Probing Strong Binary Interactions and Accretion in Asymptotic Giant Branch Stars

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1 Executive Summary

A major astrophysical accomplishment of the 20th century was the success of models of the structure and evolution of stars of all masses from adolescence to retirement. The challenges continuing into the 21st century are stellar birth, stellar death, and the impact of binary interactions on stellar evolution. The late evolution and deaths of a vast fraction of stars in the Universe are likely to be fundamentally affected by strong binary interactions. Binary interactions in particular affect our understanding of stars in general, since such interactions affect important diagnostic observables of stars and stellar populations (e.g., mass-loss and evolutionary time-scales). Binary interactions are expected to dominate a substantial fraction of stellar phenomenology, starting with the production of a couple of dozen different stellar classes. For example, compact binaries such as cataclysmic variables, the progenitors of type Ia supernovae or low- and high-mass X-ray binaries, form because of a close binary interaction between a giant and its companion (Ivanova et al. 2013). Binary interactions also cause light and gravitational wave outbursts when two stars merge, which can happen at different stages of their lives (Bond et al. 2003, Tylenda et al. 2011, MacLeod et al. 2017, Blagorodnova et al. 2017). Thus understanding these interactions is of wide astrophysical importance.

A striking example of the effect of binary interactions on stellar evolution are planetary nebulae (PNe). These beautiful objects represent the bright end-stage of most stars in the Universe that evolve in a Hubble time (i.e., those with main-sequence masses of $1 - 8\,M_{\odot}$). The PNe progenitors experience extensive mass-loss (with rates up to $\sim 10^{-4}\,M_{\odot}\ \mathrm{yr}^{-1}$) as they evolve along the Asymptotic Giant Branch (AGB), which results in the formation of PNe, with a spectacular array of morphologies (e.g., Sahai et al. 2011a). Binarity, and the associated formation of accretion disks (that presumably drive collimated, fast jets) during the very late AGB or early post-AGB phase, is widely believed to produce this dramatic morphological transformation.

But the evidence for binarity and accretion during the AGB phase that determines the evolution during this phase and produces the observed PNe population, has been difficult to obtain because of observational limitations. Exciting progress has been made recently with observations at UV and X-ray wavelengths that have broken through the observational barrier – studies using GALEX reveal a candidate population of AGB stars, generally with strongly-variable far-ultraviolet (FUV) emission (fuvAGB stars), and follow-up studies with XMM-Newton, Chandra, and HST of a *few key objects* support an "*extrinsic*" model in which a companion actively accretes material from the primary red giant. VLA observations of the most prominent of these fuvAGB stars reveal time-variable non-thermal emission, which suggests that magnetic fields may significantly influence the accretion process. However, since the above studies are sensitivity-limited, strong signatures of accretion activity have only been detected for a few objects. Thus, "*intrinsic*" models, i.e., those in which high-energy emission comes from the AGB star itself (e.g., chromospheric and/or photospheric emission, and flares associated with localized or global surface magnetic fields), cannot as yet be ruled out.

In this paper we focus on how progress can be made in this newly developing field in the coming decade and beyond[1]. First, a comprehensive, multi-epoch search in the radio and UV of a statistical sample of AGB stars, covering different spectral, chemical and stellar-variability types will help generate an unbiased sample of candidate objects with and without binary companions and active accretion. Multi-epoch observations are crucial in order to account for the episodic nature of the accretion process. Such a survey will also help to constrain the fraction of AGB stars that undergo binary interaction (complementary to the information on red giant binaries in the LMC), thus informing binary population synthesis models (used, e.g., to derive expected SN Ia rates). Second, spectroscopic and time-monitoring studies in the UV and X-ray regimes (sampling time-scales from minutes to months) of select radio-bright and UV-bright subsamples from targets discovered in the comprehensive survey, will help test intrinsic and extrinsic models, and for the latter, probe the

[1]For a broader discussion of significant scientific advances needed in our understanding of AGB stars and PNe, see white paper for the 2010 decadal survey: Sahai et al. 2010

physics of the accretion process in detail (such as infall speeds, jet outflow speeds, accretion rates and luminosities). The data from the second study will provide critical input for numerical simulations that will help improve our theoretical understanding of different interaction/accretion modes.

