ULTRAVIOLET SPECTROSCOPY OF BINARY SYSTEMS

A.K. Dupree, L. Hartmann, and J.C. Raymond
Harvard-Smithsonian Center for Astrophysics
Cambridge, MA 02138 U.S.A.

1. INTRODUCTION

The recent launch of the International Ultraviolet Explorer (IUE) satellite and its spectrographic instruments (Boggess et al. 1978a,b) suddenly made accessible large numbers of diverse types of binary systems. These range from the luminous hot supergiants with compact companions that produce copious amounts of X-rays to the dwarf solar like stars of W UMa-type. For systems such as these and many others the IUE is a new and unique tool with which to probe the structure of extended stellar atmospheres, the presence and acceleration of a stellar wind, and the appearance of stellar chromospheres and coronae.

In this review, we shall discuss four typical systems that illustrate some of the major problems in the study of binary stars. They are:

- High Luminosity X-ray sources typified by Cyg X-1 (HDE 226868) and Vela XR-1 (HD 77581).
- Low Luminosity X-ray sources (HZ Her).
- Late-Type Systems of W UMa and RS CVn type.
- Cool Supergiants with a Hot Companion (VV Cephei).

Each of these classes also shows the unique nature of ultraviolet emissions with which to investigate particular aspects of stellar atmospheres.

2. HIGH LUMINOSITY X-RAY SOURCES

These systems typically contain a hot early type supergiant star and a companion compact object. X-rays are produced by accretion of material onto the compact object either from the massive stellar wind or following Roche Lobe overflow. The luminous primary star dominates the ultraviolet spectrum although effects of the X-ray source upon the stellar wind can be found; studies of such effects were not fruitful before the advent of IUE.

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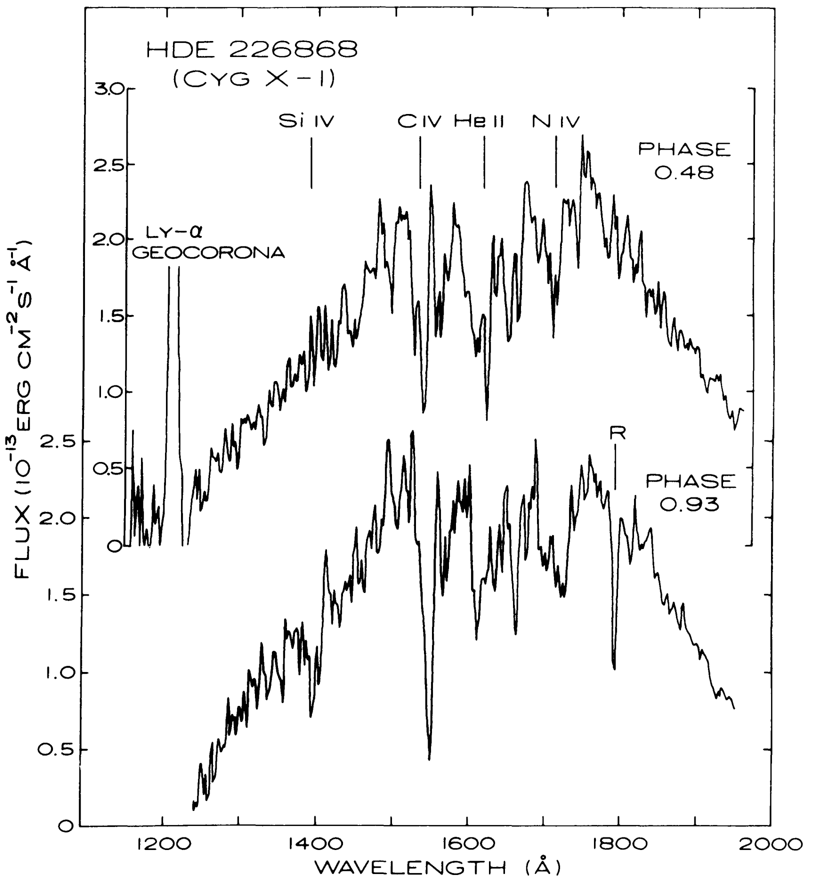

Figure 1. Low dispersion short wavelength exposures from IUE of HDE 226868 (Cyg X-1) at two orbital phases (Dupree et al. 1978). Note the weakening of the Si IV and C IV lines at phase 0.48 (near inferior conjunction of the compact object) as compared to phase 0.93. R denotes a reseau - a fiducial mark.

