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Twelve years of IUE spectra of the interacting binary VV Cephei

W. Hagen Bauer[1], R. E. Stencel[2] and D. H. Neff[2]

[1] Whitin Observatory, Wellesley College, Wellesley, MA 02181, U.S.A.
[2] Center for Astrophysics and Space Astronomy, University of Colorado, Campus Box 391, Boulder, CO 80309, U.S.A.

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Abstract. — We have examined all well-exposed high-resolution IUE spectra obtained of the eclipsing binary system VV Cephei (M2Iabep + B). The spectra cover the period from egress from primary eclipse through secondary eclipse to third quadrature. High-temperature absorption features attributable to the hot companion have been detected, and indicate that the companion (or the inner regions of its accretion disk) are as hot as a B1-B2 star. A complex chromosphere-like absorption spectrum arising from mainly singly ionized elements persists throughout the entire cycle thus far observed. Some systematic changes with phase are seen. Doubling of Fe II (UV 1) lines, with an additional narrow component redshifted by about 60 km/sec, occurs only when the B star is behind the plane of the sky containing the M supergiant, suggesting the existence of mass transfer from the red to the blue star. Absorption features from neutral elements weaken dramatically during egress, while those from ionized elements remain of nearly constant strength. During egress from primary eclipse the Mg II resonance doublet shows asymmetric double-peaked emission indicative of formation in an expanding chromosphere. As the B star moves toward first quadrature, the profiles becomes stronger and more symmetric. As the B star moves past secondary eclipse to third quadrature, the profile reverts to its previous asymmetry. In addition to these systematic changes with phase, a number of erratic changes are also observed. The most striking are the appearance of broad (up to 200 km/sec) additional absorption features associated with many lines in the chromosphere-like spectrum. In some spectra these features are red-shifted, and in others blue-shifted. They may represent accretion events onto the companion and outbursts of the companion respectively. The intermittent nature of these features is a strong indication that the outer atmosphere of the M supergiant is highly clumped.

Key words: accretion disks, stars: binaries: close, stars: chromospheres of, stars: circumstellar matter, stars: individual: VV Cephei.

1. Introduction.

The eclipsing binary VV Cephei consists of an M2 Iab supergiant primary with a hot companion orbiting within its extended atmosphere. The orbital motion of the companion provides a probe which can be used to study the structure of the extended atmosphere of the primary. Although the period is 20.3 years long, the system is close enough to show interaction between the two components. Based on the orbit derived by Wright (1977) the primary nearly fills its Roche Lobe at periastron. Wright observed the profile of Hα throughout a complete cycle and mapped out a stream of material moving from the M star to form a disk around the companion. Thus the system also provides an opportunity to observe accretion onto a 20 MO main-sequence star.

The nature of this companion has long been uncertain. Estimates in the literature range from late O to late A. In this paper, we report the unambiguous detection of absorption features arising from high-temperature gas. The presence of strong, broad Si IV absorption and weak C IV absorption indicates that the companion (or the inner regions of its accretion disk) are as hot as an early B star.

VV Cephei is often compared to the ζ Aurigae stars, binary systems consisting of a K-supergiant primary and a B-type secondary. Since the launch of the IUE satellite in 1978, considerable progress has been made in our understanding of these systems. Mass loss rates have been derived for the K-supergiant primaries (Che *et al.* 1983). Changes in line profiles with phase have been used to show that the stellar wind from the primary continues to accelerate beyond ten stellar radii (Ahmad & Stencel 1988). The variations in the C IV and Mg II line profiles have shown the presence of accretion behind the bow shock formed as the B stars orbit within the K-star winds (cf. Ahmad 1986). Emission features have demonstrated the presence of accretion disks in ζ Aur and δ Sge (Che-Bohnenstegel & Reimers 1986). Quantitative analyses of the chromospheres of several ζ Aur binaries using IUE Spectra have been carried out using curve-

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of-growth methods (Schröder 1985, 1986) and spectral synthesis (Eaton 1988).

However, the companion in VV Cephei orbits more deeply within the more extensive M-supergiant atmosphere, and the resulting spectrum is considerably more complex than those of the ζ Aur systems. Hagen *et al.* (1980) discussed IUE observations obtained in 1978 and 1979 during and shortly after egress from eclipse. High-resolution observations revealed a very rich absorption line spectrum, only a small fraction of which could be identified at the time. Between 1978 April and 1979 April, some of these lines, particularly those due to neutral elements, were seen to decrease in strength. The Mg II resonance lines showed asymmetric double-packed emission profiles indicative of formations in an expanding chromosphere. The Mg II and O I emission was seen to be considerably stronger than that of the single M supergiant α Orionis (when corrected for distance and reddening).

Bauer & Stencel (1989) were able to identify nearly all the absorption lines seen in the spectrum of the ζ Aur system 31 Cygni during chromospheric eclipse based on recent theoretical work on the iron group elements by Kurucz. The similarity of the indentified 31 Cyg spectrum to that of VV Cep, and the extended phase coverage now available, persuaded us that it would be worthwhile to reopen investigation of this interesting system.

Independently, Hack *et al.* (1989) also studied archival IUE spectra of VV Cep. Their investigation covered several aspects of the spectrum that ours did not, e.g. the low-resolution observations and radial velocity measurements, and we direct interested readers to their work. As they point out, a rich absorption spectrum consisting primarily of lines arising from singly ionized elements persists through and beyond secondary eclipse. Due to its similarity to the chromospheric eclipse spectrum of 31 Cygni, we will refer to it as the chromosphere-like spectrum. Although most of the lines of this chromosphere-like spectrum persist throughout the portion of the cycle thus far observed, significant changes in their *profiles* are observed.

Some systematic changes with phase are seen. Lines arising from neutral elements which were seen to weaken by 1979 April have essentially disappeared by 1980 June, although the strongest neutral lines appear to persist very weakly throughout the cycle thus far observed. Lines of Fe II (1) and other strong multiplets appear double while the B star is behind the plane of the sky containing the M supergiant, indicating preferential flow of material from the M star to the B star. As the B star moves in front of this plane, and we observe the hemisphere of the M-star which receives additional heating from the B-star, the Mg II profiles strengthen and change to a more symmetric shape. As the stars approach and pass third quadrature, the profiles return to their previous sense of asymmetry.

But even more striking than these systematic changes with phase is intermittent broad additional absorption shading most chromosphere-like absorption lines by up to 200 km/sec. At times these features are red-shifted, probably arising from accretion onto the B-star, and at times blue-shifted, possibly indicating an outburst from the B-star or its accretion disk. Broad emission associated with the hot companion and narrow emission probably arising from the circumsystem envelope also vary irregularly.

Section 2 discusses the system of VV Cephei and the phases at which observations were obtained. Section 3 discusses the high-temperature absorption lines arising from the hot component. Section 4 describes the systematic changes seen with phase in the absorption spectrum. The emission spectrum is discussed in Section 5: the Mg II h and k line profiles vary systematically with phase, while the emission spectrum of Fe II has both phase-dependent and irregular variation. The intermittent broad red blue shifts seen in the chromosphere-like spectrum are discussed in Section 6. A comparison of the IUE observations to the stream and disk model of Wright (1977) is presented in Section 7, and our conclusions are summarized in Section 8.

2. The system of VV Cephei and the phases of the IUE observations.

Figure 1 shows the orbit and stellar dimensions of VV Cephei to scale as determined by Wright (1977). The hot component is surrounded by an envelope giving rise to double-peaked emission at Hα and Hβ. Several groups have used the time variation in emission line profiles during eclipse to determine a size for the emission envelope. Hutchings & Wright (1971) derived a radius of 650 R$\odot$, Kawabata *et al.* (1981) found 500 R$\odot$, and Mollenhoff & Schaifers (1981) obtained 320 R$\odot$. Pfeiffer & Koch (1987) modeled the observed polarization of the system from 1977 to 1986 and found that the observations were best fit by a disk of 600 R$\odot$. In figure 1, the 650 R$\odot$ value is represented by a dotted circle.

Table 1 presents a list of the dates on which adequately exposed high-resolution spectra were obtained. In this work, all reasonably exposed spectra were examined using the facilities of the University of Colorado Regional Data Analysis Facility. At several of these times more than one exposure was made. While looking at any given feature, different exposures were compared and the exposure which was most suitable for that region was used, although only one image is listed in Table 1. The dates and times listed in Table 1 correspond to the LWR/P spectrum if both that and an SWP spectrum were obtained. The Julian dates of all spectra obtained at a given epoch in Table 1 agreed to within 0.2 days. Phases were calculated from the elements of Wright (1977) and agree to within 0.003 of those presented by Hack *et al.* (1989).

