ABSTRACT

The search for binarity in AGB stars is of critical importance for our understanding of how planetary nebulae acquire the dazzling variety of aspherical shapes which characterizes this class. However, detecting binary companions in such stars has been severely hampered due to their extreme luminosities and pulsations. We have carried out a small imaging survey of AGB stars in ultraviolet light (using GALEX), where these cool objects are very faint, in order to search for hotter companions. We report the discovery of significant far-ultraviolet excesses toward nine of these stars. The far-ultraviolet excess most likely results either directly from the presence of a hot binary companion or indirectly from a hot accretion disk around the companion.

Subject headings: binaries: general — circumstellar matter — planetary nebulae: general — stars: AGB and post-AGB — stars: mass loss

1. INTRODUCTION

There are many observational indications which lead us to believe that binarity, believed to be very common among pre-main-sequence stars (e.g., Dqunney & Mayor 1991), strongly influences the history and geometry of mass loss during the late stages of stellar evolution. The evolutionary transition from the AGB to the post-AGB phase is accompanied by significant changes in the morphology of these objects—the roughly round circumstellar mass-loss envelopes (CSEs) of AGB stars evolve into post-AGB nebulae with a dazzling variety of shapes and intriguing symmetries (e.g., Schwarz et al. 1992; Sahai & Trauger 1998; Sahai et al. 2007). Critical reviews (Soker 1998) of the properties of bipolar PNe (e.g., Corradi & Schwarz 1995) lead to the conclusion that binary models can explain all these properties, whereas single-star models (e.g., Garcia-Segura 1997) have many difficulties.

However, in spite of dedicated efforts by many researchers to search for binarity in evolved stars, direct observational evidence for binarity has been hard to come by. AGB stars are very luminous (∼few × 10^{-10} L_{\odot}) and surrounded by dusty envelopes, making it very difficult to directly detect nearby stellar companions, which are generally likely to be significantly less luminous main-sequence stars or white dwarfs. Indirect techniques such as radial velocity measurements (e.g., van Winckel et al. 1999; Sorensen & Pollacco 2003; De Marco et al. 2004) or photometric variability measurements (Bond 2000) have been used for the central stars of PNs and post-AGB objects, with some success. But these techniques cannot be easily applied to AGB stars, because the latter show strong variability intrinsic to their pulsating atmospheres, which potentially masks the corresponding variability due to a companion. Extensive observations of the central stars of planetary nebulae have resulted in detections a sum total of ≤20 binaries (Bond 2000; Ciardullo et al. 1999), implying a 10%–15% fraction of detectable close binaries among randomly selected PNe. Bond (2000) concludes that it is likely that the known short-period binaries in PNe are only the tip of an iceberg of a substantial population of longer period binaries.

Deep ultraviolet observations hold the promise of allowing us to discover substantial numbers of binary companions in AGB stars, since most mass-losing AGB stars are relatively cool objects (spectral types ∼M6 or later). The companions are likely to be main-sequence stars because of the slow dependence of evolutionary rates on stellar mass (e.g., Soker & Rappaport 2001). Thus, for a secondary-to-primary mass ratio, q = M_{\ast}/M_{\odot}, around unity, any stellar companion has a good probability of being hotter than the primary. However, it is difficult to estimate with confidence the number of such systems in which the secondary is on the main-sequence and hotter than the primary, as a fraction of the total number of primordial binaries, since the mass-ratio probability distribution, f(q), where q = M_{\ast}/M_{\odot}, is not well known. A promising approach is to carry out population synthesis studies (which are still in their infancy) such as those of Soker & Rappaport (2000), who adopt for their modeling f(q) ∝ q^{-3/2}, note that this function is not strongly peaked toward q = 1. Since observed and model spectra of cool AGB stars show that their fluxes die rapidly at wavelengths shortward of about 2800 Å, significantly favorable secondary-to-primary flux contrast ratios (>10) for companion detection may be reached in the GALEX FUV (1344–1786 Å) and NUV (1771–2831 Å) bands, for companions of spectral type hotter than about G0 (T_{\text{eff}} = 6000 K). In this paper we report on a subsample of objects from our cycle 1 pilot program which were detected in both the FUV and NUV bands and on the implications of these detections for binarity. A comprehensive study covering the full results of our survey will be presented in a forthcoming paper.

