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Variable X-Ray and UV emission from AGB stars: Accretion activity associated with binarity

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Abstract. Almost all of our current understanding of the late evolutionary stages of ($1 - 8$) $M_{\odot}$ stars is based on single-star models. However, binarity can drastically affect late stellar evolution, producing dramatic changes in the history and geometry of mass loss that occurs in stars as they evolve off the AGB to become planetary nebulae (PNe). A variety of binary models have been proposed, which can lead to the generation of accretion disks and magnetic fields, which in turn produce the highly collimated jets that have been proposed as the primary agents for the formation of bipolar and multipolar PNe. However, observational evidence of binarity in AGB stars is sorely lacking simply these stars are very luminous and variable, invalidating standard techniques for binary detection. Using an innovative technique of searching for UV emission from AGB stars with GALEX, we have identified a class of AGB stars with far-ultraviolet excesses (fuvAGB stars), that are likely candidates for active accretion associated with a binary companion. We have carried out a pilot survey for X-ray emission from fuvAGB stars. The X-ray fluxes are found to vary in a stochastic or quasi-periodic manner on roughly hour-long times-scales, and simultaneous UV observations show similar variations in the UV fluxes. We discuss several models for the X-ray emission and its variability and find that the most likely scenario for the origin of the X-ray (and FUV) emission involves accretion activity around a main-sequence companion star, with confinement by strong magnetic fields associated with the companion and/or an accretion disk around it.

1. Introduction

Intermediate mass stars lose half or more of their mass during the AGB evolutionary phase in via slowly expanding, spherical molecular outflows. In contrast, most planetary nebulae (PNe), the end products of the AGB phase, are not round. Morphologically unbiased surveys of young PNe with the Hubble Space Telescope (HST) reveal that half of these objects show bipolar or multipolar morphologies, and a third are elongated. The number of round objects is less than 4%. The search for the fundamental causes of this transition has been a subject of intense inquiry for a long time and a series of international conferences (*Asymmetrical Planetary Nebulae 1-VI*).

It has long been argued that binarity is responsible, directly or indirectly, for the dramatic and poorly-understood changes in the history and geometry of mass loss that occurs during late stellar evolution (e.g., [1, 2, 3, 4]), especially for AGB stars evolving into PNe. A variety of binary models have been proposed, which can lead to the generation of accretion disks and



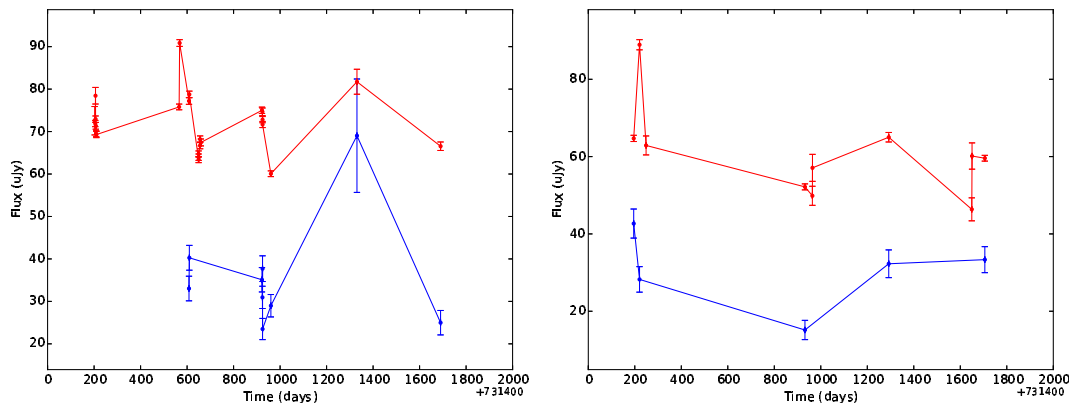


Figure 1. Two fuvAGB stars observed with GALEX that show strong variability in their FUV and NUV emission.

magnetic fields (e.g., [5]). The latter are likely the underlying physical cause for the highly collimated jets that have been proposed as the primary agents for the formation of bipolar and multipolar PNe [6, 7].