Third and fourth contacts in the optical occurred approximately 1978 January 6 and 1978 June 11 (Nakagiri & Yamashita 1979), and references to "fourth contact" in this paper refer to the optical unless otherwise specified. Unfortunately, the IUE was not launched until partial eclipse was well underway, and no spectra during totality are available. First quadrature, the time when the B star passes in front of the plane of the sky containing the M supergiant, occurs at $\varphi = 0.26$. Mid-secondary eclipse occurs at $\varphi = 0.38$, and third quadrature at 057. The observations at $\varphi = 0.366$ were made during secondary eclipse and shortly after periastron (which occurs at phase 0.34). Unfortunately the LWP spectrum is overexposed and cannot be used to determine absolute fluxes in many regions of the spectrum.

The great majority of the lines in the chromosphere-like absorption spectrum correspond to those in the chromospheric eclipse spectrum of 31 Cygni, although there are a significantly greater number of unidentified lines in the VV Cep spectrum. The similarity in the VV Cep and 31 Cyg absorption line spectra can be seen in Figure 2. Since this chromosphere-like spectrum persists even through secondary eclipse, the material producing it is either fairly near the B star or in an extended envelope surrounding both.

3. The nature of the hot companion.

In the visible spectrum, no absorption lines attributable to the hot companion are seen (McLaughlin 1951, Cowley 1969). It has usually been referred to as a Be star, as the Balmer emission is clearly associated with the hot companion: its radial velocity varies in the opposite sense to that of the M supergiant primary, and its intensity is considerably reduced during primary eclipse. A spectral type of early B was estimated by Wright & McKellar (1956) by comparison of the ground-based UV continuum to that of ζ Aur. Hutchings & Wright (1971) suggested a spectral type of 08 based on the mass of 20 $M_\odot$ derived from their radial velocity observations.

Use of low-dispersion IUE spectra has indicated considerably later spectral types. Faraggiana & Selvelli (1979) derived a spectral type of A0 from the shape of the continuum observed in 1978 June and July. As discussed by Hagen *et al.* (1980), this spectral type should not reliable, as the UV flux was still increasing due to egress from eclipse. Hack *et al.* (1989) dereddened low-resolution IUE spectra between 1979 October and 1982 February and found that the continuum closely matched that of an A0 II star. Buss & Snow (1988) used IUE low-dispersion spectra obtained well out of eclipse to estimate the spectral type from the observed absorption features. However, the spectrum as seen at high dispersion is dominated by the chromosphere-like spectrum, which consists mainly of lines of singly ionized metals. Thus it is not surprising that they derived a spectral type of late A. However, this spectral type does not represent conditions in the photosphere of the hot component.

The high-resolution IUE observations unambiguously show the presence of material at early B-star temperatures. As noted by Hack *et al.* (1989), absorption is seen in the high-temperature Si IV and C IV lines. Figure 2 presents the spectrum of VV Cephei in the regions of these lines. They are plotted along with the spectrum of 31 Cygni during chromospheric eclipse in order to aid in the separation of the broad line profiles from the chromosphere-like spectrum.

Spectral classification of B stars using ultraviolet spectra was discussed by Underhill (1982), who presented spectral sequences in the C IV and Si IV regions. (Lines from lower ionization levels cannot be used to classify the B star due to the chromosphere-like component of the spectrum). The Si IV lines are shallower but broader than those of a B1 V star (HR 1861), and considerably stronger than those of a B3 star. The C IV lines are weaker and narrower than the Si IV lines and thus less straightforward to decouple from the shell spectrum. They are probably weaker than those of a the B1 star but stronger than those of a B3 star. As spectral type advances through B0 and to 09, the C IV strengthens and the Si IV weakens (Walborn *et al.* 1985). Thus a spectral type of B1-B2 appears likely. The broad Si IV lines are reasonably symmetric and do not appear to show any effects of the wind profiles typically shown by luminous O and B stars, thus supporting a main-sequence classification.

The region of the Si IV lines was usually weakly exposed. The SWP image used in the preparation of Figure 2 was a five-hour exposure, the longest one made. As can be seen in Figure 2, the red half of the 1393 Å line is the region most free from chromospheric absorption, and was the region used to measure the line half-width, about 400 km/sec. This is broader than the profile for a B1 star given in Underhill (1982) but not as deep. If this line width is due to rotation, the velocity is about a factor of 10 less than would be expected from synchronous rotation. If the Si IV line actually arises from the inner regions of an accretion disk, a line half-width of 400 km/sec corresponds to the Keplerian velocity at a radius of about 23 $R_\odot$. However, the C IV lines in VV Cep and HR 1861 are considerably narrower than the Si IV lines, indicating that the great width of the Si IV lines is not due to rotation but rather to an optical depth and/or pressure broadening effect.

Most spectra were quite noisy at 1400 Å. When they were plotted on an expanded scale so that the continuum matched that in 1981 February, no evidence for a change in the profile was seen until the most recent observation, that of 1990 March 1. In this observation the Si IV line profiles are clearly broadened to the red as seen in Figure 3. Although the blue sides of the two lines are heavily chopped up by chromosphere-like absorption, the few clear regions do make it apparent that the profiles are asymmetric. This observation was taken at a phase in which one might expect to see into the open end of an accretion shock cone formed as the B star orbits through the M star wind.

The spectrum near the C IV lines is heavily blanketed by shell absorption, where changes with phase are less easy to observe, and no convincing changes with phase were seen.

However, the 1990 March 1 spectrum is at least consistent with increased red-shifted absorption, as can be seen in Figure 3. Also, as can be seen in Figure 7, it is possible that additional absorption in the Mg II h and k lines is seen red-shifted by about 300 km/sec (although this feature overlaps a chromosphere-like absorption line redward on the *k* line).

We suggest that the apparent inconsistency of the spectral type of the companion as determined from the high-resolution Si IV and C IV absorption features and the continuum is due to absorption within the extended circumsystem envelope of the M supergiant, from which the hot companion never emerges. Most theories of the 2175 Å interstellar extinction feature involve some form of carbonaceous material, and Snow *et al.* (1987) demonstrate that the observed 2175 Å feature in the O-rich supergiant α Sco arises from interstellar, not circumstellar extinction. As Hack *et al.* (1989) dereddened their spectra of VV Cep by removing the 2175 Å feature, they corrected only for *interstellar* extinction. Additional circumstellar extinction is likely to further redden the continuum, making the continuum of the hot companion appear cooler than it actually is.

4. Egress from eclipse.

The high-resolution spectra through 1980 June appear quite similar to the spectrum obtained near optical fourth contact, and therefore spectra obtained between 1978 May and 1980 June will be considered as obtained during "egress".

The earliest adequately exposed high-dispersion observation, made in 1978 April, about 2/3 of the way through partial eclipse, shows an underexposed continuum with much strong absorption. The *h* and *k* lines of Mg II show the double-peaked emission profile typical of the rest of the egress phase. A narrow emission-line spectrum arising from multiplets 60, 62, 63 and 78 of Fe II is seen. By fourth contact, a broader emission component of these lines has strengthened. This emission may be seen as a feature on either side of the narrow feature in the strongest lines (resulting in a triple emission feature), or as a single feature to the violet of the narrow emission. Figure 4 shows the change in this emission between the earliest spectrum and the spectrum taken near optical fourth contact. The λ 2825 line is strong enough for a double-peaked broad emission to appear, but any broad emission component to the λ 2939 line is weaker than the continuum. As will be discussed in Section 6, we ascribe the narrow feature to a circumsystem component, with the broad emission arising from an accretion disk around the hot companion.

As described by Hagen *et al.* (1980), lines arising from neutral elements weakened during egress, while those arising from ions tended to remain of more or less equal strength. Figure 5 shows this variation for multiplets S I (2) and Fe I (9). The strongest lines are seen weakly in absorption throughout the cycle thus far observed. This weakening of the neutral lines supports findings from work in the optical at previous eclipses, that ionized lines persist higher into the atmosphere than do neutral lines. Goedicke (1939) found lines of neutral elements to weaken rapidly on the time scale of a month, being nearly gone by JD 2428800 (φ = 0.023), while lines of ionized elements still had significant strength two months later. However, it is phase 0.145 before the neutral lines observed in the UV essentially disappeared.

Sharp additional red-shifted components, displaced by roughly 60 km/sec, are seen in strong lines such as Fe II (1) through egress. Spectra from φ = 0.191 and φ = 0.224 appear as if the red-shifted component had moved closer to the main line. After the stars have passed first quadrature, the lines appear single, until after third quadrature, when the lines again appear as if a redward component were close to the main line. Figure 6 shows these lines during egress phase and during secondary eclipse. This doubling is also seen in Cr II (5) and Cr II (8).

Such line doubling has only been reported in one ζ Aur system, δ Sge. Reimers and Schroder (1983) saw extra components red-shifted by 55 km/sec in Fe II (1). The period of this system is 10.2 years. The line doubling was seen 5 months before primary eclipse (which is nearly coincident with periastron), but not seen 5 months after periastron. They attributed the second component to a condensation or stream moving toward the B star.

