Galaxy evolution, including the first AGB stars

Why Galaxies Care About AGB Stars: A Continuing Challenge through Cosmic Time
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The Impact of AGB Stars on Galaxies

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Abstract. At the end of their evolution, asymptotic giant branch (AGB) stars undergo strong pulsation, mass loss, and dust production. Their mass loss results in substantial chemical and dust enrichment of the interstellar medium. Dust evolution models and isotope abundances in presolar grains suggest that AGB stars play a key role in both dust evolution and the star formation process. They are also the brightest stars in galaxies, potentially dominating in the near-infrared. As a result, AGB stars have a significant influence on the evolution and appearance of their host galaxies and thus must be accounted for when interpreting a galaxy's integrated light. I will highlight new results that describe the impact AGB stars have on galaxies, including how AGB stars are used to probe galaxy evolution.

Keywords. stars: AGB and post-AGB, stars: evolution, stars: winds, outflows, galaxies: fundamental parameters, infrared: stars

1. Introduction

At the end of their evolution, intermediate-mass stars (∼1–8$M_\odot$) ascend the asymptotic giant branch (AGB). As they evolve, AGB stars develop some of the most complex aspects of stellar physics, including dredge up, thermal pulsation, radial pulsation, dust production, and strong mass loss. This phase ends with the star shedding its circumstellar envelope, exposing the stellar core (a white dwarf), and potentially developing a planetary nebula. AGB stars have several defining characteristics that have important impacts on galaxies, despite that fact that this phase is relatively short lived. I will review recent work that illustrates this impact, including the role AGB stars play in the enrichment of the interstellar medium (ISM; §2), the effect of their bright luminosities in the infrared (IR; §3), and their usefulness as probes of galaxy evolution (§4).

2. Enrichment of the ISM

AGB stars are important sources of ISM enrichment and galaxy chemical evolution, through both the synthesis of key elements and efficient dust production.

2.1. *Nucleosynthesis*

Solar abundances cannot be explained without nucleosynthesis processes in AGB stars. AGB stars are responsible for a significant fraction of some light elements: C, N, F, and possibly Li (e.g., Kobayashi *et al.* 2011a,b). They also produce neutron-rich isotopes of O, Ne, Mg, and Si and synthesize heavy elements via the *s*-process (e.g., Karakas *et al.* 2014). These elements are dredged up to the surface and distributed into the ISM via stellar winds, having a significant impact on the chemical evolution of their host galaxies. The signatures of AGB nucleosynthesis can be seen in surface abundances and can be used to estimate a star's initial mass by comparing ratios of different elements. For example, Rb is more likely to be present in more massive AGB stars ($>4\ M_\odot$) and Ba is more likely present in low-mass stars ($<3\ M_\odot$). Abundance ratios can therefore provide insight into the star formation histories as well as the nucleosynthesis processes in galaxies (Fishlock *et al.* 2014; Cristallo *et al.* 2015). For a more detailed review of AGB nucleosynthesis, see this conference's contribution from A. Karakas.

2.2. *Dust Production*

Thermally-pulsing (TP-)AGB stars are prolific dust producers and may be an important source of dust to the ISM. We see the signatures of AGB dust in the isotopic ratios of presolar grains (e.g., Nittler 2003; Zinner 2004; Hoppe 2008), and recent results suggest that some presolar grains may have originated in an electron-capture supernova from a super-AGB star (8–10 $M_\odot$; Nittler *et al.* 2018). These grains point to a possible significant role played by AGB stars in the dust evolution of galaxies, though their importance relative to supernova dust and grain growth in the ISM remains difficult to quantify.