2. OBSERVATIONS AND RESULTS

We selected a sample of 25 AGB late-M (i.e., M5 or later) stars (which passed the GALEX mission “bright-star” and “background” tests) largely based on their inclusion in the Hipparcos astrometric catalog, with a “multiplicity” flag in the header field H59 of the main catalog, indicating that a single-star astrometric solution was not adequate. Thus, for 20/25 objects, the selection criteria of our “pilot” program were intentionally biased toward

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This was the so-called problem stars for which a double star solution with the classical parameters of separation and position angle could not be found: and were flagged as G, O, V, or X in field H59 of the main catalog.
optimizing the a priori probability of finding companions, in order to
test the validity of our technique. Three objects did not have a
“multiplicity” flag; and two are not in the *Hipparcos* catalog, but
were selected from published lists of AGB stars with molecular
envelopes detected in CO emission. Although most of our objects
had positive entries for the annual parallax, the errors were usually
large, and only for four objects were the parallax measurements
significant (i.e., greater than 3σ). The requirement that our ob-
jects be M5 (or later) or cool N-type carbon stars was included in
order to minimize the ratio of their UV fluxes to that of hotter
companions (if present).

From our original list of 25 objects, 21 objects have been
observed—20 as part of our GI program (G1-23; PI: R. Sahai)
and 1 as part of other programs—in both the NUV (1771–2831 Å)
and FUV (1344–1786 Å) bands. Nine of these were detected
in both the FUV and NUV bands, with high S/N and an intensity cut along the major axis (P – 0 m).

We now consider whether our FUV and/or NUV detections
could result from the presence of a small-filter red leak, which
could produce spurious detection of a UV signal for the extremely
red stars observed in this study. Since the *GALEX* detectors are
photon-counting MAMA detectors, there is supposedly no red leak,
since only UV photons can trigger the photoelectrons (Rich 2005);
the photocathode on the FUV detector is nonresponsive above
1800 Å, and the NUV response is suppressed below measurable
levels by multilayer coatings on the optics. According to the *GALEX*
help desk, there is no measurable red leak in either FUV band.

Even though no red leak response has been measured for the
*GALEX* filters, we have ensured that even if such a response is
present at a low level, our modeling is not affected because the
upper limits that we can set on the red leak from our data are quite
low. We have done this by comparing the ratios of the FUV and
NUV fluxes to the V-band fluxes in our survey objects and as-
suming that the lowest of these ratios is due to a red leak. From this
analysis, we find values of 2.5 × 10⁻⁷ and 4 × 10⁻⁶ for the maxi-
mum possible red leak flux in the *GALEX* FUV and NUV bands,
as a fraction of the V-band flux—and these ratios are too low to
affect our models or the detection statistics we report in this paper.

### 3. ULTRAVIOLET EXCESSES

We now investigate the origin of the ultraviolet fluxes in the
objects we have detected in the FUV band. We have fitted the
spectral energy distributions (SEDs) from 0.1 to 2 μm (Fig. 1) of
the four oxygen-rich stars with reliable FUV fluxes (i.e., RW Boo,
AA Cam, V Eri, and R UMa), using stellar atmosphere models of
AGB stars (Fluks et al. 1994), corresponding to the spectral type
of each star as given in the General Catalogue of Variable Stars
(GCVS). A visual extinction, A_V, to account for the extinction
by circumstellar dust due to the dusty mass-loss envelope of the
primary, is also determined from our fits. Archival photometry at
wavelengths redward of the *GALEX* NUV band was taken from the
Hubble Guide Star Catalog (GSC 2.2), the US Naval Observ-
atory USNO-B1.0 Catalog, and the Two Micron All-Sky Survey.

