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Recent observations of AGB stars in nearby galaxies and future perspectives

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Abstract. Thermally-pulsing Asymptotic Giant Branch (TP-AGB) stars play a variety of important roles in the Universe, from light-element enrichment of globular clusters to potential domination of a galaxy's dust production and total infrared luminosity. Advances in both ground- and space-based observatories during the previous decade have for the first time facilitated detailed studies of both individual TP-AGB stars and complete AGB populations outside of the Milky Way and the Magellanic Clouds. I will review recent multi-wavelength and multi-epoch observations of AGB stars in nearby galaxies out to approximately 4 Mpc, ranging from low-mass dwarf galaxies to the massive grand spiral M31. These recent observations have dramatically improved our understanding of the TP-AGB phase, but key gaps remain especially at low and high metallicities. I will discuss some potential future observations with planned telescopes that will fill in many of these gaps.

Key words. Stars: abundances – Stars: atmospheres – Stars: Population II

1. Introduction

To constrain models of thermally-pulsing Asymptotic Giant Branch (TP-AGB) stars at low metallicity, theorists often turn to observations of the Magellanic Clouds (MCs). The Large and Small Magellanic Clouds (LMC/SMC) are star-forming and relatively massive ($M_{\rm stars} = 1.5 \times 10^9$ and $4.6 \times 10^8\ M_\odot$, respectively; McConnachie 2012), so they harbor large populations of intermediate-mass evolved stars (>10^4 TP-AGB stars, each). Since they are nearby (<65 kpc) and at favorable viewing angles, a complete census of their TP-AGB populations exists, with multi-epoch photometry at optical to mid-infrared (IR) wavelengths (Cioni et al. 2006; Blum et al. 2006; Bolatto et al. 2007; Boyer et al. 2011), making these data ideal for calibrating stellar evolution models at low metallicity ([Fe/H] $\approx -0.2, -0.7$ dex). A primary constraint for dredge-up efficiency is the carbon star luminosity function (e.g., Groenewegen & de Jong 1993; Marigo 2001; Karakas et al. 2002). Other tests including replicating the total luminosity function with evolutionary population synthesis (e.g., Bruzual et al. 2013), comparing predictions to MC clusters (Maraston 2005; Maraston & Strömbäck 2011; Girardi et al. 2013), and replicating the photometric colors, which can constrain hot-bottom burning and dust production (Zhukovska & Henning 2013; Schneider et al. 2014; Ventura et al. 2015; Dell'Agli et al. 2015).

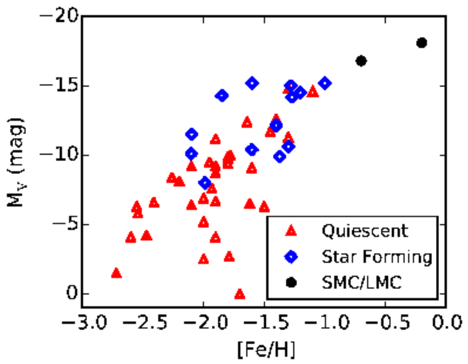

Fig. 1. The distribution of Local Group (LG; $d \lesssim$ 1.5 Mpc) dwarf galaxies in mass, as measured by visible light (M_V), and metallicity. LG dwarf galaxies are low-mass, and many are quiescent, so the AGB populations are small. They nonetheless sample very low metallicities and can be used to test the metallicity dependence of TP-AGB models. Data from McConnachie (2012).

While Magellanic Cloud observations are reasonably well-reproduced by the models, there are almost no model constraints at lower or higher metallicity. This leads to large uncertainties on the metallicity dependencies of the mass-loss and dredge-up processes, which has direct consequences for extragalactic astronomy. To interpret observations of unresolved galaxies, astronomers rely on stellar evolution models to derive parameters such as the galaxy's stellar mass and star-formation history. Since TP-AGB stars are immensely luminous, the predicted integrated flux from galaxies is strongly affected by the treatment of the TP-AGB phase. The dearth of calibration observations over a wide metallicity baseline results in large and systematic uncertainties in these derived galaxy parameters (e.g., Conroy et al. 2009).

To find TP-AGB constraints at low and high metallicity, we must move to observations of galaxies beyond the Magellanic Clouds. The difficulty lies in the large distances to suitable galaxies. For instance, the next nearest star-forming, reasonably massive galaxy is NGC 6822 ($M_* = 10^8\ M_\odot$) at 459 kpc, 7× more distant than the SMC. Despite these difficulties, recent progress has been made towards characterizing TP-AGB populations in galaxies out to ∼4 Mpc, covering a broad range in metallicity. I highlight here some of these recent efforts, though I stress that this is not a comprehensive review.

