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A. G. Michalitsianos

*NASA, Goddard Space Flight Center*

Menas Kafatos

*Chapman University, kafatos@chapman.edu*

W. A. Feibelman

*NASA, Goddard Space Flight Center*

R. W. Hobbs

*University of Durham*

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# Ultraviolet Observations of Four Symbiotic Stars

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## ULTRAVIOLET OBSERVATIONS OF FOUR SYMBIOTIC STARS

A. G. MICHALITSIANOS

Laboratory for Astronomy and Solar Physics, NASA Goddard Space Flight Center

M. KAFATOS

George Mason University, Department of Physics

AND

W. A. FEIBELMAN AND R. W. HOBBS

Laboratory for Astronomy and Solar Physics, NASA Goddard Space Flight Center

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### ABSTRACT

Observations were obtained with the *International Ultraviolet Explorer (IUE)* of four symbiotic stars. The UV spectra of YY Her, SY Mus, CL Sco, and BX Mon are characterized by varying degrees of thermal excitation. We have analyzed these low resolution spectra in terms of line-blanketed model atmospheres of early A, B, and F type stars in order to identify the nature of the hot companion in these systems. The expected emission from early main sequence stars does not fully explain the observed distribution of UV continuum energy over the entire *IUE* spectral range (1200–3200 Å). More likely the observed continuum may be originating from an accretion disk and/or hot subdwarf that photoionizes circumstellar material, and gives rise to the high excitation lines we have detected. The Bowen fluorescent excited lines of O III in SY Mus exhibit slightly broadened profiles that suggest possible turbulent motions in an extended circumstellar cloud with characteristic velocities  $\sim 300 \text{ km s}^{-1}$ .

*Subject headings:* stars: binaries — stars: combination spectra — stars: mass loss — ultraviolet: spectra

### I. INTRODUCTION

Ultraviolet observations of four symbiotic stars were obtained with the *International Ultraviolet Explorer (IUE)*. In low spectral resolution ( $\sim 6 \text{ Å}$ ) (cf. Boggess *et al.* 1978) these objects exhibit varying degrees of ionization throughout the entire wavelength range of the satellite spectrometer (1200–3200 Å). The three symbiotic stars SY Mus (Feast, Robertson, and Catchpole 1977) and YY Her and CL Sco (Allen 1979) exhibit stellar blackbody continuum emission appropriate to M stars rather than thermal emission from dust in the 1–10  $\mu\text{m}$  wavelength range.

Infrared observations of BX Mon are not available. However, on the basis of optical data and visual light curves (Mattei 1980), it is associated with a Mira variable for which the intrinsic light period of  $P = 1374$  days distinguishes BX Mon as being the longest period known Mira variable (Mayall 1940). Allen (1979) has deleted BX Mon from his general list of symbiotic stars that he has considered in context with the classification criteria of Boyarchuk (1975). We find that the UV spectrum of BX Mon is basically characteristic of emission seen commonly in symbiotic stars, and as such should be

retained in the general list of peculiar emission line objects.

These four symbiotic stars do not lend themselves to a detailed interpretation of common structure on the basis of their ultraviolet spectra. The distribution of UV continuum with wavelength as well as intensity ratios of prominent emission lines varies greatly among the four objects. Here we have attempted to deduce the nature of the ionizing source of radiation by examining the distribution of continuum energy in the near- and far-ultraviolet. A comparison of observed continuum with recent line blanketed models of Kurucz (1979) of early A and B stars indicates that these models do not provide a good fit to the data. Additionally, the presence of strong high-excitation emission lines that generally characterize the UV spectra of symbiotics requires a very strong UV radiation field. An intense UV photon flux can be provided by a hot subdwarf and/or an accretion disk that encircles the secondary. As such, we consider an interpretation of these observations on the basis of models developed by Bath (1978), who has suggested that an optically thick shell is formed around a compact secondary which is also surrounded by an accretion disk. The UV emission properties of each stars are

TABLE 1  
*IUE* OBSERVING PROGRAM

Star	Exposure No. & <i>IUE</i> Camera <sup>a</sup>	FES mag	Exposure time (min)	Epoch
BX Mon ...	SWP 6344	11.0	60	1979 Sep 1
BX Mon ...	LWR 5479	11.0	60	1979 Sep 1
CL Sco ....	SWP 9543	12.4	60	1980 Jul 19
CL Sco ....	LWR 8296	12.4	40	1980 Jul 19
YY Her ....	SWP 9773	12.5	80	1980 Aug 12
YY Her ....	LWR 8493	12.5	60	1980 Aug 12
SY Mus ....	SWP 10188	10.7	90	1980 Sep 20
SY Mus ....	LWR 8855	10.7	60	1980 Sep 20

<sup>a</sup>SWP: 1200–2000 Å; LWR: 2000–3200 Å.

discussed individually. Details concerning these satellite observations are described in the following section.

## II. OBSERVATIONS AND DATA ANALYSIS

*IUE* spectra data were obtained exclusively in the large ( $10'' \times 20''$ ) entrance aperture of the satellite spectrometer. The emission flux from these objects in the UV was such that, given the observing time that was allocated, only low spectral resolution observations were feasible. Table 1 summarizes the observing sequence and exposure times at different observing dates. The *IUE* data tapes were analyzed using the data reduction routines developed in FORTH at NASA Goddard Space Flight Center on the PDP-11/40 interactive computer system (Fahey and Klinglesmith 1979).