The first spectroscopic measurements of HDE 226868 (Cyg X-1) (Fig. 1) were taken by the IUE Commissioning Team in the low dispersion mode (Dupree et al. 1978) and appeared to be a typical spectrum of a highly reddened early - B supergiant showing characteristic P Cygni profiles indicating the presence of substantial mass loss. However, variation in the line profiles with orbital phase was apparent. From the low dispersion spectra, one finds the absorption components are strong at superior conjunction of the compact object. They become weaker near phase 0.5 when the compact object lies between us and the supergiant. Although only 2 spectra were available at first, a later more thorough study (Treves et al. 1979) of this source as part of an international collaboration of scientists from Europe, the United Kingdom and the U.S.A. confirmed the earlier result.

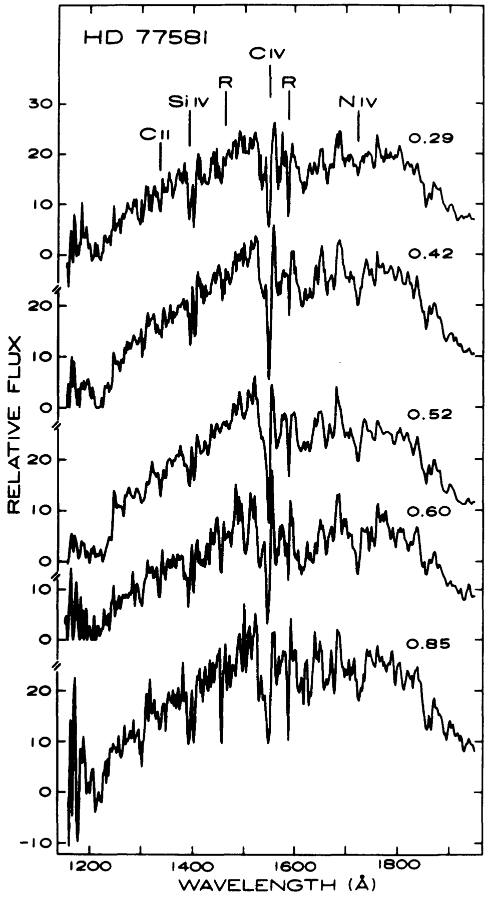

Figure 2. Low dispersion short wavelength exposures from IUE of HD 77581 (Vela XR-1) at many orbital phases (Dupree et al. 1979). Phase 0.0 corresponds to eclipse of the X-ray emitting pulsar.

Another binary system, HD 77581, identified with the X-ray source Vela XR-1 (4U 0900-40) is composed of a hot supergiant (B0.5Ib) and a pulsar with a 283 second period (McClintock et al. 1976) which is orbiting the primary with an 8.96 day period. At low dispersion (Fig. 2) the spectrum appears similar to HDE 226868 and also shows similar phase effects in the P Cygni features (Dupree et al. 1979). Fortunately, this system is relatively bright so that accurate high dispersion measurements are possible with IUE. Fig. 3 shows a portion of the high dispersion spectrum near λ1550. The extended short wavelength absorption at phase ϕ = 0.04 indicates terminal velocities V $\sim$ 1700 km s^{-1}. The most interesting aspect is the dramatic change in appearance of the P Cygni profiles. As the secondary passes in front of the primary star, the edge velocity of the profile decreases and a high velocity absorption feature appears at phase 0.52. A similar phenomenon is found in the Si IV lines.

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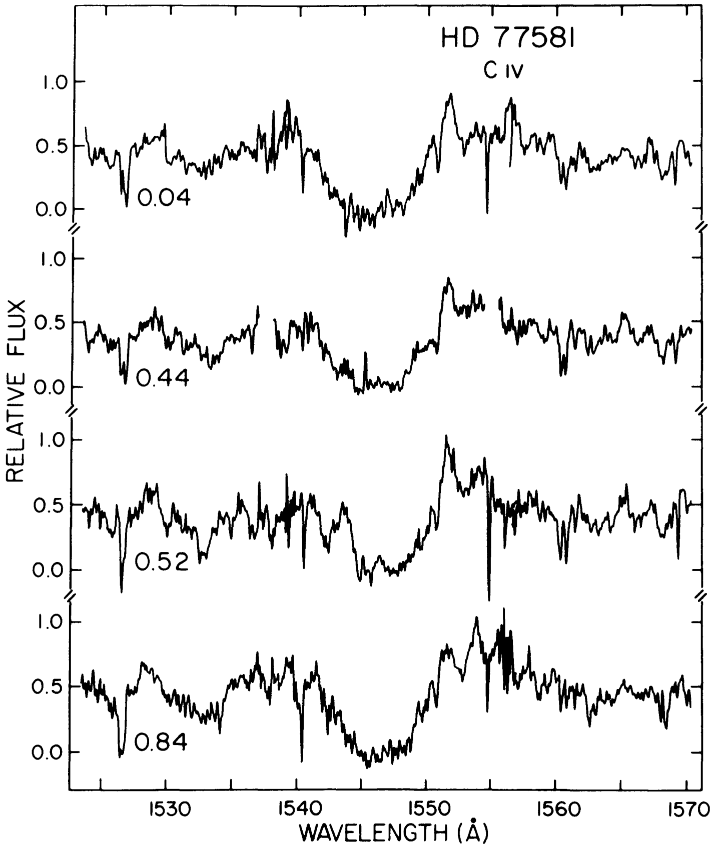

