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Fe II FLUORESCENCE AND ANOMALOUS C IV DOUBLET INTENSITIES IN SYMBIOTIC NOVAE

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ABSTRACT

Symbiotic stars frequently exhibit anomalous C IV $\lambda\lambda$1548.2, 1550.8 doublet flux ratios, in which the intensity ratio of the blue and red doublet members is below the optically thick limit of unity. Three symbiotic stars (RR Tel, RX Pup, and AG Peg) have been investigated in detail with high-resolution spectra obtained from the *International Ultraviolet Explorer* (*IUE*) archives. We have examined the deficit of C IV λ1548.2 emission relative to λ1550.8 in context with the fluorescent pumping of the Fe II multiplet (45.01) λ1548.204 by the C IV λ1548.2 line. In RR Tel the C IV λ1548.2 flux is correlated with the intensities of fluorescent-excited Fe II lines formed by the downward cascades from the $y^4H^o_{11/2}$ upper level. This suggests that a circumstellar Fe II forming region in RR Tel responds to variations of the C IV line strength, which provides further evidence in support of Fe II fluorescence in UV spectra of symbiotic stars first identified by Johansson. During periods when the C IV $I(\lambda1548.2)/I(\lambda1550.8)$ ratio in RX Pup is significantly less than the optically thick limit of unity, we find that the flux deficit of C IV λ1548.2 is approximately equal to the combined flux of the Fe II Bowen-pumped $a^4F_{9/2} \rightarrow y^4H^o_{11/2}$ transition. This could explain the anomalous C IV ratios observed in this system and several deep absorption features in the C IV λ1548 line profile, when the C IV flux ratio was substantially less than the optically thick limit of unity. Unlike RR Tel and AG Peg in which the velocity centroids of the Fe II Bowen lines correspond to the peak emission of the C IV λ1548.2 line, the Bowen-pumped Fe II lines in RX Pup exhibit a velocity range $0 \leq v_{\rm Fe\,II} \leq +80$ km s^{-1}. This could reflect the differential motion of individual gas parcels within an orbiting cloud that obscured the Mira and hot ionizing object, consistent with the model proposed by Whitelock et al. to explain the photometric behavior of RX Pup between 1982 and 1983. The cloud would be the source of Fe II fluorescent emission and would explain why the anomalous C IV doublet intensities were observed during a 3 yr period when the V and J photometric bands indicated a decrease in light.

Subject headings: binaries: symbiotic — novae, cataclysmic variables — stars: emission-line, Be — ultraviolet — stars

1. INTRODUCTION

The composite nature of symbiotic spectra at optical and infrared wavelengths is indicated by continuum and molecular TiO and VO absorption, appropriate to an M giant or a Mira variable accompanied by nebular emission from multiply ionized oxygen, nitrogen, neon, sulfur, iron, and Balmer emission. Approximately 25% of the known symbiotic stars (D-types) exhibit silicate emission in the infrared, consistent with a circumstellar dust shell. The majority of these systems (S-types) show stellar continuum between 10 and 20 μm, appropriate to blackbody emission from an M giant nearing its life on the asymptotic giant branch.

In quiescence, symbiotic stars are characterized by strong Balmer recombination emission and high-excitation forbidden line emission which is formed by intense ultraviolet radiation from a hot companion, with $25{,}000 < T_{\rm eff} < 10^5$ K (Kenyon & Webbink 1984). A significant contributor to the circumstellar region in which the binary is embedded is the cool stellar wind of the M giant (Nussbaumer 1990), as well as the hot stellar wind from the hot companion.

The nature of outbursts in symbiotic stars, however, remains controversial. A sudden change in accretion rate onto the hot companion of a main-sequence star can lead to a significant rise in luminosity in time scales of a few weeks, if the M giant envelope expands to fill its Roche lobe. During outbursts the accretion rates can become as large as the Eddington limit in the range $\sim 10^{-5}$ to 10^{-6} $M_\odot$ yr^{-1} (Bath & Pringle 1982). Equally appealing, however, are models that propose a thermonuclear runaway (Kenyon 1988); during quiescence, material deposited on the degenerate surface of a low-mass white dwarf, at rates of $\sim 10^{-7}$ to 10^{-8} $M_\odot$ yr^{-1}, leads to thermal instability that results in multiple hydrogen shell flashes (Sion & Starrfield 1986; Sion & Ready 1992). The velocities associated with mass expulsion during outbursts can range between hundreds to several thousand km s^{-1}.

In the wavelength range accessible by the *International Ultraviolet Explorer* (*IUE*) ($\lambda\lambda$1200–3200), symbiotic spectra are characterized by strong permitted line emission, e.g., N V $\lambda\lambda$1238, 1242, C IV $\lambda\lambda$1548, 1550, He II λ1640, Mg II $\lambda\lambda$2795, 2802, in addition to emission from intersystem lines, e.g., O IV] $\lambda\lambda$1397–1407, N IV] λ1487, O III] $\lambda\lambda$1660, 1666, N III] $\lambda\lambda$1747–1753, Si III] $\lambda\lambda$1883, 1892, and C III] $\lambda\lambda$1907, 1909.

[1] *IUE* Guest Investigator.

The C IV $\lambda\lambda$1548.2, 1550.8 emission doublet exhibits particularly interesting behavior unique to symbiotic stars. In a modest number of symbiotic stars that have been observed with *IUE*, the intensity ratio of C IV $I(\lambda1548.2)/I(\lambda1550.8)$ is found lesss than the optically thick limit of unity during periods when the UV line and continuum emission brightens. During a slow spectroscopic brightening of RX Pup that was observed between 1980 and 1986 (Kafatos, Michalitsianos, & Fahey 1985; Michalitsianos et al. 1988), the intensity ratio of C IV $I(\lambda1548.2)/I(\lambda1550.8)$ correlates with the absolute C IV flux, in the sense the ratio decreases (or more anomalous) with increasing C IV line and UV emission. Michalitsianos et al. (1988) suggested this effect may be the result of optical-depth variations associated with a $\sim$500 to 800 km s^{-1} high-speed wind from the hot star in RX Pup. In this interpretation, the broad P Cygni absorption trough of the λ1550 line diminishes flux at λ1548, thus reducing the ratio of the intensities of the doublet below the optically thick limit of unity at maximum UV light. The minimum velocity estimated for the wind ($\sim$500 km s^{-1}) is set by the wavelength spacing of the C IV doublet (2.6 Å), and an upper limit ($\sim$800 km s^{-1} was estimated by the absence of P Cygni absorption blueward of the C IV λ1548 line.