However, observational evidence of binarity in AGB stars has been lacking because AGB stars are very luminous and variable, invalidating standard techniques for binary detection such as radial-velocity and photometric variations due to a companion star. Sahai et al. [8] therefore used a new technique of searching for UV emission from AGB stars with GALEX that exploits the favorable secondary-to-primary photospheric flux contrast ratios reached in the UV for companions of spectral type hotter than about G0 ($T_{eff}=6000\text{K}$) and luminosity, $L \gtrsim 1L_{\odot}$. [8] detected emission from 9/21 objects in the GALEX FUV (1344 – 1786 Å) and NUV (1771 – 2831 Å) bands; since these objects (hereafter fuvAGB stars) also showed significant UV variability, [8] concluded that the UV source was unlikely to be solely a companion’s photosphere, and was dominated by emission from variable accretion activity.

2. UV and X-Ray Emission from fuvAGB Stars

2.1. UV Observations

We searched the MAST¹/GALEX archive for fuvAGB stars. We developed an efficient python-based pipeline that used a comprehensive input catalog of ~ 4000 AGB stars (includes O-rich, C-rich and S-stars) collected from various published sources and searches for counterparts in the GALEX archive within a user-specified search radius. The pipeline created a photometric database that provides (i) relevant parameters such as FUV and NUV fluxes, errors, and exposure times, for detected objects for each “visit”, and (ii) the background “sky-noise” for stars that were observed but not detected. A summary of variability properties for each of the detected objects was also created.

We detected about 100 fuvAGB stars in the FUV band at a $\gtrsim 5\sigma$ level. Even for the hottest sources in our catalog (sp.type M4), the detected FUV fluxes ($\gtrsim 20\mu\text{Jy}$) correspond to a significant excess above photospheric emission. We find that many fuvAGB stars show extreme UV variability as well (e.g., Fig.1, and Y Gem: [9]). We find that such sources show time periods where the FUV and NUV variations are correlated, suggesting changes in the emission measure (EM) and/or the obscuring column (N_H), and where they are anti-correlated, suggesting changes in the temperature of the emitting material.

¹ Mikulski Archive for Space Telescopes

In order to understand the nature of the UV emission (e.g., continuum emission from a hot accretion disk or line emission from an accretion inflow), we carried out low-resolution (grism) spectroscopy with GALEX for a sample of 10 fuvAGB stars. Unfortunately, the UV detector broke before soon after our Cycle 5 program was scheduled, so we were able to obtain both the FUV and NUV spectrum in only one object, EY Hya. The spectrum of this object shows both emission lines and an apparent weak continuum; the latter is stronger in the FUV than in the NUV. The spectrum can be fit with a composite model consisting of blackbody emission from an accretion-disk hot spot ($T \sim 27000$ K, $L \sim 3.4 \times 10^{-3} L_{\odot}$) and a nebular component likely associated with an accretion flow ($T \sim 1.9 \times 10^4$ K). The size of the latter is comparable to that of a low-mass main-sequence star ($\sim 10^{11}$ cm). However, the spectral resolution is low ($10 \text{ \AA}$ in the FUV, $25 \text{ \AA}$ in the NUV), so one cannot rule out the possibility that the continuum has a significant contribution from a blend of weak emission lines; higher resolution spectra with HST could help resolve this issue.

Other objects, such as V Hya (with only NUV spectra) show a weak continuum with strong Mg h & k ($\lambda 2798$) lines and a strong CII ($\lambda 2332$) line. Such emission may arise in a nebular component that may be associated with an accretion flow (as for EY Hya) or a chromosphere around the primary AGB star.

