W, F444W) diagram is shown in Figure 1, with gray points. Approximately 90% of the sources populate an almost vertical sequence, at (F277W – F444W) ~ 0 mag, extending up to F444W ~ 16 mag. To estimate the impact of Galactic foreground stars, we followed the method described by R. D. Blum et al. (2006), which uses the analysis of vertical sequences in near- and mid-IR color–magnitude diagrams (such as $(J - [3.6], [3.6])$), where foreground populations appear vertical due to the smearing of magnitudes over varying distances while maintaining constant colors, and found that approximately 12% of the stars above the tip of the RGB are Galactic foreground dwarfs and giants, with the relative contamination typically decreasing at fainter magnitudes. To estimate the Galactic foreground contamination we applied the same method by using the F090W and F150W fluxes, and we

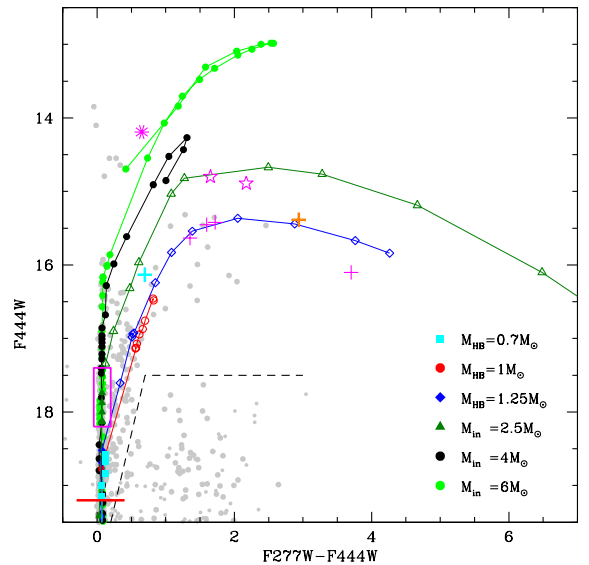


Figure 1. Distribution of the evolved stellar population of Sextans A, indicated with gray dots, in the (F277W – F444W, F444W) diagram. The thick, red, horizontal line indicates the location of the tip of the RGB predicted by the models. Sources 94328, 92104, 86434, and 94477 investigated by M. L. Boyer et al. (2025) are indicated with magenta crosses; two stars exhibiting significant IR excess with star symbols; and a bright source, possibly a massive AGB undergoing hot bottom burning, as an asterisk. The crosses refer to the other two sources with MIRI/LRS spectroscopy by M. L. Boyer et al. (2025): 90428 (orange), which shows evidence of SiC, and 90034 (cyan), which shows an oxygen-rich chemical composition. The colored points indicate various evolutionary phases of stars of different initial mass. Full points refer to the phases during which the star is O rich, whereas open symbols indicate C-rich phases. Note that for the 0.7, 1, and 1.25 $M_{\odot}$ cases, which experience a helium flash, the masses refer to the start of the core helium-burning phase (see text for details). The magenta box indicates the region partly populated by C stars with little or no dust in the circumstellar envelope. The region delimited by the dashed, black lines is dominated by background galaxies.

found that the contribution from foreground stars is below 5% of the sources in this sequence. Consequently we conclude that the nearly vertical sequence is almost entirely populated by AGB stars belonging to Sextans A. In regard to background galaxies, we follow the discussion in M. L. Boyer et al. (2025) to locate them in the faint (F444W > 17.5 mag) and red ($0 < \text{F277W} - \text{F444W} < 2$ mag) region of the (F277W – F444W, F444W) diagram, enclosed within the black, dashed lines in Figure 1 (R. D. Blum et al. 2006).

In the following part of this section we first provide a general description of the expected excursion of the evolutionary tracks of stars of different mass across the aforementioned color–magnitude diagram. We then focus on the dust-free objects, which populate the blue side of the diagram, and discuss the use of the F444W flux as a luminosity indicator and the expected spectral type of these objects. Finally, we describe the sources surrounded by dust and propose a characterization of them in terms of mass and formation epoch of the progenitor stars.

3.1. The Evolution of Asymptotic Giant Branch Stars along the (F277W – F444W, F444W) Diagram

Before entering the interpretation of the distribution of the Sextans A AGB stars on the (F277W – F444W, F444W) diagram, it is important to note that the modeling of the stars of mass below $\sim 2 M_{\odot}$, which experience a helium flash, requires

an assumption regarding the mass lost during RGB evolution, which determines the mass with which the stars start the core helium-burning phase. For these stars, the masses quoted in the text and in the figure captions refer to the start of the core helium-burning phase and will be labeled as M_{HB} . The analysis of the morphology of the horizontal branch (HB) in globular clusters, together with constraints from asteroseismology, shows that during the ascent of the RGB low-mass stars lose between 0.1 and $0.3 M_{\odot}$ of their envelopes (A. Miglio et al. 2012; I. McDonald & A. A. Zijlstra 2015; M. Tailo et al. 2021; K. Brogaard et al. 2024). Asteroseismic measurements provide the strongest quantitative evidence of RGB mass loss and suggest that its efficiency increases with decreasing metallicity (K. Brogaard et al. 2024). As a consequence, M_{HB} is definitely smaller than the mass with which the stars formed, which will be labeled as M_{ZAMS} . Accounting for the difference between M_{HB} and M_{ZAMS} is particularly relevant for the analysis of the evolution of stars of mass below $\sim 1 M_{\odot}$, because the description of their AGB phase is highly sensitive to the mass of the envelope at the beginning of the AGB lifetime.

To understand the distribution of the stars in Figure 1, we follow the analysis of the AGB evolution discussed in P. Ventura et al. (2022), who introduced three typical cases, namely: (a) low-mass stars, which never reach the C-star stage, as they lose their envelope before the surface C/O exceeds unity; (b) intermediate-mass stars, which become carbon stars (surface C/O ratio > 1) after experiencing a series of thermal pulses and third dredge-up episodes (I. Iben 1974); and (c) massive AGB stars, which undergo ignition of the hot bottom burning process (A. I. Boothroyd et al. 1993), which prevents them from becoming carbon stars. The mass thresholds separating the three groups are sensitive to the metallicity of the stars. For the chemical composition considered in the present investigation, the minimum mass of the star at the start of the core helium-burning phase required to become a carbon star (thus separating type (a) from type (b) behavior) is $M_{\text{HB}} \sim 0.8 M_{\odot}$ (D. Kamath et al. 2023), while the minimum mass to ignite hot bottom burning at the base of the envelope is $M_{\text{ZAMS}} \sim 3 M_{\odot}$ (P. Ventura et al. 2013).