The C IV line profile structure also suggests a low-velocity ($\sim$100 to 200 km s^{-1}) wind from narrow P Cygni profile structure in RX Pup that truncates emission from the underlying broad C IV profile. The red wings of the C IV lines became very extended during this spectroscopic brightening phase, when the C IV lines were $\sim$ +200 to +400 km s^{-1} (full basewidth). Several narrow, deep absorption features are evident at the C IV line core and redward of line center in RX Pup. Structure of this character was also observed in a similar system, the R Aqr–central H II region (Michalitsianos et al. 1988). The Wolf-Rayet character of the C IV profiles during enhanced UV emission suggests a broad underlying turbulent region of $\sim$500 km s^{-1} (full basewidth) that occurs when C IV doublet ratios are most anomalous. With a slow decrease in UV line emission, the C IV doublet ratio assumes values close to the theoretical optically thick limit of unity.

Anomalous C IV doublet intensities are observed in a number of other symbiotic stars in addition to RX Pup; these include R Aqr (central region) Michalitsianos et al. 1988), Z And (Cassatella, Fernandez-Castro, & Oliversen 1988), AG Peg (Chochol, Komarek, & Vittone 1988), the recurrent nova RS Oph (Shore & Aufdenberg 1991), and CH Cyg, from spectra we have examined. In all cases, the C IV λ1548 component appears weaker compared with the λ1550 line during slow outbursts, but never completely disappears. According to Michalitsianos et al. (1988), the wind velocities would be highly constrained because the maximum speed could not greatly exceed 800 km s^{-1}. Otherwise, a deep P Cygni trough would be evident in the violet wing of the C IV λ1548.2 line; this is not observed.

Alternatively, the anomalous C IV intensities could be explained by strong optical-depth effects in the C IV emitting region that substantially increases self-absorption in the core of strong resonance lines. This interpretation is consistent with the presence of O I] λ1641.3 which is found in some symbiotic stars when the C IV doublet ratio is $\leq$1. O I] λ1641.3 is formed from the same upper level ($3s^3S^o$) as the O I λ1302 line. When the medium is optically thick, substantial reabsorption of the zero-volt level of O I λ1302 will occur. The decay from the $3s^3S^o$ upper level will take place through the O I] λ1641.3 line ($3s^3S^o \rightarrow 2p^4\ ^1D$ transition) first suggested by Hack (1982). O I] λ1641.3 emission was identified during a recent outburst in the recurrent nova RS Oph (Shore & Aufdenberg 1991). O I] λ1641 emission was clearly resolved from He II λ1640 emission in HIRES (high resolution) *IUE* spectra obtained of RX Pup near maximum UV light during its slow brightening between 1981 and 1986 (Kafatos et al. 1985) which peaked around 1981 June 11; O I] λ1641 disappeared entirely in 1985, when the C IV $I(\lambda1548.2)/I(\lambda1550.8) \sim 1.0$.

Another process which is important for explaining the presence of deep broad absorption features, and which can account for a significant fraction of the flux deficit of the C IV λ1548.2 line during slow brightening phases, is the fluorescence pumping of Fe II. Bowen-pumping of the Fe II multiplet (45.01) λ1548.204 that selectively pumps the upper $y^4H^o_{11/2}$ level by C IV λ1548.2 was first identified by Johansson (1983) in RR Tel. The C IV λ1548.2 line coincides almost exactly in wavelength with Fe II λ1548.204 $\{a^4F_{9/2}$–$y^4H^o_{11/2}\}$ transition. Fluorescence is indicated by the presence of 10 strong emission lines of Fe II (209), (243), and (282) in RR Tel that correspond to the downward cascades from the $y^4H^o_{11/4}$ level (Johansson 1983). Bowen-pumping of the Fe II multiplet (45.01) by C IV λ1548.2 was subsequently also found in AG Peg (Penston & Allen 1985).

We have analyzed the fluxes of the Fe II Bowen-excited lines in RR Tel from the HIRES *IUE* SWP and LWR/LWP archives which were obtained over a decade of monitoring, in order to determine if the C IV λ1548.2 intensity and the strengths of the fluorescent-excited Fe II lines are correlated. Bowen-pumped excited Fe II multiplets (168), (209), and (282) have been identified in RX Pup. Our analysis includes HIRES spectra of the S-type symbiotic star AG Peg where Fe II Bowen emission was identified by Penston & Allen (1985). AG Peg is in a state of decline following a major outburst that occurred in 1850. The results are as follows.

1. The C IV doublet intensity ratios in RR Tel were not anomalous between 1979 and 1989, and the ratio had typical values consistent within the optically thin range, i.e., $1 \leq$ C IV $I(1548.2)/I(\lambda1550.8) \leq 2$, with a mean value $\sim$1.3. The intensity of individual Fe II Bowen-excited lines is correlated with the C IV λ1548.2 flux. This suggests the presence of a foreground Fe II region (or shell) in which fluorescent-excited material responds to flux variations of C IV λ1548.2. The velocity centroids of the Fe II Bowen lines correspond to the peak flux of the C IV λ1548.2 line and suggest a circumstellar region that is essentially at rest with respect to the hot ionizing source in this system.

2. In RX Pup the combined fluxes of Fe II Bowen-pumped lines can account for an appreciable fraction of the flux deficit in the C IV λ1548.2 line when the C IV doublet ratio is less than the optically thick limit of unity. The combined fluorescent emission ΣFe II (Bowen) can equal (or exceed) the deficit of flux needed, such that C IV $I(\lambda1548.2)/I(\lambda1550.8) \sim 1$. The Fe II Bowen lines in RX Pup exhibit a velocity range of $0 \leq v_{\rm Fe\,II} \leq +80$ km s^{-1}, where several strong Fe II emission lines correspond to deep absorption structure in the C IV λ1548.2 line profile.