Several works in the last 20 years have pointed to a dust budget "crisis", wherein the ISM dust masses observed in distant quasars is higher than the expected dust input from AGB stars and supernovae (e.g. Bertoldi *et al.* 2003; Robson *et al.* 2004; Beelen *et al.* 2006). However, recent observations in both the Small and Large Magellanic Clouds (SMC/LMC) are beginning to suggest that AGB stars may be a dominant source of dust. The Surveying the Agents of Galaxy Evolution *Spitzer* program (SAGE; Meixner *et al.* 2006; Gordon *et al.* 2011) was able to identify every dust-producing AGB star in both galaxies (Blum *et al.* 2006; Boyer *et al.* 2011) and quantify the dust input using several different techniques (Srinivasan *et al.* 2009, 2016; Matsuura *et al.* 2009; Riebel *et al.* 2012; Boyer *et al.* 2012). The total AGB dust input from these studies disagree by up to a factor of 5 owing primarily to the choice of dust optical constants. Recently, Nanni *et al.* (2016); Nanni *et al.* (2018) compared the SAGE TP-AGB infrared colors in the SMC to new AGB model spectra using a variety of different optical constants. They find that the best agreement is obtained when using optical constants that produce dust masses on the *high* end of the possible range estimated by the SAGE studies. Furthermore, Gordon *et al.* (2014) used *Herschel* data to revise the ISM dust masses in the SMC and LMC down by factors of 4–5, compared to previous dust mass estimates (Leroy *et al.* 2007; Bot *et al.* 2010). The decreased ISM dust mass and the increased AGB dust input from Nanni *et al.* both suggest than AGB stars can be a significant source of ISM dust. Dust evolution models from Zhukovska & Henning (2013) and Schneider *et al.* (2014) both imply that AGB dust can account for 15–70% of the total ISM dust even when including dust destruction, suggesting that the dust budget crisis observed in some quasars needs to be revisited.

Carbon stars can easily form their own condensation material and dredge it up to the surface for dust formation, but it is thought that oxygen-rich AGB stars require pre-existing condensation seeds. As a result, metal-poor oxygen-rich stars should have difficultly forming dust at low metallicity. This has consequences for the early Universe, suggesting that AGB dust input is delayed until the lower-mass carbon stars form ($t_{\rm age} > 100$–300 Myr). However, new evidence from the DUST in Nearby Galaxies with *Spitzer* (DUSTiNGS) survey suggests that oxygen-rich AGB stars can form significant dust masses even in very metal-poor galaxies. These stars were classified as O-rich (M type) using *HST*, and their [3.6]–[4.5] *Spitzer* colors suggest dust masses at least as high as those seen in their C type counterparts (Fig. 1; Boyer *et al.* 2017). The galaxies surveyed have very low gas-phase oxygen abundances ($12 + \log(O/H) \lesssim 8$), implying that even the youngest stars are metal-poor. AGB stars with metallicities $\sim$1 dex lower than the SMC may therefore contribute dust in the early Universe, as soon as 30 Myr after they form.

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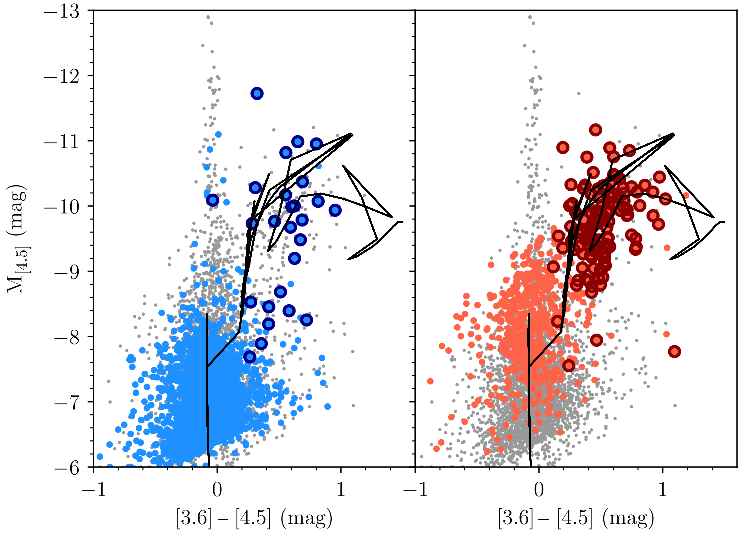

Figure 1. *Spitzer* and *HST* observations of metal-poor, star-forming dwarf galaxies show the presence of both M type (left) and C type (right) AGB stars that are producing dust (large, dark circles). Less-dusty AGB stars are marked with small blue (M) or red (C) symbols. These data suggest that, like C stars, primordial M type AGB stars can form substantial dust masses, similar to what is seen in the comparatively metal-rich Magellanic Clouds. This implies that massive AGB stars can contribute dust at very early times (∼30 Myr) in a galaxy's evolution. Produced using data from Boyer *et al.* (2017); isochrones from COLIBRI (Nanni *et al.* 2016).