Model calibrations rely on several observables, including (1) AGB counts, (2) bolometric luminosities, (3) circumstellar dust, (4) stellar pulsation, and (5) C and M star spectral classification. For the LMC and SMC, all five of these observables exists, and in Sections 2–4, I review the state of affairs in Local Group (<1.5 Mpc) dwarf galaxies, M33, M31, galaxies out to 4 Mpc, and unresolved galaxies, in each case referring back to this list of observables. Finally, in Section 5, I describe future prospects for TP-AGB observations with planned new facilities.

2. Local Group dwarf galaxies

The Local Group (LG; $d \lesssim$ 1.5 Mpc) includes at least 15 star-forming dwarf galaxies. They span a wide range of stellar masses (0.14–$100 \times 10^6\ M_\odot$) and metallicities ($-2.1 <$ [Fe/H] < -0.8 dex) and have a variety of star-formation histories (McConnachie 2012; Weisz et al. 2014). Many studies have been dedicated to identifying carbon stars and long-period variables (LPVs) in the largest and most nearby LG dwarfs. These studies typically rely on optical ground-based facilities, though near-IR ground-based observations have recently become more common. For some galaxies, the full checklist of observables from Section 1 exists. For others, rapid progress is being made. While these galaxies are the most nearby metal-poor galaxies, they are also low mass, so their AGB populations are small (Fig. 1). Nonetheless, studies of their AGB stars build statistics of the short-lived TP-AGB phase at very low metallicities.

In this section, I focus on several very recent studies of IC 1613 to demonstrate the advances made towards characterizing TP-AGB stars in LG dwarfs. IC 1613 is a dwarf irregular galaxy, with ≈0.25× the stellar mass SMC. Its distance is 755 kpc and its metallicity is [Fe/H] ≈ −1.6, an order of magnitude lower than the bulk population of the SMC (for a summary of IC 1613's parameters, see McConnachie 2012). Skillman et al. (2014) measured the star-formation history and found a constant star-formation rate over the galaxy lifetime.

2.1. Carbon stars

Several works have used the CN/TiO narrow-band filter technique to identify carbon stars in LG dwarf galaxies (for a review, see Groenewegen 2006). Albert et al. (2000) is the corresponding work in IC 1613. They found a possible large radial metallicity variation as traced by the C/M ratio, with metallicity decreasing out to the half-light radius, then increasing sharply. While the CN/TiO technique is an accurate way of identifying carbon stars, it excludes carbon stars that are obscured at optical wavelengths by circumstellar dust, which can be a sizable fraction of the total carbon star population. Two recent studies in IC 1613 instead used standard JHK near-IR filters to identify carbon stars (Sibbons et al. 2015; Chun et al. 2015), which has been shown to be reliable at these metallicities (Cioni et al. 2006; Boyer et al. 2015a) and is less susceptible to the effect of circumstellar dust. Sibbons et al. (2015) and Chun et al. (2015) found $C/M = 0.52 \pm 0.04$ and 0.46 ± 0.05, respectively, corresponding to $[Fe/H] = -1.23$ to -1.26, according to the relationship derived by Cioni (2009, we caution that C/M also depends on the star formation history and is not fully accounted for here). In both studies, there is no strong evidence to support a radial C/M gradient. This suggests that, indeed, a large population of dusty C stars is missing from the Albert et al. (2000) narrow-band survey.

2.2. Long Period Variables

Menzies et al. (2015) monitored IC 1613 in the near-IR for 3 years with the InfraRed Survey Facility (IRSF) and derived light curves of LPVs within the central 4′. They find periods and amplitudes for five O-rich and nine C-rich Mira variables. Four of the O-rich variables are young, with one showing lithium absorption in its spectrum – a clear indication that it is undergoing hot bottom burning. Using the period-luminosity (P-L) relationship, they derive a distance of 750 kpc, in agreement with other estimates. They also deduce that the P-L slope is consistent with those in the LMC and in NGC 6822 (Whitelock et al. 2013), suggesting little variation with metallicity. However, they note that with such a small LPV population, stochastics can bias the results. Studies like these that characterize the P-L relationship for Mira variables will be valuable in the era of LSST (Section 5).

