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Observations of AGB and Super AGB stars

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Abstract. Multi-wavelength and multi-epoch surveys of Asymptotic Giant Branch (AGB) stars in galaxies have provided critical observational constraints in heretofore unexplored parameter space. I will review the current inventory of AGB observations in nearby galaxies, from metal-poor dwarfs to the metal-rich, star-forming spiral, M31. In particular, I will discuss efforts to identify and characterize the massive hot bottom burning and super-AGB stars in the Magellanic Clouds, and the lessons we can apply to more distant galaxies where data is less abundant.

Key words. Stars: abundances – Stars: AGB and post-AGB – Galaxies: stellar content

1. Introduction

All stars with mass ≈1–8 $M_{\odot}$ go through a brief asymptotic giant branch (AGB) phase at the end of their evolution. During this phase, AGB stars are characterized by their incredibly high luminosities, dust production, pulsation, and unique nucleosynthesis (e.g., of s-process elements). Dust production and nucleosynthesis make AGB stars important contributors to galactic evolution (e.g. Karakas & Lattanzio 2014; Zhukovksa et al. 2008), and the high luminosities have a strong effect on the integrated light of galaxies, particularly in the near-infrared (Melbourne et al. 2012). AGB properties also make them a useful diagnostic for a galaxy's distance, metallicity, and star-formation history.

During the final part of the AGB phase, the star undergoes thermal pulses (TP) which lead to long pulsation periods, dredge up, and dust production. On the upper end of the mass range ($\gtrsim$4 $M_{\odot}$), AGB stars undergo hot-bottom-burning (HBB; Boothroyd et al. 1993), wherein proton-capture nucleosynthesis at the base of the convective envelope and continued dredge up alter the surface composition. HBB AGB stars may in fact be responsible for the abundance anomalies in globular clusters (e.g., Gratton et al. 2004, 2012; Ventura & D'Antona 2009). At even higher masses (≈8–12 $M_{\odot}$) are the possible super-AGB stars, which still undergo dredge up and HBB, but may end their lives as electron-capture supernova (Seiss 2006).

The HBB AGB phase is extremely short-lived ($\lesssim$100 Myr), so examples of HBB AGB (and super-AGB) stars are scarce. In this brief review, I summarize some recent observations of massive AGB stars in the Magellanic Clouds (MCs), in more metal-poor dwarf galaxies, and the metal-rich spiral, M31.

2. HBB stars in the Magellanic Clouds

The MCs are excellent galaxies for studying the TP-AGB phase. Both galaxies are nearby and relatively massive, and they probe two distinct metal-poor regimes ($\frac{1}{2}$ and $\frac{1}{5}$ $Z_{\odot}$). Several surveys in the last 1–2 decades have targeted the MCs, including multi-wavelength imaging (Zaritsky et al. 2004; Skrutskie et al. 2006; Meixner et al. 2006), spectroscopy (van Loon et al. 2008; Kemper et al. 2010), and time series programs (Soszyński et al. 2009; Riebel et al. 2015). The result is tens of thousands of TP-AGB stars with well-constrained bolometric luminosities, pulsation periods and amplitudes, and mass-loss rates.

Among the MC sample are a handful of known HBB AGB stars, confirmed by the detection of lithium (Plez et al. 1993; Smith et al. 1995) and/or rubidium (García-Hernáandez et al. 2009). Of 112 stars surveyed by Smith et al., 35 showed evidence for lithium in their optical spectra, most of which are brighter than $M_{\rm bol} \simeq -5.5$ mag. Most of the lithium-rich AGB stars are brighter than their non-lithium-rich counterparts, approaching, and in two cases, even surpassing the classical AGB luminosity limit ($M_{\rm bol} = -7.1$ mag). Their periods (clustering around ∼600 days) are also longer than the non-lithium-rich stars, which are mostly confined to $P < 400$ days. Both characteristics suggest the lithium-rich giants are evolved. The majority of the lithium-rich giants are oxygen-rich, as expected for HBB AGB stars. However, 6 are carbon stars, perhaps pointing to the destruction of some oxygen by HBB or to additional dredge-up events after HBB has ceased (Karakas & Lattanzio 2014).