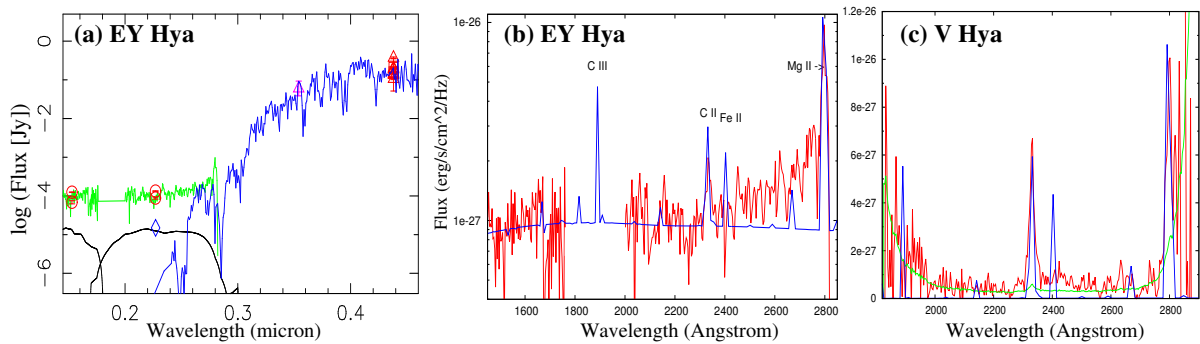


Figure 2. (a) GALEX grism spectrum (green), and broad-band fluxes – GALEX NUV & FUV and ground-based optical (red symbols) of fuvAGB star EY Hya – and a M7III model fit to the optical SED (blue). The expected UV fluxes (blue diamonds) from the AGB star, obtained by convolving the model with the GALEX bandpasses (black) lie far below the observed values (FUV lies below x-axis). (b) GALEX FUV+NUV grism spectrum of EY Hya (red), and a composite model (blue) consisting of an accretion-disk hot spot and an accretion flow. (c) GALEX NUV grism spectrum of V Hya (red, & noise green), and a nebular component (blue) with $T \sim 2 \times 10^4$ K.

2.2. X-Ray Observations

We carried out a pilot search for X-ray emission from a small subset of fuvAGB stars. A sensitive search for such emission in two AGB stars by Kastner & Soker [10] only yielded upper limits. An archival study using XMM and ROSAT revealed 2 AGB stars with X-ray emission, however the low signal-to-noise (S/N) ratio prevented an accurate estimate of the emission properties [11].

We observed a total of 5 (13) targets with XMM in observing cycles AO-12 (AO-13), and 6 targets with CXO cycle 15 (3 of which were common with the XMM observations). Typical integration times were 10 – 15 ksec. Our analysis of the XMM AO-12 and CXO cycle 15 data yielded high-quality X-ray spectra for 3 objects (Fig. 3a,b), and sensitive upper limits for the remaining. The Optical Monitor (OM) was used to obtain simultaneous UV observations,

providing us UV light-curves for these 3 sources. We also obtained X-ray and UV light curves. We summarize the main results from this study [12] below.

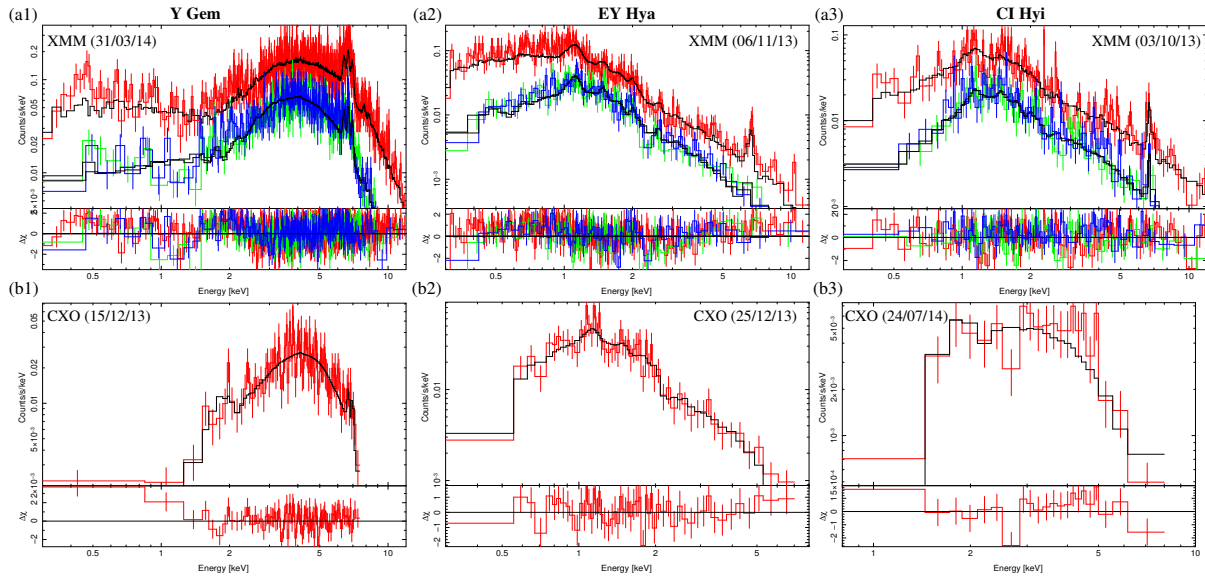


Figure 3. X-ray spectra (colored curves) and model fits (black curves) of the fuvAGB stars Y Gem, EY Hya and CI Hyi. Panels rows show XMM/EPIC (pn: red, MOS1: green, MOS2: blue), and CXO (ACIS-S). Spectra shown include the background; the ISIS model fitting procedure takes the latter into account (see text for details).