Line doubling has also been seen during ingress into the 1956 eclipse of VV Cephei in the optical, with a doubling of nearly all chromospheric lines seen between four and two months before totality (Wright & McKellar 1956, McKellar *et al.* 1957). There was a trend toward decreasing separation of the components as ingress continued, from 30-22 km/sec for most lines. The most pronounced doubling was seen for Ti II $\lambda\lambda$ 3759 and 3761, about 50 km/sec. After second contact, the region between the components emerged as an emission line, which is reminiscent of the circumsystem components in the Fe II lines for VV Cep.

5. The emission spectrum.

Although the ζ Aurigae stars show emission spectra during eclipse, outside eclipse they tend to show few emission lines other than the Mg II resonance lines (but see Che-Bohnenstengel & Reimers 1986). A comprehensive listing and discussion of the emission spectrum seen in VV Cephei is presented by Hack *et al.* (1989). The strongest of these are the Mg II resonance lines. By far, the majority of the emission lines arise from Fe II multiplets 60, 61, 62, 63, 78, and 191. No emission lines arising from double or higher levels of ionization are seen. This is in contrast to the spectra observed for symbiotic stars, and in evidence that the companion is a main-sequence star and not a compact object.

5.1. The Mg II h and k lines.

The peak fluxes and the V/R ratios of the Mg II lines were presented by Hack *et al.* (1989). In order that these changes might be more clearly visualized, we present representative line profiles in Figure 7. The double-peaked profiles presented in Hagen *et al.* (1980) persist from partial eclipse through the egress phase. The asymmetry seen is indicative of formation in an expanding chromosphere. The flux in the k-line is approximately twice that in the h-line. This agrees with their relative f-values, indicating that the region responsible for the emission is optically thin.

From the end of egress through quadrature, the emission strengthens and becomes more symmetric. More and more of the visible hemisphere of the M star is being heated by the B star. The optically thick Mg profile is now mainly produced by the heated surface of the M supergiant. Unfortunately, the exposure made during secondary eclipse was overexposed and the only conclusion that can be drawn from it is that the 2802 A line is at least as strong as that seen at $\varphi = 0.292$.

By third quadrature, the Mg II profiles have reverted to the asymmetry indicative of formation in an expanding envelope, but their intensity is comparable to the intensity at first quadrature. The intensities are not in the optically thin ratio. Nearly the same fraction of the visible surface is illuminated at phases 0.292 and 0.546. However, the contribution from the heated surface of the M supergiant is reduced, as the B-star is approximately 1.8 times as far from the M-star surface in its orbit.

Throughout the cycle thus far observed, a single central absorption persists in the Mg II line profiles. This profile is very different from those of the ζ Aur stars, which tend to show a P-Cygni profile with two absorption components, an interstellar component near rest wavelength and a blue-shifted component due to the stellar wind. In VV Cep the interstellar and circumstellar components are blended into a single feature due to the lower wind velocity of the M-supergiant primary. Wind velocities in the ζ Aur stars range from 70-160 km/sec (Ahmad & Stencel 1988), whereas optical observations of VV Cep indicate a wind velocity of about 20 km/sec (McLaughlin 1951, Hagen *et al.* 1980).

5.2. The Fe II emission spectrum.

As was shown in Figure 4, a single narrow peak is seen at the positions of strong lines in at least the multiplets of 60, 62, 63 and 78 of Fe II in the earliest spectrum. A narrow peak continues to be seen in most spectra taken around the cycle thus far observed. If a narrow peak is not seen, a high point in the continuum is. The intensity of this feature varies erratically over the cycle by about a factor of 2. Its persistence throughout the cycle and its narrow nature associate it with the permitted and forbidden emission in the visual which is attributed to a circumsystem envelope. The FWHM as measured from the Fe II λ 2925.585 line is 50 km/sec, not inconsistent with the 20 km/sec expansion velocity of the circumstellar envelope as measured from optical spectra. The absorption dip to the blue of the circumsystem component matches the wavelength scale of the chromosphere-like spectrum. Thus, the circumsystem component may in fact be P-Cygni in nature.

The strongest line of UV multiplet 60 is at 2926.585 A, and it is not blended in the chromospheric spectrum of 31 Cyg. The behavior of this line with phase thus provides a good opportunity to study the behavior of the emission, and is shown in Figure 8. By fourth contact, a triple structure typical of most later spectra is seen. The red and blue components of this are probably the double-peaked emission from an accretion disk. The separation of the two peaks is approximately 200 km/sec, consistent with that of Hβ as measured by Mollenhoff & Schaifers (1981).

A strong line of Fe II (62), λ 2724.879, is also reasonably unblended in the chromospheric spectrum of 31 Cyg. It also shows a triple profile whose components vary consistently with those of the λ 2925 line. Furthermore, the broad dip marked with a dotted line in the φ =0.224 spectrum in Figure 8 appears in other Fe II emission lines at that phase as well.

Other lines in these multiplets of Fe II show only two, not three, emission peaks. For example, the 3002.650 line of Fe II (78) is seen in Figure 5. The narrow peak is again at approximately the same wavelength as the chromospheric spectrum. The broader component emerges to the blue of the narrow component. This is consistent with the behavior of the higher members of the Balmer series, which are generally seen with reverse P Cygni profiles, although occasionally the longward emission component has appeared (McLaughlin 1951, Mollenhoff & Schaiffers 1981).

McLaughlin (1951) reported that the 4233 Å line of Fe II has a similar structure. A narrow emission line probably arising in a circumsystem envelope which produces the [Fe II] emission is usually accompanied by a weaker emission "with a width and structure similar to that of the hydrogen lines".

Mollenhoff & Schaifers (1981) observed the profiles of Hα and Hβ through the 1976-1978 eclipse and found them consistent with a rotating envelope (accretion disk) around the B-star . The blue component emerges from eclipse earlier than the red component. During the part of partial eclipse covered by the IUE observations, both components were rising, which is the behavior seen for the broad emission components of the Fe II lines in the earliest spectra. Too few UV observations were obtained in order to use emergence from eclipse for assessing the accretion disk model.

The broad emission gains in strength until fourth contact (see Fig. 5 in Hagen *et al.* 1980). From this time until the end of the egress phase, it varies irregularly, although in the triple-peaked features, the red and violet components tend to vary together (see the observations of egress in Fig. 8).

The relative strengths of the broad and narrow emission vary irregularly through the egress phase. Note that Hack *et al.*'s (1989) Figure 9 which plots the strengths of the violet and red components of Fe II λ 2756 is in fact plotting the strengths of the blue "disk" component and the circumsystem component.

The egress observations plotted in Figure 8 were made at $\varphi = 0.084$ and 0.089. The circumsystem feature remains at nearly the same intensity, while both the continuum and the broad emission vary between the two observations. Figure 9 compares the peak flux in the violet component of the broad emission to that in the nearby continuum for the large-aperture observations made during egress, and the two tend to vary together, indicating that the radiation from the B-star is responsible for the excitation of the broad emission.

The Balmer lines have also been seen to vary irregularly. Peery (1966) reported that occasionally the Balmer emission was "all but absent". Mollenhoff & Schaifers (1981) observed irregular variations of Hβ nearly a factor of 2 on a time scale of a few days. Kawabata *et al.* (1981) also found instances in which the emission intensity varied abruptly by a factor of two or more over a time of one to a few days.

The strongest emission lines in the SWP spectra are those of Fe II (191). This multiplet consists of three lines, $\lambda\lambda$ 1785.262, 1786.738 and 1787.997. This region of the spectrum is heavily chopped by chromospheric absorption and the edges of the emission features are probably determined by the shell spectrum. The dotted vertical lines in the first panel of Figure 10 mark the three lines of Fe II (191); these lines were seen in absorption in the chromospheric spectrum of 31 Cyg. Other chromospheric absorption features in the spectrum of 31 Cyg are marked with solid lines. Most of the profile of the λ 1787.997 line is eaten by a strong line of Ni II (5), and strong apparent separation between the other two lines is due at least in part to absorption in Fe II λ 1785.922. However, despite the messiness of the region, the profiles vary systematically with phase.

During the egress phase, the lines are characteristically double-peacked, with the two peaks arising from the two long wavelength lines. Occasionally the third line is represented by a blue-shifted peak corresponding to the short-wavelength portion of the other two features. An example of this type of profile is plotted in Figure 10 ($\varphi = 0.050$). The absorption dips marked with dotted lines match the wavelength scale of the chromosphere-like spectrum. The peaks to the right of them may be related to the circumsystem spectrum. The top three panels of Figure 10 show representative egress profiles. The shapes of these features change between observations, although the two peaks appear similar to each other. No correlations have been found between the shapes of these profiles and any other spectral features.

By $\varphi = 0.177$, the emission has changed to 3 single emission peaks, one representing each line of the multiplet. The positions of these peaks agree with the blue peaks seen in the egress profiles, and the ratios of the peak intensities correspond qualitatively to the ratios of the lines' f-values. From $\varphi = 0.191$ through secondary eclipse, the emission further changes to have four peaks. The profiles and intensities of these peaks vary between the observations, but they are significantly different from the egress profiles. The figure showing Fe II (191) in Hack *et al.* (1989) is one of these spectra. The four peaks are largely two double-peaked features arising from the two longest-wavelength lines, although the redward component of the middle line has a variable contribution from the blue peak of the longest λ line. In the spectrum at $\varphi = 0.546$, the emission is missing (see discussion of observations at this phase in the next section). At phase 0.620 the emission again has three peaks, and strongly resembles that at phase 0.177.