Figure 3. High dispersion IUE observations of the spectrum near λ1550 in HD 77581 showing the C IV P Cygni type profile and its variation with phase. Note the appearance of a high velocity feature at phase 0.52.

Such behavior can be understood in terms of the heating and ionization caused by an X-ray source immersed in a stellar wind as suggested by Hatchett and McCray (1977). Fig. 4 schematically illustrates the volume in which C IV can be ionized by an X-ray source in a system such as HD 77581. Within the broken line surrounding the X-ray source, C IV is assumed to be nonexistent. It is easy to see how the apparent edge velocity of the wind will decrease and an absorption feature can appear at high velocities. Calculations of the expected blue wing of the line profile (Fig. 5) confirms the appearance of an absorption feature as the X-ray source passes in front of the primary star.

It is noteworthy that HD 153919, an 06f star identified with the X-ray source 4U 1700-37 does not show such phase dependent behavior (Dupree et al. 1978) apparently because the large optical depths of the strong resonance lines mask any changing ionization state in the wind.

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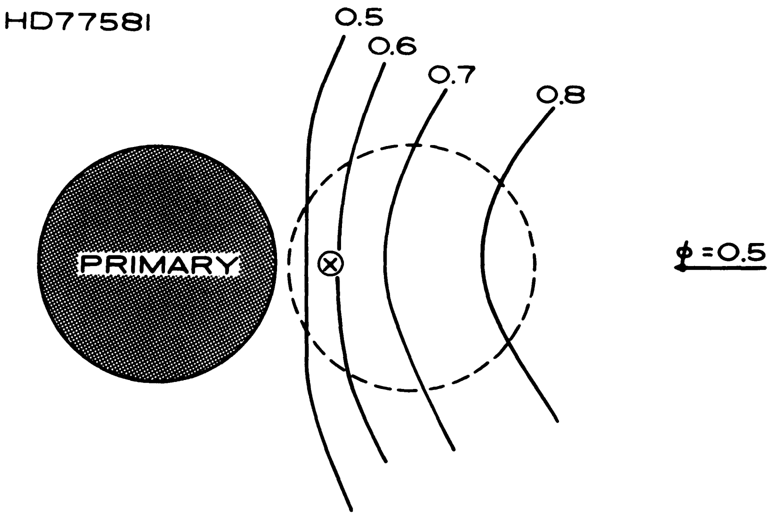

Figure 4. Schematic diagram of the HD 77581 system showing a typical ionization volume (broken line) surrounding the X-ray source marked by X. Within this volume a selected ionic species is absent. The solid lines mark the locus of a constant value of V/V_∞ where V_∞ is the wind terminal velocity.

The size of the ionized cavity in the wind sensitively depends upon the X-ray spectrum and the mass loss rate. Thus studies of binaries containing X-ray sources provide criteria to test our understanding of X-ray emission and stellar winds. The detailed structure of the velocity law in the wind can also be evaluated. In HD 77581, the terminal velocity of 1700 km s^{-1} is higher than the 950 km s^{-1} derived on the basis of Abbott's (1978) theory that the terminal velocity should be three times the escape velocity (corrected for continuum radiation pressure). But the velocity agrees with the empirical relation between terminal velocity and escape velocity derived by Lamers, van den Heuvel, and Petterson (1976).

3. LOW LUMINOSITY SOURCES (HZ Her)

The complex and fascinating X-ray binary HZ Her = Her X-1 was also observed with IUE as part of a collaborative effort of American and European astronomers (Gursky et al. 1979). Fig. 6 indicates typical spectra of HZ Her, similar to those reported by Dupree et al. (1978). The very strong Ly α feature is geocoronal in origin. The dominant features are the N V λ1240 and C IV λ1550 emission lines superposed on a relatively flat, featureless continuum. He II λ1640 is also present at a weak level. There is evidence for Si IV λ1394, λ1403 emission as well. O V λ1371, N IV λ1719, and N III λ1750 may be present but are not apparent in all spectra.