The spectra for these objects in Figures 1 through 4 are plotted in absolute intensity units for which the data reduction was made using the corrected intensity transfer function adopted for *IUE* echelle images (Cassatella *et al.* 1980). The spectra shown in the figures are not corrected for interstellar absorption. Absolute line intensities for prominent lines are given in Table 2 where positive identification of particular ion species was possible. Table 3 lists additional lines that are not common to all objects, and indicates wavelengths for a number of unidentified lines.

Generally, the long wavelength redundant (LWR) wavelength region in all four objects presents a large number of confusing emission features that might possibly arise from low excitation metals such as Fe II multiplets (2) and (3), Cr II, Si II, Al II multiplet (2), etc.

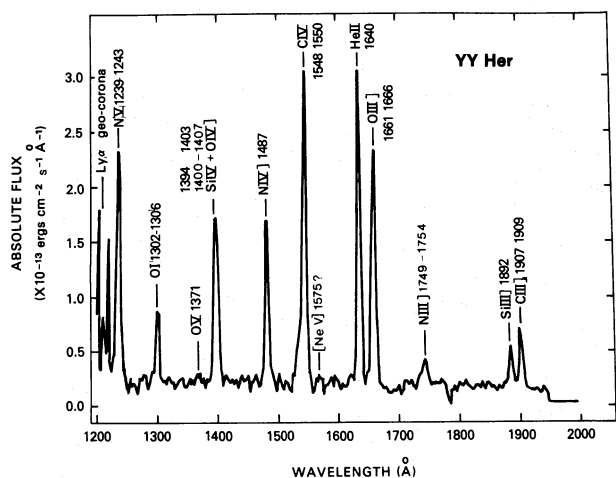


FIG. 1a

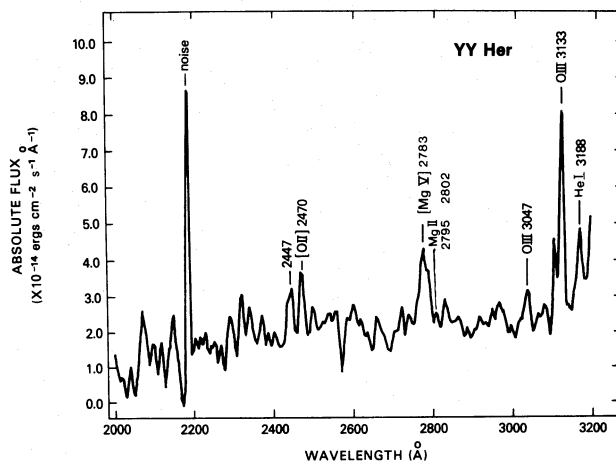


FIG. 1b

FIG. 1.—(a) Low dispersion spectra of YY Her that are plotted in absolute intensity flux units. The strength of the high excitation lines of N V, C IV, and He II is not consistent with emission excitation found by Allen (1979). Wavelength identification of ions are laboratory or rest wavelengths. (b) Low dispersion spectrum in the 2000–3200 Å wavelength range. [Mg V] is tentatively identified at 2783 Å, although emission at 2929 Å is not clearly evident. The continuum rises gradually with increasing wavelength. R indicates reseau marks.

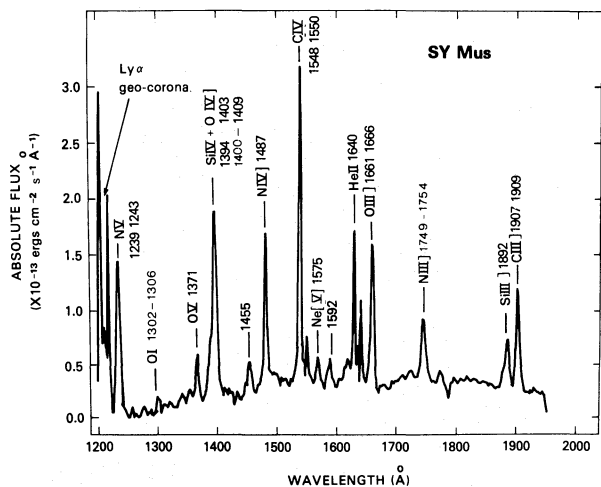


FIG. 2a

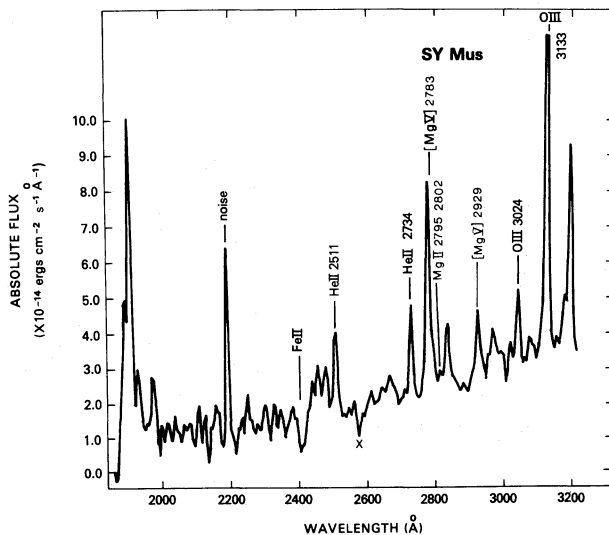


FIG. 2b

FIG. 2.—(a) Low resolution spectrum of SY Mus in which the C IV (1548 Å, 1550 Å) and He II (1640 Å) exhibit possible structure. High resolution spectral observations are required to discern possible macroscopic mass motions in the system. (b) [Mg v] is identified in the long wavelength range at 2784 Å and 2929 Å. The O III series in addition to He II is present, although He I emission is possibly suggested.