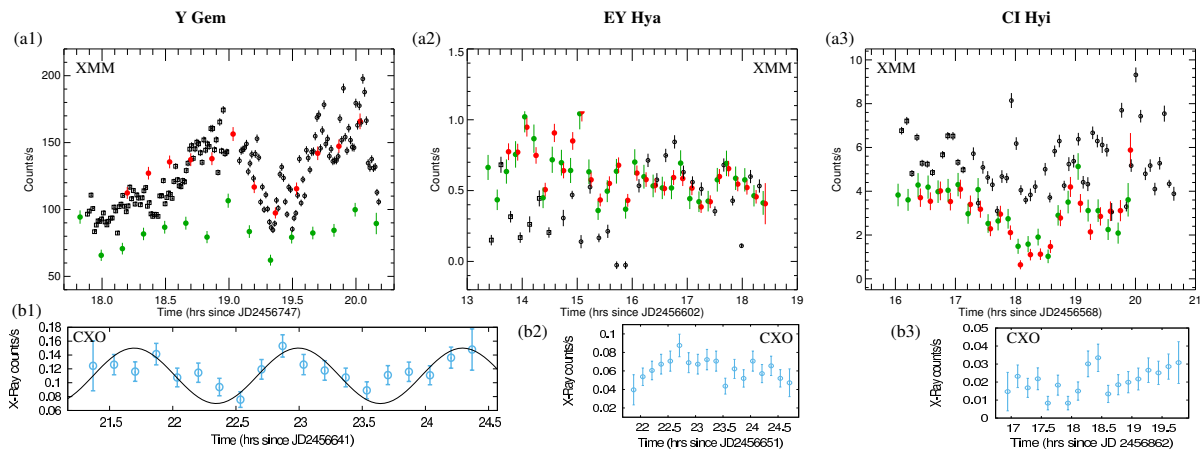


Figure 4. X-ray and UV light-curves of the fuvAGB stars Y Gem, EY Hya and CI Hyi. Panels show data from XMM (EPIC=pn+MOS1+MOS2: red, MOS=MOS1+MOS2: green, UVM2: black squares, UVW2: black circles), and CXO (ACIS-S). The EPIC, MOS and UVM2 data have been respectively re-scaled as follows: 80, 130, 2.5 (Y Gem), 2, 5, 0.8 (EY Hya), 20, 30, 2.5 (CI Hyi). A sinusoidal fit (by eye) with period, $P=1.35$ hr is shown for Y Gem. All data are background-subtracted; error bars are $\pm 1\sigma$. In order to facilitate the comparison between the XMM and CXO light curves, the widths of the two panels for each source have been adjusted so that similar time-intervals have similar lengths (on the horizontal axes).

Table 1. Models of X-Ray Emission for fuvAGB Stars

Name	Sp. Typ.	n(H) 10^{22} cm^{-2}	log(Tx) K	Lx $10^{-3} L_{\odot}$	d kpc
CIHyi	M6	0.33 – 2.8	7.87	7.8 – 7.9	0.58
EYHya	M7	0.05 – 0.095	7.57 – 7.74	2.0 – 2.4	0.35
Y Gem	M8	8.1 – 15.6	8.1 – 8.2	226 – 115	0.58
T Dra	C6,2	0.21	7.8	8.7	0.42

Short-term flux X-ray variations are seen during the course of each observation, spanning a factor $\sim (2 - 3.5)$ on hour-long timescales (Fig. 4a,b). For CIHyi and EYHya, the variations appear to be stochastic or quasi-periodic. In Y Gem, the light-curves give stronger evidence of a discrete period of about 1.2–1.4 hr, best seen in the CXO/ACIS-S light curve (Fig. 4b1) that spans a longer period than the EPIC one. For the longer time-scales between the XMM and CXO observational epochs for each source, we find changes in the observed fluxes up to a factor 1.8 (in Y Gem and EYHya); however a direct comparison cannot be made between the spectra as these were taken with different instruments.