3. In AG Peg the C IV λ1548.2 flux deficit cannot be explained by Fe II fluorescent absorption alone when the C IV doublet ratio anomaly is at an extreme. In this case optical depths associated with a wind from the hot star significantly affect radiative transfer of line and continuum radiation, substantially increasing self-absorption. This is supported by the N V $\lambda\lambda$1238, 1242 resonance lines, which do not fluorescentally excite other ionic species, but do exhibit anomalous doublet intensities similar to the C IV doublet.

2. DATA ANALYSIS

HIRES *IUE* SWP $\lambda\lambda$1200–2000 and LWR/LWP $\lambda\lambda$2000–3200 spectra ($\Delta\lambda \sim 0.1$ Å limiting spectral resolution) from the data archives of the Regional Data Analysis Facility (RDAF) at NASA Goddard Space Flight Center were analyzed using RDAF astronomical IDL application programs. We reprocessed all spectra using the most recent intensity transfer function (ITF) of LWP/LWR spectra. The SWP and LWR/LWP spectra sets for a given epoch were chosen carefully to assure that the SWP spectra with the C IV doublet were not saturated, and the exposure times for the LWR/LWP cameras were sufficiently long to detect the Fe II Bowen lines. The wavelengths and absolute lines intensities were obtained using the current ITF *IUE* extraction software. The wavelength centers are weighted averages from the reprocessed images obtained using the *IUE* data archives.

Three of the fluorescent-excited lines arising from Fe II multiplets (168) $\lambda\lambda$2211, 2219, 2227 are located in a low-sensitivity region of the LWR/LWP cameras (2000 Å $\leq \lambda \leq$ 2300 Å), and spectra available from the *IUE* archives were not sufficiently long to detect these lines above background. However, six lines of Fe II multiplets (209), (243), (282) were found, which arise from the downward cascade of the $y^4H_{11/2}$ level. In Table 1, the *IUE* camera, sequence numbers, and exposures times are given for spectra used to obtain absolute C IV and Bowen Fe II line intensities for RR Tel. In Figure 1, we have plotted the absolute intensities of two Fe II Bowen lines that have the largest *gf*-values (Fe II $\lambda\lambda$2458, 2771: *filled and open rectangles*, respectively) against the C IV 1548.2 flux for RR Tel. We included Fe II multiplet (1) λ2599 for comparison (*open circles*), which is not fluorescent-excited.

The flux of Bowen-pumped lines correlate with the C IV λ1548.2 intensity. The difference in slopes between the Fe II λ2458 and λ2771 may be explained by contributions from at least four other *LS* states that affect the population of the $y^4H^o_{11/2}$ of the λ2771.15 line (Johansson 1983). Mixing from neighboring subordinate levels can also populate the $y^4H^o_{11/2}$ level. Nevertheless, the Fe II Bowen-pumped lines correlate with C IV λ1548.2 strength, in the sense of a linear dependence,

TABLE 1

LIST OF *IUE* OBSERVATIONS FOR RR TELESCOPII FLUORESCENCE LINES

Camera/Image Sequence Number	Date (Julian)	Date	Exposure (minutes)
SWP 8609	2444331	1980 Apr 2	10
LWR 7356	2444331	1980 Apr 2	15
SWP 9510	2444435	1980 Jul 14	20
LWR 8234	2444435	1980 Jul 14	20
SWP 14727	2444828	1981 Aug 12	25
LWR 11293	2444828	1981 Aug 12	25
SWP 14729	2444828	1981 Aug 12	25
LWR 11296	2444828	1981 Aug 12	25
SWP 18371	2445297	1982 Nov 24	20
LWR 14466	2445297	1982 Nov 24	20
SWP 28293	2446563	1986 May 13	30
LWP 8180	2446563	1986 May 13	25
SWP 28740	2446636	1986 Jul 25	20
LWP 8728	2446636	1986 Jul 25	20
SWP 28745	2446637	1986 Jul 26	40
LWP 8729	2446637	1986 Jul 26	40

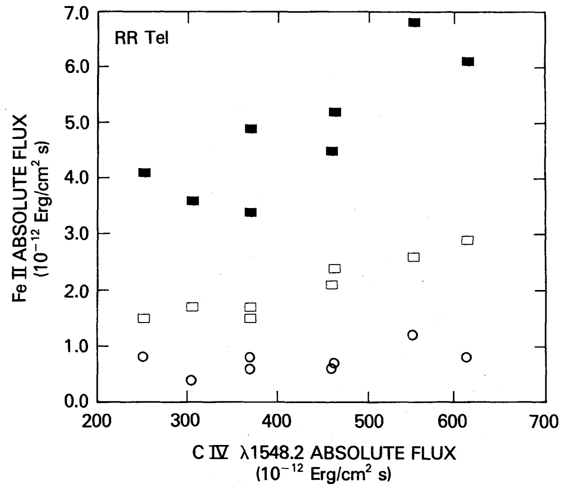

FIG. 1.—The absolute Fe II intensities plotted against the absolute intensity of C IV λ1548.2 in RR Tel; *filled squares*, Bowen pump Fe II multiplet (209) λ2458.8; *open squares*, Bowen pumped Fe II multiplet (282) λ2771.1. We also show collisionally excited Fe II multiplet (1) λ2599.4 (*open circles*) for comparison.

while the collisionally excited Fe II λ2599 emission is independent of the C IV intensity.

However, the relationship between Bowen-pumped Fe II and C IV fluxes is considerably different in RX Pup and AG Peg. The absolute fluxes for RX Pup and AG Peg are shown in Tables 2 and 3, respectively, together with radial velocities obtained for each line. In Table 2, the intensity of Bowen-pumped Fe II lines in RX Pup is shown for two epochs when the UV light was near maximum on 1981 June 11 (Fig. 2*a*), and during one epoch (1983 October 20; Fig. 2*b*).