On the other hand, the mid-IR properties of the lithium-rich stars point to modest dust-production. Ruffle et al. (2015) classified several of the SMC lithium-rich giants as O-rich AGB stars in an 'early' phase of evolution based on their mid-IR spectra. The lithium-rich giants show no evidence for dust features in their spectra, but they do show evidence for some continuum dust emission. Together with their long periods and high luminosities, Ruffle et al. suggested these stars are in a phase just prior to the onset of dust production.

García-Hernáandez et al. (2009) identified an additional 5 stars (4 in the LMC and 1 in the SMC) that show evidence for rubidium in their optial spectra, also indicative of HBB. None of these stars are in common with the lithium-rich sample described above, though two do show lithium in addition to rubidium in their spectra. These 5 stars all have luminosities at or surpassing the classical AGB limit and have periods in excess of 1000 days. Unlike the lithium-rich giants from Smith et al. (1995) and Plez et al. (1993), the rubidium-rich giants show strong dust emission that place them among the dustiest O-rich stars in the MCs, suggesting that they are in the final superwind phase of their evolution. Using OGLE periods (Soszyński et al. 2009) and luminosities from Riebel et al. (2012), Boyer et al. (2015a) computed pulsation masses for all LMC AGB stars pulsating in the fundamental mode following the relation described by Vassiliadis & Wood (1993). Based on this relationship, there are 14 additional massive AGB candidates in the MCs that have not yet been probed for lithium or rubidium. All of these show a dust excess in their *Spitzer* colors. Figure 1 compares the bolometric magnitude, pulsation period, and dust-production rate for these candidates compared to the lithium-rich and rubidium-rich giants. Stars identified via their pulsation mass overlap more closely with the lithium-rich giants, but show stronger dust-production rates and longer periods, suggesting they are at a later phase in their evolution, potentially approaching the superwind phase.

Theoretical models put the lithium-rich giants at masses of around 4–4.5 $M_{\odot}$ (Ventura et al. 2000). The higher luminosities of the rubidium-rich giants suggest they may be more massive, around 6–7 $M_{\odot}$. The stars identified via their pulsation masses appear to fall intermediate to these two populations, perhaps around 4.5–5 $M_{\odot}$. It is difficult to know whether any of these stars might be super-AGB candidates (>8 $M_{\odot}$), thought the rubidium-rich giants are the best candidates.

The most massive AGB stars might be discovered among the dustiest objects identified in the SAGE surveys, though it can be difficult to distinguish the dustiest AGB stars from other infrared sources (young stellar objects, background galaxies). Boyer et al. (2011) identified a class of AGB candidates in the MCs that are very bright at 24 μm, dubbed far-infrared (FIR) stars. Srinivasan et al. (2016)

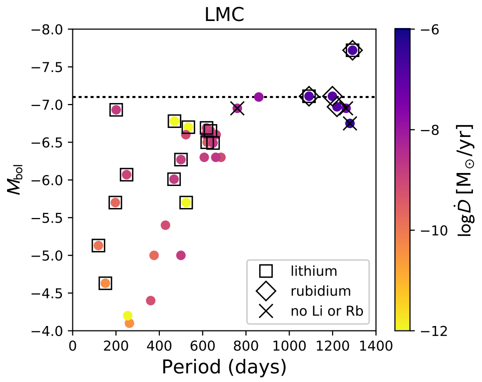

Fig. 1. HBB AGB stars in the LMC with additional HBB candidates (see text). The dotted line is the classical AGB limit. Data are from Smith et al. (1995) and García-Hernáandez et al. (2009). Dust-production rates are from Goldman et al. (2017), Groenewegen et al. (2009), or Riebel et al. (2012). Periods are from Soszyński et al. (2009).

fit these with dust radiative transfer models and found that 17 are well fit by O-rich AGB models, implying they are massive AGB stars rather than lower-mass carbon stars. These stars are so heavily dust enshrouded that optical spectra and optical lightcurves are difficult to measure, so very little is known about their nature. However, one star among the FIR sample is the rubidium-rich giant IRAS 04498-6842, which is the brightest source in Figure 1.