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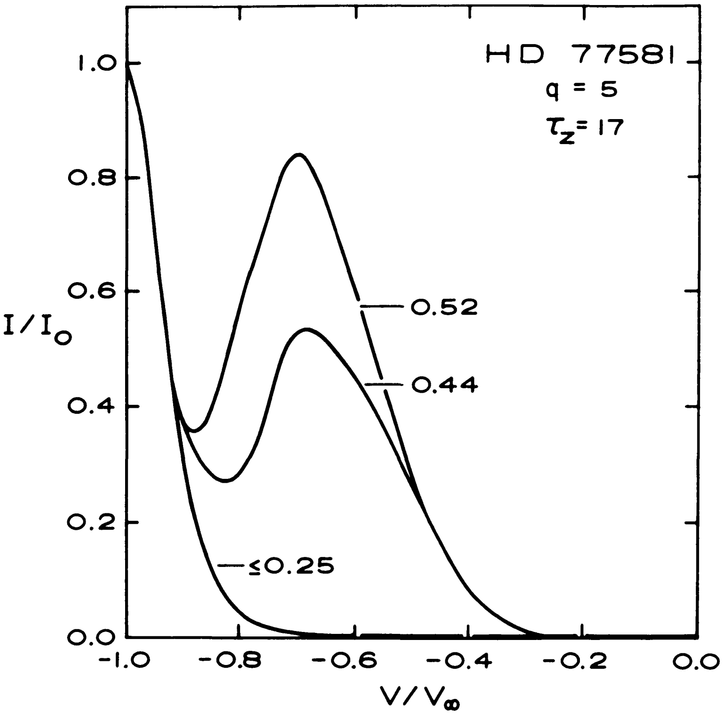

Figure 5. Calculated blue absorption wing of P Cygni profiles at three phases (0.52, 0.44, ≤ 0.25). High velocity absorption appears at phases close to inferior conjunction of the secondary.

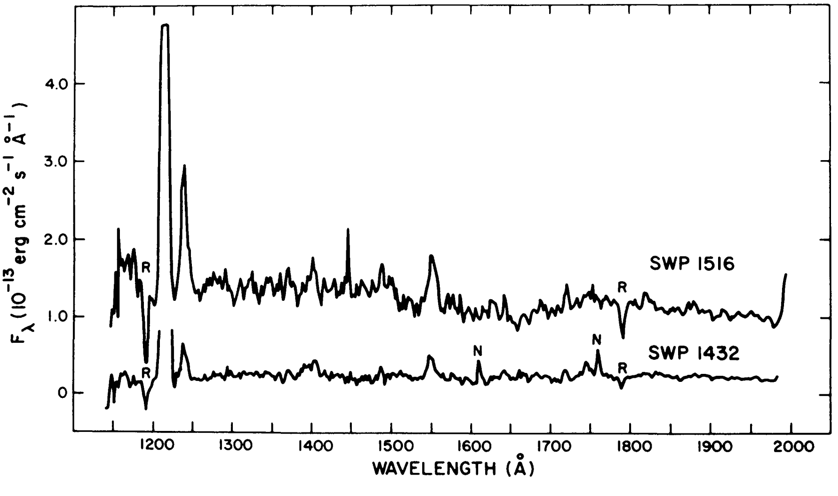

Figure 6. Low dispersion IUE spectra of HZ Her (Gursky et al. 1979) at two orbital phases: $\phi = 0.143$ (SWP 1432) and $\phi = 0.350$ (SWP 1516). Fiducial marks are denoted by R (reseau); noise spikes are indicated by N.