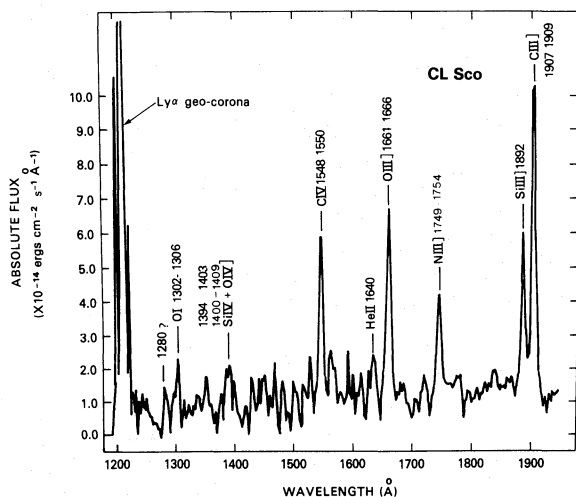


FIG. 3a

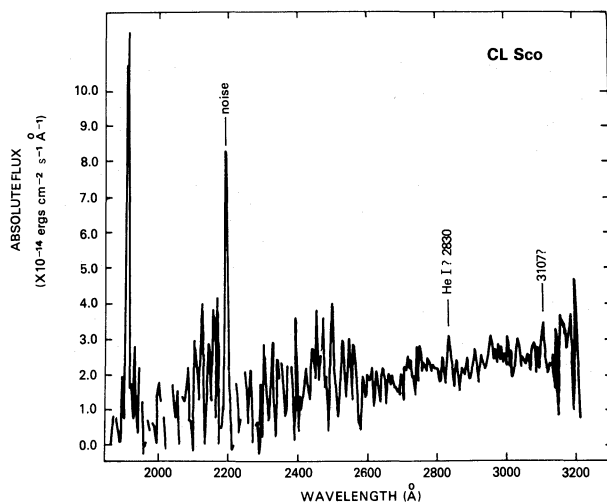


FIG. 3b

FIG. 3.—(a) Emission lines in CL Sco are not as pronounced as in YY Her and SY Mus. N v is not present, and an unidentified line at 1280 Å is indicated. S III] and C III] relative to C IV are stronger as compared to YY Her and SY Mus. (b) Spectrum in the 2000–3200 Å wavelength range is dominated by continuum that rises gradually with increasing wavelength. He I is possibly present and possible emission at 3034 Å and 3107 Å is indicated.

Our resolution of  $\sim 6$  Å makes identification difficult in almost all cases because a clear sequence of lines that correspond to particular multiplets is not usually evident. However, the presence of [Mg v] in SY Mus is confirmed on the basis of the doublet identification at 2783 Å and 2929 Å (Table 3) and is also tentatively identified in YY Her. Forbidden Mg v is noteworthy because it is the highest excitation emission line found

among the four objects surveyed here. A detailed discussion concerning the observed properties of each of the stars investigated follows:

#### a) YY Herculis

YY Her exhibits especially strong high-excitation emission throughout the short wavelength prime (SWP) wavelength range for which N v, C iv, He II, and O III]

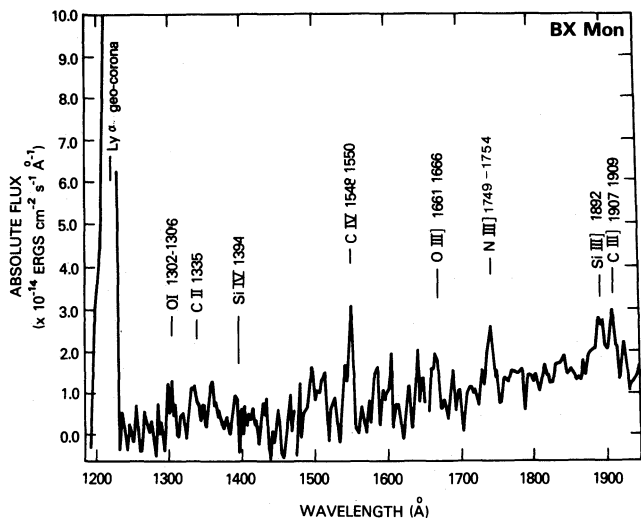


FIG. 4a

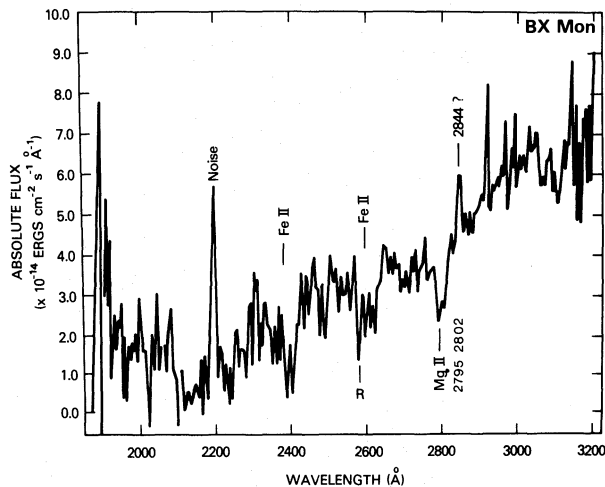


FIG. 4b

FIG. 4.—Emission lines relative to the continuum are weakest in BX Mon. C IV, Si III], and C III] and a number of modest excitation lines are present. (b) In contrast to the previous three emission line stars, BX Mon does not exhibit line emission in the long wavelength range. Prominent absorption features are present and attributed to blends of Fe II and Mg II absorption seen typically in spectra of early A and B type stars in *OAO 2* data. The continuum distribution is stellar-like and is possibly explained by a F0 giant with line blanketed continuum emission.