To understand how stars of different mass move across the (F277W – F444W, F444W) diagram, we show in Figure 1, overlaid on the data points, the evolutionary tracks of some selected model stars, to represent the three cases discussed above. As an example of case (a) we show the $M_{\text{HB}} = 0.7 M_{\odot}$ model star. As for the evolution of type (b), regarding the stars that reach the C-star stage, we show three cases, corresponding to the masses $M_{\text{HB}} = 1 M_{\odot}$, $M_{\text{HB}} = 1.25 M_{\odot}$, and $M_{\text{ZAMS}} = 2.5 M_{\odot}$, to represent stars that accumulate different quantities of carbon in the surface regions, thus heterogeneous in the rate of carbon dust production experienced. Finally, the case (c) is represented by the $M_{\text{ZAMS}} = 4$ and $6 M_{\odot}$ model stars.

Regardless of mass, the evolutionary tracks draw approximately vertical sequences during the first part of the AGB evolution, as a consequence of the gradual growth of the core mass, which produces a rise in luminosity (T. Bloeker 1993), and thus in F444W flux. When dust formation in the wind begins, the SED is gradually shifted toward the IR part of the spectrum and the evolutionary tracks move to the red (E. Marini et al. 2020, 2021). This behavior is not shared by the $0.7 M_{\odot}$ model star, as the stars belong to group (a), which evolve as oxygen-rich objects during the entire AGB phase, producing dust at very low rates. In the study of the dusty stars

in the LMC, aimed at interpreting the data taken with the Infrared Spectrograph on board Spitzer, E. Marini et al. (2020) concluded that some dust production, though in limited quantities, occurs during the evolution of low-mass stars in the O-rich phase. However, that result does not hold in the present context, as the metallicities typical of the stars in Sextans A are significantly lower than those adopted by E. Marini et al. (2020), as the scarcity of silicon prevents the formation of significant quantities of dust. This conclusion is supported by studies of low-mass, low-metallicity stars in Galactic globular clusters (M. L. Boyer et al. 2008, 2009; I. McDonald et al. 2011a, 2011b), which similarly show very low dust production in such environments.

Regarding the model stars undergoing the evolution of type (b) discussed above, we distinguish between the first part of the AGB evolution, during which they evolve as M-type objects and the evolutionary tracks develop vertically, and the phases following the achievement of the C-star stage, when significant quantities of carbon dust are formed and the evolutionary tracks move to the red. After reaching the C-star stage, the $1 M_{\odot}$ model star evolves to the red side of the diagram until (F277W – F444W) ~ 1 mag, and to brighter F444W fluxes up to F444W ~ 16.5 mag; this is again related to the gradual luminosity increase, which grows from ~ 4800 to $\sim 5200 L_{\odot}$ during the C-star phase. The 1.25 and $2.5 M_{\odot}$ model stars follow a different behavior. First, the horizontal extension of the tracks is much wider and increases with the initial mass of the star: the reddest points reached are (F277W – F444W) $\sim 1, 4.5$, and 9.5 mag for the $1, 1.25$, and $2.5 M_{\odot}$ cases, respectively. Furthermore, unlike the lower-mass counterpart, for the 1.25 and $2.5 M_{\odot}$ cases the F444W flux first rises, then decreases after reaching a maximum value, which increases with the initial mass of the star. Colors (F277W – F444W) > 5 mag are reached only by stars with mass in the $2\text{--}3 M_{\odot}$ range, and during the very final evolutionary phases, when the evolutionary timescales become progressively shorter. The low probability of detecting stars evolving across this fast evolutionary phase and the small AGB population of Sextans A are the main reasons for the lack of sources in the (F277W – F444W) > 5 mag region of the diagram.

These differences arise because the $2\text{--}3 M_{\odot}$ model stars experience more third dredge-up events than the $1 M_{\odot}$ counterpart. As a result, larger quantities of carbon accumulate in the surface regions, triggering more intense dust production. Consequently, the peak of the SED is shifted to wavelengths longer than $4.44 \mu\text{m}$ and the F444W flux decreases. This behavior is shown in Figure 2, particularly in the top right and bottom right panels, which show, respectively, the time variation of the carbon excess with respect to oxygen (defined as $\epsilon_{\text{C}} - \epsilon_{\text{O}} = (n_{\text{C}} - n_{\text{O}})/n_{\text{H}}$) and of the DPR of the three models discussed, derived following the method described in Section 2. We see that $(\epsilon_{\text{C}} - \epsilon_{\text{O}})$ grows until 2×10^{-4} , 6×10^{-4} , and 10^{-3} for the $1, 1.25$, and $2.5 M_{\odot}$ cases, respectively, and the largest DPRs are 2×10^{-9} , 10^{-7} , and $10^{-6} M_{\odot} \text{ yr}^{-1}$.

The excursion of the evolutionary tracks to the red side of the diagram, in the (F277W – F444W) > 1 mag region, occurs during the final AGB phases, mostly the very last interpulse when the stars expand; the mass-loss rate increases significantly, and so does the DPR. When reaching this stage, the core mass of the stars has reached its final value, with which