6. Intermittent red and blue shifts.

Many of the spectra show broad additional absorption which shades the shell absorption features. This extra absorption is best seen on the SWP spectra, where it affects essentially all absorption features. Examples are seen in Figure 11. Figure 12 shows the orbital positions at the times of the SWP observations, marking those wich showed symmetric line profiles and those with additional red or blue shifts. No dependence with phase is seen, and the observations are too widely spaced to determine any other periodicity.

Similar phenomena have been seen in the optical. MacLaughlin (1951) found occasional strong absorption satellites displaced +100 to +200 km/sec from the normal central absorptions in Hδ and higher members of the Balmer series and in the Ca II H and K lines. The hydrogen satellites can equal or exceed the normal absorption at their strongest, and such satellites were once seen in some Fe II and Ti II lines. McLaughlin found no evident periodicity, with the phenomenon typically persisting for a few weeks.

The most extreme example of a blue-shifted spectrum is that of phase 0.546, just before third quadrature. A comparison of this spectrum to the one obtained at phase 0.620 is given in Figure 13. Dotted lines point to emission in Fe II (60) in the later spectrum. The most unusual aspect of this spectrum is the absence of the emission spectrum associated with the hot component. (See also Fig. 8 which compares these two spectra at Fe II (60) and Figure 10, which compares them at Fe II (91).)

In figure 13, dotted lines point to emission in Fe II (60) and solid lines point to Fe II (78). Other high regions in the continuum are depressed, as if reverse P-Cygni emission components to the shell absorption lines had been eaten away by the additional blue shift. However, the spectra are so crowded that it is difficult to verify the impression of reverse P-Cygni profiles. In the less crowded section of the spectrum near 1800 A shown in Figure 11, the lines do not appear to show reverse P-Cygni profiles.

This extreme blue-shifted observation also showed a reduced UV continuum to shorter wavelength, as if the opacity had increased. The ratio of the continuum at 1300 A to that at 1800 A was reduced by about a factor of 2 in this observation relative to other post-egress observations.

In Figure 13, notice that the absorption features associated with Fe II (78) are narrower than the other absorption features. These narrow absorption features are also seen in some lines of Fe II (60) (see Fig. 8).

Other blue-shifted spectra appear at phases 0.191 and 0.224. These also show weakened Fe II emission, but the blue shifts and the degree of weakening are reduced.

This behavior is reminiscent of the binary system 17 Lep, which consists of an M1 giant filling its Roche Lobe with a late BV companion with a period of 260 days (Cowley 1967, and Smith & Struve 1942). The steady-state spectrum is dominated by shell-type absorption arising from neutral and singly-ionized elements. This shell spectrum has a blue shift of 30-60 km/sec relative to the B star. Outbursts (which are not strictly periodic but tend to recur on time scales of about 150 days) can last from a week to over a month. When the system is in outburst, the lines broaden, and then shade to the violet. The radial velocity of the violet component may reach − 170 km/sec.

17 Lep shows similar effects in its ultraviolet spectrum in outburst; strong blue-shifted components were seen on one IUE spectrum and weaker blue-shifted absorption in others (Molaro *et al.* 1982, 1983). However, VV Cep apparently shows a P Cyg nature in its "steady-state" spectrum that 17 Lep does not.

VV Cep also shows a similarity to the semi-detached short-period Algol system U Cep (McCluskey *et al.* 1988). In U Cep, outbursts are seen which recur on time scales of 5 to 10 years in which the ultraviolet continuum is reduced by more than half and narrow components are seen blue-shifted by up to 800 km/sec.

The M star itself is not affected much by the outburst as the Mg II emission profiles are very similar between the two latest observations. We suggest that clumpiness in M star atmosphere, combined with the response of the accretion disk around the B star may be responsible. Instabilities in the disk might set off the "outbusts".

The intermittent changes seen in the spectrum of VV Cephei strongly indicate that the B star is orbiting within a patchy M-star atmosphere. Optical evidence also demonstrates its clumpy nature: e.g. the variable satellite lines seen by McLaughlin (1951), and the occasional appearance of Ti II absorption over a significant portion of the cycle (Goedicke 1939).

7. Comparision of IUE observations to Wright's stream model.

Wright (1977) mapped out a stream of gas moving from the M-star toward and around the B-star by analyzing an extensive data base of plates taken at Hα over nearly an entire cycle. In order to remove the contribution to the Hα profile by the M-supergiant, the Hα profile of α Ori was subtracted. The resulting profiles were seen to have fairly symmetric emission wings, and the extension of these wings to make a symmetric emission profile was used as the continuum from which absorption and emission features attributed to the stream were determined.

He followed a fairly complex set of absorption and emission features around the cycle. We will not attempt to reproduce his discussion here. However, we will point out parts of it that are relevant to our ultraviolet observations. Wright gave all velocities relative to the B-star in its orbits; however, here we will give velocities (including Wright's) relative to the center-of-mass of the system.

Wright attributed broad red-shifted absorption seen from egress from primary eclipse until secondary eclipse to the stream. The red shifts involved varied from about 30 km/sec near egress to about 10 km/sec near secondary eclipse. Thus this stream absorption is probably not related to the line doubling seen in Fe II (1). Wright did observe weak absorption red-shifted by about 100 km/sec, but this was seen sporadically throughout the whole cycle and did not show the phase dependence of the Fe II (1) line doubling.

From phase 0.15 - 0.41 a component line blue-shifted by about 40 km/sec appeared weakly at first, increased in intensity and reached a maximum at phase 0.30, and disappearing at phase 0.41, shortly after secondary eclipse. Wright suggested that this absorption is produced by material moving around the secondary, outside the emission region. Two of our observations with additional blue-shifted absorption occured during this phase range, and the additional features were blue-shifted by approximately 40 km/sec. However tempting it may be to associate these phenomena, other spectra taken within this phase range showed symmetric lines (phases 0.18 and 0.29) and red shifts (phases 0.145 and 0.366).

Just after secondary eclipse, phase 0.42, Wright observed the Hα profile to change significantly: a blue-shifted emission component appeared which persisted nearly into ingress into primary eclipse. From phase 0.42 until well past the phase of our most recent observation, no significant changes in the Hα profiles were seen, with the exception of the sporadic appearance of the 100 km/sec red-shifted feature mentioned above. No large variations were seen that would correspond to the differences seen in our spectra at phases 0.546 and 0.620.

Wright also mentioned the occasional occurrence of additional lines with velocities of 100-200 km/sec. These lines appeared sporadically and frequently, and both red- and blue-shifted. Wright did not treat them any further, suggesting that they may be produced by discrete condensations. These lines may be related to our additional absorption components.

8. Conclusions.

We have examined all well-exposed high-resolution IUE spectra of VV Cephei. These spectra cover nearly three quarters of an orbital cycle, from egress from primary eclipse through secondary eclipse and on to third quadrature. A rich absorption spectrum consisting mainly of lines from singly ionized elements persists throughout the entire cycle thus far observed. This absorption spectrum is very similar to that of the chromospheric eclipse of the ζ Aurigae system 31 Cygni, and most likely indicates that the B star never emerges from the extended atmosphere of the M supergiant. However, the radial velocity resolution of the IUE is not sufficient to exclude the possibility that the absorption occurs in material very close to the B star itself.

IUE observations clearly show strong, broad Si IV absorption from the hot companion. Weaker C IV features are also seen, although the chromosphere-like absorption confuses that region. A comparison of these features with IUE observations of O and B stars indicates that the companion (or the inner regions of its accretion disk) are as hot as a B1-B2 star. The hot companion is most likely a main-sequence star: the wind features seen in the ultraviolet spectra of more luminous B stars are not there, nor is the high-ionization emission seen in binaries with compact objects.

Sharp additional red-shifted components, displaced by about 60 km/sec, are seen in strong lines such as Fe II (1) when the B star is behind the plane of the sky containing the M supergiant, but are absent when the B-star is in front of this plane. This indicates preferential motion of material in the direction from the M star to the B star.

During egress from primary eclipse, the Mg II *h* and *k* lines show a double-peaked emission profile whose asymmetry is indicative of optically thin formation in an expanding envelope. From the end of egress past first quadrature, the emission strengthens and becomes more symmetric as more and more of the visible hemisphere of the M star is being heated by the B star. At third quadrature, the Mg II profiles have reverted to the asymmetry characteristic of an expanding envelope, although their intensities are not in the optically thin ratio.