The C IV λ1548.2 emission in RX Pup increased by $\sim$8% between 1981 June 11 and 1983 October 29, while the C IV 1550.8 line decreased by $\sim$20% over this same period. The C IV doublet ratios for these dates (Fig. 2*a*, *b*: top and bottom) were $\sim$0.6 and $\sim$0.8, respectively. In AG Peg, the C IV λ1548.2 increased relative to λ1550.8, as the doublet ratio became more "normal," i.e., of order unity. The C IV doublet ratio in AG Peg was $\sim$0.2 at maximum UV light when the doublets exhibited velocity-broadened wings (1979 September 15). The ratio $\sim$1.0 when the UV flux decreased (1981 January 8) and acquired more optically thin values of $\sim$1.5 (1989 October 15); in AG Peg the variation of the doublet ratio exhibits the widest range of the three three symbiotic stars investigated.

In Figure 3, the C IV line profiles for AG Peg are shown for three dates, respectively. The C IV line profiles exhibit considerable emission structure. In particular, several weak emission components are visible blueward and redward of the rest frame of the star, suggesting velocity-shifted C IV emitting regions. A number of these components visible around the λ1548 line have corresponding components at λ1550, determined by their appropriate wavelength separation of 2.6 Å.

3. RESULTS AND DISCUSSION

Johansson (1983) provided an explanation for the presence of a number of unidentified lines in the UV spectral atlas of RR Tel (Penston et al. 1983) as fluorescent-excited Fe II emission that is pumped by C IV λ1548.2. The Fe II Bowen lines correspond to the downward cascades from the $y^4H^o_{11/2}$ level. We found that the intensity of the Fe II Bowen-pumped lines are correlated with the C IV λ1548.2 intensity, consistent with this

TABLE 2

Fe II FLUORESCENCE LINES IN RX PUPPIS

Ion	λ(lab) (Å)	log gf[c]	1981 June 11[a] $\lambda(IUE)$ (Å)	1981 June 11[a] Absolute Flux[d]	1981 June 11[a] $V_{\rm Fe\,II}$[e] (km s^{-1})	1983 October 29[b] $\lambda(IUE)$ (Å)	1983 October 29[b] Absolute Flux[d]	1983 October 29[b] $V_{\rm Fe\,II}$[e] (km s^{-1})
Fe II multiplet (168).........	2211.0	−1.58		Very weak?			Very weak?	
Fe II multiplet (168).........	2219.8	−0.53		Very weak?			Very weak?	
Fe II multiplet (168).........	2227.3	−1.44	2227.9	2.8	+71		Very weak?	
Fe II multiplet (209).........	2436.2	−0.85	2436.4	11.3	+ 6	2436.4	0.8[f]	+10
Fe II multiplet (209).........	2458.8	0.46	2459.2	2.8	+39	2459.0	0.6[f]	+14
Fe II multiplet (243).........	2481.0	−0.68	2481.7	0.7	+69	2481.5	1.3	+41
Fe II multiplet (243).........	2492.3	−0.74	2492.3[e]	1.3[f]	+72[g]	2492.6	1.4[g]	+30
Fe II multiplet (282).........	2771.1	−1.64	2771.4	5.6	+16[g]	2771.3	1.4	+13

[a] C IV (λ1548.2)/C IV (λ1550.8) ~ 0.6, C IV $I(\lambda1548.2) = 34.9 \times 10^{-13}$ ergs cm^{-2} s^{-1}.
[b] C IV (λ1548.2)/C IV (λ1550.8) ~ 0.8, C IV $I(\lambda1548.2) = 38.5 \times 10^{-13}$ ergs cm^{-2} s^{-1}.
[c] Log gf-values from Kurucz 1981.
[d] Flux is in units of 10^{-13} ergs cm^{-2} s^{-1}.
[e] Corrected for radial velocity ~ +11 km s^{-1} (Wallerstein 1986).
[f] Weak feature.
[g] Emission feature is broad.

fluorescence process, which suggests the existence of a low-excitation emitting region where Fe II fluorescent-excited emission responds to flux variations in the C IV emitting region.

We can estimate the nebular parameters for the Fe II absorbing shell. Taking a velocity spread parameter $b \sim 40$ km s^{-1} for Fe II emitting material, we have from Spitzer (1978)

$$\tau_{\rm Fe\,II}(\lambda1548.2) \sim 1.5 \times 10^{-18} f_{12}\, L N_{\rm Fe\,II}(a^4F_{9/2}) n_e\,, \quad (1)$$

where the f-value f_{12} can be obtained from Kurucz (1981), $f_{12} \sim 5.83 \times 10^{-5}$. Here "1" refers to the lower level $a^4F_{9/2}$ and "2" to the upper level $y^4H^o_{11/2}$. In equation (1) we assumed cosmic abundances for iron. Assuming $\tau_{\rm Fe\,II}$ (λ1548.2) ≥ 1, we find $Ln_e N_{\rm Fe\,II}(a^4F_{9/2}) \sim 1.1 \times 10^{22}$ cm^{-2}. The number of Fe II ions in the $a^4F_{9/2}$ state is difficult to estimate because of the multitude of transitions involving Fe II. However, an upper limit can be found from the Boltzmann formula, if only transitions between the ground state term a^6D and the excited state a^4F are considered; that is, $N_{\rm Fe\,II}(a^4F_{9/2}) \sim 0.25$. Taking the other low-lying levels into consideration, we expect that $N_{\rm Fe\,II}(a^4F_{9/2}) \ll 1$. If $T_e \sim 10^4$ K, we then find $Ln_e \geq 4.4 \times 10^{22}$ cm^{-2}. On the other hand, if $T_e = 10^3$ K, then $Ln_e \geq 5.5 \times 10^{23}$ cm^{-2}. Typically, $n_e \sim 10^{10}$ cm^{-3} for RX Pup (Kafatos et al. 1985), which yields for $T_e = 10^4$ K, which is a lower size limit of the Fe II shell of $\sim 4.4 \times 10^{12}$ cm. This size is typical of radii associated with evolved M giants, which in the case of RR Tel is a 387^d period Mira. The size and densities suggest that Fe II emission occurs in the extended atmosphere or circumstellar shell.