The UV fluxes also show short-term variations like the X-ray fluxes (Fig. 4a). Since the UVM2 and UVW2 data were taken sequentially (the OM can take data only through one filter at a time), we scaled the UVW2 count rate to match that of UVM2 at the time of transition between the two. We find that the UV and X-ray variations appear reasonably well correlated in the case of Y Gem and CIHyi. For EYHya, the correlation appears to be weaker.

The ISIS package [13] and the Astrophysics Plasma Emission Code (APEC, [14]) were used to fit the spectra with thermal models. For XMM, we simultaneously fit the data from the EPIC pn, MOS 1 and MOS 2 detectors.

All 3 sources also show a weak line feature at $\sim 6.3 - 6.8 \text{ keV}$ in their XMM spectra, that is likely due to emission from (a) the FeXXV,XXVI lines complexes at $\sim 6.7 \text{ keV}$ from the very hot plasma that we have found in these objects, and/or (b) the 6.4 keV FeI $K\alpha$ line. The origin of FeI $K\alpha$ line may be the same as in Young Stellar Objects (YSOs), where it has been inferred to be fluorescent emission from cold, neutral ($< 1 \text{ MK}$) material in a disk irradiated with energetic ($E \gtrsim 7.1 \text{ keV}$) X-rays [15].

The most robust parameters from our models are the X-ray temperature (Tx) and the emission measure (EM), followed by the hydrogen absorption column density (NH) – these provide us with the intrinsic X-ray luminosity (Lx) of each of our objects. We find that $Lx \sim (0.002 - 0.2) L_{\odot}$ and $Tx \sim (35 - 160) \text{ MK}$ for our detected objects (Table 1). For the minor FeI line component, our derived values of the line flux are sensitive to the emission measure (EM) of the hot plasma that contributes to the nearby FeXXV,XXVI complex, and are less robust than indicated by the formal uncertainties derived from the least-squares fitting.

3. Models for X-ray Emission from fuvAGB Stars

Based on the time-scale ($\sim 1.3 \text{ hr}$) of the quasi-periodic variations – similar to the period of material orbiting close to the inner radius of an accretion disk around a sub-solar mass companion, i.e., with $M_c \lesssim 0.35 M_{\odot}$ (implying a semi-major axis $a \lesssim 3 \times 10^{10} \text{ cm}$). [12] argue that the most likely model for the X-ray emission from fuvAGB stars is that it arises at or near the magnetospheric radius in a truncated disk, or the boundary layer between the disk and star.

Direct accretion onto a stellar or brown dwarf companion is ruled out as such accretion produces a maximum temperature of $T_s = 3.44 \times 10^6 K (M_c/R_c)$, too low to explain the observed high Tx values; WD (or more compact) companions are needed. However, none of our X-ray emitting AGB stars is known to be a symbiotic star with a WD companion. For EYHya, an optical spectrum taken with the Palomar 5m telescope shows no emission lines in the 3889–5436 Å region. Thus, if accretion onto WD companions is responsible

Table 2. UV Variability & X-Ray Emission for fuvAGB Stars

Name	FUV σ/median	FUV (max-min)/median	X-Ray detection?
Y Gem	1.9	5.13	Y
EY Hya	0.39	0.93	Y
CI Hyi	0.67	1.33	Y
R Uma	0.15	0.36	Y
T Dra	0.069	0.20	Y
V Hya	0.27	0.54	N
del01 Aps	0.052	0.024	N
NU Pav	0.13	0.26	N

for the X-ray emission, then these must be rather cool (i.e. with effective temperatures $T_{eff} < 20,000 \text{ K}$.) However, if an adequate mass of accreting gas can be pre-accelerated to high speeds (v_s) by magnetic reconnection, then the shock temperature is, $T_s = (3/16 k_B) \mu m_H v_s^2 \sim 70 \text{ MK} (v_s/1500 \text{ km s}^{-1})^2$, assuming a mean molecular weight, $\mu = 1.33$, and is not constrained by the mass-to-radius ratio of the companion.