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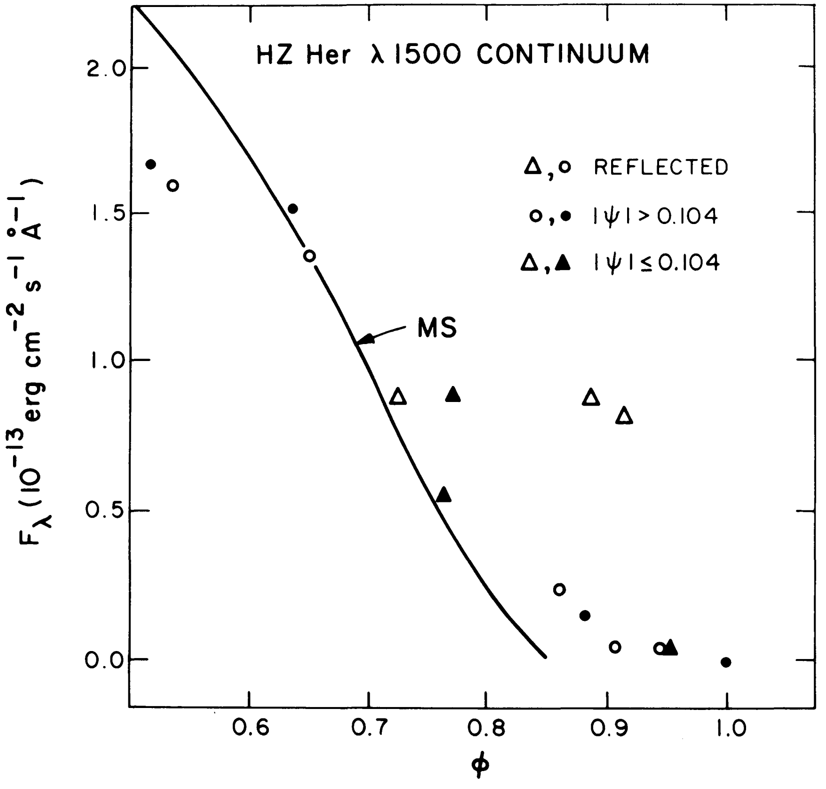

Figure 7. Observed and predicted (denoted MS) flux variation of HZ Her at λ1500 as a function of phase.

Fig. 7 shows the behavior of the 1500Å continuum flux of HZ Her as a function of orbital phase ϕ. The solid line is the prediction of the Milgrom & Salpeter (1975) model of the X-ray heated photosphere of the primary star. The agreement indicates that the heated photosphere is a primary component of ultraviolet flux. However, there is another source of emission which is especially apparent near eclipse ($\phi \sim 0$) for certain 35-day phases ψ. Gerend and Boynton (1976) noted similar excess fluxes near eclipse for $\psi \sim 0.0$, 0.5 in optical data. They attributed this excess emission to radiation from a tilted disk, precessing with a 35-day period, which is most strongly visible when oriented at its most face-on towards Earth.

Gerend and Boynton estimated the disk parameters as $T \sim 10{,}000$K and r (disk radius) $\sim$ 1.6 x 10" cm. Our results suggest $T \gtrsim 20{,}000$K and r $\sim$ 1 x 10" cm. The discrepancy in temperature is not surprising, for the ultraviolet spectral region is bound to be more sensitive to high-temperature material. However, it does indicate the importance of acquiring UV data in arriving at a physically meaningful picture of disk properties.

The general behavior of the C IV and N V lines strongly suggests that they are principally formed in or near the heated photosphere as is the continuum, particularly N V, for which the equivalent width is roughly constant as a function of orbital phase. Simple calculations using the results of Hatchett, Buff, & McCray (1976) indicate that the heated photosphere can account for the N V flux; this same model predicts a C IV flux which is of magnitude larger than observed, suggesting that optical depth effects may be important. The C IV flux does not vary as much as N V with its equivalent width increasing as one approaches eclipse. Most of the optical emission lines show no strong correlation with orbital phase (e.g. Crampton and Hutchings 1974; Barbon et al. 1974). The N V and C IV line behavior suggests that the phase-dependent modulation increases with increasing temperature of formation, again indicating the importance of UV data in investigating variations in physical conditions.

4. RS CVn AND W UMa BINARIES

Binary systems containing late-type giants or dwarf members are typically strong sources of ultraviolet emission. The RS CVn stars are late-type giant and subgiant binaries whose surface activity has been known from optical studies to be peculiar, in that large spots cover their surfaces (Caston & Hall 1979). Ultraviolet observations with Copernicus and IUE of members of this class such as λ And, HR 1099, and HR 4665, have shown that these stars are powerful emitters in transition-region lines, with much higher surface fluxes than the quiet sun. RS CVn binaries have also been shown to be strong soft X-ray sources (Walter, Charles, and Bowyer 1978). This combination of high chromospheric and coronal activity with spot activity makes it plausible to interpret these phenomena as extreme analogues of solar activity.