However, in RX Pup and AG Peg the relationship between C IV λ1548.2 emission and the strength of fluorescent-excited Fe II lines is quite different compared with RR Tel. In Figure 4, we have plotted the C IV λ1548.2 line profile and the Fe II Bowen-pumped lines of RX Pup in velocity space (relative to the laboratory rest wavelength) against absolute intensity, when the C IV doublet ratio was $I(\lambda1548.2)/I(\lambda1550.8) \sim 0.6$ on 1981 June 11; the systemic velocity of the system is ~ +11 km s^{-1} (Wallerstein 1986). The Fe II Bowen-pumped lines $\{a^4F_{9/2} \rightarrow y^4H^o_{11/2}\}$ exhibit a velocity range $0 \leq v_{\rm Fe\,II} \leq +80$ km s^{-1}, where the individual multiplet components are labeled: (b) Fe II λ2436.2 and (e) λ2771.1 correspond to a deep

TABLE 3

Fe II FLUORESCENCE LINES IN AG PEGASI

Ion	λ(lab) (Å)	log gf[d]	1979 Sept. 15[a] $\lambda(IUE)$ (Å)	1979 Sept. 15[a] Absolute Flux[e]	1979 Sept. 15[a] $V_{\rm Fe\,II}$[f] (km s^{-1})	1981 Jan. 8[b] $\lambda(IUE)$ (Å)	1981 Jan. 8[b] Absolute Flux[e]	1981 Jan. 8[b] $V_{\rm Fe\,II}$[f] (km s^{-1})	1989 Oct. 15[c] $\lambda(IUE)$ (Å)	1989 Oct. 15[c] Absolute Flux[e]	1989 Oct. 15[c] $V_{\rm Fe\,II}$[f] (km s^{-1})
Fe II multiplet (168).........	2211.0	−1.58	2211.2	3.6[g]	+ 5		Very weak?			Very weak?	
Fe II multiplet (168).........	2219.8	−0.53	2220.0	7.2	+ 8		Very weak?			Very weak?	
Fe II multiplet (168).........	2227.3	−1.44	2227.3	8.3	− 8	2227.4	5.5	+ 0		Very weak?	
Fe II multiplet (209).........	2436.2	−0.85	2436.2	10.5	−20	2436.0	7.4[h]	−37	2436.2	5.9	−10
Fe II multiplet (209).........	2458.8	0.46	2458.8	13.4[h]	−15	2459.1	11.8	−41	2458.7	8.3	−23
Fe II multiplet (243).........	2481.0	−0.68	2481.0	12.6	− 7	2480.8	6.2	−36	2481.0	10.3[h]	−19
Fe II multiplet (243).........	2492.3	−0.74	2492.3	11.2	−11	2492.1	9.8	−37	2492.3	6.9	−10
Fe II multiplet (282).........	2771.1	−1.64	2771.1	13.1	−14	2771.0	11.0	−26	2771.0	8.0	−21

[a] C IV (λ1548.2)/C IV (λ1550.8) ~ 0.2, C IV $I(\lambda1548.2) = 409.0 \times 10^{-13}$ ergs cm^{-2} s^{-1}.
[b] C IV (λ1548.2)/C IV (λ1550.8) ~ 0.9, C IV $I(\lambda1548.2) = 1130.0 \times 10^{-13}$ ergs cm^{-2} s^{-1}.
[c] C IV (λ1548.2)/C IV (λ1550.8) ~ 1.5, C IV $I(\lambda1548.2) = 642.0 \times 10^{-13}$ ergs cm^{-2} s^{-1}.
[d] Log gf values from Kurucz (1981).
[e] Flux is in units of 10^{-13} ergs cm^{-2} s^{-1}.
[f] Corrected for radial velocity ~ +16 km s^{-1} (Slovak & Lambert 1988).
[g] Weak feature.
[h] Emission feature is broad.

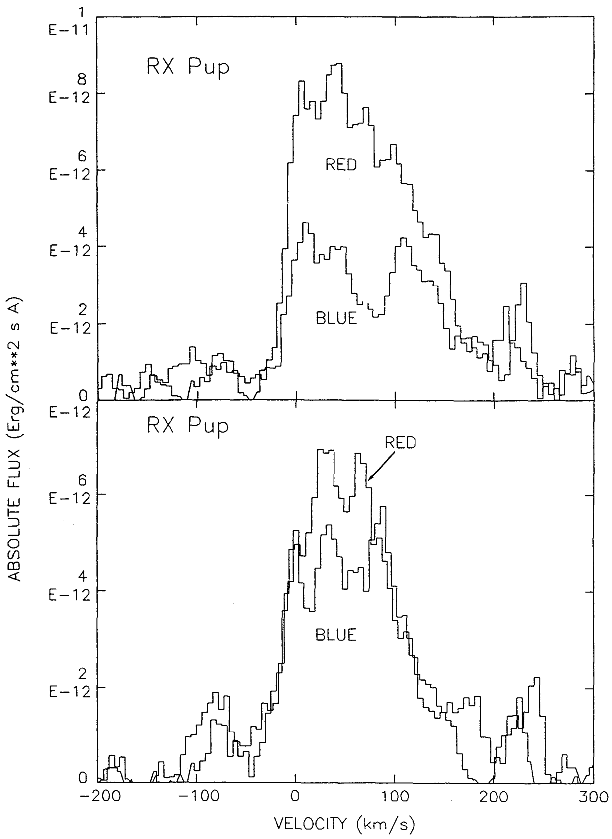

FIG. 2.—Both spectra are shown on common velocity scales obtained relative to the laboratory rest wavelength and are not corrected for the radial velocity of the system; Wallerstein (1986) gives $V_R \sim +11$ km s^{-1}. (*a*) C IV $\lambda\lambda$1548.2, 1550.8 observed in RX Pup for two epochs when the C IV $I(\lambda 1548.2)/I(\lambda 1550.8) = 0.6$ on 1981 June 11 (*top panel*). (*b*) C IV $I(\lambda 1548.2)/I(\lambda 1550.8) = 0.8$ on 1983 October 29 (*bottom panel*).