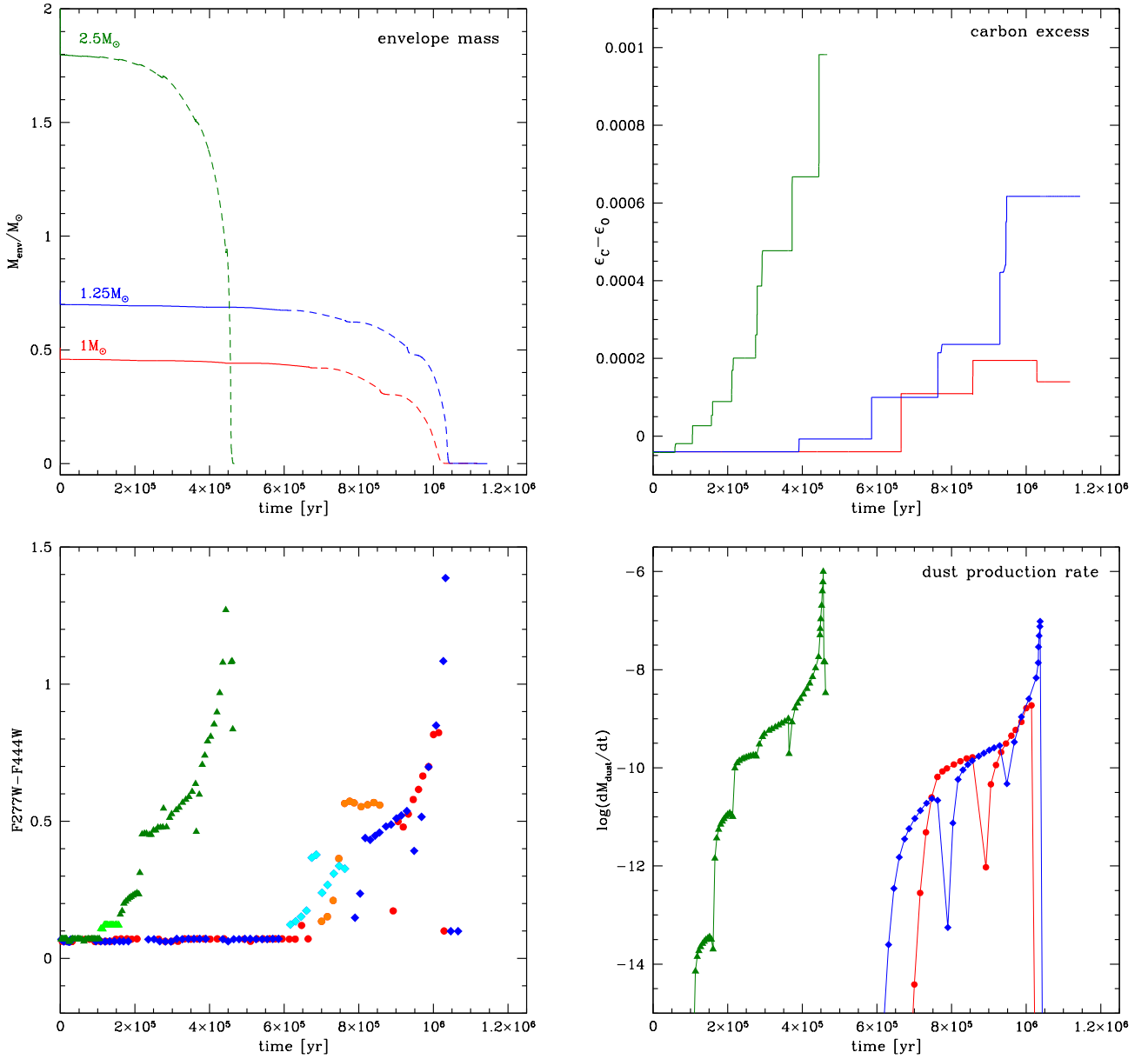


Figure 2. Variation of the mass of the envelope (top left panel), carbon excess with respect to oxygen (top right), $(F277W - F444W)$ color (bottom left), and carbon DPR (bottom right) during the AGB phase of model stars of initial mass 1, 1.25, and $2.5 M_{\odot}$. Times are counted from the ignition of the first thermal pulse, which is experienced after 6.3, 3, and 0.5 Gyr since the formation time for the three model stars considered. The solid and dotted part of the tracks in the top left panel indicate the O-rich and the C-rich phases, respectively. Orange full circles, cyan diamonds, and light green triangles in the bottom left panel refer, respectively, to selected evolutionary stages of the 1, 1.25, and $2.5 M_{\odot}$ model stars, during the interpulse period following the achievement of the C-star stage. The vertical axis of the bottom left panel is limited to $(F277W - F444W) = 1.5$ mag, in order to preserve detail in the track morphology; a wider range would make the first part of the evolution indistinguishable.

they enter the post-AGB and planetary nebula phases. The final core mass is higher for stars with larger initial masses. Given the tight connection between core mass and luminosity, this implies that the luminosity of the stars populating the $1 < (F277W - F444W) < 4$ mag region of the diagram grows with the initial mass of the star, ranging from $\sim 6000 L_{\odot}$, for the stars of mass slightly above $1 M_{\odot}$, to $\sim 18,000 L_{\odot}$, for $3 M_{\odot}$ stars. The vertical spread in the distribution of the C-rich sources on the red side of the $(F277W - F444W, F444W)$ diagram is therefore due to the differences in the initial mass of the stars that reach the C-star stage, with the additional uncertainty associated with variability effects, discussed earlier in this section.

As far as the group (c) stars is concerned, we see in Figure 1 that the evolutionary tracks of the 4 and $6 M_{\odot}$ model stars first develop vertically, up to $F444W \sim 16.5$ and ~ 16 mag, respectively, then turn to the red, when the activation of strong hot bottom burning leads to the production of silicates at high rates. The tracks are seen to return to the blue during the very final AGB phases, because the hot bottom burning loses efficiency, the luminosity decreases, and the mass-loss rate and the wind density decrease as well, thus reducing the DPR (P. Ventura et al. 2012).

3.2. Dust-free Stars

We now focus on the objects populating the vertical strip at $(F277W - F444W) \sim 0$ mag, where the stars spend the

majority (or the totality, as in the example of the $0.7 M_{\odot}$ star discussed above) of their AGB lifetime. Since these stars are almost (or completely) dust free, we refer to this region as the dust-free sequence (DFS). In general, stars of higher mass evolve more massive cores, thus they reach higher luminosities during the AGB phase. Therefore, as we move toward the brighter part of the DFS, we expect to find the progeny of stars of higher mass, thus formed in more recent epochs.

The F444W flux is a reliable luminosity indicator for the stars populating the DFS, which are characterized by similar effective temperatures ($T_{\text{eff}} \sim 3800\text{--}3900$ K). The comparison with the evolutionary tracks shows that the following relationship between the luminosity of the star and the F444W flux holds:

$$\log\left(\frac{L}{L_{\odot}}\right) = -0.35 \text{ F444W} + 10.15. \quad (1)$$

The relationship given by Equation (1) is a linear fit to the synthetic photometry and bolometric luminosities derived from the evolutionary tracks. It is important to note that this diagnostic is valid only for stars in the DFS, for which the peak in the SED is located at wavelengths significantly shorter than $4 \mu\text{m}$. This same calibration could hardly be applied to the sources populating the $(\text{F277W} - \text{F444W}) > 1$ mag region, since dust reprocessing causes the F444W flux to deviate from the bolometric trend given by Equation (1).

With regard to the chemical spectral type, the models indicate that most of the sources populating the DFS are M-type objects. This is definitely true for the lowest masses, those following the behavior of type (a) mentioned above, and for the massive AGB stars experiencing hot bottom burning (type (c)), which never become carbon stars. The stars that reach the C-star stage move to the red shortly after the surface C/O exceeds unity. Here a distinction is required according to the initial mass of the star, because the residual mass of the envelope when the C-star phase is reached changes with the initial mass of the stars: as shown in the top left panel of Figure 2, the residual envelope mass when the C-star phase begins decreases from $\sim 1.75 M_{\odot}$ for the $M_{\text{ZAMS}} = 2.5 M_{\odot}$ star to $\sim 0.45 M_{\odot}$ in the $M_{\text{HB}} = 1 M_{\odot}$ case.