2 Binarity and the AGB-to-PN Transition

PNe and their progenitors (AGB stars) have wide-ranging astrophysical importance, covering diverse topics (Fig. 1) such as mass-loss and its effect on stellar evolution, the chemical evolution of the ISM, the cosmological distance ladder, astrophysical jets, common-envelope evolution (CEE), and intermediate-luminosity transients (ILOTs). The mass-loss ejecta carry the products of nucleosynthesis, such as C and N, and the α-elements such as O, Ne, Ar, and S, and oxygen-rich and carbon-rich dust grains. Thus a better knowledge of PNe and their formation is necessary for understanding not only the final fate of stars like our Sun, but also the chemical evolution of the Milky Way and other galaxies (e.g., Stanghellini et al. 2012, Garcia-Hernandez & Gorny 2014). The [OIII] planetary nebula luminosity function (PNLF) has provided distances to > 60 galaxies ranging from Local Group systems like the Magellanic Clouds out to members of the Coma Cluster at ~ 100 Mpc, and uniquely cross-checks rungs of the extragalactic distance ladder based on standard candles of only a specific stellar population type, or on geometrical methods. The bright-end fit to the PNLF appears invariant to galaxy type and age – an inexplicable conundrum because bright PNe should not exist in elliptical galaxies (Ciardullo 2016). This problem may be utimately resolved by invoking binarity in PN formation, e.g., merging binaries, perhaps related to blue stragglers (Ciardullo et al. 2005), CEE (Frankowski & Soker 2009), or ionization from accreting WDs (Soker 2006).