LPVs and Mira variables have been detected and monitored in only a few other star-forming LG dwarf galaxies. For example, Lorenz et al. (2011) constructed *i*-band light curves for >500 LPVs in NGC 147 and NGC 185 and Whitelock et al. (2013) constructed K_S light curves for ≈60 LPVs in NGC 6822.

2.3. Circumstellar dust

Surveys at mid-IR wavelengths beyond the MCs have been sparse owing to limited sensitivity and angular resolution. Jackson et al. (2007a,b) presented *Spitzer Space Telescope* observations of IC 1613 and WLM and showed that at these distances, it is impossible to distinguish dusty TP-AGB stars from unresolved external galaxies and active galactic nuclei because they overlap in mid-IR color-magnitude space. However, they were able to determine the size of of the TP-AGB population statistically by subtracting the background contamination. Boyer et al. (2009) followed up with a similar survey in 6 additional LG star-forming dwarf galaxies.

The survey of DUST in Nearby Galaxies with *Spitzer* (DUSTiNGS; Boyer et al. 2015c,b) overcame the background confusion issue by observing galaxies in 2 epochs over a 6-month baseline to identify dusty TP-AGB candidates by their variability. DUSTiNGS found 34 extremely dusty carbon star candidates in IC 1613 (Fig. 2) and 526 candidates total among 19 other galaxies. The colors of the DUSTiNGS variables are similar to the ex-

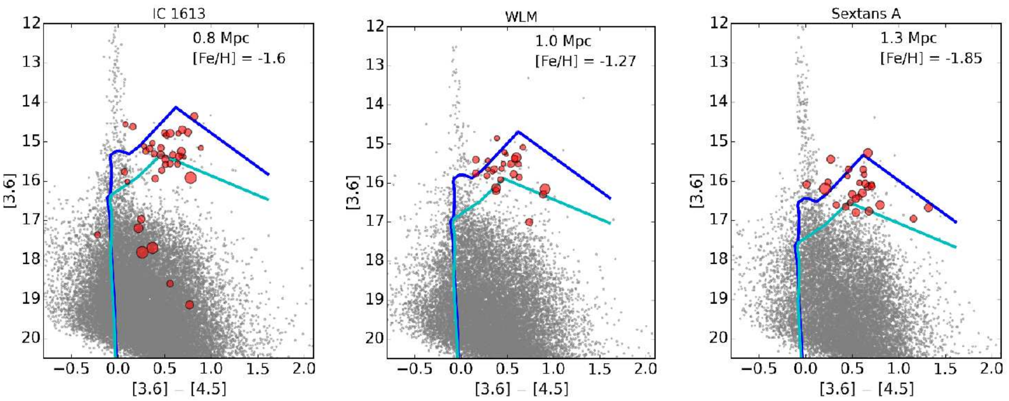

Fig. 2. Example color-magnitude diagrams from the DUSTiNGS survey, including IC 1613 (Boyer et al. 2015c,b). Dark and light blue lines mark the Padova isochrones for log(age) = 9 and 8.6, respectively (Marigo et al. 2008). Red circles mark the variable TP-AGB candidates, with larger symbols indicating a larger amplitude (2 epochs, 6-month baseline). Confusion with unresolved background galaxies at these wavelengths and distances is significant.

treme AGB stars in the MCs (Blum et al. 2006; Boyer et al. 2011), suggesting that dust formation in TP-AGB stars is similarly efficient over at least 1.5 dex in metallicity, forming in galaxies as metal-poor as [Fe/H] ≈ -2.1 dex.

3. Massive Local Group galaxies

3.1. M33

M33 is a spiral galaxy, with stellar mass about twice that of the LMC and roughly solar metallicity. AGB work in M33 has so far focused on circumstellar dust and pulsation. McQuinn et al. (2007) compiled 6 epochs of *Spitzer* data at 3.6–8 μm and found approximately 2000 LPVs. To identify the dustiest TP-AGB stars, Montiel et al. (2015) used 4 epochs of *Spitzer* 24 μm data. They find 24 candidates with high mass-loss rates ($>10^{-5}\ M_\odot\ \mathrm{yr}^{-1}$). Most of these have very large pulsation amplitudes, even at 24 μm, and are likely oxygen-rich. They include 5 sources that may be super AGB stars.

In the near-IR, Javadi, et al. (2011a,b, 2013) monitored the inner 1 kpc^2 of M33 over 4 years. These papers identify variable AGB stars, estimate the mass-loss rates, and use the LPVs to derive a star-formation history at intermediate ages. Javadi, et al. (2014) has begun similar analysis on the disk.