lines are particularly prominent. The ionization potential for Mg IV at 109 eV and N IV at 77.5 eV suggest that YY Her at the time of our observations was in a hot thermal phase. An upper limit to ionization excitation of 30 eV found by Allen (1979) from optical data is in conflict with these results, but can be reconciled if we conclude the YY Her undergoes vast changes in thermal excitation over some undetermined time scale. Mg II resonance doublet emission at 2795 Å and 2802 Å is present but very weak relative to [Mg v], which has a very high ionization potential of ~140 eV. The forbid-

den O II line and the Bowen lines of O III in the LWR region are prominent.

Bohlin *et al.* (1980) have discussed the absolute calibration of *IUE* low dispersion spectra and find agreement between the observed and theoretically predicted models for B3 V type stars at the 5–10% level. The error bars shown in Figure 5 indicate the actual continuum level within 20–25% confidence level. Longer exposures for YY Her of the order of hours are feasible and would increase the signal-to-noise ratio of the continuum. Symbiotic stars such as YY Her, however, have

TABLE 2  
ABSOLUTE LINE INTENSITIES

Ion	$\lambda$ (Å) Laboratory	$\lambda$ (Å) <i>IUE</i> YY Her <sup>a</sup>	$\lambda$ (Å) <i>IUE</i> SY Mus <sup>a</sup>	$\lambda$ (Å) <i>IUE</i> CL Sco <sup>a</sup>	$\lambda$ (Å) <i>IUE</i> BX Mon <sup>a</sup>
N v.....	1239–1243	1236.6	1236.4	...	...
O I.....	1302–1306	1304.0	1301.6	1304.0	1300.2
O v.....	1371	1374.0	1366.2	...	...
Si iv + O iv]bl...	1394–1403 + 1400–1407	1399.8	1398.4	1397.0	1394.4
N iv].....	1487	1482.8	1483.0	...	...
C iv.....	1548–1550	1549.4	1545.2	1549.4	1551.2
[Ne v].....	1575	1574.2	1570.8	...	...
He ii.....	1640	1636.8	1637.2	1634.4	1643.2
O iii].....	1661–1666	1664.2	1662.2	1665.2	1670.3
N iii].....	1749–1754	1749.6	1748.6	1749.6	1744.0
Si iii].....	1892	1887.4	1886.2	1887.4	1894.4
C iii].....	1906–1909	1909.8	1907.6	1909.8	1910.8

<sup>a</sup>  $\times 10^{-13}$  ergs  $\text{cm}^{-2}$   $\text{s}^{-1}$   $\text{Å}^{-1}$ .  
<sup>b</sup> Saturated.

TABLE 3  
PROBABLE AND UNIDENTIFIED LINES

$\lambda$ (Å) Measured	$\lambda$ (Å) Laboratory	Probable Ion	Flux (ergs cm <sup>-2</sup> s <sup>-1</sup> )
YY Herculis			
2475 .....	2470	[O II]	$2.85 \times 10^{-13}$
2782 .....	2783	[Mg v]	$4.45 \times 10^{-13}$
2925 .....	2929	[Mg v]?	$5.22 \times 10^{-14}$
3044 .....	3047	O III	$1.26 \times 10^{-13}$
3128 .....	3133	O III	$6.63 \times 10^{-13}$
SY Muscae			
1455 .....	?	?	$2.22 \times 10^{-13}$
1592 .....	?	?	$1.50 \times 10^{-13}$
2514 .....	2511	He II	$1.76 \times 10^{-13}$
2731 .....	2734	He II	$3.01 \times 10^{-13}$
2780 .....	2783	[Mg v]	$8.77 \times 10^{-13}$
2839 .....	2830	He I?	$1.96 \times 10^{-13}$
2930 .....	2929	[Mg v]	$3.08 \times 10^{-13}$
3049 .....	3047	O III	$1.96 \times 10^{-13}$
3129 .....	3133	O III	$1.39 \times 10^{-12}$
CL Scorpii			
1280 .....	?	?	$1.03 \times 10^{-13}$
2839 .....	2830	He I?	$1.40 \times 10^{-13}$