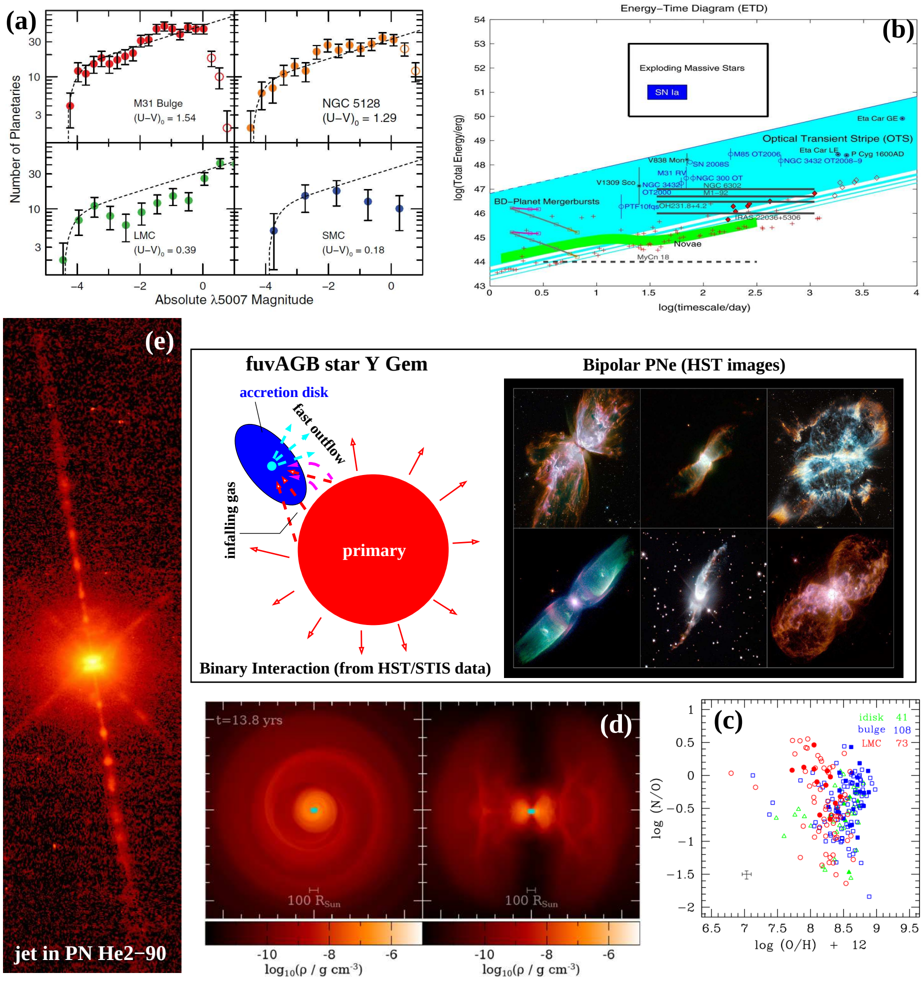

Figure 1: Binary interactions likely transform most $1 - 8M_\odot$ stars to aspherical Planetary Nebulae (*center*). Panels *a*–*e* represent some of the diverse astrophysical topics that require an understanding of these interactions (*a*) PNLFs (from four different galaxies of different colors) used to measure distances (Ciardullo 2016), (*b*) observed transient events on the energy-time plot (Soker & Kashi 2012): the Optical Transient Strip (OTS: blue) is a roughly constant luminosity region populated by accretion powered events such as ILOTs, major LBV eruptions, and predicted BD-planet mergerbursts – several well-known PNe and PPNe lie in the OTS , (*c*) Elemental abundance patterns for the MW disk and bulge, and the LMC (Chiappini et al. 2009), (*d*) Numerical simulation of a common envelope interaction between a red giant and a compact companion, showing density in the orbital plane and orthogonal to it, at 14 yr (Reichardt et al. 2019), (*e*) A highly collimated jet in the PN, He2-90 (Sahai & Nyman 2000).

But PNe formation is not well understood – a long-standing puzzle is that while modern imaging surveys indicate that the vast majority of PNe deviate strongly from spherical symmetry (e.g., Schwarz, Corradi & Melnick 1992, Manchado et al. 1996, Sahai & Trauger 1998 [ST98], Sahai et al. 2011a, Stanghellini et al. 2016), the progenitors of PNe, AGB stars, generally have overall spherically-symmetric circumstellar envelopes (CSEs) resulting from mass-loss. The spherical geometry of AGB mass-loss implies that possible causes of asymmetry present during the main-sequence phase (e.g., stellar rotation, which is very small and can be ignored at ages $> few \times 10^8$ yr) do not significantly affect mass-loss on the AGB and beyond. Binarity provides a source of angular momentum, as well as a preferred axis to a stellar system, and is now widely believed to dramatically affect the evolutionary transition from the AGB to the planetary nebula (PN) phase (e.g., Balick & Frank 2002). ST98 proposed that highly-collimated, fast jet-like outflows at the late-AGB or pre-PN (PPN) phase sculpt the AGB mass-loss envelopes from the inside-out, producing the observed aspherical morphologies of PPNe (Sahai et al. 2007) and PNe. The engines that drive these outflows must reside in accretion disks that can be produced as a result of binarity and resulting mass-transfer and accretion modes such as Bondi-Hoyle-Littleton (BHL), Roche lobe (RLOF) and wind Roche lobe overflow (WRLOF), and CEE (e.g., Blackman & Lucchini 2014, Sahai 2018a).

If binarity plays a significant role in PN formation, one may question whether the PN population is representative of all $1 - 8\,M_{\odot}$ stars, and one may need to significantly revise how PNe are used as diagnostics of stellar and chemical evolution (e.g., De Marco & Izzard 2017, Kwitter et al. 2014, Akashi & Soker 2013, Ciardullo et al. 2002). Hence, obtaining observational constraints on binarity and its effects on the general population of AGB stars is vital.