The relatively high values of Tx that we have found in our fuvAGB sources argues against the X-ray emission coming from stellar coronae, which typically show values of Tx in the range $\sim (2 - 10) \text{ MK}$ and rarely as high as the lowest Tx value in our sample, $\sim 40 \text{ MK}$ (e.g., [16]). In addition, coronal emission from a main-sequence companion is strongly ruled out because the large observed values of Lx imply unrealistically large companion masses, using the Lx/Lc relationship determined by Pizzolato et al. [17].

If coronal gas is present on the AGB star, it has to be magnetically confined and heated, requiring a relatively strong field, $B_{av} = (0.3 - 15) \text{ G}/f_{agb}$, where f_{agb} is the fraction of the AGB's star's surface covered by the B field ($f_{agb} \sim 1$ for a large-scale field and $f_{agb} \ll 1$ for localized fields). Since we also need to produce substantial amounts of plasma implied by our derived values of the X-ray emission measure, around the fuvAGB stars, and since these objects are cool late-type stars, with three of them known to drive cool, dusty molecular winds (EY Hya, T Dra, R Uma), the surface filling factor of the coronal gas (and thus f_{agb}) is likely to be relatively small. Although recent studies show that such values of B_{av} are plausible [18], a sensitive XMM search for X-ray emission in two AGB stars with known or suspected strong B-fields yielded null detections [10], making coronal emission from the AGB star a less likely candidate for producing the observed X-ray emission.

4. Emerging Trends from X-ray and UV-observations

(i) X-ray emission is found only in fuvAGB stars. For example, all 8 AGB stars, including 2 ROSAT detections reported by Ramstedt et al. [11], that have been confidently detected in X-rays are fuvAGB stars. SS Vir, also a fuvAGB star, shows a tentative XMM detection ($4.8 \pm 1.3 \text{ counts ks}^{-1}$) that may be real or may be due to optical loading [11].

(ii) The GALEX FUV/NUV flux ratio $R_{fuv/nuv}$ tentatively appears to be a better indicator of X-ray emission than the FUV (or NUV) flux. We find $R_{fuv/nuv} > 0.17$ in the fuvAGB stars with X-ray emission. Amongst the stars not detected in X-rays, we find $R_{fuv/nuv} < 0.12$ (Fig.5), except for V Hya and V Eri which were not detected.

(iii) A tabulation of FUV variability indicators – standard deviation/median and (maximum-minimum)/median – versus the presence/absence of X-ray emission shows that the former is a good indicator of X-ray emission (Table2), and supports our model in which the X-ray and FUV emission is related to a variable accretion process.

(iii) The (non-coeval) UV flux does not appear to be a good predictor of the X-ray flux – e.g., both T Dra and R Uma, detected in X-rays, are fairly weak FUV sources with fluxes of 8.4 and