3. Integrated Flux

Their high luminosities and cool temperatures place TP-AGB stars among the brightest objects in galaxies, especially in the near-IR. TP-AGB stars are short-lived and therefore rare, but the presence of even a small population has a strong impact on the integrated light of galaxies. For instance, population synthesis models from (Melbourne *et al.* 2012) show that TP-AGB stars are responsible for up to 70% of the 1.6 μm flux, with TP-AGB stars dominating over other bright stars by redshift ∼4–5.

3.1. *Near-IR*

Stellar population synthesis (SPS) models have difficulty reproducing the observed TP-AGB near-IR contribution, with model/data disagreements ranging from 0.2–3 in the 1–5 μm range (e.g., Johnson *et al.* 2013; Rosenfield *et al.* 2016). Uncertainties in the treatment of TP-AGB stars, particularly with metallicity, are responsible for these differences, with outcomes differing substantially depending on which models are applied in the population synthesis (e.g., Conroy *et al.* 2009). These uncertainties are thought to be due to the treatment of mass loss and dredge up, which both affect the stellar lifetime. Changes in the lifetime affect both the number of TP-AGB stars and their maximum luminosities, and therefore affect the integrated flux of the population. The ramifications of not accurately reproducing the TP-AGB luminosity contribution can be dramatic, since integrated near-IR light is often used to estimate galaxy stellar masses, mean ages, metallicities, and star formation histories (SFHs) using SPS models. For example, Conroy *et al.* (2009) find systematic biases in the derived galaxy stellar masses, with uncertainties up to 0.6 dex.

Baldwin *et al.* (2018) recently compared the effect that different models have on SFHs derived from optical and near-IR spectra of distant galaxies. They tested four different

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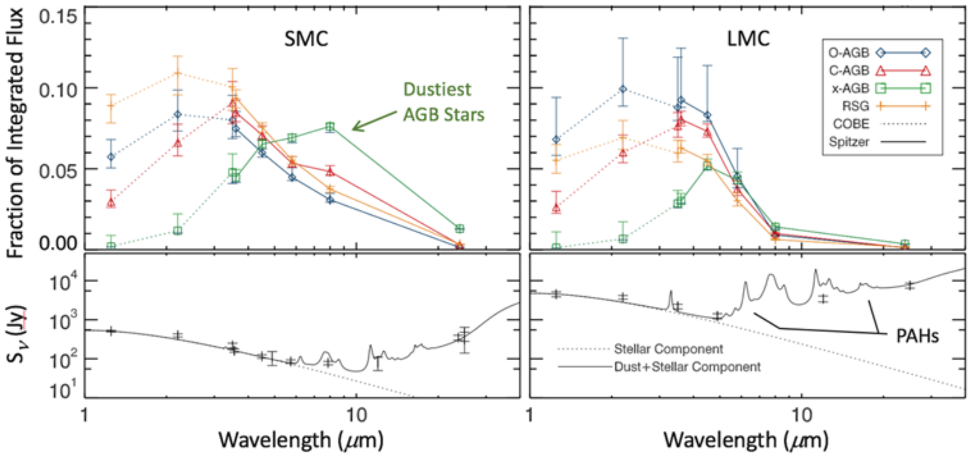

Figure 2. TP-AGB stars contribute a substantial fraction (up to 70%) of a galaxy's global flux, especially at 1–3 μm. Shown here is the measured contribution in the Magellanic Clouds, reproduced with permission from Melbourne & Boyer (2013). The lower panels show the global spectral energy distributions. In early-type galaxies or metal-poor galaxies with little ISM dust/PAHs, the contribution from dusty TP-AGB stars remains high out to 8 μm (e.g., in the SMC). In more metal-rich galaxies with strong star-formation, the mid-IR contribution is dominated by PAH emission (e.g., in the LMC).