2.1 The Challenge of Finding Binarity in AGB Stars

Until recently, observational evidence of binarity in AGB stars has been sorely lacking simply because AGB stars are very luminous and variable, invalidating standard techniques for binary detection (e.g., radial-velocity and photometric variations due to a companion star, or direct imaging.) An innovative technique to search for FUV and NUV emission in AGB stars with GALEX has now provided a large candidate sub-class of AGB stars with close binary companions (Sahai et al. 2008 [Setal08], Sahai et al. 2011b [Setal11], Sahai et al. 2016, Sahai 2018a). In this sub-class, for objects with emission in the FUV (1344-1786Å) (fuvAGB stars), the observed FUV fluxes are typically a factor $> 10^6$ larger than expected for the primary's photospheric emission (Setal08), and show strong variability (Fig. 2). It should be noted that fuvAGB stars in general (based on their optical spectra) do not belong to the well-studied class of symbiotic stars (red giant stars with white-dwarf [WD] companions) and have never been classified as such. So if the compact companions in fuvAGB star systems are WDs, then these must be quite cool ($T_{eff} \lesssim 20,000$ K) (Sahai et al. 2015 [Setal15]).

2.2 X-ray, UV & Radio Emission

The FUV source in fuvAGB stars is most likely dominated by emission due to variable accretion activity associated with a close companion (Setal08, Setal11, Ortiz & Guerrero 2016, Ortiz et al. 2019). Small X-ray surveys using XMM-Newton and Chandra support this hypothesis, finding X-ray emission in about 50% of fuvAGB stars. The X-ray emission is characterised by relatively high luminosities L_X$\sim (0.002 - 0.11)\,L_{\odot}$, and very high plasma temperatures T_X$\sim (35 - 160) \times 10^6$ K (Fig. 3, adapted from Setal15). Amongst fuvAGB stars, objects with large FUV/NUV ratios, $R_{fuv/nuv} > 0.2$, have a much higher probability of being detected in X-ray emission (Sahai et al. 2016), and are almost certainly binaries with accretion activity powering the high-energy emission.

The UV and X-ray emission is variable on time-scales much shorter than the pulsation periods of these objects, with both periodic and stochastic components – signatures of active, ongoing accretion (Setal15). A recent STIS spectroscopic study of the prototype high FUV/NUV ratio star, Y Gem, shows the presence of UV flickering on time-scales of $\lesssim$20 s and high-velocity infall and outflows, and thus directly supports the binary/accretion hypothesis (Sahai et al. 2018); optical flickering (with significantly lower amplitudes) has been found by Snaid et al. (2018). This object (and objects like it) may represent the earliest phases of an AGB star transferring mass to a companion, resulting in a growing accretion disk around the latter, which will ultimately produce collimated jets that will sculpt the round circumstellar envelopes of AGB stars into bipolar/multipolar PNe.

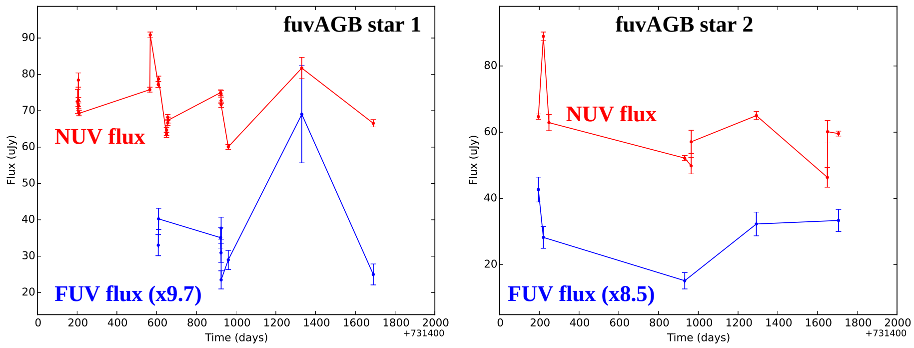

Figure 2: Two fuvAGB stars observed with GALEX showing strong variability in their FUV (blue) and NUV (red) emission, indicating variable accretion (the FUV fluxes have been scaled up by arbitrary factors.)