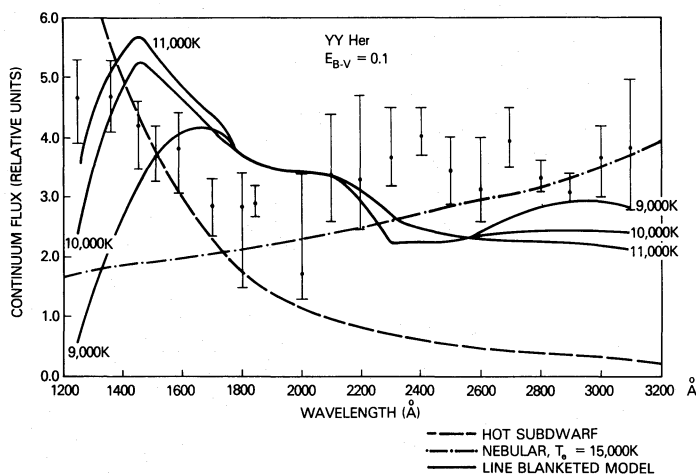


FIG. 5.—Error bars indicate uncertainties in the exact continuum level of the SWP spectrum of YY Her when an  $E_{B-V} = 0.1$  is applied to the data. A line-blanketed model for an early type giant with  $\log g = 3$  and  $T_{\text{eff}} = 10,000$  K shows the best fit but in the SWP range only. Nebular free-bound and free-free continuum may contribute significantly in the LWR range, thus possibly explaining the disparity between theoretically predicted UV continuum emission and observed fluxes. Also shown is the Rayleigh-Jeans portion for a blackbody continuum for a hot subdwarf with  $T_{\text{eff}} = 5 \times 10^4$  K to  $10^5$  K.

numerous strong emission lines that easily saturate the detector with hour-long exposures. Accordingly, exposure times are selected so that the intensity of both continuum and emission lines fall well within the dynamic range of the detector. Even given these uncertainties of the observed continuum level, however, the SWP region suggests that the continuum rises slightly with decreasing wavelength.

Plotted in Figure 5 together with the UV continuum energy distribution that we have corrected for interstellar extinction using  $E_{B-V} = 0.1$  are theoretically predicted continua for early A and B stars from Kurucz (1979) for giants with corresponding surface gravities  $\log g = 3$  and  $T_{\text{eff}} = 9000$  K, 10,000 K, and 11,000 K. Wavelengths chosen to evaluate the fitting are sufficiently removed from emission lines that they do not

affect our estimates for the continuum level. The models are generally not very sensitive to  $\log g$ , and cosmic abundances are assumed applicable to symbiotic stars.

The closest correspondence between observed and theoretically predicted stellar continua occurs in the SWP wavelength range for  $T_{\text{eff}}=10,000$  K. The measured continuum in the LWR range is significantly above that expected from line-blanketed models for this temperature. Here the addition of nebular recombination continuum arising from a photoexcited gas at  $T_e=15,000$  K (Fig. 5) could bring into better agreement this portion of the spectrum if combined with a  $T_{\text{eff}}=10,000$  K star. Also shown in Figure 5 is the Rayleigh-Jeans portion of a blackbody curve that corresponds to a star with  $T_{\text{eff}}\gtrsim 50,000\text{--}100,000$  K. The disparity between observed and predicted continua for a hot subdwarf is far greater in both the SWP and LWR regions of the spectrum than for the  $T_{\text{eff}}=10,000$  K star previously considered, unless nebular continuum is added to the hot subdwarf continuum.

The M2 primary in YY Her by virtue of its temperature makes essentially no contribution in the UV where the hot companion dominates the emission. We find that the modest absorption indicated by the dip in continuum at  $\lambda\lesssim 2200$  Å corresponds to an  $E_{B-V}=0.1\text{--}0.2$ . The onboard FES monitor of *IUE* recorded an apparent magnitude  $m_V\sim 12.5$ . Assuming an M2 II–III star for the primary, we estimate from Allen (1976)  $M_V\sim -2.4$  to  $-0.6$  that corresponds to a distance of  $\sim 8300$  pc and 3600 pc, respectively, and apparent  $m_V\sim 13.7$  for the secondary, or  $\Delta m=1.2$  mag between primary and companion.

#### b) SY Muscae

Infrared observations of SY Mus in the  $1\text{--}10$   $\mu\text{m}$  wavelength range by Glass and Webster (1977) suggest the presence of an M star. Feast, Robertson, and Catchpole (1977) determined an extinction of  $E_{B-V}=0.23$  and a spectral type M3 II–III for the primary. The general line excitation present in SY Mus is reminiscent of YY Her, although He II, N v, and O III] are weaker (Table 2). On an expanded wavelength scale (not shown) the Bowen excited lines of O III are slightly broadened by  $\sim 3\text{--}4$  Å. By fitting a Gaussian profile to the O III  $\lambda 3133$  the extra broadening of the line profile indicate possible turbulent motion with characteristic velocities  $\sim 300$  km s $^{-1}$  in a tenuous circumstellar gas. The asymmetric extended blue-wing profile of O III at 3133 Å is attributed to a blend of the O III  $\lambda 3122$  with O III  $\lambda 3133$  Å. High dispersion observations of this object are required in order to examine possible kinematic motions of circumstellar material in more detail.

In contrast to YY Her, the LWR region (Fig. 2b) exhibits a number of strong emission lines that does not

typify the long wavelength region of other symbiotic stars we have investigated previously (cf. Kafatos, Michalitsianos, and Hobbs 1980a). [Mg v] is identified at 2783 and 2929 Å, and O III is prominent in addition to a number of identified lines (Table 3). Continuum absorption at  $\sim 2400$  Å is attributed to Fe II (2) at 2367 and 2473 Å, and generally typifies features observed in standard early type stars from *OAO 2* data. A strong unidentified emission feature at 2839 Å here in SY Mus is also seen in CL Sco, and is possibly attributed to low excitation ion emission. We cautiously attribute it to He I at 2830 Å, making this emission highly redshifted with corresponding Doppler velocities  $\sim 1000$  km s $^{-1}$ .

#### c) CL Scorpii

This symbiotic star indicates overall low thermal excitation in comparison to the previous two stars discussed, with no suggestion of N v at 1239 and 1242 Å and very weak He II 1640 Å emission (Fig. 3a). The LWR region is dominated mainly by continuum that in a similar manner to the preceding stars rises with increasing wavelength.