C IV absorption feature centered at $\sim +25$ km s^{-1}. Fe II (*d*) λ2481.7 and (*a*) λ2227.3 coincide with a broad C IV absorption feature at $\sim +80$ km s^{-1}. The deep absorption structures evident in the C IV λ1548.2 line are not seen in the λ1550.7 line (Fig. 2).

The velocity range exhibited by the Fe II Bowen lines in RX Pup is not found in RR Tel (Fig. 5), where the velocity centroids of the Bowen Fe II line multiplets (209), (243), and (282) coincide with the peak flux in C IV λ1548.2, at -47 km s^{-1} (rest is with respect to the laboratory rest wavelength). The radial velocity of RR Tel relative to interstellar lines is ~ 114 km s^{-1}, and a systematic difference between absorption and emission lines $V_{\rm em} - V_{\rm abs} = -80 \pm 7$ km s^{-1} was found by Penston et al. (1983). Similarly, the velocity centroids of Fe II Bowen lines in AG Peg $\sim \pm 10$ km s^{-1} of the peak emission of C IV; this is close to the radial velocity of the system, where $V_R \sim -16$ km s^{-1}.

Thus, the kinematic structure of the fluorescent Fe II forming region in RX Pup is distinct compared with RR Tel and AG Peg. It is interesting to note that the period over which the C IV $I(\lambda 1548)/I(\lambda 1550)$ was less than unity in RX Pup coincided with a decrease in brightness in both V and J photometric bands found by Whitelock et al. (1984). Our *IUE* observations of 1981 June 11 were obtained at the start of the decline in photometric brightness in J and V. Whitelock et al. (1984) found that $V = 10.7$ in 1982 and $V = 11.0$ in 1983, at the Mira phase $\phi = 0.55$. They attribute this decrease in V to an obscuration of the 580^d period Mira in RX Pup by a dust cloud in orbit in the system.

Based upon additional J photometry data obtained of RX Pup kindly provided by P. A. Whitelock, the decrease in the J brightness appears to have started in 1981 June and persisted for ~ 3 yr. The decline in photometric brightness occurred during our *IUE* observations of 1981 June 11. The C IV doublet ratio gradually increased to values of order unity by 1984 (cf. Kafatos et al. 1985). This provides evidence that the anomalous C IV doublet ratio is associated with this obscuration event. The velocity range $0 \le v_{\rm Fe\,II} \le +80$ km s^{-1} found here may reflect the differential motion of gas parcels within the obscuring cloud that have mainly positive radial velocity components with respect to the line of sight.

The relative intensities of the individual Bowen multiplets in RX Pup do not correspond to the predicted intensities based on the multiplet oscillator strengths. This could result from the

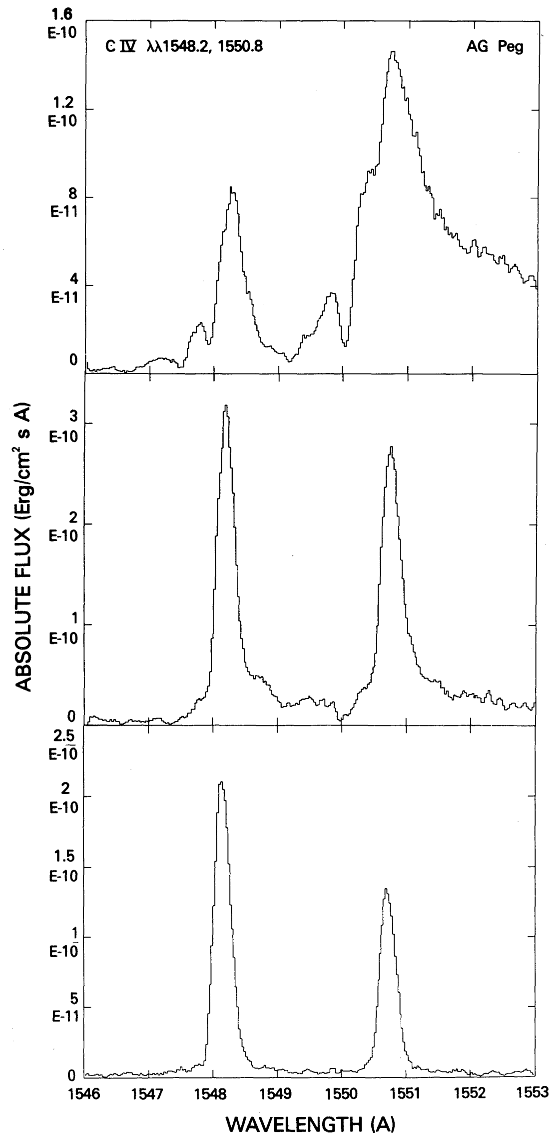

FIG. 3.—C IV $\lambda\lambda$1548.2, 1550.8 observed in AG Peg for three epochs: C IV $I(\lambda 1548.2)/I(\lambda 1550.8) = 0.2$ on 1979 September 15 (*top panel*), 0.9 on 1981 January 8 (*middle panel*), and 1.5 on 1989 October 15 (*bottom panel*).

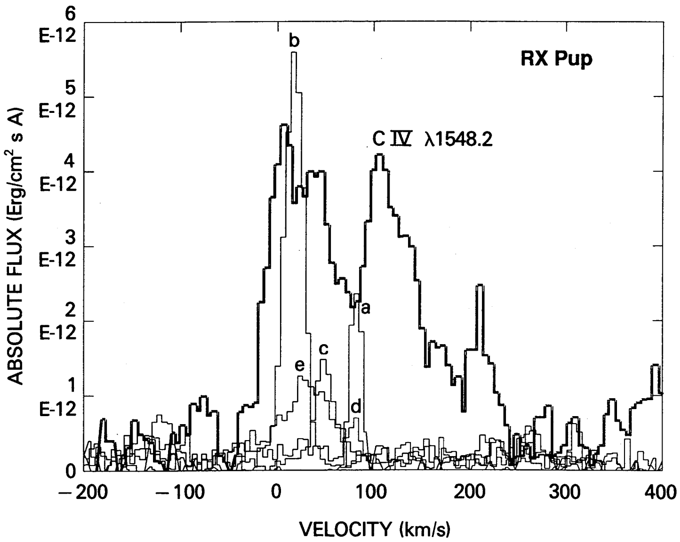

FIG. 4.—C IV $\lambda1548.2$ plotted in velocity space with Bowen-pumped Fe II emission lines in RX Pup. Emission line (*a*) Fe II $\lambda2227.3$, (*b*) Fe II $\lambda2436.2$, (*c*) Fe II $\lambda2458.8$, (*d*) Fe II $\lambda2481.0$, (*e*) Fe II $\lambda2771.1$.