Alternative hypotheses have been proposed for the high-energy emission which do not require binarity. For objects with little or no FUV emission, i.e., with $R_{fuv/nuv}\lesssim0.1$, which dominate the population of UV-emitting AGB stars, the UV emission may have a different source. From an analysis of the NUV emission in 179 AGB stars, Montez et al. (2017) argue that the origin of the GALEX-detected UV emission is intrinsic to the AGB star (chromospheric & photospheric emission), and is unrelated to binarity. However, the short-term variability ($\lesssim few\,days$) of the UV spectra of some sources do not follow the pulsation cycle, arguing in favor of binarity (Ortiz et al. 2019). Indeed, a study of a volume-limited sample (<0.5 kpc) of 58 AGB stars, concludes that the detection of NUV emission with a very large observed-to-predicted ratio, $Q_{NUV} > 20$, is evidence for binarity in these objects (Ortiz & Guerrero 2016). For X-ray emission, Kastner & Soker (2004) suggest the possibility of flares on the primary AGB star associated with localized or global surface magnetic fields, but sensitive searches for X-rays in two AGB stars with known strong magnetic fields were unsuccessful. Hence, binarity and associated accretion activity provides the most likely explanation of the UV and X-ray emission from AGB stars.

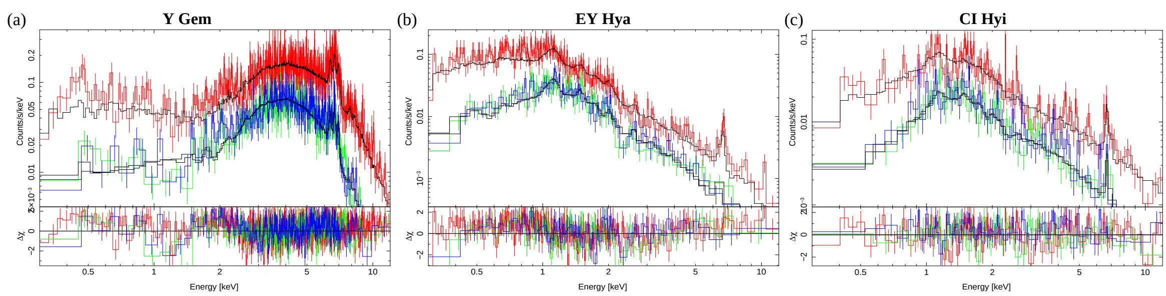

Figure 3: X-ray spectra of fuvAGB stars Y Gem, EY Hya and CI Hyi using XMM/EPIC detectors pn (*red*), MOS1 (*blue*), MOS2 (*green*), together with APEC model fits (*black*); bottom panels show residuals – which imply relatively high X-ray luminosities and plasma temperatures, likely resulting from accretion associated with a compact (main-sequence) companion.

Radio observations can also probe accretion activity in AGB stars, determine the mass of ionized gas in the disk and/or accretion streams, and whether or not the latter are constrained/influenced by magnetic fields, as demonstrated by our VLA study of Y Gem (Sahai & Claussen 2019, *in prep*). In this source, we found an unresolved radio source with fluxes that are far larger (factor ∼100) than that expected from photospheric emission. The radio emission varied in strength by more than a factor of 10 over a two-year period at low frequencies. In Dec 2012, the spectral-index, α, is ~ 2 in the (22–30.5) Ghz range, and ~ 1.65 in the (5.5–30.5) GHz range, arguing against the emission arising in a simple ionized outflow. Interpreting the (22–30.5) GHz SED as optically-thick emission from an ionized gas structure (size $\theta < 0.03''$ or 17.5 AU at 580 pc, with an average electron density, $n_e > 8 \times 10^6\,\mathrm{cm}^{-3}$, likely a disk), we find that there is a significant excess above such emission at

5.5 GHz, clearly requiring an additional source at the low-frequency end – a plausible mechanism for the latter is gyrosynchrotron radiation.