Interstellar absorption in the direction of CL Sco has not been determined from optical observations. The LWR continuum at  $\lambda\lesssim 2200$  Å suggests modest absorption even though our signal level in this region of the spectrum is low. This extinction feature is entirely removed when applying an  $E_{B-V}=0.1\text{--}0.2$  to the data. From unpublished observations, He II  $\lambda 4686$  was not present in emission along with strong Balmer line emission from ground-based observations obtained within one month of our *IUE* data, in collaboration with W. P. Blair of McGraw-Hill Observatory. He II at 1640 Å is comparatively weaker than He II at 4686 Å measured approximately one month apart, and suggests possible short term variations in intensity on a time scale of weeks. More observations are required of this object that is known to undergo small irregular variations in magnitude (Swope 1941).

#### d) BX Monocerotis

Mayall (1940) noted that the peculiar emission line star BX Mon=H.V. 10446 is an extremely long period variable for which  $P=1374$  days. From objective prism surveys, BX Mon exhibits H $\gamma$  and H $\delta$  emission and is included in the emission line surveys of Merrill and Burwell (1950) and Bidelman (1954). Spectra of BX Mon were obtained by Minkowski at Mount Wilson, but apparently the data have not appeared in publication, and as such, BX Mon essentially has gone unnoticed by observers. The *IUE* FES monitor recorded an apparent magnitude of  $m_V\sim 11$ , which places the variable nearly midway between its extremes in ob-



served apparent magnitudes ( $m_V = 9.5-13.4$ ; Kukarkin *et al.* 1969), and is also in agreement with the magnitude recorded for the star on 1951 April 8, at which time it exhibited broad H $\beta$ , H $\gamma$  and H $\delta$  emission and an absorption spectrum of type M4 (Bidelman 1954).

In the UV, BX Mon exhibits strong absorption features in the LWR wavelength range which makes it rather distinct from the previous three symbiotic stars considered here. The continuum distribution in the 2000–3200 Å wavelength range is similar to that expected from an early type star with line blanketing and exhibits strong absorption features that we attribute to Fe II (3) 2327–2381 Å, Fe II (1) 2586–2631 Å, Mn II (1) 2576–2606 Å, and Mg II at 2795 and 2802 Å. These absorption features are seen in *OAO 2* spectra of A and F type stars, and further supports the view that the spectrum is dominated by stellar emission.

The SWP wavelength range exhibits medium-excitation emission lines of C IV, N III], O III], Si III], and C III] that are superposed on what appears to be the tail end of the LWR stellar continuum. The SWP and LWR continua can be fitted by line-blanketed models from Kurucz (1979) with either a middle A or early F star. However, as will be discussed shortly, a fully self-consistent model of BX Mon cannot be developed yet that explains the relative magnitudes of the primary and secondary, the spectral type of the secondary and the observed medium excitation emission lines.

Linsky (1980) has recently reviewed stellar chromosphere observations obtained with *IUE*. Generally, he finds that stars of spectral type F0 and later up to and including K and early M giants are associated with transition zone and chromospheric emission lines. The presence of medium-high excitation lines in BX Mon indicates that the hot companion could in fact be an early F type star. We have examined the properties of the UV continuum following our previous method in order to determine if the UV continuum distribution is consistent with this interpretation. The continuum at  $\lambda \lesssim 2200$  Å suggests interstellar absorption of  $E_{B-V} = 0.1-0.2$ . Following similar reasoning as before, the continuum can be approximately matched by an F0–F2 star.

We find that the relative apparent magnitudes between primary and secondary are such that the hot companion is nearly as bright as the M star for the values of extinction and absolute magnitude considered. As such, the apparent magnitude of the secondary of  $m_V \sim 13.2$  is likely an upper limit. If we consider larger values of interstellar absorption which decreases the apparent magnitude of the secondary, the resultant absolute magnitude of the secondary is more appropriate to an A star. The appearance of chromospheric type emission lines in this case however, is inconsistent with Linsky (1980). Additionally, A stars cannot supply

enough ionizing photons to excite circumstellar nebulosity that would explain the observed line emission. An optical spectrum of BX Mon could indeed exhibit composite features that reflect the presence of both an M star and early F companion.

As indicated by the most prominent emission lines, we find that a chromospheric flux of  $\sim 10^9$  ergs cm $^{-2}$  s $^{-1}$  is required to explain the observed medium excitation lines in BX Mon. Hence, the UV emission lines are possibly the result of a combination of effects that could involve chromospheric emission and excitation that arises from tidal interaction in the system.

### III. DISCUSSION AND CONCLUSIONS

The nature of symbiotic stars has been argued in the literature from diverse viewpoints. Wood (1974) considered a single star model consisting of a Mira variable that undergoes relaxation oscillations during its ascendancy on the asymptotic giant branch. Kwok and Purton (1979) have discussed the high excitation line emission observed in symbiotics as the result of the dislodging of the outer envelope of the M giant, thus exposing the hot nuclear core which photoionizes an expanding tenuous shell. Additionally, Nussbaumer and Schild (1981) find that a single star model adequately explains their *IUE* high dispersion spectrum of V1016 Cyg. Alternatively, a number of symbiotic stars that are known to undergo eclipse cycles such as CI Cyg (Stencel *et al.* 1982) and very recently R Aqr (Mattei 1981) are consistent with a binary star interpretation. Additionally, analysis of UV spectra from *IUE* observations of the canonical star Z And by Friedjung (1980) and AG Peg by Keyes and Plavec (1980) further support the binary star hypothesis, as do optical and infrared observations by Allen (1979). Ultraviolet spectra of Mira variables and M giants that are known single stars are generally devoid of line or continuum emission (cf. Linsky 1980; Kafatos, Michalitsianos, and Hobbs 1980*b*). Accordingly, any comprehensive model that attempts to explain the ultraviolet spectral properties of symbiotic stars must account for the rich emission line spectrum as well as the observed continuum energy distribution.