3.2. M31

M31 is the nearest massive ($M_* \sim 10^{11}\ M_\odot$; Sick et al. 2015) spiral galaxy and it is also the one of the only nearby metal-rich galaxies. AGB studies in M31 are tricky both because of its distance (783 kpc; McConnachie 2012) and stellar crowding. The checklist of observables listed in Section 1 is thus mostly incomplete, especially regarding pulsation and C/M.

Brewer et al. (1995) studied the C/M ratio using CN/TiO narrow-band filters in five fields across the southwest disk. They found a dearth of C stars in the innermost fields (<80 carbon stars per 2.5 kpc^2), consistent with a metallicity higher than solar.

The Panchromatic Hubble Andromeda Treasury (PHAT; Dalcanton et al. 2012b) program spent 3 years covering a large portion of M31's northeast disk at UV to near-IR wavelengths. This survey has the potential to boost the statistics of metal-rich TP-AGB stars, and is thus the best option currently available for calibrating models at high (solar and supersolar) metallicities. Figure 3 shows the location TP-AGB stars (those brighter than the tip of the red giant branch), along with the recent star-formation rate derived using the PHAT data (Lewis et al. 2015). The TP-AGB stars are dis-

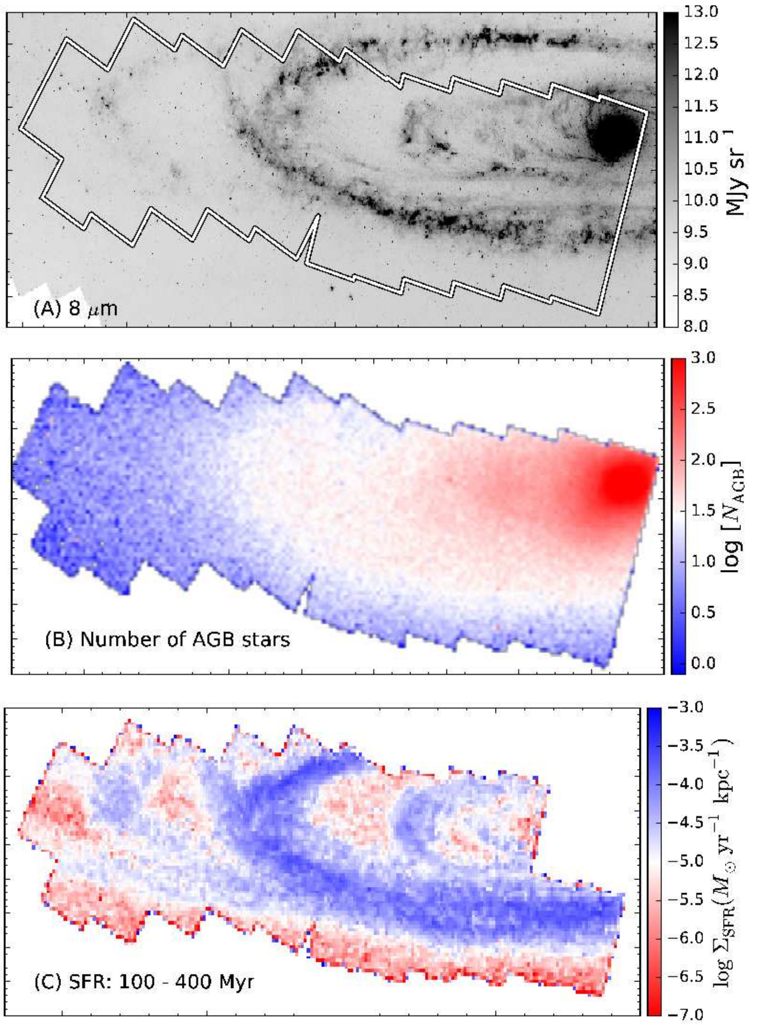

Fig. 3. *(A)* 8-μm image of M31 (Barmby et al. 2006) showing dust lanes on the northeast side of the disk. The white line outlines the PHAT coverage. *(B)* TP-AGB star density from PHAT, derived by counting stars above the near-IR RGB tip. *(C)* Recent star-formation rate (SFR) measured from the PHAT data, adapted from Lewis et al. (2015). While the SFR traces the galaxy's dust rings, the TP-AGB distribution is smooth from the bulge to the outer disk.

tributed smoothly, with no trace of the structure seen in the star-forming rings.