The rich emission spectrum of Fe II shows both systematic effects with phase and intermittent variation. During partial eclipse, a narrow emission spectrum is seen for Fe II multiplets 60, 62, 63, and 78, which is attributed to circumsystem material. By fourth contact, the strongest lines show a triple structure typical of most later spectra. The red and blue components are probably double-peaked emission features from an accretion disk around the B star. Many other lines show only two emission peaks, the circumsystem component and the blue component of the disk emission. The relative values of the disk and the circumsystem components vary irregularly. The strongest emission lines in the SWP spectra are those of Fe II (191). Although the region is heavily chopped up by the chromosphere-like spectrum, some systematic variation with phase is seen.

Although the chromosphere-like spectrum persists throughout the cycle thus far observed, the profiles of the absorption features sometimes show additional red- or blue-shifted absorption displaced by up to 200 km/sec. There is no discernable pattern to the presence or sense of this additional absorption with orbital phase. The red shifts are likely due to episodes of accretion onto the hot companion, perhaps as it passes through a denser clump in the extended M star atmosphere. The most dramatic example of blue-shifted absorption occurs in the observation made at phase 0.546 (near third quadrature). In this spectrum, emission lines other than the Mg II *h* and *k* lines are absent or have been reduced to the level of the continuum, indicating some sort of disruption of the accretion disk around the B star.

The high degree of intermittent behavior on the time scale of weeks to months in this binary with a 20-year period is evidence that the extended atmosphere of the M star is highly clumpy in nature.

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TABLE 1. *IUE observations of VV Cephei.*

Date (U.T.)	J. D. 2440000+	Phase	IUE Image	IUE Image
1978 Apr 23	3622.4	0.037	LWR 1374	
1978 May 20	3649.1	0.041	LWR 1525	
1978 Jun 5	3665.0	0.043		SWP 1725
1978 Jun 15	3674.9	0.044	LWR 1673	
1978 Jul 10	3699.9	0.048	LWR 1807	
1978 Jul 29	3718.9	0.050		SWP 2140
1978 Jul 31	3721.4	0.051	LWR 1931	
1978 Aug 18	3739.3	0.053	LWR 2109	
1978 Sep 28	3780.0	0.059	LWR 2488	
1978 Nov 9	3821.7	0.064	LWR 2886	
1978 Nov 12	3825.1	0.065	LWR 2923	SWP 3322
1978 Dec 25	3867.8	0.070	LWR 3272	
1979 Jan 11	3885.3	0.073	LWR 3458	SWP 3888
1979 Feb 28	3933.3	0.079	LWR 3896	
1979 Mar 10	3943.1	0.080		SWP 4575
1979 Apr 21	3975.2	0.084	LWR 4243	
1979 May 15	4009.2	0.089	LWR 4524	SWP 5241
1979 Jul 23	4077.9	0.098		SWP 5907
1979 Oct 10	4157.4	0.109	LWR 5804	
1979 Nov 25	4202.6	0.115	LWR 6221	SWP 7218
1980 Jan 15	4253.7	0.122	LWR 6666	SWP 7657
1980 Feb 22	4292.1	0.127		SWP 8012
1980 Jun 28	4418.8	0.145	LWR 8140	SWP 9390
1981 Feb 27	4662.6	0.177	LWR 10031	SWP 13374
1981 Feb 28	4664.3	0.178	LWR 10037	SWP 13383
1981 Jun 8	4764.2	0.191	LWR 10811	SWP 14220
1982 Feb 10	5010.7	0.224	LWR 12540	SWP 16301
1983 May 28	5483.4	0.288		SWP 20090
1983 Jul 1	5517.2	0.292	LWR 16276	
1984 Dec 29	6063.4	0.366	LWP 5095	SWP 24770
1988 Aug 26	7399.3	0.546	LWP 13918	SWP 34136
1990 Mar 1	7952.4	0.620	LWP 17446	SWP 38281

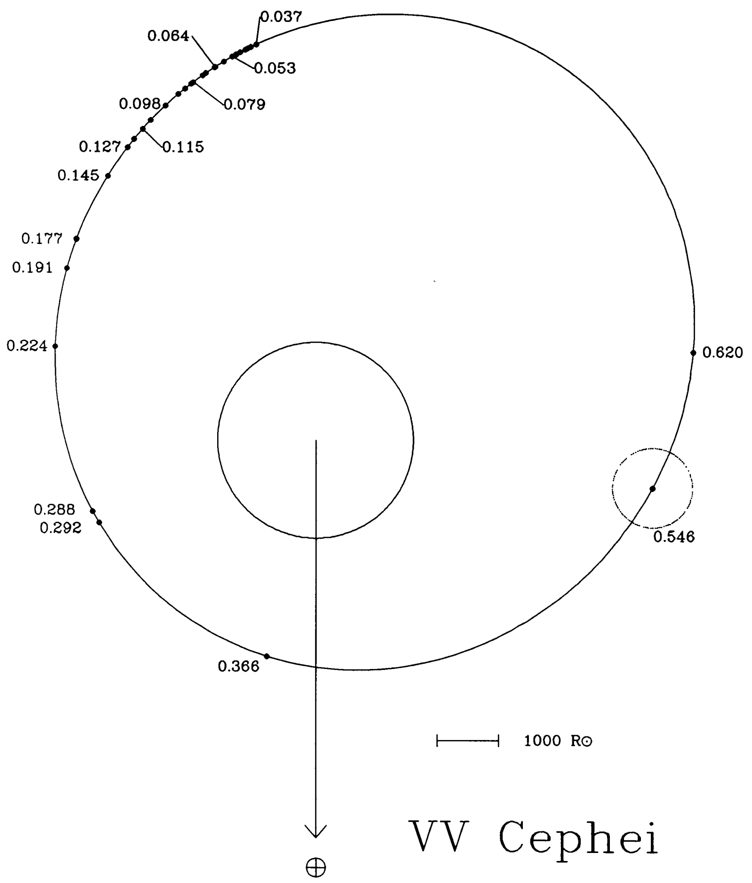

FIGURE 1. The system of VV Cephei to scale (Wright 1977). The dotted circle represents the disk around the B star; the B star itself is smaller than the solid circle at the center of the disk. The size of the disk was measured near primary eclipse (when the system is near apastron). Orbital positions of most of the IUE observations are labeled with their phases.

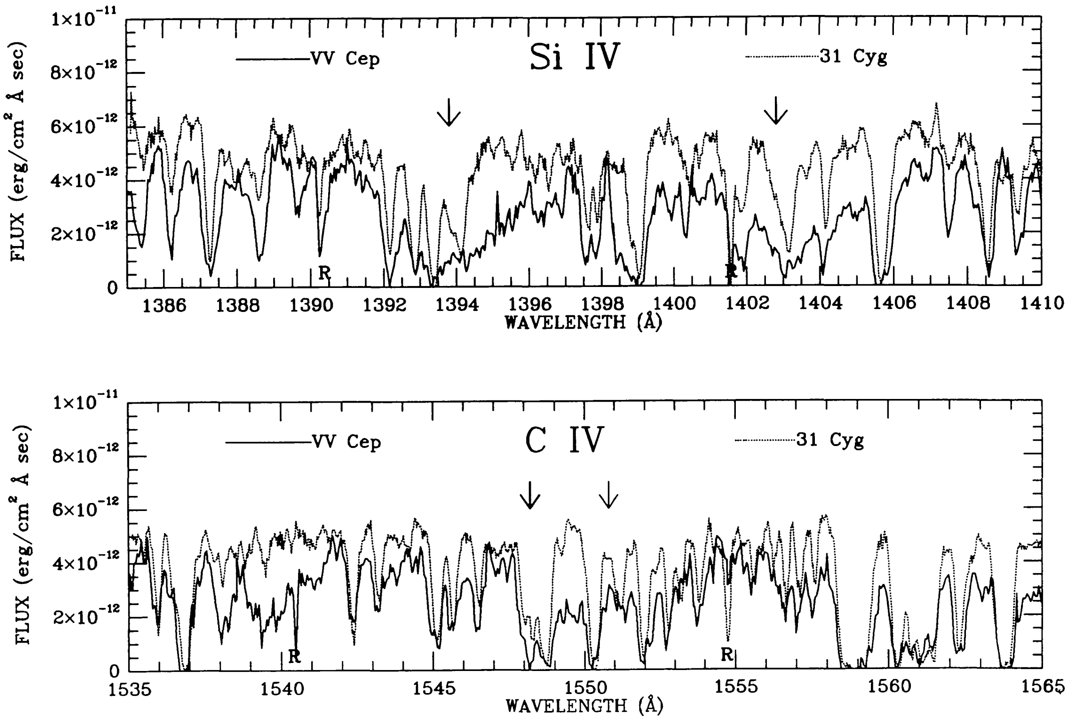

FIGURE 2. The Si IV and C IV features in VV Cephei and 31 Cygni. The dotted line represents the spectrum of 31 Cygni (K4 Ib + B 4 V) during chromospheric eclipse. The broad absorption in the spectrum of VV Cephei at the position of the Si IV lines demonstrates that the companion (or the outer regions of its accretion disk) are as least as hot as an early B star. Note that the flux scale for the 31 Cygni spectra runs from 0 to 2.3 × 10^{-9}.