#### TABLE 1

<table>
<thead>
<tr>
<th>Target</th>
<th>Band</th>
<th>Epoch</th>
<th>Exposure Time</th>
<th>Flux</th>
</tr>
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<tr>
<td>RW Boo</td>
<td>FUV</td>
<td>4220.75</td>
<td>1726</td>
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<td>3861.15</td>
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<td>1691</td>
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<td>1532</td>
<td>0.22</td>
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</tr>
<tr>
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<td>3425.29</td>
<td>1693</td>
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<tr>
<td>NUV</td>
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<td>0.032</td>
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<td>3678.20</td>
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</tr>
<tr>
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<td>1704</td>
<td>0.14</td>
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</tr>
<tr>
<td>TW Hor</td>
<td>FUV</td>
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<td>4381</td>
<td>0.026</td>
</tr>
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<td>NUV</td>
<td>3351.2</td>
<td>1345</td>
<td>0.032</td>
<td></td>
</tr>
<tr>
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</tr>
<tr>
<td>NUV</td>
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<td>1003</td>
<td>0.15</td>
<td></td>
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<tr>
<td>TW Hor</td>
<td>FUV</td>
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<td>0.023</td>
</tr>
<tr>
<td>NUV</td>
<td>3706.6</td>
<td>586</td>
<td>0.033</td>
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<tr>
<td>V Y UMa</td>
<td>FUV</td>
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<td>0.034</td>
</tr>
<tr>
<td>NUV</td>
<td>4018.8</td>
<td>747</td>
<td>0.027</td>
<td></td>
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<tr>
<td>V Hya</td>
<td>FUV</td>
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<tr>
<td>NUV</td>
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<td>0.14</td>
<td></td>
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<tr>
<td>AF Peg</td>
<td>FUV</td>
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<td>4381</td>
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<td>1345</td>
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<td>V Y UMa</td>
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<td>0.78</td>
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<tr>
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<td>339</td>
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</tr>
<tr>
<td>V Hya</td>
<td>FUV</td>
<td>3280.70</td>
<td>1551</td>
<td>0.011</td>
</tr>
<tr>
<td>NUV</td>
<td>3280.70</td>
<td>1551</td>
<td>0.090</td>
<td></td>
</tr>
<tr>
<td>R UMa</td>
<td>FUV</td>
<td>3742.14</td>
<td>1703</td>
<td>0.041</td>
</tr>
<tr>
<td>NUV</td>
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<td>1703</td>
<td>0.12</td>
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<td>V Y UMa</td>
<td>FUV</td>
<td>3742.50</td>
<td>1704</td>
<td>0.0061</td>
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<td>3742.50</td>
<td>1704</td>
<td>0.23</td>
<td></td>
</tr>
</tbody>
</table>

* a JD –2,450,000.
* b Observed at multiple epochs; data from epochs separated by ≤0.1 day are
taken together in the individual-epoch rows.
* c Observed at two epochs in the NUV band only; quoted fluxes are for AF Peg
using a two-Gaussian fit to the image of the latter and the partially blended nearby
star, for epoch 1.
* d Vizier Online Data Catalog, 2250, 0 (N. Samus et al., 2004).
We find that the observed FUV (NUV) fluxes are a factor $>10^6$ (>5) larger than expected for the photospheric emission of the primary, accounting for the finite filter bandwidth, the filter response, and the steeply sloping spectrum in the UV. Hence, even though the photometric variability of the primary stars makes our fit somewhat uncertain, it certainly cannot account for the FUV excesses because they are very large. Moreover, there is no systematic relationship between the light-cycle phases of the various photometric data points used to fit the primary model which could conspire to produce such an excess in each of our three sources. The detailed SED fitting described could not be carried out for the four carbon-rich stars in Table 1 because for these objects model atmospheres for $k = 2300$ are not available (D. Luttermoser, private communication). We therefore used blackbody spectra based on $T_{\text{eff}}$ values from Bergeat et al. (2001) and scaled these to fit the NIR and optical photometry of each object. We find that even for the object with the smallest FUV excess (VY UMa) the model FUV flux of the primary AGB star is lower than the observed value by a factor of 30. V Hya stands out among the nine FUV-detected stars as having the highest FUV-to-NUV flux ratio ($\sim 1$), but the coolest photosphere ($T_{\text{eff}} = 2160$ K) for the primary. We discuss our detection of the FUV/NUV excess in this object in more detail in § 4.

We note that Wood & Karovska (2004), based on International Ultraviolet Explorer (IUE) spectroscopic data of several Mira AGB stars at multiple phases, conclude that this class of objects does not produce any detectable emission below 2000 Å. We have examined the IUE database for the sources in our survey and find that only three objects in our survey sample were observed: R LMi, V Hya, and TW Hor. R LMi and TW Hor were observed with both the long-wavelength (LWR and LWP) and short-wavelength (SWP) instruments (Boggess et al. 1978a, 1978b), whereas V Hya was observed only with the long-wavelength instrument. For both R LMi and V Hya, the signal-to-noise ratio (S/N) over the observed bandpasses ($1910 - 3300$ Å for LWR/LWP and $1150 - 1975$ Å for the SWP) is close to zero. For TW Hor the situation is similar except at wavelengths longer than 2500 Å, where significant flux is detected; the steady rise in the spectrum toward the red end of the bandpass indicates that this flux is most likely due to the primary star. We have convolved the IUE spectra with the GALEX FUV and NUV filter bandpasses in order to compute the GALEX-equivalent fluxes (or upper limits) for these sources. For R LMi we find 3σ upper limits of 0.032 mJy (FUV) and 0.16 mJy (NUV). For the other two sources, the derived fluxes (3σ errors) are 0.096 ± 0.051 mJy (FUV) and 0.41 ± 0.05 mJy (NUV) for TW Hor, and 0.12 ± 0.11 mJy (NUV) for V Hya.