In stars descending from $M_{\text{HB}} < 1.5 M_{\odot}$ progenitors, dilution of the material dredged up during the third dredge-up with the thin (in mass) convective envelope favors a significant increase in the carbon excess with respect to oxygen, which, in turn, leads to high rates of dust production; these stars are expected to move to the red as they become carbon stars, thus they evolve within the DFS during the M-type phase only. On the other hand, the higher-mass counterparts become C stars after experiencing a number of thermal pulses and third dredge-up episodes, when only a small fraction of the envelope mass has been lost. In this case, the dilution between the dredged-up material processed by helium burning and the external convective zone is highly efficient, so that, when the C-star stage is reached, the carbon excess is small and little dust formation takes place. Unlike the lower-mass counterparts, these sources continue to evolve along the DFS during the early evolutionary phases after becoming C stars, and evolve to the red only in a later phase, after developing a significant carbon-to-oxygen excess. The only exception to this behavior is found for the stars of initial mass close to the minimum threshold required for hot bottom

burning ignition, whose SED is shifted to the mid-IR from the onset of the C-star phase. This peculiar behavior is driven by their lower surface gravities than their lower-mass counterparts; indeed stars in this mass range reach higher luminosities, which leads to a significant expansion of the structure. The resulting lower surface gravity makes the outer envelope less gravitationally bound, thereby facilitating an earlier onset of intense mass loss. This creates the dense and cool circumstellar conditions necessary for dust grains to condense more efficiently, even at the very beginning of the C-star stage.

In summary, we conclude that the DFS observed in Figure 1 is mostly populated by oxygen-rich stars, but it also harbors a smaller fraction of C stars, descending from progenitors with masses in the $1.5\text{--}2.5 M_{\odot}$ range. The results from stellar evolution modeling indicate that the luminosities of the model stars in the mass interval given above, upon reaching the C-star stage, span the $5000\text{--}10,000 L_{\odot}$ range, which corresponds to $17.4 < \text{F444W} < 18.2$ mag. This region of the diagram is indicated with a magenta box in Figure 1. C stars are not expected at fainter F444W fluxes nor in the brighter part of the DFS, in the region above $\text{F444W} \sim 17.4$ mag.

On the basis of the present analysis, we identify three distinct regions in the vertical DFS of the $(\text{F277W} - \text{F444W}, \text{F444W})$ diagram. In the $\text{F444W} > 18.2$ mag part we find a mixture of O-rich stars, different in mass and formation epoch, evolving across the AGB phase. Most of these sources, for reasons connected to the shape of the initial mass function and to the evolutionary timescales of this phase, descend from stars of mass $M_{\text{HB}} < 1.5 M_{\odot}$, formed earlier than ~ 1.7 Gyr ago. The brighter region of the strip, with $17.4 < \text{F444W} < 18.2$ mag, harbors both M-type objects and C stars descending from 1.5 to $2.5 M_{\odot}$ progenitors, which formed between 0.5 and 1.5 Gyr ago. Based on the relative duration of the C-rich and O-rich phases, and taking into account the initial mass function and the AGB timescales of stars of different mass, we estimate that if the star formation rate did not change significantly during those epochs, the fraction of C-rich stars in this region of the diagram is $\sim 20\%$. Finally, in the bright region of the diagram, at $\text{F444W} < 17.4$ mag, we expect to find only stars of mass above $3 M_{\odot}$, during the evolutionary phases following the ignition of hot bottom burning.

It is important to note that our sample is based on single-epoch observations. As shown, for instance, by the DUST-INGS survey with Spitzer (M. L. Boyer et al. 2015b), the magnitudes of AGB stars at wavelengths $\lambda \sim 3\text{--}4 \mu\text{m}$ can vary with amplitudes up to 0.5 mag. This introduces additional uncertainty in the interpretation of the data reported in Figure 1. In particular, while we consider it most likely that C stars along the DFS populate the $17.4 < \text{F444W} < 18.2$ mag strip, the possibility that a few carbon-rich objects are located within ~ 0.2 mag outside the F444W thresholds given above cannot be ruled out. However, because the AGB lifetime is much longer than the pulsation period, these effects average out across the total population, and the relative proportions of stars in each region (e.g., the $\sim 20\%$ C-star fraction estimate) remain statistically valid for characterizing the intermediate-age population. The single-epoch nature of the observations does not affect the validity of Equation (1), as far as sources populating the DFS are considered. Assuming a typical variability amplitude of ± 0.25 mag for these sources, the uncertainty propagated into the calculated luminosity is ~ 0.09 dex. Despite this

single-epoch scatter, the relation provides a robust estimate of the average luminosity of the DFS population, as the dispersion is smaller than the typical range of luminosities spanned by the AGB phase.

3.3. Dusty Objects

E. Tarantino et al. (2026, in preparation) show that Sextans A harbors ~ 20 very dusty AGB stars, which are visible in Figure 1 as stars populating the region of the diagram redward of the DFS discussed above. As discussed earlier in this section, this part of the color–magnitude diagram harbors stars with carbonaceous dust in their surroundings, whose formation is driven by the significant quantities of carbon accumulated in the surface regions.

The majority of these objects, in particular those populating the $0 < (F277W - F444W) < 1$ mag region, are interpreted as the progeny of stars of mass below $\sim 1.5 M_{\odot}$, which have recently become C stars. This understanding is consistent with the morphology of the evolutionary tracks in Figure 1, which in fact overlap with the positions of these sources.

The redder objects found in the region $1 < (F277W - F444W) < 4$ mag exhibit a significantly higher IR excess, consistent with their identification as stars that have experienced a sequence of third dredge-up episodes that favored the rise in the surface C/O up to ~ 10 . Based on the comparison between the position of these sources and the evolutionary tracks reported in Figure 1, we deduce a dominant presence of stars descending from $M_{\text{HB}} < 1.5 M_{\odot}$ progenitors, plus the two brightest ones, indicated with magenta stars in the figure, at $F444W \sim 15$ mag, which likely descend from progenitor stars with $M_{\text{ZAMS}} \sim 2.5 M_{\odot}$, formed ~ 0.5 Gyr ago.

In Figure 1 we indicated with magenta and orange crosses five out of the six sources with available MIRI/LRS spectroscopy, recently studied by M. L. Boyer et al. (2025), which populate the $(F277W - F444W) > 1$ mag region of the color–magnitude diagram. The position of these objects is well reproduced by the track of the $1.25 M_{\odot}$ model star; however, taking into account possible variability effects, we can reasonably assume progenitor masses for these stars in the $1.15 < M < 1.5 M_{\odot}$ range. The five objects, which according to our interpretation represent the final evolutionary phases of stars formed ~ 2 – 3 Gyr ago, ideally trace a sequence of stars enriched in carbon, which are currently producing carbonaceous dust at different rates, from 10^{-8} to $10^{-7} M_{\odot} \text{ yr}^{-1}$. Most of the dust is released in the form of amorphous carbon, while the contribution of SiC is not expected to exceed $\sim 5\%$: this is consistent with the results from M. L. Boyer et al. (2025), who find clear evidence of SiC only in the SED of source 90248, which is indicated in orange in Figure 1. The JWST/LRS spectra of these five sources clearly show the presence of the acetylene (C_2H_2) absorption band at $7.5 \mu\text{m}$, confirming their carbon-star nature. Their strength increases with the star color, indicating a larger carbon excess as expected from the $1.25 M_{\odot}$ model (see Figure 2).