The W UMa stars are late-type, dwarf binaries which are orbiting so closely together that they may share a common convective envelope (Lucy 1976; Flannery 1976; Shu, Lubow & Anderson 1976). Two W UMa systems have been observed with IUE: VW Cep (G5) and 44 Boo (G2). The system VW Cep was recently discovered to be an X-ray source by the NRL experiment on HEAO-A (Cruddace 1978). These stars are contact binary systems that eclipse with periods of less than one day. Both stars have ultraviolet spectra that are very similar. The short wavelength spectrum of 44 Boo is shown in Fig. 8. High temperature emission lines, N V, C IV, and Si IV are apparent, as is He II λ1640.

In Fig. 9, the stellar surface fluxes in the binary systems are compared to that of the quiet sun, assuming that the chromospheric activity is uniformly distributed across the stellar surface. The fluxes for λ And and HR 1099 were taken from Linsky et al. (1978). The surface fluxes show a general progression of increasing enhancement with increasing temperature much like that found for a solar active region (Dupree et al. 1973) and for active dwarfs (Hartmann et al. 1979). However, the fluxes of the W UMa stars are an order of magnitude larger than typical solar

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active regions. The He II λ1640 line is strongly enhanced, which may reflect photoionization by increasing coronal emission measures (Hartmann et al. 1979).

There appears to be a dependence of the surface flux upon orbital period. The W UMa stars 44 Boo and VW Cep have periods $0^{d}.7$; the RS CVn stars have longer periods: HR 1099 ($2^{d}.8$) λ And ($20^{d}.5$); HR 4665 ($64^{d}.4$). The results in Fig. 6 suggest that the flux is enhanced with decreasing orbital period. Because of tidal synchronization, the rotational periods should be close to the orbital periods; this is verified by the spot light curve periods in RS CVn stars. Thus the behavior of emission strength with orbital period may be viewed as an extension of the general increase of chromospheric flux with increasing rotation rate originally found for dwarfs (Kraft 1967; Skumanich 1972). Observations of such a general relationship encompassing stars of very different interior structure provide important constraints on theories of chromospheric and coronal heating.

5. COOL SUPERGIANTS WITH A HOT COMPANION

Binary systems composed of a late-type supergiant with a hot companion offer the unique situation in which to probe the structure of an extended atmosphere with continuous source of radiation. Particularly fortuitous was the egress from eclipse of the secondary of VV Cephei during the first

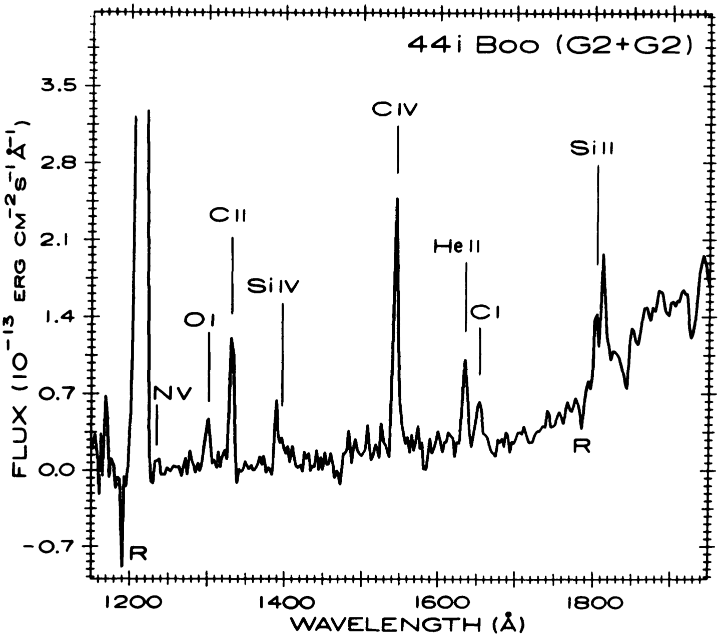

Figure 8. Short wavelength low dispersion IUE spectrum of a W UMa - type star: 44 Boo.