complex kinematics of the Fe II emitting foreground cloud. We assume that the pumped Fe II multiplet (45.01) $\lambda1548.204$ probably has a width comparable to that of the downward cascade transitions, which for Fe II $\lambda2436.2$ is ~ 40 km s^{-1} (FWHM); the width of the C IV $\lambda1548.2$ line is nearly 6 times larger. The absolute strength of the Fe II fluorescent lines will be largely determined by the relative velocity of the Fe II gas parcels with respect to C IV emitting region. Parcels with speeds in excess of $\geq \pm 125$ km s^{-1} will be Doppler-shifted outside of the C IV emission profile, substantially decreasing the pumping efficiency.

The extent to which fluorescent pumping of Fe II effectively scatters C IV $\lambda1548.2$ radiation into the iron spectrum is reflected by the combined strength of the downward cascades of

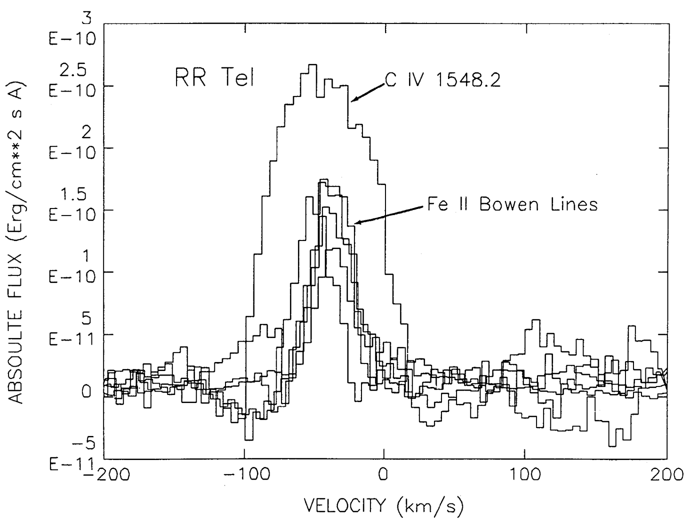

FIG. 5.—The C IV $\lambda1548.2$ line plotted on a common velocity scale with Fe II Bowen lines $\lambda\lambda2436.2$, 2458.8, 2481.0, 2492.3, and 2771.1. The absolute flux of the Fe II lines have been scaled by a factor of 50 in order to better compare the velocity centroids with C IV. The rest velocity is determined by the laboratory rest wavelengths, and the plots are not corrected for the radial velocity of the system (see text).

Bowen multiplets. In Table 2 the observed absolute fluxes of the Bowen-pumped Fe II lines are shown for RX Pup. If we take the C IV flux ratio for 1981 June 11, when the C IV $I(\lambda1548.2)/I(\lambda1550.8) \sim 0.6$, the total flux in the Fe II Bowen lines can be compared to C IV $\lambda1548.2$ emission. Assuming circumstellar and interstellar absorption is negligible, the total flux of the fluorescent-excited Fe II lines is $\Sigma I\{\text{Fe II Bowen}\} \sim 10^{-13}$ ergs cm^{-2} s. Adding this value the total flux to the C IV $\lambda1548.2$ intensity, we find

$$\frac{\Sigma I\{\text{Fe II Bowen}\} + \text{C IV } I(\lambda1548.2)}{\text{C IV } I(\lambda1550.8)} \sim 1.2 , \tag{2}$$

which is a lower limit. This suggests that a substantial fraction of C IV $\lambda1548.2$ flux can be absorbed by this process.

Equation (2) does not include the effects of differential extinction. If the absorption is largely circumstellar as might be the case for D-types such as RR Tel and RX Pup, correcting the C IV line intensities arising from this effect is complicated because the form of the circumstellar reddening law appropriate is not well known. Whitelock (1988) finds that variations in the IR light curve of systems such as RX Pup may be the result of spontaneous large-scale mass transfer from the Mira onto the secondary, and that the reddening in objects such as RX Pup and R Aqr may be time-dependent and caused by eclipses of an obscuring cloud associated with the hot companion. As such, circumstellar reddening and dust emission in the IR can have a strong influence in the observed colors of Miras in symbiotic systems (Whitelock 1988).

As a first-order approximation, we can adopt the Savage & Mathis (1979) galactic extinction law for correcting differential reddening in RX Pup. We find that

$$\frac{\Sigma I\{\text{Fe II Bowen}\} + \text{C IV } I(\lambda1548.2)}{\text{C IV } I(\lambda1550.8)} \sim 1.0 , \tag{3}$$

which is $\sim 20\%$ of the value obtained from equation (2). Thus, fluorescent pumping of Fe II by C IV 1548.2 can explain an appreciable fraction of the flux deficit in the blue doublet member when the C IV flux ratio is smaller than the optically thick limit of unity.

However, in AG Peg the flux deficit of C IV 1548.2 cannot be explained by fluorescent pumping of Fe II alone. When the C IV $I(\lambda1548.2)/I(\lambda1550.8) \sim 0.2$ (Table 3; 1979 September 15), the combined ΣFe II Bowen flux constitutes only 17% of the C IV $\lambda1548.2$ flux, and fluorescent pumping of Fe II multiplet (45.01) cannot explain the total flux deficit of C IV $\lambda1548.2$ entirely. Moreover, the N V $\lambda\lambda1238$, 1242 doublet (Fig. 6) also shows anomalous doublet line intensities and is very similar to the C IV doublet in this system. The N V $\lambda\lambda1238$, 1242 doublet is not known to fluorescentally excite other atomic species. We suspect, therefore, that the anomalous doublet intensities evident in both C IV and N V are the result of strong optical-depth effects associated with wind. The region containing the optically thick wind is enclosed by a circumstellar material that is nearly at rest with respect to the UV ionizing source, based upon the velocity centroids of the Fe II Bowen lines relative to the peak flux of the C IV $\lambda1548.2$ line profile.