This interpretation does not apply for source 90034, indicated with a cyan cross in Figure 1, which exhibits a significantly lower IR excess. The strong water feature around $6.5 \mu\text{m}$ and the lack of C_2H_2 in the JWST/LRS spectrum of this object indicates that it is not a carbon star. Furthermore, the presence of a featureless dust continuum was associated by M. L. Boyer et al. (2025) to the presence of metallic iron dust. A dominant contribution from iron dust with respect to

silicates can be obtained during the very final evolutionary phases of metal-poor, massive AGB stars, because the hot bottom burning experienced is so efficient as to cause a severe depletion of surface oxygen and magnesium (F. Dell’Agli et al. 2018), which, in turn, leads to a dramatic decrease in the rate at which silicates are formed (E. Marini et al. 2019); on the other hand, the formation of solid iron is not affected by the lack of gaseous silicon and magnesium. Therefore, we tentatively identify 90034 as the descendant of an ~ 4 – $5 M_{\odot}$ star, in agreement with the large luminosity of $\sim 20,000 L_{\odot}$ estimated by M. L. Boyer et al. (2025) for this object.

In the brightest part of the diagram we note a paucity of objects with $14 < F444W < 15$ mag and $(F277W - F444W) \sim 0$ mag, which may be identified as either red supergiants (RSGs) or massive AGB stars. The AGB interpretation is the more likely for the source marked with a magenta asterisk. Its position on the diagram, which is reproduced by the evolutionary track of the $6 M_{\odot}$ model star, deviates significantly from the DFS, suggesting that either it is surrounded by silicates and alumina dust, or, similarly to source 90034, by metallic iron dust. The latter hypothesis is consistent with recent JWST/LRS results, which indicate that silicate features may be rare among the AGB sources of this galaxy (M. L. Boyer et al. 2025). We note, however, that this star is near the saturation limit of the NIRC2 detector, and possible nonlinear effects may impact its measured magnitude and color. Despite this caveat, it remains a valid candidate for being a massive AGB star.

While this classification provides a characterization of the sources on the red side of the diagram in terms of the progenitor mass and the dust produced in their circumstellar envelope, a more detailed analysis of the dust mineralogy surrounding these objects requires the MIRI data, as the silicates and SiC features are found in the 10 – $20 \mu\text{m}$ spectral region. This analysis will be addressed in the next section.

4. Interpretation of the MIRI Imaging Data

For some of the sources shown in Figure 1 MIRI photometry in the F770W, F1000W, F1130W, and F1280W bands is available. To further validate the general understanding presented in the previous section, particularly in the interpretation of the reddest objects discussed in Section 3.3, we analyze the distribution of the stars in Sextans A in the $(F444W - F1000W, F444W)$ and $(F444W - F1130W, F444W)$ diagrams. We consider these two diagrams only, because the COMARCS atmospheres (B. Aringer et al. 2009) of carbon stars used as input for the code DUSTY do not account for the depressions of the flux in the 7–8 and 12–13 μm spectral regions related to the presence of C_2H_2 molecules (G. C. Sloan et al. 2016); the synthetic approach would clearly overestimate the F770W and F1280W fluxes, with the exception of the stars surrounded by large quantities of dust, where the radiation released from the photosphere is entirely reprocessed by the dusty region of the circumstellar envelope.

The distribution of the AGB sources of Sextans A on the aforementioned color–magnitude diagrams is shown in Figure 3. The evolutionary tracks of selected model stars are overplotted on the data points and are particularly useful for the present analysis.

On the blue, faint side of the diagrams we note the presence of ~ 20 objects at $(F444W - F1000W) \sim 0.1$ mag and

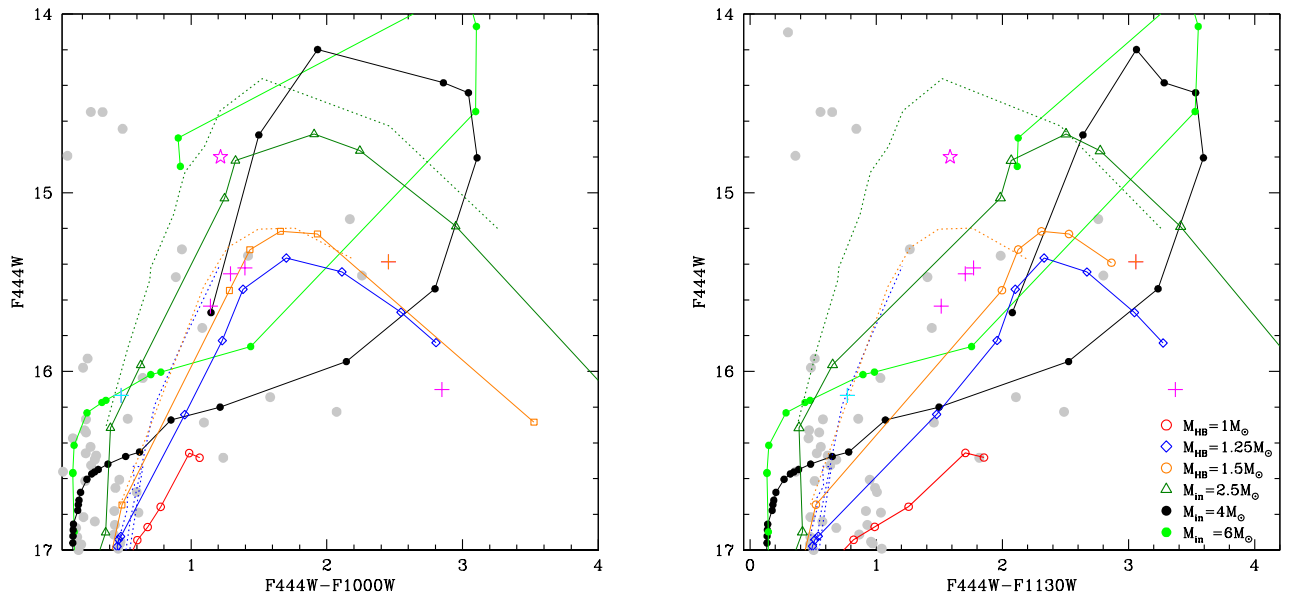


Figure 3. Distribution of the evolved stellar population of Sextans A, indicated with gray dots, in the (F444W – F1000W, F444W; left panel) and (F444W – F1130W, F444W; right panel) diagrams. Crosses, stars, asterisks, and model symbols connected by solid lines have the same meaning as in Figure 1. Dotted lines indicate the evolutionary tracks for metallicity $Z = 4 \times 10^{-4}$.