3. Identifying massive AGB stars beyond the Magellanic Clouds

Metallicity has a strong effect on the mass ranges for the onset of various mixing, dredge-up, and nucleosynthesis events in AGB stars (Karakas & Lattanzio 2014), though this metallicity dependence is not well constrained (Conroy et al. 2009). The MCs cover a relatively narrow metallicity range: the ISM gas-phase metallicities, which trace the metallicities of the massive star populations, span $-8.3 < 12 + \log(O/H) < -8.6$ (Toribio San Cipriano et al. 2017), compared to a solar value of -8.69 (Asplund 2009). Other star-forming galaxies in the the Local Group span a much broader metallicity range, though their distances and/or stellar crowding have made AGB classifications challenging.

Table 1. Additional LMC HBB candidates

Name[a]	P (days)	$\log \dot{D}$ $[M_\odot/yr]$	$M_{\rm bol}$ (mag)
J050538.98-685400.6	608	-8.8	-6.3
J050928.25-684751.8	636	-8.7	-6.6
J051334.23-693732.4	613	-8.9	-6.6
J052019.38-693528.9	859	-7.9	-7.1
J052733.04-700108.4	523	-9.1	-6.6
J052012.07-694029.6	685	-9.1	-6.3
J045926.59-675338.4	661	-8.7	-6.3
J045855.66-664541.5	662	-8.9	-6.6
J050652.85-684112.5[b]	500	-8.8	-5.0
J05054890-6838001[c]	428	-9.2	-5.4
J045142.40-682554.2	360	-9.2	-4.4
J050410.04-692135.1	376	-9.7	-5.0
J051547.43-700431.4	262	-10.5	-4.1
J051607.53-694426.0	254	-12.0	-4.2

Notes— Additional HBB AGB candidates in the LMC, identified via pulsation mass (Boyer et al. 2015a). Periods are from OGLE (Soszyński et al. 2009), dust-production rates ($\dot{D}$) and bolometric magnitudes are from Riebel et al. (2012).
[a] The prefix is SSTISAGEMC for most sources.
[b] The prefix for this source is SSTISAGEMA.
[c] The prefix for this source is 2MASS.

3.1. Spectroscopic surveys

There is one known HBB star beyond the MCs: G3011 in IC 1613, confirmed via detection of ZrO and the Li I 6707Å line (Menzies et al. 2015). This star has a period of 550 days and a bolometric magnitude around 1 mag fainter than that classical AGB limit. These characteristics place it above the period-luminosity relationship derived from other long-period AGB stars in IC 1613, lending further support that it is in fact a HBB star. Three other stars occupy the same region of the P-L diagram, and Menzies et al. conclude these are similar HBB stars. Isochrones from Marigo et al. (2008) suggest they have masses around 3.5 $M_\odot$, a lower mass than is typically assigned to HBB stars in the MCs owing to the lower metallicity. IC 1613 has a metallicity of $12 + \log(O/H) = -7.64$, measured from H II regions (Lee et al.