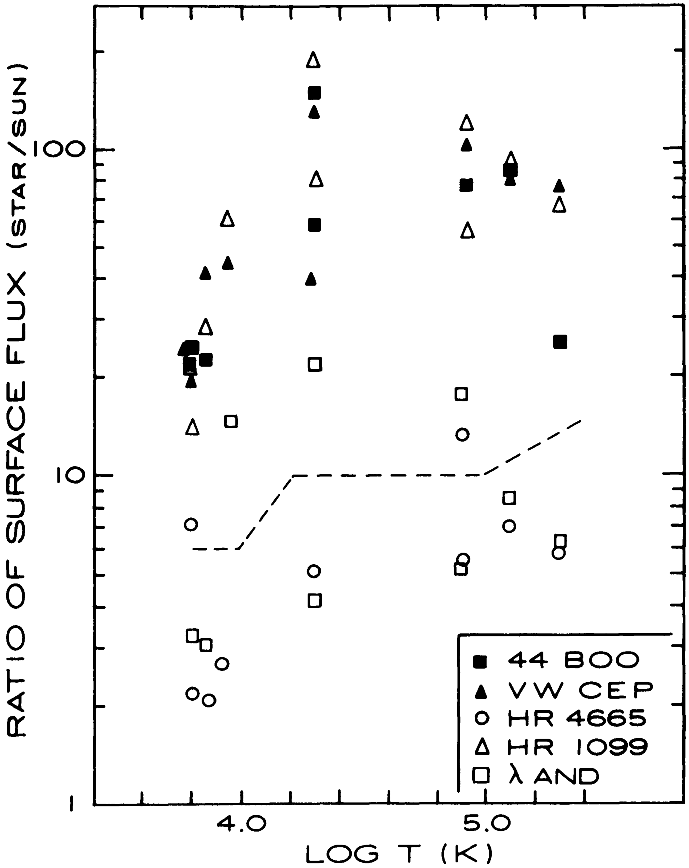

Figure 9. The ratio of stellar surface flux to solar flux in various emission lines as a function of temperature of formation of the ionic species. These stars are all binary systems. The broken line indicates the ratio for a typical solar active region.

months after the launch of IUE. This eclipsing binary system (M2 Iabep + B) was monitored by Faraggiana and Selvelli (1979) and Hagen et al. (1980) during 1978 and 1979. Fig. 10 shows ths appearance of the short wavelength ultraviolet spectrum as the general flux level increases reflecting the changing path length through the atmosphere of the M supergiant. This variation is used by Hagen et al. (1980) to determine the density law in the atmosphere. Egress in the ultraviolet lagged visible egress by several months due to the higher opacity of the M star atmosphere in the ultraviolet. Fluorescent emission lines dientified by Hagen et al. dominated this spectrum. These features result from the excitation of species in the atmosphere of the M supergiant by the ultraviolet continuum of the hot companion. Later, the hot continuum becomes blanketed by absorption lines arising in the extended atmosphere of the supergiant. High dispersion spectra (Fig. 11) show the stratification

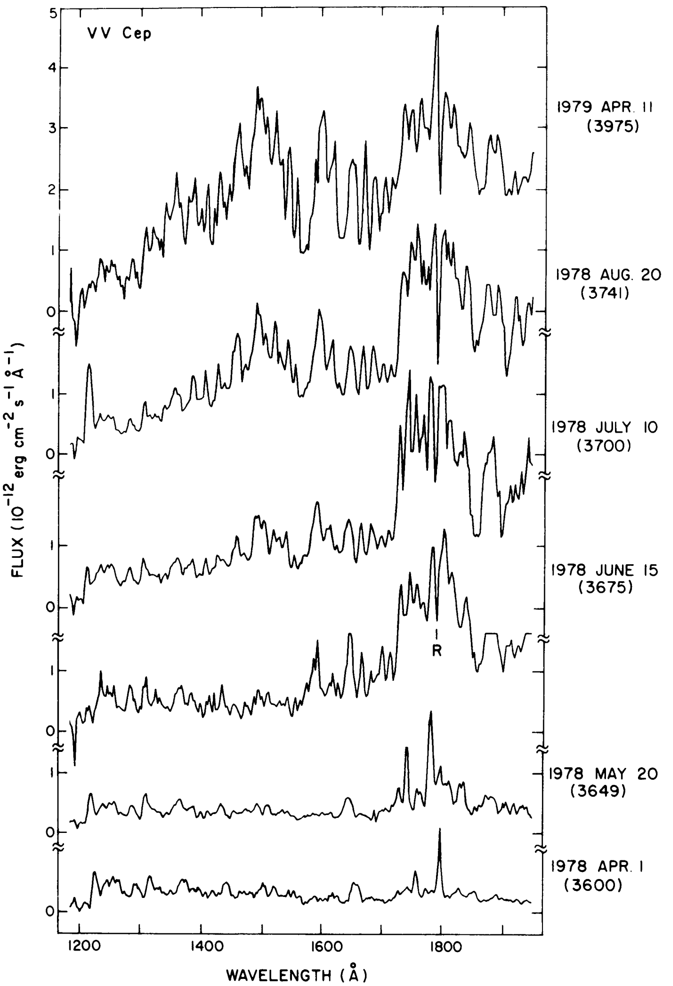

Figure 10. The short wavelength IUE spectra of VV Cephei as the secondary emerged from eclipse (Hagen et al. 1980).

of ionic species as marked by the weakening or disappearance of Fe I absorption features. Apparently, neutral iron does not extend as far out in the envelope as Fe II. The Fe II emission profiles change dramatically with time. For example, between 20 May and 15 July 1978 a sudden enhancement of the blue emission peaks relative to the red peaks of these lines was observed, although the total fluxes of the lines remained roughly constant (Hagen et al. 1980).