$16.2 < F444W < 17$ mag, which were found to populate the upper part of the DFS shown in Figure 1. The position of these objects is well reproduced by the evolutionary tracks of $4\text{--}7 M_{\odot}$ stars, which follow an approximately vertical path until the strongest hot bottom burning conditions are reached and formation of silicates takes place. We therefore interpret these objects as the progeny of massive AGB stars, formed between 50 and 200 Myr ago, currently undergoing negligible or soft hot bottom burning at the base of the envelope.

The behavior of the tracks of the stars that reach the C-star stage, in this case represented by the 1.25 , 1.5 , and $2.5 M_{\odot}$ cases, is qualitatively similar to that discussed in Figure 1: (a) the tracks develop redward, owing to the gradual increase in the surface carbon, which enhances the DPR; and (b) toward the final evolutionary phases, the F444W flux, after reaching a maximum value that depends on the progenitor mass, eventually decreases as the peak of the SED of very dusty stars is found at wavelengths above $5 \mu\text{m}$.

Massive AGB stars experiencing hot bottom burning, here represented by the 4 and $6 M_{\odot}$ model stars, follow a different behavior. The evolutionary tracks follow an anticlockwise trajectory, which can be explained on the basis of the arguments presented at the end of Section 3.1: the initial excursion to the red side of the diagrams is driven by the progressively increasing production of silicates characterizing the first part of the AGB evolution, while the return to the blue begins after the peak of the strength of hot bottom burning is reached and dust formation occurs at lower and lower rates.

The bright blue sources located in the $14 < F444W < 15$ mag and $(F277W - F444W) \sim 0$ mag region (see Figure 1) were identified as either RSGs or massive AGB stars in Section 3.3. However, their distribution in the MIRI color-magnitude diagrams (Figure 3) can be used to assess their nature. Indeed the positions of these sources lie notably blueward of the AGB evolutionary tracks, which favors their interpretation as RSGs, with the possible exception of the single source marked with an asterisk, which remains a strong massive AGB candidate.

As discussed in the previous section, source 90034 can be identified as the progeny of a massive AGB star, based on the large luminosity and the characteristics of the SED. Although the final points of the evolutionary tracks of the $4 M_{\odot}$ model star shown in Figure 3 correspond to luminosities $\sim 30\%$ higher and colors ~ 1 mag redder than those estimated by M. L. Boyer et al. (2025) for this source, it is still plausible that 90034 originates from an $\sim 4 M_{\odot}$ progenitor that is currently evolving through the very final AGB phases. These stages are not included in the evolutionary tracks shown in Figure 3 due to numerical convergence limitations.

The characterization of the individual sources based on the results reported in the two panels of Figure 3 is slightly different from that deduced on the basis of the analysis of Figure 1. The results of Figure 1 show that the position of the sources in the $1 < (F277W - F444W) < 4$ mag region of the diagram is nicely reproduced by the evolutionary tracks of model stars of mass $M_{\text{HB}} = 1$ and $1.25 M_{\odot}$ and $M_{\text{ZAMS}} = 2.5 M_{\odot}$. On the other hand, we note in Figure 3 that the position of the same sources in the (F444W – F1000W, F444W) and (F444W – F1130W, F444W) diagrams is not well reproduced by the evolutionary tracks of the same model stars. This is reflected in an attribution of slightly higher masses to the progenitors of the individual sources, with respect to those deduced in the previous section. For instance, if we consider the five reddest objects studied by M. L. Boyer et al. (2025), indicated with magenta and orange crosses in Figures 1 and 3, we concluded in the previous section that they were the progeny of $M_{\text{HB}} = 1.2\text{--}1.3 M_{\odot}$ stars, whereas, based on their position on the (F444W – F1000W, F444W) and (F444W – F1130W, F444W) diagrams, we would derive a progenitor mass of $M_{\text{HB}} \sim 1.5 M_{\odot}$ and $M_{\text{ZAMS}} \sim 2 M_{\odot}$, respectively. A further example is provided by the bright, red source indicated with a magenta star in Figure 3, which is associated with a progenitor mass of $M_{\text{ZAMS}} = 2.5 M_{\odot}$ when considering the (F277W – F444W, F444W) and (F444W – F1000W, F444W) diagrams, while the analysis of the (F444W – F1130W, F444W) diagram suggests a progenitor mass around $M_{\text{ZAMS}} = 3 M_{\odot}$.

To understand the reasons for the discrepancy between the conclusions drawn from the analysis of the color–magnitude diagrams obtained with the NIRCcam and MIRI filters, we note that both the F1000W and F1130W fluxes of carbon stars are strongly affected by the feature in the SED centered at $11.3\ \mu\text{m}$, associated with the formation of SiC. We first consider the possibility that the choice of the optical constants related to SiC could play a role in this context. The evolutionary tracks shown in Figure 3, which are more consistent with the interpretation of dusty objects given in Section 3.3, are obtained using the B. Pegourie (1988) optical constants. Use of the optical constants by A. Laor & B. T. Draine (1993) leads to colors that are too red by ~ 0.5 mag with respect to the position of the data points, which cannot be reproduced by any of the evolutionary tracks of $1.25\text{--}3\ M_{\odot}$ stars, which we have seen to reach the C-star stage.

We are left with the option that the present modeling, while well reproducing the gradual shift to longer wavelengths of the SED of stars as they evolve toward the final phases of the AGB evolution, overestimates the amount of SiC formed. This is supported by the fact that among the five carbon stars identified by M. L. Boyer et al. (2025), only one shows clear evidence of SiC in its JWST/LRS spectrum. Indeed, the presence of SiC in the circumstellar envelope is irrelevant for the location of the stars on the (F277W – F444W, F444W) diagram, while it affects the position on the (F444W – F1000W, F444W) and (F444W – F1130W, F444W) diagrams. We tested the possibility that lower values of the sticking coefficient α_{Si} of gaseous silicon on solid SiC particles could partly inhibit the formation of SiC, thus leading to less prominent SiC features, and hence redder (F444W – F1000W) and (F444W – F1130W) colors. However, we find that the results are largely independent of the choice of α_{Si} , because SiC easily reaches saturation, being the most stable compound formed in the circumstellar envelopes of carbon stars (A. S. Ferrarotti & H.-P. Gail 2006).

A possible way to decrease the efficiency of the formation of SiC is to assume that the old stellar component of Sextans A is composed of stars whose metallicity is lower than the $[\text{Fe}/\text{H}] = -1.4$ value adopted here. This would be consistent with the analysis by S. Sakai et al. (1996), who derived a metallicity $[\text{Fe}/\text{H}] \sim -1.8$, based on the morphology of the RGB of the galaxy, and was recently adopted by M. L. Boyer et al. (2025), who assumed an initial metallicity of $Z = 0.0004$ for their computations. This hypothesis would also be consistent with the results by G. C. Sloan et al. (2012), who compared the height of the SiC features in carbon stars in the galaxies Leo I, Carina ($[\text{Fe}/\text{H}] \sim -1.4$), and Sculptor ($[\text{Fe}/\text{H}] \sim -1.8$). While the SED of the C stars in the first two galaxies exhibit a SiC feature with a 0.2 excess with respect to the continuum, the counterparts in Sculptor are characterized by an SiC-free SED.