Although in several of the cases considered here the UV continuum is crudely approximated by emission from an early type main-sequence A or B star, the appearance of emission lines is inconsistent with this assertion. This follows because early A or B stars are generally not associated with transition-zone type line emission (Linsky 1980), and because early type main-sequence stars lack a sufficient flux of ionizing UV photons to excite a circumstellar nebula or shell. On the other hand, a hot subdwarf or a white dwarf is capable of photoionizing circumstellar material directly, and an accretion disk around such an object formed through

mass transfer from the cool primary would provide an additional source of ionizing radiation. We shall also see shortly that mass transfer from the extended envelope of the cool primary star onto a compact subdwarf can proceed at more moderate rates than that required for mass transfer to a main-sequence star, and this becomes an important consideration when one attempts to develop an evolutionary model for such systems.

Bath (1978) has discussed models of symbiotic stars that involve the formation of an accretion disk through mass transfer to the secondary. His theoretical analysis points to the need for considering these observations in terms of various distinct processes that collectively explain the observed UV spectra. Lacking a fully developed theory for mass accretion, the following discussion is concerned with the general range of temperatures in the disk that are relevant to the photoexcitation of line emission observed. The minimum temperature of the inner region of the accretion disk when LTE holds in the optically thick case depends on various parameters as follows (cf. Shakura and Sunyaev 1973):

$$T_{\min} \sim 1.3 \times 10^3 \left( \frac{\dot{M}}{10^{-8} M_{\odot} \text{ yr}^{-1}} \right)^{1/4} \times \left( \frac{M}{10 M_{\odot}} \right)^{1/4} \left( \frac{r}{10 R_{\odot}} \right)^{-3/4}, \quad (1)$$

where  $\dot{M}$  is the mass accretion rate,  $M$  is the mass of the accreting star, and  $r$  is the radial distance from the accreting object. Equation (1) is appropriate for accretion onto a giant type star. For more compact objects with higher surface gravities, a higher minimum temper-

ature results, which is expressed as follows:

$$T_{\min} \sim 1.3 \times 10^5 \left( \frac{\dot{M}}{10^{-8} M_{\odot} \text{ yr}^{-1}} \right)^{1/4} \times \left( \frac{M}{1 M_{\odot}} \right)^{1/4} \left( \frac{r}{0.01 R_{\odot}} \right)^{-3/4}. \quad (2)$$

On the basis of the general ionization potentials involved in a number of the high excitation lines observed, we will assume that  $T_{\min} \gtrsim 25,000$  K (cf. Bath 1978). Writing the total luminosity of the disk as  $L = \beta_1 \dot{M} c^2$ , we have the ratio involving the Eddington luminosity  $L_{\text{Edd}}$  as

$$L/L_{\text{Edd}} \sim 0.6 \left( \frac{\dot{M}}{10^{-8} M_{\odot} \text{ yr}^{-1}} \right) \beta_1 \left( \frac{10 M_{\odot}}{M} \right), \quad (3)$$

where  $\beta_1$  is the efficiency of converting accreting mass into radiation. Novikov and Thorne (1973) estimate the maximum efficiency of accretion onto a white dwarf as  $10^{-4}$ , which we adopt here as an upper limit. For hot subdwarfs the efficiency would be lower. It is assumed that the inner boundary of the accretion disk is at a distance  $\gtrsim$  stellar radius (Lamb 1979), and therefore  $\dot{M}$  represents a lower limit for our assumed  $T_{\min} \gtrsim 25,000$  K. For simplicity we assume parameters for the four stars that correspond to an  $E_{B-V} = 0.2$ , except for SY Mus where  $E_{B-V} = 0.23$  from Feast, Robertson, and Catchpole (1977). Table 4 summarizes the various parameters that are important for mass accretion onto main sequence stars and white dwarfs (WD). The values of  $\dot{M}$  shown represent those which are necessary to produce the temperatures in the disk than can account for observed UV line emission.

TABLE 4  
MASS ACCRETION PARAMETERS<sup>a</sup>

IUE Target	Secondary Type	$r (R_{\odot})^b$	$\dot{M} (M_{\odot} \text{ yr}^{-1})^c$	$\beta_1^d$	$L/L_{\text{Edd}}^e$
YY Her .....	B5 V	2.5	$3.3 \times 10^{-5}$	$6 \times 10^{-7}$	$1.8 \times 10^{-3}$
	WD	0.01	$2.0 \times 10^{-7}$	$10^{-4f}$	$10^{-2}$
SY Mus .....	A0 V	3.1	$1.2 \times 10^{-4}$	$3.9 \times 10^{-8}$	$8.9 \times 10^{-4}$
	WD	0.01	$4.8 \times 10^{-8}$	$10^{-4f}$	$2.8 \times 10^{-3}$
CL Sco .....	B8 V	3.2	$10^{-4}$	$6.4 \times 10^{-8}$	$8.2 \times 10^{-4}$
	WD	0.01	$6.6 \times 10^{-8}$	$10^{-4f}$	$3.9 \times 10^{-3}$
BX Mon .....	F0 II-III	6.1	$6.7 \times 10^{-4}$	$10^{-8}$	$9.2 \times 10^{-4}$

<sup>a</sup>Computed for  $E_{B-V} = 0.2$  for all stars except SY Mus where  $E_{B-V} = 0.23$  is adopted.