We now examine two plausible explanations for the FUV excesses, both of which involve the presence of a companion star.  

### 3.1. A Hot Companion

The NUV and FUV excesses may result from the presence of a companion star which is significantly hotter than the primary. We have therefore made least-squares fits to the FUV and NUV...
TABLE 2
MODEL RESULTS

<table>
<thead>
<tr>
<th>Target</th>
<th>Primary Spectral Type</th>
<th>$D$ (kpc)</th>
<th>$A_V$</th>
<th>$T_{eff}^a$ (K)</th>
<th>$L^a_{c}$ ($L_{\odot}$)</th>
<th>$L_p/L_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>RW Boo</td>
<td>M5</td>
<td>0.32</td>
<td>2.3</td>
<td>8200 ($-500$, 300)</td>
<td>18 ($-5$, 7)</td>
<td>280 ($-80$, 110)</td>
</tr>
<tr>
<td>AA Cam</td>
<td>M5</td>
<td>0.5</td>
<td>1.0</td>
<td>8200 ($400$, 400)</td>
<td>1.1 ($-0.6$, 0.7)</td>
<td>3200 ($1300$, 4500)</td>
</tr>
<tr>
<td>V Eri</td>
<td>M6</td>
<td>0.22</td>
<td>2.9</td>
<td>10,000 ($-700$, 4100)</td>
<td>6.2 ($-2.9$, 2.2)</td>
<td>910 ($-240$, 810)</td>
</tr>
<tr>
<td>R UMa</td>
<td>M3–M9</td>
<td>0.5</td>
<td>1.3</td>
<td>9200 ($-300$, 1100)</td>
<td>0.85 (0.2, $-0.4$)</td>
<td>5300 ($-900$, 4700)</td>
</tr>
</tbody>
</table>

$^a$ The numbers in parenthesis represent 3 $\sigma$ modeling uncertainties; temperature and luminosity uncertainties are inversely correlated.

In our models we adopted the extinction curve as tabulated by Whittet (1992). Our quoted modeling uncertainties do not take into account uncertainties in the extinction curve at NUV and FUV wavelengths. We repeated the modeling using extinction curves for the LMC supershell and the SMC bar (Gordon et al. 2003), which along with the Galactic extinction roughly cover the range of curves found in circumstellar dust and are well studied. The results are shown in Table 3. Although the best-fit temperatures all shifted up when the LMC and SMC extinction curves were used, the cooler companion models (i.e., for RW Boo and AA Cam) proved reasonably insensitive to the choice of extinction curve, while dramatic differences were found for R UMa and V Eri. In general, we could not obtain a good fit even with the highest temperature models available (39,000 K) while using the LMC or SMC curves for these two sources.

3.2. Accretion onto a Companion Star

Five out of nine objects in Table 1 were observed on more than one epoch in one or both of the GALEX bands—in each instance, significant photometric variability was observed (Table 1). We have checked that this variability is not due to systematic calibration uncertainties because the average and median fractional differences of the fluxes for the brightest 40 field objects in the images are the same for the different epochs and are negligible.

A plausible interpretation for the photometric variability is related to the presence of a nearby companion. This interpretation is motivated by ultraviolet observations of Mira, a symbiotic star in which Mira A is the AGB primary and Mira B is a compact companion (at a separation of 0.6") which is accreting matter from Mira A's wind. IUE spectra of Mira in the wavelength region covered by the GALEX bands show the presence of strong emission lines ascribed to Mira B (Reimers & Cassatella 1985). The strongest of these (due to O, N, and C, seen by IUE during 1979–1995) were found to fade by a factor $>20$ by 1999–2001 and then start increasing back to their original levels by 2004 (Wood & Karovska 2006). Assuming a distance of 107 pc to Mira as recomputed by Knapp et al. (2003) from the Hipparcos Intermediate Astrometric Data using improved astrometric fits and chromaticity corrections, the combined maximum fluxes of such emission lines, if present in our sources, would correspond to an artificial continuum in GALEX’s broadband FUV filter of about 0.1 mJy at a