A lower $[\text{Fe}/\text{H}]$ would significantly affect the formation of SiC, as the amount of the latter dust species that can be formed is tightly connected to the silicon content available in the surface regions of the stars (A. S. Ferrarotti & H.-P. Gail 2006). To quantify the effects of a metallicity change, we calculated evolutionary sequences of $Z = 4 \times 10^{-4}$ model stars of initial mass in the $1.25\text{--}2.5\ M_{\odot}$ range. More metal-poor stars of a given initial mass evolve with more massive cores than their higher-metallicity counterparts; thus they

reach brighter luminosities. The formation of carbon dust is less efficient in metal-poor environments, owing to the hotter effective temperatures, which partly inhibit the formation of dust in the circumstellar envelope.

On the (F277W – F444W, F444W) diagram shown in Figure 1 the evolutionary tracks of the $Z = 4 \times 10^{-4}$ model stars would be slightly brighter than those corresponding to the $Z = 10^{-3}$ case, and in general they do not reach the extremely red colors attained by $Z = 10^{-3}$ stars. The same interpretative approach adopted in the previous section would allow to characterize three out of the five sources (sources 94328, 92104, and 86434) identified as carbon stars and discussed in M. L. Boyer et al. (2025), with progenitor masses slightly smaller than those deduced in the previous section.

For what concerns the MIRI color–magnitude diagrams, the $Z = 4 \times 10^{-4}$ evolutionary tracks are significantly bluer than the $Z = 10^{-3}$ ones (see the dotted lines in Figure 3), owing to the lower amount of SiC formed, which decreases the F1000W and F1130W fluxes. The metal-poor tracks reported in Figure 3 lay on the blue side of the MIRI color–magnitude diagrams with respect to the position of the sources populating the $1 < (\text{F277W} - \text{F444W}) < 4$ mag region in Figure 1, thus the progenitor masses estimated for these objects would be smaller than those deduced in Section 3.3. We therefore find a reverse situation with respect to the results obtained when applying the $Z = 10^{-3}$ tracks, which we showed to be too red to explain the same sources. From this comparative analysis we conclude that consistency between the results based on the NIRCcam and MIRI data is obtained when an intermediate metallicity between $Z = 4 \times 10^{-4}$ and 10^{-3} is adopted. Overall, this interpretation provides further support to the hypothesis that the intermediate-age stellar population of Sextans A is characterized by metallicities slightly lower than the $[\text{Fe}/\text{H}] \sim -1.4$ value adopted in our reference models.

5. The Dust Production Rate

While the mineralogy of the dust surrounding the stars is primarily constrained by using MIRI data, we base the discussion of the DPR on the NIRCcam colors, because MIRI photometry is available for only part of the entire sample.

As discussed in Section 3.3, the dust release in Sextans A is mostly provided by ~ 20 AGB sources, located on the red side of the observational color–magnitude diagrams shown in Figures 1 and 3, whose SEDs exhibit a strong IR excess. This result is similar to those obtained by M. Matsuura et al. (2009), M. L. Boyer et al. (2011, 2012), D. Riebel et al. (2012), and S. Srinivasan et al. (2016), who found that about 90%–95% of the dust in the SMC and LMC is coming from the reddest, “extreme” AGB stars. The discussion in Section 3.3 outlined that the ~ 20 sources considered here are carbon stars, which leads to the conclusion that the global DPR of Sextans A is dominated by this class of objects. The dominant role of C stars in the dust production can be explained based on the arguments presented in Section 3.1, which focus on the sensitivity of the mineralogy of the dust released by AGB stars to the progenitor mass and to the evolutionary phase.

Little or no dust is released by low-mass stars that fail to reach the C-star stage, i.e., those discussed in point (a) in Section 3.1; indeed the DPR is generally low during the O-rich phases of low-mass stars (P. Ventura et al. 2012), and even more so in the case of Sextans A, whose stellar population is metal poor. Significant dust production takes place in the

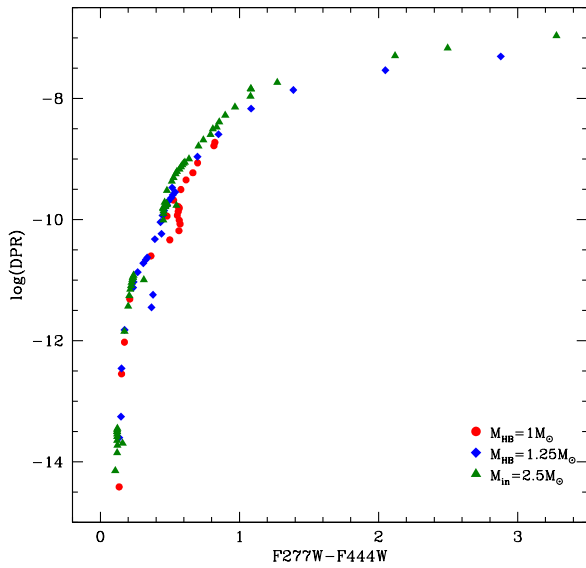


Figure 4. Variation of the DPR as a function of the $(F277W - F444W)$ color during the AGB evolution of the same model stars shown in Figure 2.

winds of massive AGB stars during the evolutionary phases near the luminosity peak, when the hot bottom burning intensity reaches its maximum (P. Ventura et al. 2012, 2014). The contribution from this class of objects, discussed in point (c) in Section 3.1, is significant in galaxies hosting a solar- or slightly subsolar-metallicity young stellar component, such as the LMC (F. Dell’Agli et al. 2015b), M33 (A. Javadi et al. 2013), and M31 (C. Gavetti et al. 2025). Although some studies (e.g., M. L. Boyer et al. 2015b) indicate substantial dust production from AGB stars even at low metallicity, in the specific case of Sextans A the relative contribution of refractory dust species from O-rich and massive AGB stars is expected to be modest, because of the scarcity of silicon, aluminum, and iron. In contrast, carbon dust production remains efficient, as discussed above. Overall, even considering that all the sources populating the $(F277W - F444W) < 0.2$ mag region of the $(F277W - F444W, F444W)$ diagram shown in Figure 1 are M-type stars, their individual DPRs barely reach $10^{-10} M_{\odot} \text{ yr}^{-1}$ (see Figure 4), thus indicating that their contribution to the global DPR of the galaxy is below 1%.