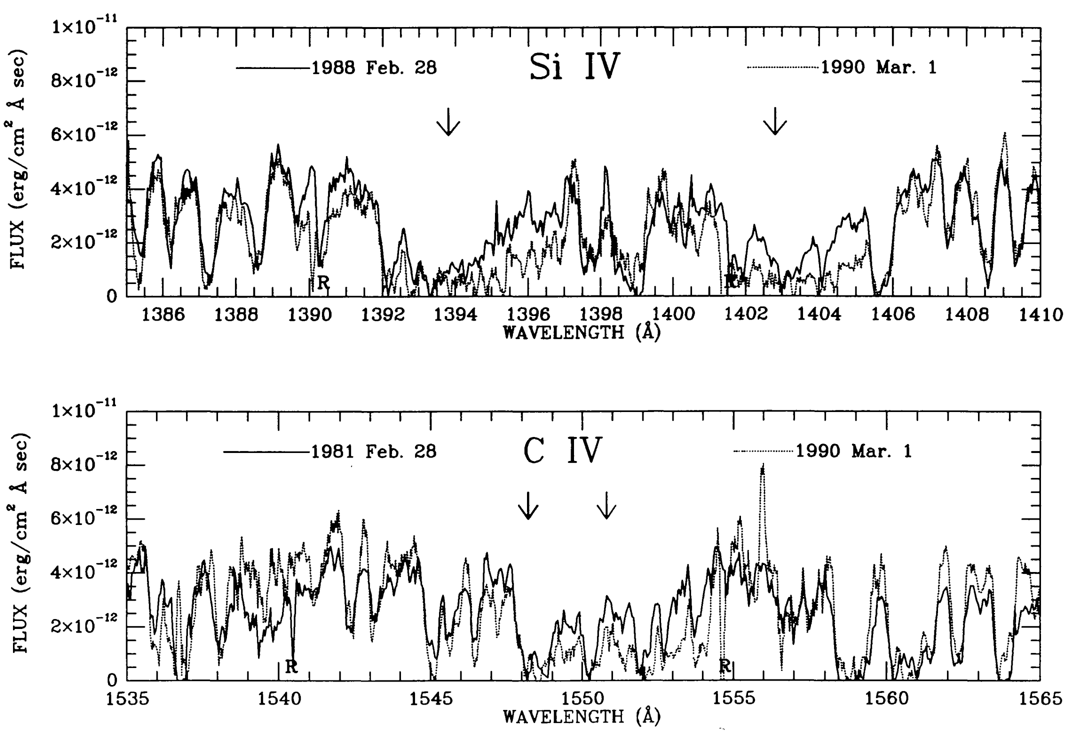

FIGURE 3. Change in the Si IV and C IV features in VV Cephei with time. The most recent observation (φ = 0.620, dotted line) shows possible asymmetry in the sense of additional red-shifted absorption.

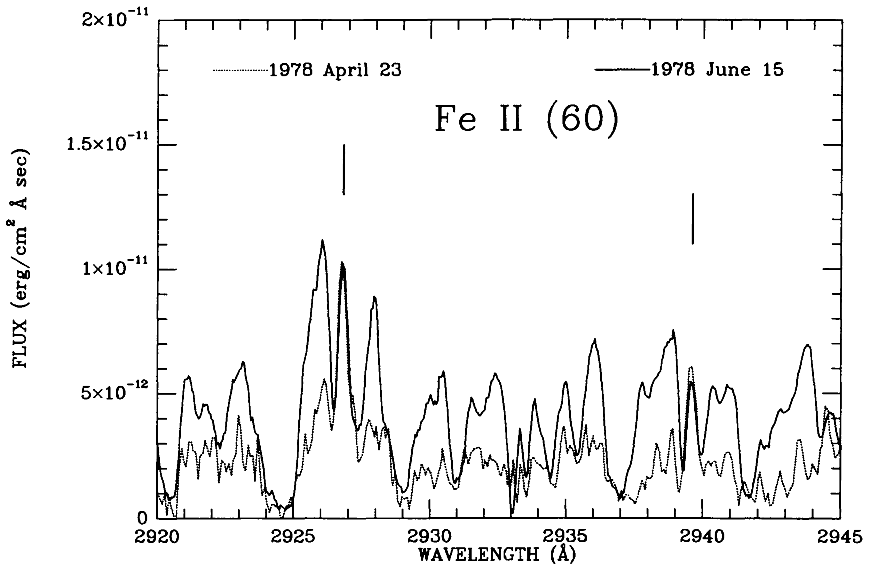

FIGURE 4. Circumsystem and disk emission in Fe II (60). The wavelength of two lines of Fe II (60) are marked with vertical lines. The dotted line represents the spectrum obtained during the partial phase of egress, and sharp emission features are seen in these lines. By optical fourth contact (solid line), the double-peaked disk emission seen for the strongest lines has emerged.

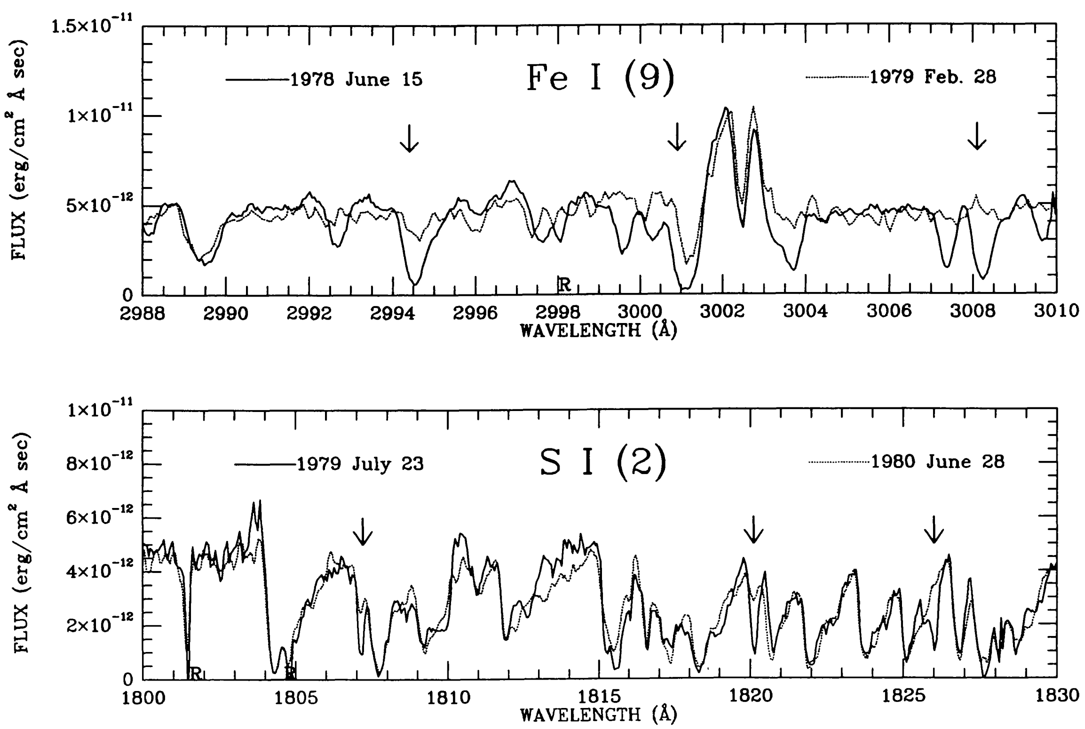

FIGURE 5. The weakening of absorption features from neutral elements. Arrows point to the positions of lines of Fe I and S I. The neutral lines are weaker in the observations taken later in the egress from eclipse (dotted lines).

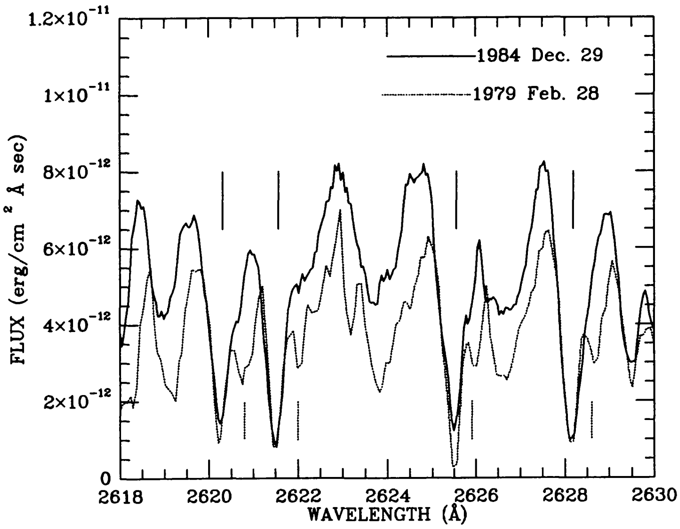

FIGURE 6. Line doubling seen in Fe II (1). The solid line represents a spectrum obtained while the B star was closer to earth than the M star, and the dotted line a spectrum obtained while the B star was more distant. Solid vertical lines mark the positions of lines in Fe II (1), and dotted vertical lines mark the additional red-shifted components observed when the B star is more distant than the M star, indicating mass flow from the M star toward the B star.