SPS models (Bruzual & Charlot 2003; Conroy & Gunn 2010; Maraston & Strömbäck 2011; Vazdekis *et al.* 2016) and found that, while fits to optical spectra produced similar SFHs for all four models, the fits to the near-IR spectra produced SFHs that both disagree with each other and disagree with the optically-derived SFHs. All four SPS models produced reasonably similar optical SFHs for a given galaxy, but often produced four radically different SFHs in the IR. These results point to the importance of improving the TP-AGB models for SPS.

In addition, Baldwin *et al.* (2018) suggests that it may be the stellar spectral library, rather than the treatment of the TP-AGB phase, that drives the uncertainties. They tested this by inserting a new, high-resolution spectral library (C3K; see Conroy *et al.* 2013; Villaume *et al.* 2017) into the Flexible SPS models from Conroy & Gunn (2010) and testing the FSPS outcome using both the Padova (Marigo *et al.* 2008) and MIST (Choi *et al.* 2016) stellar evolution models. When the C3K library is used, the Padova and MIST models both produce reasonably good agreement between the optical and IR data and with each other.

3.2. *Mid-IR*

Circumstellar dust emission from TP-AGB stars can affect the integrated mid-IR flux of galaxies, particularly in early-type galaxies with little-to-no interstellar dust. Using the stellar catalogs from the Spitzer SAGE survey (Blum *et al.* 2006; Boyer *et al.* 2011), Melbourne & Boyer (2013) measured the contribution of each TP-AGB subclass to the light of the SMC and the LMC. They find that ≈350 stars in the superwind phase (the so-called extreme, or x-AGB stars) produce ∼10% of the 8-μm flux in the SMC, approximately equal to the contribution from the other ∼10,000 TP-AGB stars combined and suggesting a strong stochasticity in the mid-IR flux of low-mass, star-forming galaxies. However, the 8 μm TP-AGB contribution decreases to just 1–2% in the LMC, where emission from polycyclic aromatic hydrocarbons (PAHs) in star-forming regions has a much stronger contribution at these wavelengths (Fig. 2). Since PAH emission decreases

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precipitously at low metallicity (Sandstrom *et al.* 2010), we can expect the TP-AGB contribution to the mid-IR to increase in metal-poor galaxies. Beyond 10 μm, diffuse interstellar dust (if present) dominates the galaxy spectrum.

In quiescent, early-type galaxies that lacking cold interstellar dust, the signature of a TP-AGB population can be seen via the circumstellar 10 μm and 18 μm silicate features. Villaume *et al.* (2015) show models that can account for these features in early-type galaxy spectral energy distributions without invoking an interstellar dust component. These features are easily detectable in their sample of galaxy spectra, and their models suggest that the strength of the feature depends strongly on the age of the stellar population, with younger populations producing stronger silicate features. This particular AGB signature is therefore a useful tracer of population age in distant galaxies, particularly as high sensitivity mid-IR observations become possible with the launch of the *James Webb Space Telescope* (JWST). However, Simonian & Martini (2017) show that models of AGB dust may need some adjustments given their inability to reproduce the WISE colors ([3.4]–[12] and [3.4]–[22]) of a large sample of early-type galaxies.

In post-starburst galaxies, which have younger populations than their early-type counterparts, the mid-IR contribution from TP-AGB stars is less clear even in the case where there is no evidence for cold interstellar dust. For example, Alatalo *et al.* (2016) measured the WISE colors of several post-starburst galaxies and found them to be intermediate to the expected colors of TP-AGB stars and embedded active galactic nuclei (AGN). The mid-IR spectra may thus be a combination of the two, and inferences that rely on TP-AGB models in these systems must use caution.

3.3. *Long Period Variables*

AGB variability also produces a measurable signature in the integrated light of galaxies. Individual long-period variables (LPVs) can currently be identified out to distances of roughly 5 Mpc (See the P. Whitelock contribution). In distant and totally unresolved galaxies, the luminosity fluctuations of an LPV population averages out and is undetectable. However, there is an intermediate regime where these fluctuations are detectable both in semi-resolved galaxies and in crowded regions such as galactic bulges. Conroy *et al.* (2015) show that in the case where individual pixels contain $\lesssim$10 LPVs, the variability of this small number of stars can produce a pixel-shimmer effect across different observational epochs. This shimmer can be modeled, and tuning the LPV weight in the applied SPS models has a strong effect on the derived stellar age of the population, providing a potential age diagnostic for semi-resolved stellar populations.