2003), and [Fe/H] = −1.6, measured from the red giant branch morphology (Bernard et al. 2010), so these HBB stars are presumably more metal-poor than those in the SMC. However, Menzies et al. note that the strength of the iron 6710.5Å line in G3011 indicates a star that has a metallicity similar to the SMC and emphasize the need for a more detailed abundance analysis of stars in IC 1613. At the high metallicity end, the SPLASH survey (Gilbert et al. 2012) is a large optical spectroscopic survey of the super-solar metallicity galaxy M31. SPLASH included 1867 AGB stars, including 103 carbon stars. The program has identified long-period variables among their survey by searching for Hα emission which is a result of shocks in the lower photosphere due to pulsation (Prichard et al. 2017). A handful of these are bright O-rich stars that may be on the upper end of the TP-AGB mass range. In addition, Guhathakurta et al. (in prep) has identified several M type stars in SPLASH that show weak CN, indicating the stars have undergone some dredge up. Several of these overlap with isochrones representing 5–12 $M_{\odot}$ stars, and are thus interesting HBB and super-AGB star candidates. Further analysis is underway.

3.2. Pulsation

Spectroscopic surveys and infrared surveys of AGB stars in galaxies beyond the MCs are rare, and there are no other examples of confirmed massive TP-AGB stars in other galaxies. Identification thus relies on other markers, namely the bolometric flux, dust, pulsation, and spectral type. A number of variability surveys in Local Group dwarf galaxies combined with spectral types measured from CN/TiO photometry provide a sample of massive and super-AGB candidates in a wide variety of environments. A notable example is the survey of NGC 185 and NGC 147 from Nowotny et al. (2003) and Lorenz et al. (2011). The former classified the AGB star using CN/TiO narrow-band photometry, and the latter constructed the period-luminosity diagram with hundreds of AGB stars. The fundamental pulsation mode is well populated for both galaxies, and there are 4 examples of stars with similar properties (periods and luminosities) to those identified in IC 1613, described above. Both galaxies have metallicities intermediate to the SMC and IC 1613. Another interesting case is V12 in the nearby dwarf irregular galaxy NGC 6822, which has metallicity similar to the SMC. Whitelock et al. (2013) find this star is brighter than the classical AGB limit ($M_{\rm bol}$ = −7.7 mag), and has a period of 854 days. These properties make it similar to the rubidium-rich AGB stars in the MCs discussed above, and suggest it could be massive super-AGB candidate.

3.3. Dust

Work in the MCs described above shows that infrared excess, which is indicative of circumstellar dust, can be a tracer of massive AGB stars at the end of their evolution, especially when combined with pulsation properties and bolometric flux. However, limitations in sensitivity and angular resolution make dust mass estimates difficult beyond the MCs. The survey of DUST in Nearby Galaxies with *Spitzer* (DUSTiNGS; Boyer et al. 2015c) identified several candidate dust-producing TP-AGB stars over a wide range of metallicities in dwarf galaxies throughout the Local Group, but was unable to identify spectral types and, consequently, estimate stellar masses. Using follow-up near-IR data from the *Hubble Space Telescope* (HST), they are able to separate these dusty candidates into O-rich and C-rich giants (Boyer et al., in preparation). They find ~25 dusty M type AGB stars among 6 dwarf galaxies, including in galaxies up to 10× more metal-poor than the SMC. Figure 2 shows the resulting infrared color-magnitude diagram for IC 10. The latest COLIBRI isochrones (Marigo et al. 2017) suggest some of these candidates have masses >4 $M_{\odot}$, and at least one star may be as massive as 6–7 $M_{\odot}$ (the brightest cyan square in Figure 2). The same work finds a handful of additional candidates in even more metal-poor galaxies: Sextans A, Sag DIG, and Sextans B.