<sup>b</sup>This is the minimum radius of the accretion disk assuming it ends near the surface of the star.

<sup>c</sup>Minimum accretion rate to achieve at least a temperature  $\sim 25,000$  K in the inner region of the disk.

<sup>d</sup>Maximum efficiency corresponding to the minimum accretion rate.

<sup>e</sup> $M = 1 M_{\odot}$  is assumed for white dwarf models; for smaller stellar masses the ratio would be larger.

<sup>f</sup>This value is an upper limit for white dwarfs and subdwarfs.

From this general analysis we can conclude that if a main sequence or giant type secondary star is the companion in these systems, the accretion rates are in the range a few  $\times 10^{-5} \lesssim \dot{M} \lesssim$  a few  $\times 10^{-4} M_{\odot} \text{ yr}^{-1}$  for  $10^{-8} \lesssim \beta_1 \lesssim 10^{-6}$  and  $L/L_{\text{Edd}} \sim 10^{-3}$ . If the companion is a subdwarf or white dwarf, the average accretion rate should be  $\dot{M} \sim 10^{-7} M_{\odot} \text{ yr}^{-1}$  with larger efficiencies of  $\lesssim 10^{-4}$  and  $L/L_{\text{Edd}}$  a few  $\times 10^{-3}$  (Table 4). In this case the emission lines may arise from photoionization of circumstellar material from the hot subdwarf directly (cf. Kafatos, Michalitsianos, and Hobbs 1980a) and/or from the accretion disk. The efficiency being unknown constrains us to consider only limits for the accretion rates which are  $10^{-3} \gtrsim \dot{M} \gtrsim 10^{-7} M_{\odot} \text{ yr}^{-1}$ ,  $10^{-8} \lesssim \beta_1 \lesssim 10^{-4}$ , and  $10^{-3} \lesssim L/L_{\text{Edd}} \lesssim 10^{-2}$ . Larger values of  $\dot{M}$  (lower  $\beta_1$ ) are appropriate for main-sequence stars or early type giants, and lower values of  $\dot{M}$  (higher  $\beta_1$ ) correspond to white dwarfs or central stars of planetary nebulae.

It should be noted that the continuum observed in these objects cannot be attributed directly to blackbody thermal emission from a white dwarf, although hot subdwarfs or central stars of planetary nebulae are sufficiently luminous to account for this emission. However, a white dwarf could manifest its presence in a more subtle manner. Bath (1978) has proposed a model in which accretion onto a compact object would create an optically thick shell near Eddington luminosities around the central gravitating source. As such, the observed continuum distribution could be formed from blackbody thermal emission from a shell (possibly expanding) that outwardly gives the appearance of a main sequence type star.

In this regard, if radial velocities  $\sim 10^3 \text{ km s}^{-1}$  are representative of the escape velocity from the central ionizing source, and if the mass is  $\sim 1 M_{\odot}$ , the corresponding stellar radius is  $\sim 0.28 R_{\odot}$ , appropriate to hot subdwarfs or central stars of planetary nebulae. Accordingly, the disparity between the line blanketed models that we have compared our data to might be explained by an object whose luminosity and surface temperature, following mass transfer and the formation of a hot

optically thick shell, is comparable to that of an early A or B main-sequence star, but whose chemical abundance and opacity properties differ greatly from early standard type stars. This interpretation is speculative at best because the physical structure for such objects is presently unknown. Here, we emphasize that, given *IUE* observations, the nature of the secondary at present is unknown. We speculate, however, that the observed continuum energy distribution is likely to be a combination of mechanisms that involve free-free and free-bound nebular recombination, and thermal emission from a hot subdwarf possibly associated with an accretion disk.

Mass accretion onto a white dwarf or central star of a planetary nebula is a more attractive model than mass transfer to an early main-sequence star or giant. In the case of accretion that involves an early type star, the M star would have to fill its Roche lobe for significant mass transfer to occur through the Lagrangian point (cf. Bath 1978). Under these circumstances Roche lobe overflow would produce accretion rates that exceed the usual mass loss rates typically associated with single M stars (cf. Gehrz and Woolf 1971) of  $10^{-5} \lesssim \dot{M} \lesssim 10^{-8} M_{\odot} \text{ yr}^{-1}$ , and would make the symbiotic phase of such systems small in relation to evolution time scales in the giant branch.

The stars examined here quite likely represent a quiescent state, although higher mass accretion rate phases during the course of the evolution of the system could produce outbursts. A more detailed analysis is required that addresses the kinematic properties of streaming gas in the system. As such, high-dispersion spectral observations of UV emission line profiles with *IUE* are necessary to better model the systems.

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W. A. FEIBELMAN, R. W. HOBBS and A. G. MICHALITSIANOS: Laboratory for Astronomy and Solar Physics, NASA Goddard Space Flight Center, Code 685, Greenbelt, MD 20771

M. KAFATOS: Department of Physics, George Mason University, Fairfax, VA 22030