3.4. *Recent Model Updates*

Modeling TP-AGB stars is notoriously difficult due to several complex processes: dredge up, mass loss, pulsation, etc. The clear effect of TP-AGB stars on galaxy integrated light is a strong motivation to improve the models, and significant progress has been made in recent years. Villaume *et al.* (2015), Dell'Agli *et al.* (2015a,b), and Nanni *et al.* (2018) have each presented new model results for circumstellar dust that provide good agreement to observed infrared colors, particularly in the Magellanic Clouds. The latest COLIBRI and MIST models both show significant improvements to both the expected number of TP-AGB stars and their expected near-IR flux, resulting in better agreement with observed TP-AGB luminosity functions in the Magellanic Clouds (Choi *et al.* 2016; Pastorelli *et al.* 2019) and in more distant resolved galaxies (Rosenfield *et al.* 2014, 2016).

4. Probes of Galaxy Evolution

Here, I describe examples of how AGB stars can trace galaxy evolution by providing population age diagnostics and morphological diagnostics. Their usefulness does not end at the termination of the TP-AGB phase; their end-products (post-AGB stars) can also shed light on the process of star-formation quenching in galaxies.

4.1. *Ionization*

When comparing the strength of galaxy emission line-intensity ratios (the BPT diagram), a class of galaxies with strong [N II] $\lambda6583/\mathrm{H}\alpha$ and weak [O III] $\lambda5007/\mathrm{H}\beta$ (e.g., Ho 2008) stands out. These galaxies account for a large fraction of massive galaxies (>30%) and have typically been classified as low-ionization nuclear emission line regions, or LINERs, with the ionization mechanism initially thought to be an AGN. However, there are problems with the AGN scenario that are difficult to explain, including an energy budget deficit (e.g., Eracleous *et al.* 2010), lack of correlation with radio emission (e.g., Best *et al.* 2005), and some hints that the emission line flux radial profile is extended beyond what is expected for a nuclear ionizing source (e.g., Sarzi *et al.* 2010). One possible alternative mechanism is photoionization by hot evolved stars distributed throughout the galaxy, especially post-AGB stars (de Serego Alighieri *et al.* 1990; Binette *et al.* 1994).

Recent spectral surveys that have high spatial resolution (SDSS-IV MaNGA, CALIFA) are able to investigate the spatial distribution of LINER emission in galaxies to test the AGN vs. post-AGB scenarios (e.g. Singh *et al.* 2013; Belfiore *et al.* 2016). Belfiore *et al.* (2016) analyze MaNGA data for 646 galaxies and show that LINER-like emission is present in many types of galaxies, sometimes in the outer halos and/or in the central regions of star-forming galaxies, and sometimes extended throughout the entire galaxy body. They find that the Hα surface brightness radial profiles are typically shallower than $1/r^2$ and that the ionization parameter of the gas shows a flat gradient, pointing to LINER emission originating from diffuse stellar sources rather than from a central nuclear source. Given the spatial information, they renamed LINERS to LIERS (omitting the 'nuclear' part), and noted cLIER (central) and eLIER (extended) subclasses.

The Belfiore *et al.* (2016) work points to post-AGB stars as the most likely candidate for the ionization mechanism, and SPS models indicate that post-AGB stars can easily produce LIER emission in galaxies, even when their luminosities are decreased by a factor of two (Byler *et al.* 2017). If post-AGB stars are indeed the source of the LIER emission, it suggests a possible galaxy evolutionary sequence that quenches star-formation from the inside-out, wherein star-forming galaxies evolve into green valley AGN, which evolve into quenched eLIERs (e.g. Sánchez *et al.* 2018). AGB evolution and their end-products (post-AGB stars) are clearly important to tracing the quenching process in galaxies.