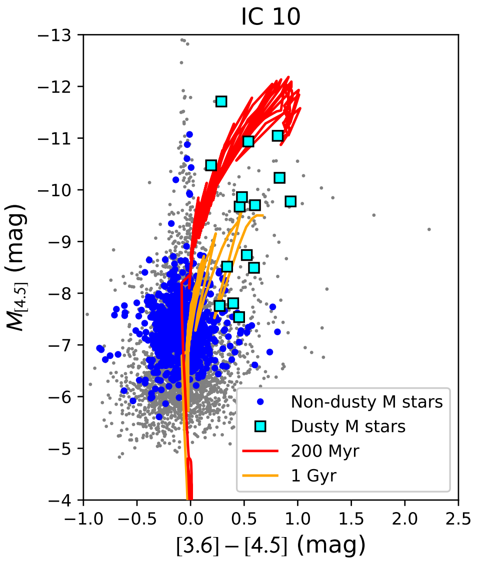

Fig. 2. Confirmed M type (O-rich) stars (blue dots) in IC 10, plotted with their DUSTiNGS colors from Boyer et al. (2015c). Spectral types were identified with medium-band HST photometry (Boyer et al., in preparation). M type stars with dust excess are marked with cyan squares. COLIBRI isochrones from Marigo et al. (2017) are also plotted.

3.4. Beyond the LG

While galaxies in the Local Group sample a wide range of metallicities, the metal-poor galaxies are low-mass dwarfs that are unlikely to harbor many examples of rarer stellar types, as evidenced by the mere handful of HBB AGB candidates identified to date. At larger distances, there are several metal-poor, more massive galaxies that may be excellent places to search for examples of massive AGB stars. Rosenfield et al. (2016) compare optical and near-IR color-magnitude diagrams from HST to the COLIBRI AGB models (Marigo et al. 2017) and find several galaxies that appear to harbor large populations of HBB stars, e.g. in UGCA 292, UGC 4305, and NGC 2403. All three galaxies are near the masses of the MCs and have metallicities of $-1.2 < [\mathrm{Fe/H}] < -0.5$ for stars <1 Gyr old. Optical data for these galaxies exists or is possible to obtain with existing facilities. Near-infrared and mid-infrared observations will become possible with upcoming observatories, including Euclid, WFIRST, and JWST, enabling a more complete characterization of stellar properties, including dust mass, bolometric flux, and abundances.

4. Conclusions

Examples of massive, HBB AGB stars outside the Milky Way are few in number. The presence of lithium and/or rubidium in a star's optical spectrum is a clear signature of HBB and has been seen in about 40 stars in the Magellanic Clouds. The lithium-rich stars have modest dust-production rates and pulsation periods. They also tend to be slightly fainter than the Classical AGB Limit. Models suggest they have masses near 4–4.5 $M_{\odot}$. The rubidium-rich giants have dust-production rates that are two or more orders of magnitude larger than their lithium-rich counterparts. Their pulsation periods are also up to 2× larger and they are at or brighter than the Classical AGB limit. These properties suggest the rubidium-rich giants are more massive than those that show just lithium, perhaps as high as 6–7 $M_{\odot}$. There is an additional population of 14 AGB stars in the LMC that can be identified via their pulsation masses, which is derived from a combination of the pulsation period and the luminosity. These stars have not been surveyed spectroscopically, but their properties (dust, pulsation, and luminosity) place them intermediate to the lithium-rich and rubidium-rich giants, suggesting they are also HBB AGB stars. Beyond the MCs, only one spectroscopically-confirmed HBB star exists. This star is in IC 1613, and may be the most metal-poor HBB star known. At high-metallicity, the SPLASH spectroscopic surveys has identified a number of interesting HBB candidates in M31 on the basis of Hα emission and the presence of weak CN in M stars. However, lithium and rubidium remain undetected as yet. Barring spectroscopy, HBB stars in other nearby galaxies must be identified via their pulsation, luminosity, and dust properties. Pulsation points to several candidates in nearby galaxies, including NGC 185, NGC 147, and NGC 6822, which all have SMC-like metallicities. Several candidates have also been identified by their dust excess, including several in IC 10 and a few each in Sextans A, Sextans B, and Sag DIG. The latter 3 galaxies are among the most metal-poor star-forming dwarf galaxies within 1.5 Mpc. HBB stars in these galaxies may thus be analogs of the early HBB stars responsible for polluting globular clusters. (Karakas & Lattanzio 2014)

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