TABLE 3
BEST-FIT TEMPERATURES (IN KELVINS) UNDER DIFFERENT EXTINCTION CURVES

<table>
<thead>
<tr>
<th>Target</th>
<th>$A_V$</th>
<th>Galactic $^a$</th>
<th>LMC $^a$</th>
<th>SMC $^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>RW Boo</td>
<td>2.3</td>
<td>8200 ($-500$, 300)</td>
<td>8700 ($-500$, 400)</td>
<td>No fit</td>
</tr>
<tr>
<td>AA Cam</td>
<td>1.0</td>
<td>8200 ($400$, 400)</td>
<td>8500 ($-400$, 500)</td>
<td>9000 ($-400$, 1400)</td>
</tr>
<tr>
<td>V Eri</td>
<td>2.9</td>
<td>10,000 ($-700$, 4100)</td>
<td>No fit</td>
<td>No fit</td>
</tr>
<tr>
<td>R UMa</td>
<td>1.3</td>
<td>9200 ($-300$, 1100)</td>
<td>33,000 ($-22,000$) $^a$</td>
<td>No fit</td>
</tr>
</tbody>
</table>

$^a$ The numbers in parenthesis represent 3 $\sigma$ modeling uncertainties.

$^b$ The 3 $\sigma$ upper limit for R UMa fell beyond the range of available models.
We would like to thank an anonymous referee for his/her thoughtful review of our paper. We acknowledge discussions with Patrick Morrissey related to the possibility of red leaks in the GALEX FUV and NUV bands. R. S.’s contribution to the research described in this publication was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA. R. S. thanks NASA for financial support via a GALEX award and an LTSA award. K. F. was partially funded by a SURF scholarship and through the Cornell Presidential Research Scholars (CPRS) program. A. G. d. P. is partially financed by the Spanish Ramón y Cajal program and the Programa Nacional de Astronomía y Astrofísica under grant AYA 2006-02358. C. S. C. is partially funded for this work by the Spanish MICYT under project AYA 2006-14876 and the Spanish MEC under project PIE 2007/0028.

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4. DISCUSSION

Our small survey of 21 AGB stars for UV excesses has resulted in a substantial number of NUV and/or FUV detections. Nine of these were detected in the FUV band and are the subject of this paper. A detectable FUV flux at a level of even a few microjanskys is several orders of magnitude too high to be explained by photospheric emission from the relatively cool primary stars in our sample, and hence is an “excess” which requires an alternative explanation—most likely the presence of a binary companion. The excesses arise either as a result of photospheric emission from a hotter companion, and/or from an accretion disk around the companion. Spectroscopic monitoring in the FUV of these sources is needed in order to distinguish between these two mechanisms.

We detected NUV fluxes in 19/21 of our objects with high S/N, many of which are also likely to be “excesses,” but for which such an inference is more uncertain because of the significantly larger contribution of the primary in the NUV compared to the FUV. A discussion of the detection statistics of, and the biases in, our full sample is deferred to a forthcoming paper.

Although our discovery of a UV excess attributable to a different star than the primary AGB star does not directly imply that the former is a gravitationally bound companion, it is the most likely explanation. This is because the UV sky is rather “empty” (i.e., much more scarcely populated than at optical wavelengths), and hence the probability, $P_{\text{false}}$, that the FUV-emitting object is simply positionally coincident on the sky with the primary (i.e., lying within a radius of 2° from the primary) is very small. Using the object number count (per deg² mag) versus magnitude plot for the GALEX FUV band (Bianchi et al. 2007), we find that for AA Cam (the faintest of our modeled sources), $P_{\text{false}}$ for an object of FUV magnitude lying within a 0.5 mag bin centered around the FUV mag of AA Cam, is $8 \times 10^{-5}$. The Galactic latitudes of our objects are similar to those of the fields used by Bianchi et al.; hence, it is appropriate to use their point-source densities.

V Hya, which has the largest FUV flux as well as the highest FUV-to-NUV flux ratio among all our targets, is well known for its collimated, high-velocity, outflows, an extended dusty torus, and an inner hot disk. The outflows were first seen via infrared absorption lines in the CO 4.6 μm vibration-rotation band (Sahai & Wannier 1988); recent interferometric mapping of the millimeter-wave CO line emission shows the collimated structure of the fast outflow (e.g., Hirano et al. 2004). More recently, observations with the Hubble Space Telescope (HST) Space Telescope Imaging Spectrograph (STIS) reveal the presence of a high-velocity blob moving away from the central source at (projected) speeds up to 220 km s⁻¹ and a hot, slowly expanding (10–15 km s⁻¹) central disklike structure (Sahai et al. 2003). Although the expansive kinematics of the latter implies that it is not an accretion disk, the structure may result from a recent phase of equatorially enhanced mass loss, which may be enhancing the accretion process. V Hya is thus the best example to date of an evolved star with an active, collimated outflow, dense equatorially flattened structures possibly related to a central accretion disk, and an inferred binary companion from our UV excess measurements.