4.2. *Spatial Distribution*

Most dwarf galaxies show radial age gradients, with the youngest stars concentrated at the centers and old red giant branch (RGB) stars present in the outskirts. This is often interpreted as evidence for outside-in growth, where star formation starts in galaxy outskirts and migrates to the center over time. El-Badry *et al.* (2016) proposed an alternate inside-out growth scenario, wherein short bursts in star formation lead to gas outflows (and subsequently, inflows as the gas cools). Stars inherit this motion, which leads to stellar migration. They show that in this scenario, most stars form in the galaxy center and migrate outwards on relatively short timescales. In this case, one would expect the

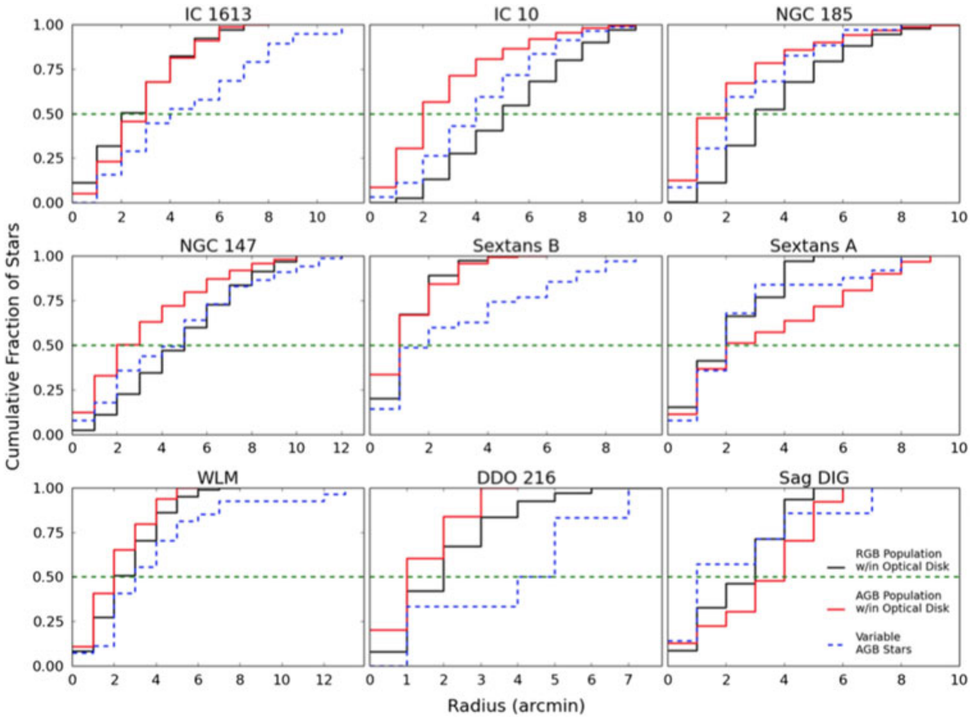

Figure 3. Radial profiles of evolved stars in nearby dwarf galaxies showing that TP-AGB stars (red; and blue indicating known LPVs) and RGB stars (black) are mixed at large radii, suggesting inside-out growth. Reproduced with permission from McQuinn *et al.* (2017).

intermediate-aged population (namely, AGB stars) to be mixed with the older population in dwarf galaxy outskirts, while the youngest stars remain concentrated in the centers.

Recently, the DUSTiNGS survey (Boyer *et al.* 2015a) obtained large 3–5 μm maps of 50 nearby dwarf galaxies that extend to well beyond the effective radii (R_e). We used this data to identify the AGB populations, using (1) statistical arguments that are able to isolate the TP-AGB population from unresolved AGN, which have similar IR colors and luminosities; and (2) multi-epoch data that leverage the long-period pulsation of TP-AGB stars (Boyer *et al.* 2015b). In McQuinn *et al.* (2017), we showed that the TP-AGB population is well mixed with the old RGB population out to $>3\times R_e$ (Fig. 3). These AGB radial profiles are evidence for inside-out growth, providing an additional diagnostic for understanding galaxy evolution.

5. Summary

AGB stars have a strong impact on galaxies, via the material they produce through nucleosynthesis and dust production and via their high luminosities, which peak at IR wavelengths. They also provide important insight into galaxy evolution.

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Discussion

Srinivasan: Dust opacities in the sub-mm are typically extrapolated from the mid-IR and are much lower than lab measurements. This contributes significantly to the ISM dust mass estimates. As a result, there may not be a high-redshift dust budget crisis.

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