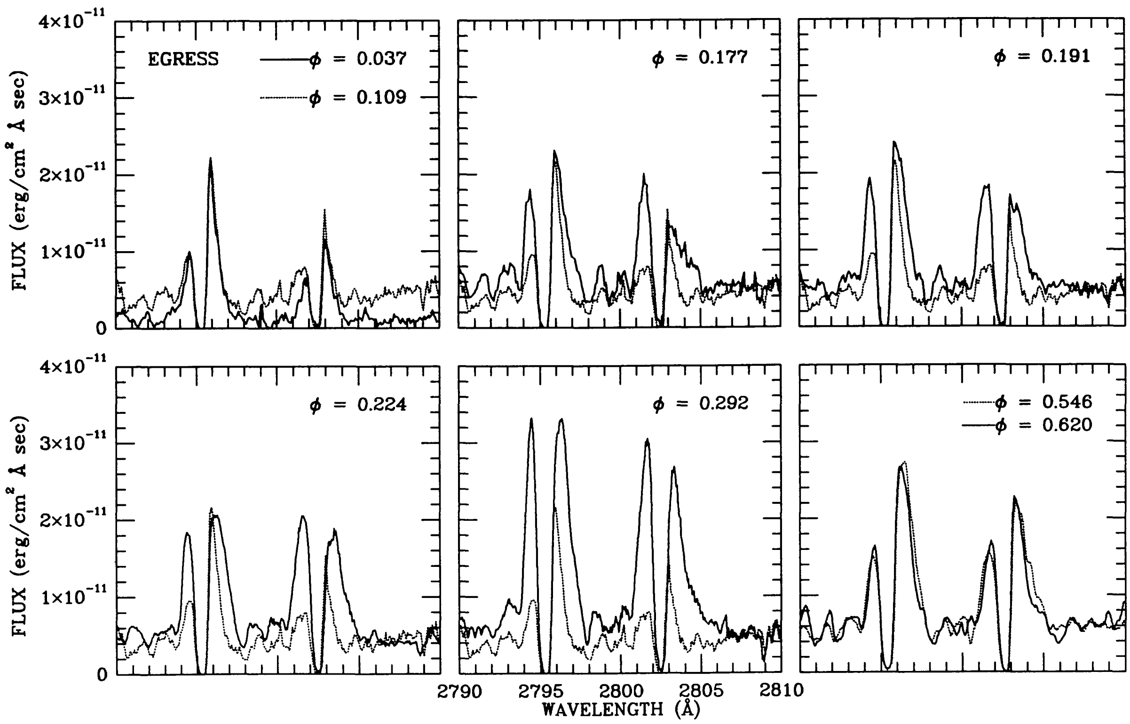

FIGURE 7. Variation in the Mg II *h* and *k* line profiles with phase. The emission showed little variation during the egress phase (through 1980 June). In the first five panels, the dotted line represents a typical egress profile. The line profiles are asymmetric in the sense expected for an expanding chromosphere, and the intensities are roughly in the proportion of the line *f*-values, indicating optically thin formation. As the B star moves in front of the M star, the profiles strengthen and begin to appear more optically thick. The final panel presents the two most recent spectra (near third quadrature). The lines have reverted to their previous asymmetry but are of nearly equal strength.

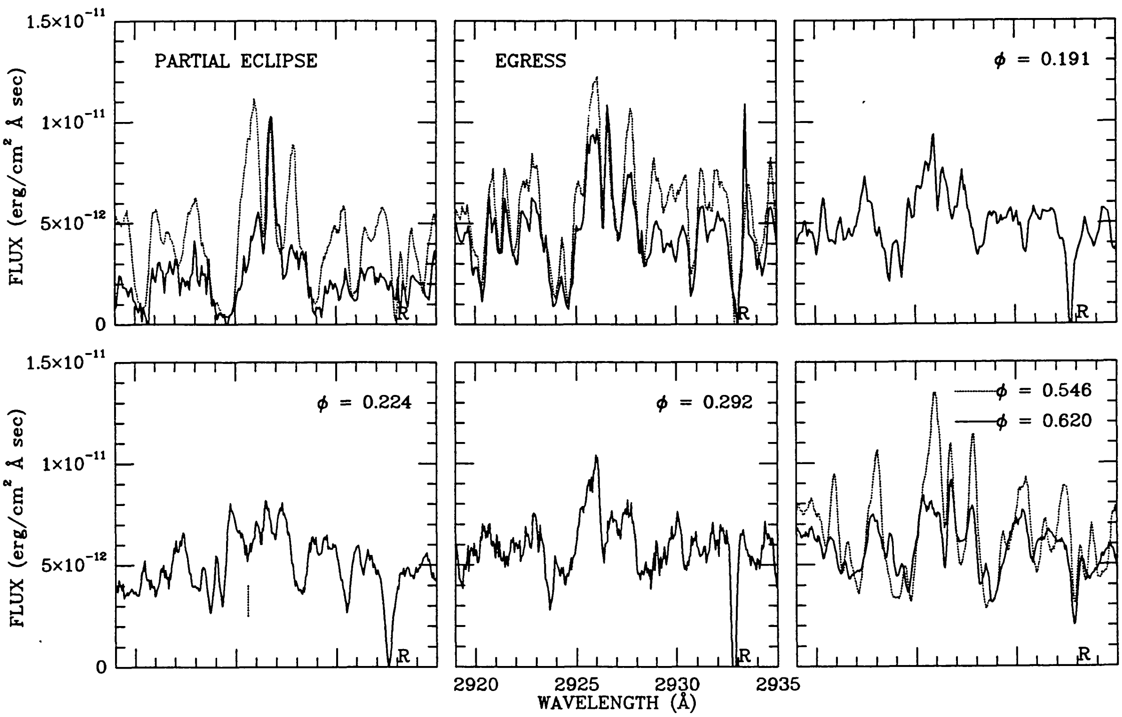

FIGURE 8. Variation in Fe II (60) λ 2927 emission profiles. The first panel presents spectra obtained during partial eclipse (solid line) and near optical fourth contact (dotted line), distinguishing the circumsystem and disk emission (see also Fig. 4). Two representative spectra obtained during the egress phase are presented in the second panel: $\varphi = 0.084$ (solid line) and $\varphi = 0.089$ (dotted line). Note that the relative strength of the circumsystem and disk components varies, although the three-peaked structure is seen through egress. The next three panels show the variety of features seen post-egress but before secondary eclipse. The dip marked with a dotted line in the $\varphi = 0.224$ observation is also seen at that phase in other Fe II emission lines. The final panel depicts the two observations made near third quadrature.

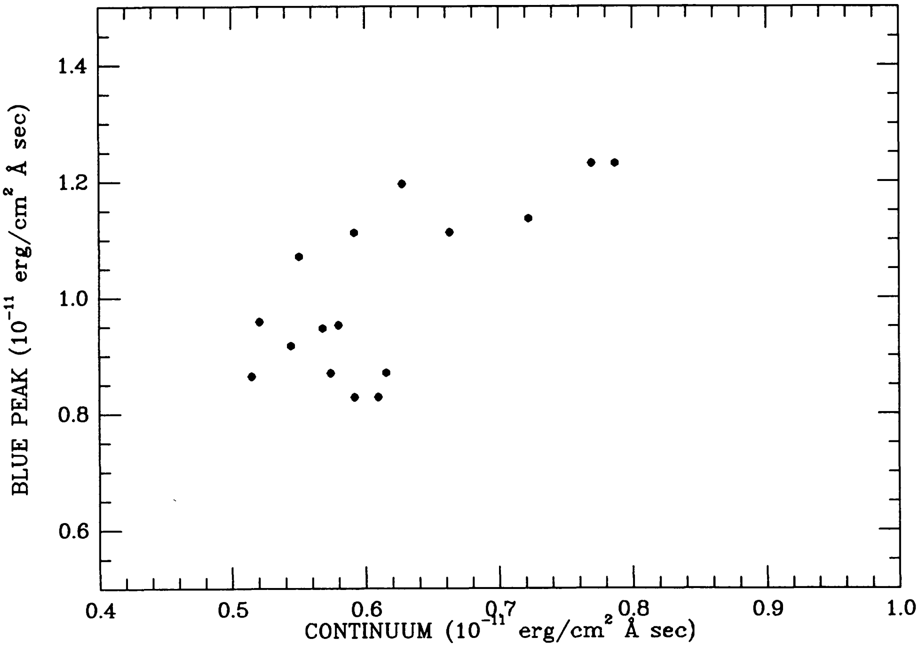

FIGURE 9. Flux in the blue peak of the broad emission in Fe II (60) λ 2927 *vs.* the flux in the nearby continuum. These tend to vary together, indicating that the B star is responsible for exciting the broad emission component.