C and M stars are indistinguishable in the broad-band filters used for the PHAT survey. However, Hamren et al. (2015) spectroscopically identified 1867 M stars and 103 C stars within the portion of the PHAT footprint that covers the outer disk. That work computed the C/M ratio as a function of several parameters derived with the PHAT photometry, including the metallicity (derived by fitting the morphology of the RGB), the mean SFR, and the age of the population. They found that the C/M–metallicity relationship follows that for the more metal-poor LMC derived by Cioni (2009).

Because of stellar crowding, the Hamren et al. (2015) spectral survey is limited in its ability to probe the inner disk, where metallicity is highest. Ground-based adaptive optics have been used to look for C stars in the inner disk (Davidge et al. 2005), but the AO field of view is prohibitively small. However, Boyer et al. (2013) showed that it is possible to separate C and M stars using the *Hubble* medium-band near-IR filters, akin to the narrow-band CN/TiO method. The *Hubble* filters sample around a CN+C_2 absorption band in C stars and a wide H_2O absorption feature in M stars. This technique has the advantage of being insensitive to circumstellar extinction, except in the most extreme cases where dust veils near-IR molecular features (e.g., Blum et al. 2014).

4. Beyond the Local Group

4.1. Resolved galaxies, 1.5–4 Mpc

Beyond the LG, there are many star-forming galaxies with resolvable stellar populations and $-0.4 < [\mathrm{Fe/H}] < -2.3$. At these distances (1.5–4 Mpc), space telescopes and/or large ($\gtrsim$8m class) telescopes are required to resolve the stars. For this reason, studies with sufficient wavelength coverage and photometric depth are rare and the observables checklist (Sect. 1) beyond the LG is mostly incomplete. Most surveys are limited to measuring only AGB luminosities and there are few studies on C/M, dust, or pulsation, though some do exist (e.g., LPVs in NGC 5128; Rejkuba et al. 2003).

The ACS Nearby Galaxies Survey Treasury (ANGST; Dalcanton et al. 2009) and its follow up program (Dalcanton et al. 2012b) observed 69 galaxies at optical wavelengths and 23 at near-IR wavelengths with *Hubble*. Girardi et al. (2010) and Rosenfield et al. (2014) used population synthesis to model the luminosity functions. They find that Reimers' mass-loss prescription predicts too many TP-AGB stars and that the modeled stars are too luminous. The luminosity functions are best reproduced by using a modified version of the Schröder & Cuntz (2005) mass-loss scaling relation, which increases the mass loss and thus decreases the TP-AGB lifetime by a factor of two or more.

Using the same dataset, Melbourne et al. (2012) estimated the total flux contribution from TP-AGB and red supergiant stars to the integrated near-IR flux of the ANGST galaxies. They found that, in the current epoch, the TP-AGB stars contribute ≈20% of the global near-IR flux. Using stellar population synthesis, they examined how the TP-AGB contribution evolves over time and found that for an extended starburst or a constant star-formation rate, the TP-AGB near-IR contribution peaks near redshift (z) 3–5 at ≈60%, and can be as high as 70% for a multi-starburst galaxy. This has strong implications for the interpretation of the spectral energy distributions (SEDs) of high-z unresolved galaxies.

4.2. Unresolved galaxies

Several studies, including those described above, show that TP-AGB stars can have a dramatic effect on the SEDs of unresolved galaxies. Recently, Villaume et al. (2015) tested the TP-AGB influence on the integrated IR flux of early-type galaxies and find good agreement between their models and observations. They also note that circumstellar silicate dust around TP-AGB stars can have a strong effect on the 10-μm region of a galaxy's SED, and that the strength of the feature significantly increases for younger stellar populations. Therefore, in galaxies with little to no interstellar dust (and with no active galactic nucleus), this feature can potentially be used to ascertain the age of the stellar population.

5. Future surveys

A treasure trove of TP-AGB populations lies just beyond the reach of most currently available telescopes, but sensitivity and angular resolution gains of future planned observatories will dramatically improve the situation, especially in the IR. Four facilities are particularly well-suited to AGB surveys: the Large Synoptic Survey Telescope (LSST; Ivezić & the LSST Science Collaboration 2013),

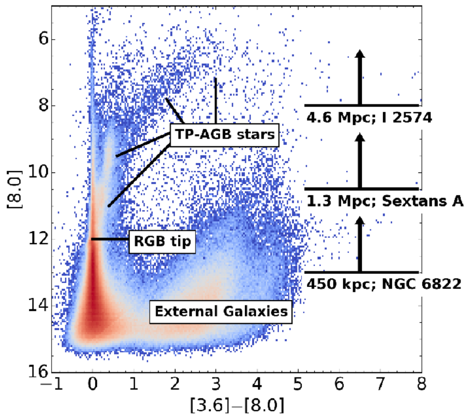

Fig. 4. Mid-IR color-magnitude diagram for the LMC (50 kpc) from the *Spitzer* SAGE survey (Meixner et al. 2006). The lines on the right indicate the approximate photometric depth achievable with JWST at different distances, with examples of galaxies at those distances. JWST's high angular resolution will mitigate contamination from external galaxies.