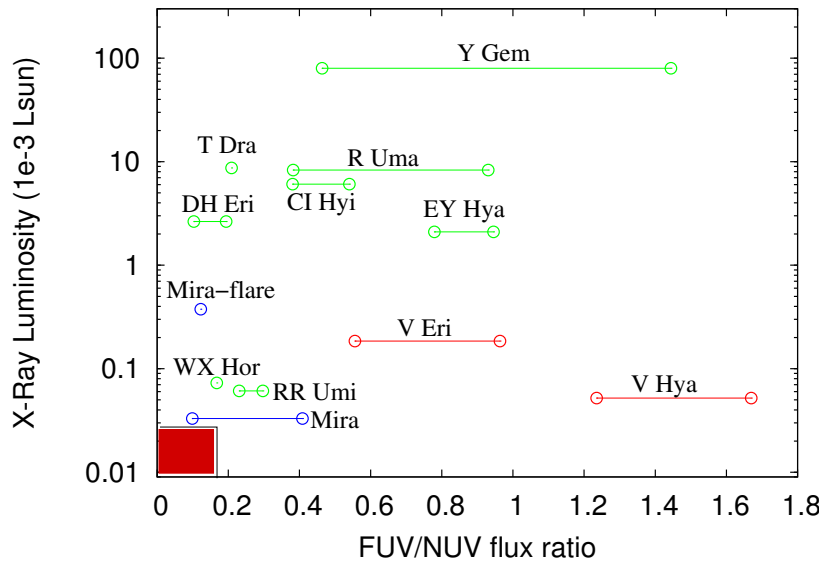


Figure 5. X-ray luminosity, L_x , versus the FUV-to-NUV flux ratio, $R_{fuv/nuv}$. Symbols show fuvAGB stars with $R_{fuv/nuv} > 0.17$ that have been observed in X-rays (red symbols show 3σ upper limits for L_x). The red box covers a region with 7 additional fuvAGB stars that are not detected in X-rays – for these, $R_{fuv/nuv} < 0.17$. For stars with multiple X-ray (UV) observations, the mean (full range of $R_{fuv/nuv}$) is shown. The plot also shows data for the symbiotic star, Mira – its quiescent L_x versus the $R_{fuv/nuv}$ range, as well as L_x during a flare versus $R_{fuv/nuv}$ from a near-contemporaneous epoch.

11 μJy , whereas our 2 non-detections from XMM AO-12, del01 Aps and NU Pav, have much stronger FUV emission (326 and 385 μJy). This may be partly because the UV and X-ray observations are not contemporaneous, and both are variable – we see UV variability on the time-scale of ~ 1 -year in many stars with multi-epoch GALEX data. The XMM data from our survey show that X-ray and UV fluxes vary in a stochastic or quasi-periodic manner on roughly hour-long times-scales. Comparison with the CXO spectra obtained for CI Hyi, EY Hya, & Y Gem at a 2nd epoch show variations on several month-long time-scales as well.

5. Implications for Binarity, Accretion & Magnetic Fields

Our current working hypothesis, first proposed to explain our serendipitous discovery of extremely strong and variable UV emission in the late-M star, Y Gem [9], and that is consistent with these trends, is (a) fuvAGB stars have binary companions and associated variable (possible episodic) accretion which produces variable UV and X-ray emission, and (b) AGB stars without UV-excesses are either single stars, or if they have companions, the associated accretion activity when they were observed was too weak to produce detectable UV emission.

The observed short-term X-ray and UV light-curves, especially that of EY Hya, show that, in addition to the quasi-periodic variations presumably associated with orbital motion at the inner radius of an accretion disk, there is a second mechanism that produces stochastic variability. A plausible mechanism for the latter is flare activity, that in the case of YSOs, is believed to arise from reconnection events associated with long magnetic loops connecting the star and a circumstellar disk that get sheared due to orbital motion in the disk. However, the variations we find in fuvAGB stars do not look like the flares seen in YSOs that have short rise times and long decay time (e.g. [19]). One possibility is that fuvAGB stars have multiple weak, partly

overlapping flares that wash out the individual rise and fall signatures. However, with only a couple of stars where such light curves are available currently, it is not possible to draw general conclusions.

6. Broad Impact on Binary Stellar Astrophysics

FuvAGB stars have a strong synergy and evolutionary connection with two other well-studied classes of stars. The first of these are the central stars of planetary nebulae (CSPNe). The “ChanPlaNS” survey of X-ray emission from a sample of nearby PNe has resulted in the surprising and exciting discovery of relatively hard ($\gtrsim 0.5$ keV) X-ray emission from CSPNe in 20/59 objects, that is not photospheric but results either from self-shocking stellar winds from the CSPNe or coronal emission from magnetically active companions [20]. The origin of the activity in such companions is unknown, but could result from them being “rejuvenated” during the AGB phase, e.g., by wind accretion from the primary [21]. If so, then fuvAGB stars are the progenitors of the PNe with magnetically-active companions.

The second class consist of symbiotic stars (red giants with WD companions) that are strong UV and X-ray emitters (e.g., [22]), and a classification scheme for the spectra that is diagnostic of the emission processes has been developed. FuvAGB stars with “cold” WD companions may represent the evolutionary progeny of symbiotic stars.

No quantitative theoretical models exist as yet to explain the X-ray and FUV emission that we have discovered in fuvAGB stars. Our current data is too sparse to robustly test our favored hypothesis or others, and it is eminently possible that more than one mechanism is responsible for the X-ray and UV emission in these objects.

An extended survey of a statistically significant sample of fuvAGB stars, with co-eval X-ray and UV observations, can robustly confirm the tentative trends described earlier, and provide the crucial “missing” data on the earliest stages of binary interaction in AGB stars with companions and the necessary observational impetus for theoretical work in this field.

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