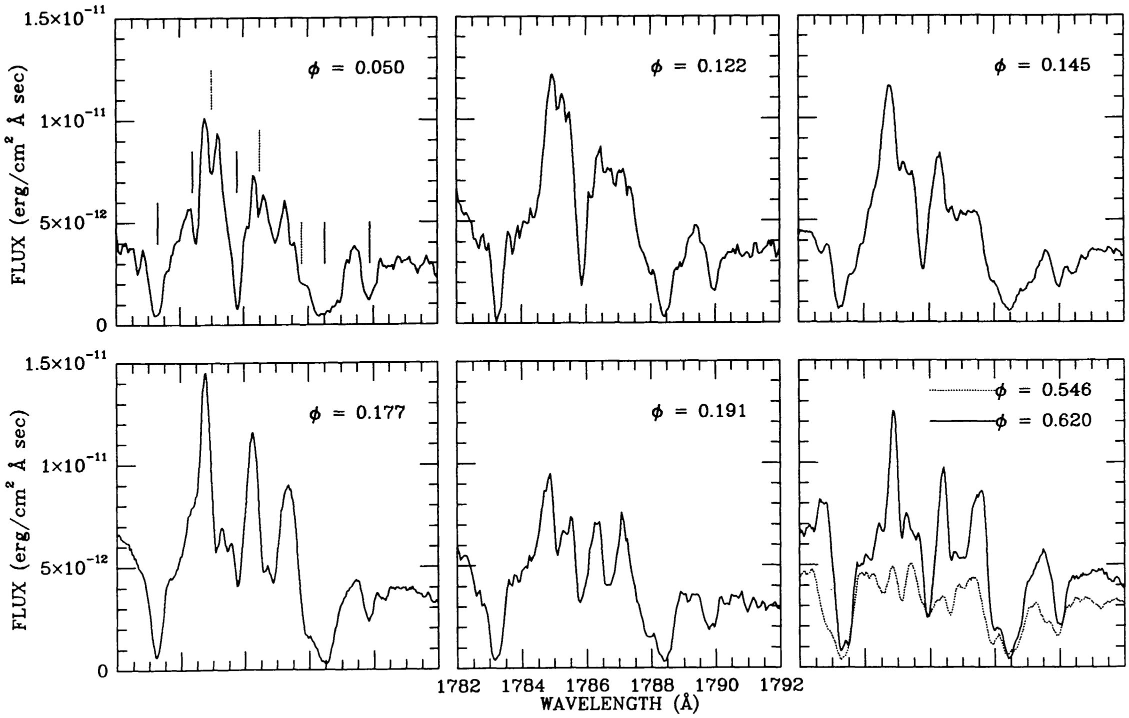

FIGURE 10. Variation in the Fe II (191) emission profiles. In the first panel, vertical lines mark the positions of absorption features seen in the chromospheric eclipse spectrum of 31 Cygni: dotted lines mark Fe II (191) and solid lines mark other lines. The first three panels present typical profiles seen during egress. The fifth panel presents a four-peaked profile typical of those seen from $\varphi = 0.191$ through secondary eclipse. The final panel shows the two spectra obtained near third quadrature.

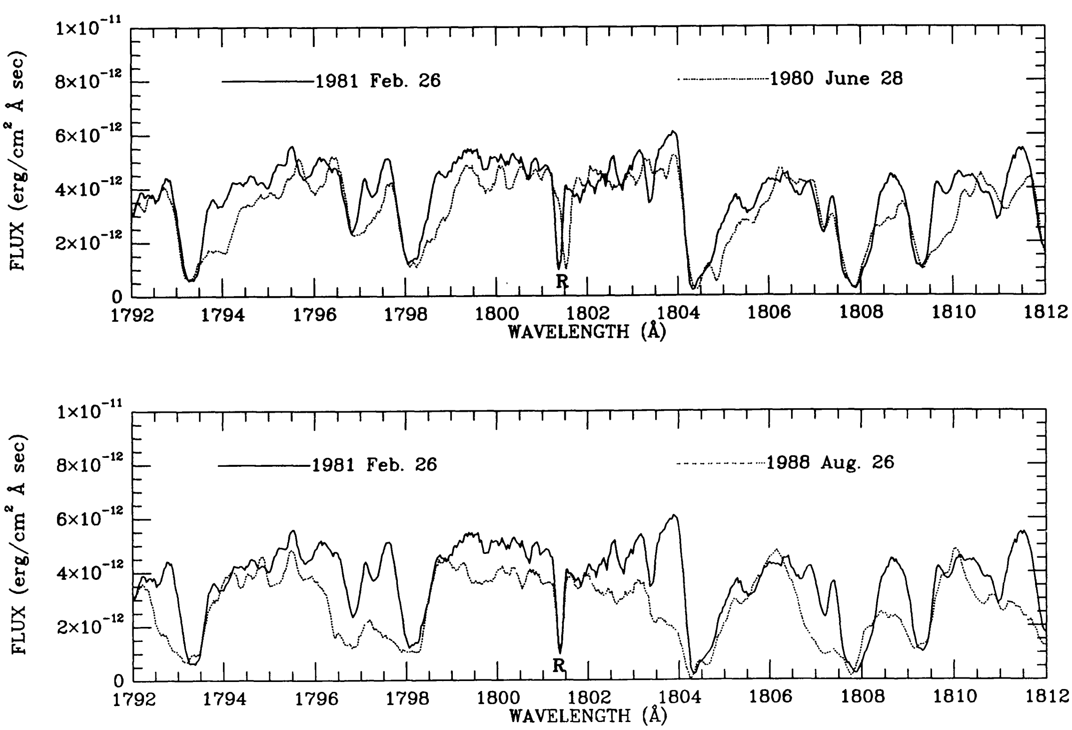

FIGURE 11. Intermittent red and blue shifts. The solid line in both panels represents a spectrum with symmetric line profiles, and the dotted lines spectra showing additional absorption components.

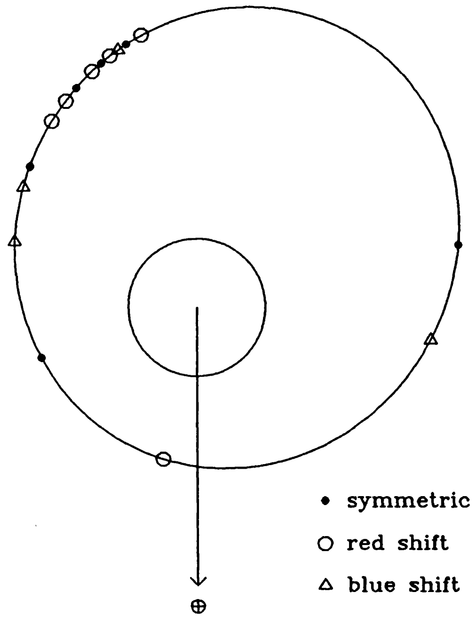

FIGURE 12. Orbital positions at which intermittent red and blue shifts were observed. No apparent periodicity or correlation with phase is visible.

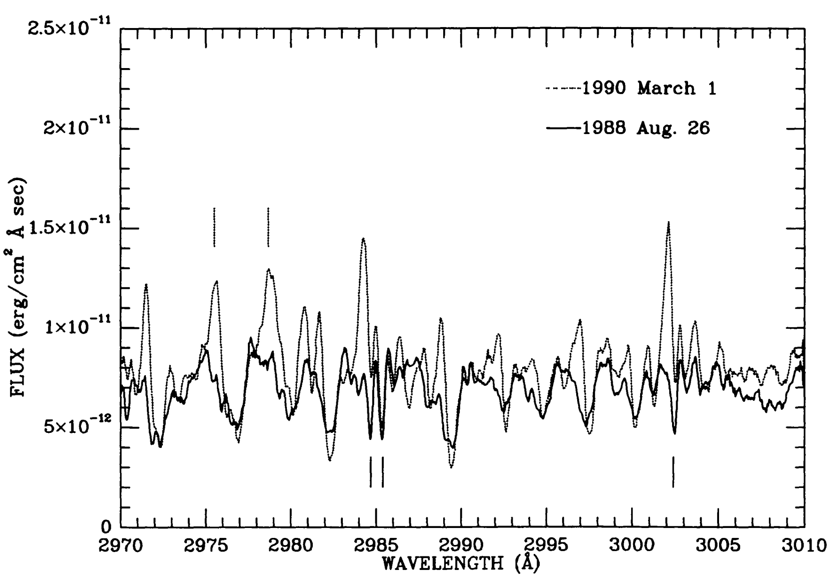

FIGURE 13. Spectra near third quadrature. Vertical lines mark the positions of lines of Fe II multiplets 60 (dotted) and 78 (solid). The solid line represents the $\varphi = 0.546$ observation, and the dotted line $\varphi = 0.620$. Note that the emission is missing in the $\varphi = 0.546$ observation. (see also Figs. 8 and 10).