Given the poor contribution of low-mass stars and massive AGB stars, most of the dust release comes from the stars that become C stars (point (b) in Section 3.1), descending from progenitors of mass in the $1-3 M_{\odot}$ range, formed between 0.5 and 6–7 Gyr ago. For the same reasons related to the low metallicity of Sextans A stars, we can restrict our attention to the C-rich phase, neglecting the dust formed during the initial part of the AGB evolution, during which the stars are O rich.

The evolution of these stars, in terms of change in the surface chemical composition, rate of dust release, and change in the $(F277W - F444W)$ color, is shown in Figure 2. We note the significant rise in the DPR during the C-rich phase, which increases as more carbon is carried to the surface regions by the various third dredge-up episodes. This leads to redder $(F277W - F444W)$ colors, owing to the effects of dust reprocessing on the shape of the SED. During the C-star phase, the DPR is correlated with $(F277W - F444W)$, as shown in Figure 4. It increases from $10^{-8} M_{\odot} \text{ yr}^{-1}$ at $(F277W - F444W) = 1$ mag, to $10^{-7} M_{\odot} \text{ yr}^{-1}$ at $(F277W - F444W) = 4$ mag, up to $10^{-6} M_{\odot} \text{ yr}^{-1}$ at $(F277W - F444W) = 8$ mag.

The results reported in Figure 4 indicate an overall spread in the DPR at a given $(F277W - F444W)$ of a factor ~ 2 , due to the differences among the DPRs of stars of different mass evolving at the same $(F277W - F444W)$ color, and in turn, related to the differences in the progenitor masses, in the $1-3 M_{\odot}$ range. Indeed the stars descending from higher-mass progenitors evolve at higher AGB luminosities, which favor larger mass-loss rates, and consequently a higher efficiency of the dust formation process.

The predicted tight relation between the DPR and the $(F277W - F444W)$ color shown in Figure 4 is a promising diagnostic for estimating dust production by AGB stars using JWST/NIRCam data. In the $(F277W - F444W) > 0.5$ mag domain this relation can be approximated by

$$\frac{\dot{M}_{\text{dust}}}{10^{-8} M_{\odot} \text{ yr}^{-1}} = (F277W - F444W)^{1.7}.$$

The results from AGB evolution and dust formation modeling indicate that most of the dust is produced by stars with $(F277W - F444W) > 0.5$ mag. Using the relation above, we find that the reddest stars in Sextans A have DPRs ranging between 10^{-10} and $10^{-7} M_{\odot} \text{ yr}^{-1}$. These stars are expected to produce primarily amorphous carbon dust, with a minor contribution from SiC (below 5%) in terms of the production rate. The bluer stars, while more numerous, contribute a negligible amount to the total dust production. These findings are consistent with the common understanding of dust production in metal-poor environments, such as Sextans A, where in fact we expect a dominant contribution from solid carbon to the global dust budget.

The conclusions above in regard to the dustiest objects of Sextans A are based on the assumption that they are not part of binary systems. Leaving aside the unlikely possibility that these objects are currently experiencing a strong binary interaction, and the irrelevant (for the present analysis) case that they belong to binary systems with large separation, such that no mass transfer took place, we consider the possibility that these sources are the former secondary components of binary systems and received mass from the companion, when the latter was evolving through the RGB. The mass transfer would result in higher envelope masses at the start of the AGB phase, so that their evolution would be similar to that experienced by higher-mass progenitors. The results in terms of dust production given above, particularly the relation between DPR and the $(F277W - F444W)$ color, would not be significantly affected; with regard to the characterization of these sources, discussed in Section 3.3, the derivation of the mass at the start of the core helium-burning phase M_{HB} would remain substantially unchanged, while the progenitor masses M_{ZAMS} would be smaller and the derived ages correspondingly older.

6. Conclusions

We use recent JWST observations to study the evolved stellar population of the metal-poor galaxy Sextans A. The proposed interpretation is based on the comparison between the distribution of the stars in the various observational color-magnitude diagrams, built by combining NIRCam and MIRI data, with the evolutionary tracks of stars of different mass and metallicity $Z = 0.001$ (corresponding to $[\text{Fe}/\text{H}] \sim -1.4$), obtained by means of stellar evolution and dust formation modeling.

Over 90% of the AGB sources are distributed along an approximately vertical sequence at (F277W – F444W) ~ 0 mag, on the blue side of the (F277W – F444W, F444W) diagram, and exhibit little or no IR excess, indicating negligible ongoing dust production. This region of the diagram harbors a miscellany of stars, ranging from old, low-mass stars, now experiencing the late phases of their AGB lifetime, to the progeny of $1\text{--}3 M_{\odot}$ stars, taken during the evolutionary phases preceding the formation of large quantities of carbonaceous dust, and young, massive AGB stars, now evolving through the early AGB or the initial part of the AGB phase, before the activation of strong hot bottom burning conditions. The majority of the stars in the vertical strip are interpreted as M-type objects, although we also expect the presence of a small fraction of carbon stars, evolving in the $17.4 < F444W < 18.2$ mag region. For all these sources we find a tight correlation between the F444W flux and luminosity, which makes the measured F444W a robust luminosity indicator.

The evolved stellar population of Sextans A includes a subset of ~ 20 stars populating the red side of the various observational color–magnitude diagrams considered, which exhibit significant IR emission. As far as the (F277W – F444W, F444W) diagram is concerned, the position of these red objects is well reproduced by the evolutionary tracks of $1.25\text{--}2.5 M_{\odot}$ stars during the final part of the AGB evolution, after significant quantities of carbon were accumulated in the surface regions and dust was produced at high rates. We find that the majority of these objects, including five of the six stars with MIRI/LRS spectroscopy recently studied by M. L. Boyer et al. (2025), descend from 1.25 to $1.5 M_{\odot}$ progenitors, formed $2\text{--}3$ Gyr ago. These stars are currently producing dust at rates between 10^{-8} and $10^{-7} M_{\odot} \text{ yr}^{-1}$, with amorphous carbon being the dominant component and SiC contributing less than 5%.

These results are further confirmed by the analysis of the distribution of the sources in the (F444W – F1000W, F444W) and (F444W – F1130W, F444W) diagrams. In the latter cases, the masses derived for the progenitor stars are slightly higher than those estimated from the NIRCам data alone; this is likely connected to an overestimation of the SiC production, possibly suggesting that the oldest stellar population of the galaxy is more metal poor, with $[\text{Fe}/\text{H}] \sim -1.8$.

Overall, this study confirms the key role of low- and intermediate-mass AGB stars in dust enrichment, especially in low-metallicity environments, and offers critical constraints for refining theoretical models of dust production. The combination of NIRCам and MIRI data allows the determination of the quantity and mineralogy of the dust produced by the individual sources, which are of paramount importance for a critical evaluation of the predictions from dust formation modeling in the winds of evolved stars.

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Software: DOLPHOT (A. E. Dolphin 2000, 2016), JWST Pipeline (H. Bushouse et al. 2023).

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