The onset of an optically thick wind in AG Peg could result following episodes of enhanced mass transfer from the M star (or Mira) onto the hot compact secondary. At luminosities near the Eddington limit, a critical phase can be achieved when the pressure due to accretion balances the luminosity of the accretion boundary region around the compact star. This could explain the formation of a wind emanating from the hot

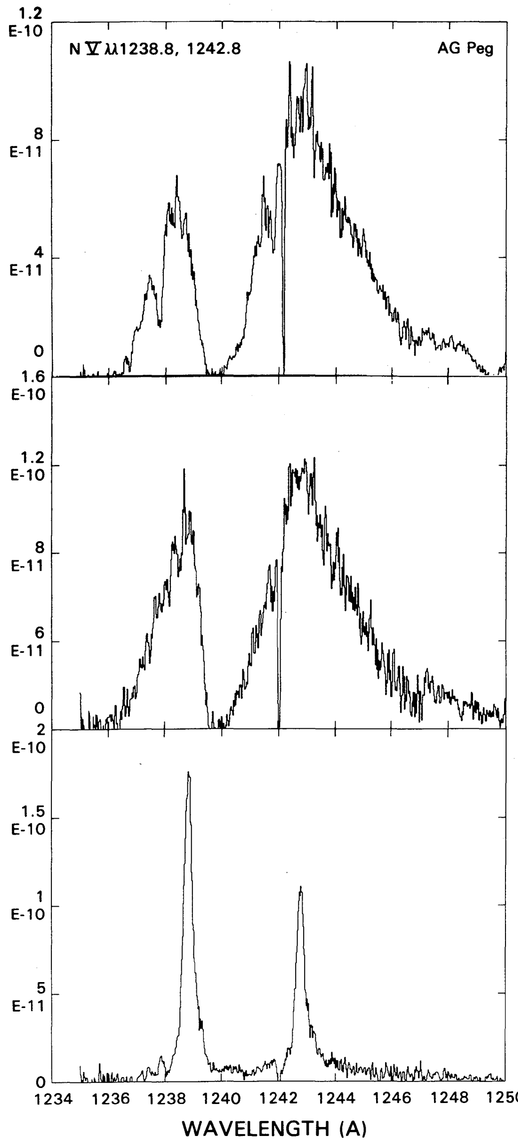

FIG. 6.—N V λλ1238.8, 1242.8 observed in AG Peg for three epochs (*top, middle, bottom*) for the dates shown in Fig. 3. The N V $I(\lambda1238.8)/I(\lambda1242.8)$ doublets exhibit anomalous ratios similar to the C IV profiles (*top panel*) during outburst.

secondary that has appreciable column densities. Based upon the temporal variations observed in the UV line intensities in RX Pup (Kafatos et al. 1985), the optically thick region expands and cools on time scales of ∼1 yr, enabling EUV radiation to escape.

4. SUMMARY AND CONCLUSIONS

We have examined the variation of absolute intensities of Bowen-excited Fe II emission in three symbiotic stars: RR Tel, RX Pup, and AG Peg. Emission lines corresponding to the Fe II $a^4F_{9/2}$–$y^4H^o_{11/2}$ transition are pumped by C IV λ1548.2 due to a coincidence in wavelength with Fe II λ1548.02 multiplet (45.01). In RX Pup the combined flux from Fe II multiplets formed by the downward cascade from the $y^4H^o_{11/2}$ level is sufficient to explain the flux deficit of C IV λ1548.2 relative to λ1550.8 and explain the anomalous doublet C IV intensities observed in this system.

In RR Tel where the C IV doublet ratio is not less than unity, we find that the flux of the Fe II Bowen-excited lines correlate with the intensity of the C IV λ1548.2, which pumps the Fe II $\{a^4F_{9/2}$–$y^4H^o_{11/2}\}$ transition. Moreover, the Fe II Bowen lines coincide with the velocity centroid of the C IV λ1548.2 line profile. This argues for a low-excitation circumstellar Fe II emitting region that is essentially at rest with respect to the high-excitation C IV emitting source in this system. This provides further evidence in support of Fe II fluorescent pumping by C IV λ1548.2, first identified by Johansson (1983) in RR Tel.

The Fe II Bowen-pumped lines in AG Peg coincide closely to the velocity centroid of the C IV λ1548.2 line similar to RR Tel. This suggests a circumstellar low-excitation region that is essentially near the rest frame of the central UV source. However, unlike RR Tel, the absolute intensities of the Bowen-pumped lines are anticorrelated with the absolute C IV flux. Optical depth variations in an optically thick wind may affect the ionization state of the circumstellar region, causing Fe II emission to decrease as the flux of C IV increases. Moreover, the combined absolute intensities of the Fe Bowen-pumped lines cannot explain the flux deficit of C IV 1548.2 relative to C IV 1550.8 when the doublet ratio is most extreme.

In RR Pup the combined flux ΣFe II (Bowen) of the fluorescent-excited Fe II lines can explain the deficit of flux of the C IV λ1548.2 line relative to C IV λ1550.8 line. Several deep absorption features prominent in the C IV λ1548.2 line coincide in velocity with two of the Fe II Bowen-pumped lines. This explains the more complex line profile structure exhibited by C IV λ1548 compared with λ1550.8. In contrast with RR Tel and AG Peg, the Fe II Bowen-pumped lines in RX Pup exhibit a velocity range of $0 \leq v_{\rm FeII} \leq +80$ km s^{-1} with respect to the velocity centroid of C IV λ1548.2. The velocity range over which the Bowen-pumped lines are found may indicate differential motions within an obscuring cloud of dust which Whitelock et al. (1984) proposed had decreased light from the Mira in *J* and *V* photometric bands in RX Pup. We find that the C IV doublet was significantly less than the optically thick limit during the occultation period which lasted ∼3 yr.

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