The surface fluxes of the chromospheric emission line Mg II and Fe II are substantially enhanced over the values found for single stars of comparable spectral type. Such enhancement may result from the presence of a hot companion. The spectral type of the companion is still indeterminate

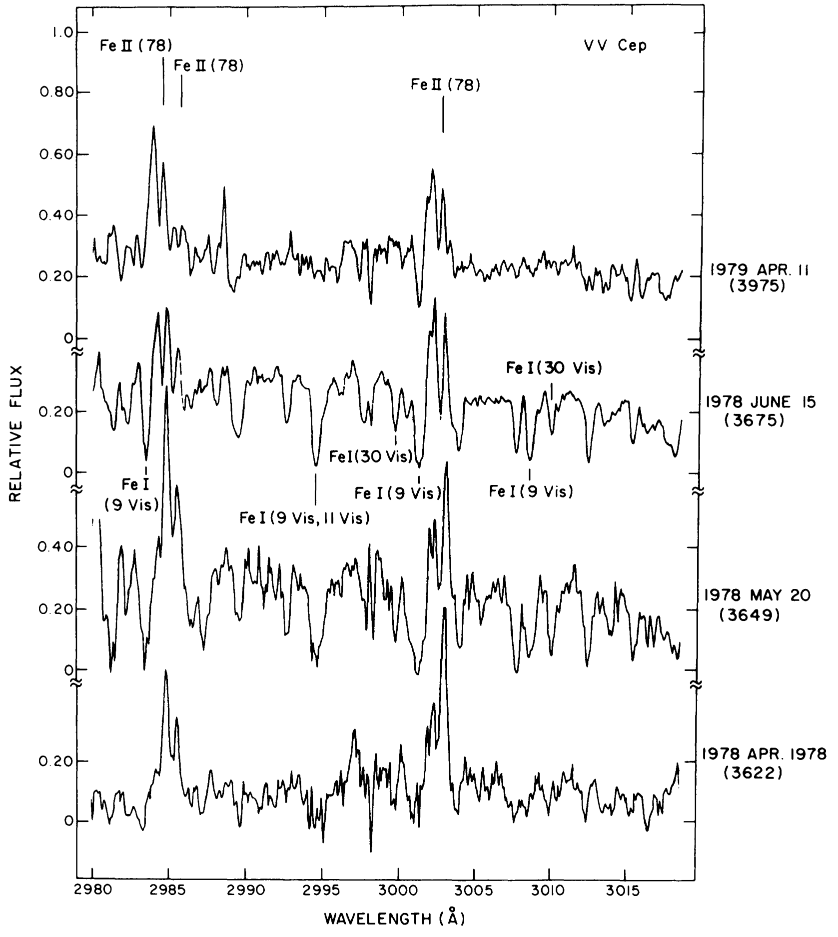

Figure 11. A section of a high dispersion spectrum of VV Cep near λ3000. Note the changing strength of the emission components of the Fe II transitions, and the disappearance of the Fe I multiplets by LL April 1979 (Hagen et al. 1980).

(April 1979) due to the proximity to eclipse and/or the interaction bebween the components of the system. Work is continuing on this complex and important system in order to form a more comprehensive physical picture of the extended atmospheres of late supergiant stars.

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DISCUSSION FOLLOWING DUPREE, HARTMANN AND RAYMOND

Hack: You said that CIV and SiIV in Vela were destroyed by X-ray radiation. What about NV?

Dupree: We expect NV to behave in a similar way as C IV and Si IV However because of its higher ionization potential the volume affected by the X-rays will be smaller than those for C IV and Si IV. The NV transitions at λ1240 are weakly exposed on our IUE spectra and it is not possible to comment on any variation.

Plavec: I noticed in your IUE spectra that the N V line is always much weaker than the C IV line, as usual in stellar transition regions.

I observed similar lines in my long-period interacting binaries, but arising under clearly very different physical conditions. The N V line is actually stronger than the C IV line. Moreover, the power radiated in either line is very much larger than in the systems you have observed.

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