3 Key Advances

Although the observations described above have provided a valuable first glimpse into binary-associated accretion activity in AGB stars, these are sensitivity-limited to the brightest few ($\lesssim$10) objects of the full sample of UV-emitting AGB stars. Thus, alternative hypotheses that do not require binarity to explain the high-energy emission cannot be ruled out as yet.

Further progress in this newly developing field first requires generating an unbiased sample of candidate objects with and without binary companions and active accretion. This can be accomplished with a comprehensive, multi-epoch search in the radio (using the ngVLA: Murphy et al. 2018) and UV (using LUVOIR: Bolcar et al. 2018) of a statistical sample of AGB stars, selected to cover different spectral, chemical (oxygen-rich, carbon-rich and S-type stars) and stellar-variability (Mira, semi-regular and irregular variables) types. The ngVLA's large collecting area (Selina et al. 2018) can enable a search for emission over the $\sim$3-90 GHz frequency range with relatively short integration times per source (15 min) to achieve a 5σ sensitivity that is a factor $> few \times 100$ lower than Y Gem's flux at > 10 GHz (see Sahai 2018b for details). Such radio observations are currently prohibitive in terms of time for the VLA even for the mere detection of AGB stars at the few μJy/beam level (the VLA also lacks the sensitivity to probe the short-term variability of these objects – see below). A comphrehensive radio/UV survey will help in constraining the fraction of AGB stars that undergo binary interaction, thus informing population synthesis models and helping resolve existing problems such as the SN Ia formation rate in nearby galaxies being higher than predictions from current models (which may be due to an underestimation of the initial binary fraction.)

Important diagnostics of the high-energy emission can be obtained by probing the short and long-term variability – accretion-related radio emission is expected to have both thermal and non-thermal components and display significantly time-variability on short time-scales (minutes to weeks), whereas chromospheric emission is expected to be thermal, possibly with time-variability but only on long time-scales (many months to a year). The X-ray and UV variability on long time-scales (months) in fuvAGB stars is likely related to the variability of the primary, producing variations in the accretion mass-flux. Variability on a medium time-scale (of a few days) may arise due to variations in the inner regions (few$\times$100 AU) of a fast outflow (e.g., a jet powered by the accretion disk) as found for the Hα profile of Y Gem (Sahai et al. 2018b). The shortest variability timescale of $\sim$ 20 s is due to the flickering phenomenon that characterizes active accretion disks.

Spectroscopic and time-monitoring studies in the UV and X-ray regimes (sampling time-scales from minutes to months) of select radio-bright and UV-bright subsamples from the above sample, will probe the physics of the accretion process in detail (such as infall speeds, jet outflow speeds, accretion rates and luminosities) and help improve current models of mass transfer (e.g., via BHL, RLOF of WRLOF processes) and resulting accretion, which are still rather poor (e.g., Reichardt et al. 2019, Staff et al. 2016). NASA's LUVOIR and Lynx missions (X-ray: Gaskin et al. 2018) and the selected large X-ray observatory Athena (Nandra et al. 2013) by ESA (with possible NASA participation), are needed to provide the required sensitivity for such studies. Observations in multiple bands spanning the wide frequency coverage provided by the ngVLA of our select subsample will enable decomposition into thermal and non-thermal radio components.

Since the ngVLA also covers the low-J lines of several molecular species that are typically detected in the winds from AGB stars (e.g., CO, ^{13}CO, HCN, SiO, CS), a survey of these lines in our key subsamples, together with observations using the Atacama Large Millimeter Array (ALMA) of higher-excitation lines, can help to probe the gas mass-loss rates and kinematics of the inner regions of the outflow, and the presence/absence of torii and/or disks in stars with and without binary interaction.

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