Euclid[1], the Wide Field InfraRed Survey Telescope (WFIRST[2]), and the James Webb Space Telescope (JWST; Gardner et al. 2006).

The LSST will operate from 0.3–1.1 μm, and survey the entire southern sky every few nights. It is scheduled to begin regular survey operations in 2022 and will construct light curves for TP-AGB stars as distant as 6 Mpc. This will not only enable observational constraints on the pulsation physics of AGB stars, but will also help to refine distances to their host galaxies using the AGB P-L relationship.

Euclid is a space-based observatory scheduled to launch in 2020 that will survey about a third of the sky. Its wavelength range is 0.5–2 μm, and it will achieve sensitivity ≈6 mag deeper than 2MASS in the *J*-band.

WFIRST will launch in 2023. It will have a 0.3 deg^2 field-of-view, and span λ = 0.8–2 μm. In the *J*-band, it will reach 10 mag fainter than 2MASS.

These three observatories are particularly complementary to one another. LSST is most sensitive around 0.4–0.7 μm, Euclid near 0.8 μm, and WFIRST from 1–2 μm, each expected to reach an AB magnitude of ≈27 mag at those wavelengths (5 σ)[3]. WFIRST can cover portions of the sky missed by both LSST and Euclid, and its wide field-of-view will enable fast surveys of large galaxies. For example, while the PHAT survey of M31 required 432 HST fields observed over 3 years, WFIRST can image the same region in a mere two pointings (Fig. 3).

The JWST will cover mid-IR wavelengths (1–30 μm) and will be ∼40× more sensitive than *Spitzer* at 3.5 μm and ∼6× more sensitive at 25 μm.[4] JWST photometric observations can thus reach the 8-μm RGB tip out to ∼500–800 kpc (e.g., in NGC 6822), and the dusty extreme AGB stars as far as 4–5 Mpc (Fig. 4). JWST will also be capable of mid-IR spectroscopy. Its sensitivity will enable detailed studies of circumstellar dust mineralogy out to the edge of the LG.

WFIRST and JWST will have angular resolution similar to *Hubble*, enabling resolved stellar population work at least out to 5 Mpc, and much farther in less crowded regions. Euclid and LSST angular resolutions are about 2 and 3 times larger than *Hubble*, respectively.

Including these more distant galaxies improves the statistics at all metallicities by dramatically increasing the number of star-forming galaxies, especially those at least as massive as the LMC, which harbors ∼25 000 TP-AGB stars (Boyer et al. 2011). These galaxies also include a rich variety of star-formation histories (e.g., Weisz et al. 2011), allowing for the disentanglement of these two interconnected galaxy properties.

[1] `http://sci.esa.int/euclid/42822-scird-for-euclid/#`

[2] `http://wfirst.gsfc.nasa.gov/science/sdt_public/WFIRST-AFTA_SDT_Report_150310_Final.pdf`

[3] Fig. 2 from `http://wfirst.gsfc.nasa.gov/science/sdt_public/WFIRST-AFTA_SDT_Primer_Final_130524.pdf`

[4] `https://jwst.stsci.edu/science-planning/performance--simulation-tools-1/sensitivity-overview.html`

6. Conclusions

Nearby galaxies offer the opportunity to test the metallicity dependence of TP-AGB models. While the large distances involved make TP-AGB observations beyond the Magellanic Clouds challenging, recent surveys have made great strides. Within the LG, several surveys have measured TP-AGB luminosities, pulsation periods, and C/M. Progress is also being made to identify and characterize TP-AGB dust production throughout the LG. At larger distances (1.5–4 Mpc), surveys are using the TP-AGB luminosity function to constrain early (pre-dust) mass loss and estimating the TP-AGB contribution to the host galaxy's IR flux.

The future of TP-AGB observations in nearby galaxies is bright. Four planned observatories (LSST, Euclid, WFIRST, and JWST) will operate at optical to mid-IR wavelengths and have sufficient sensitivities to reach TP-AGB stars out to at least 4 Mpc.

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