Rapid Mass-Loss Transients in VV Cephei

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ABSTRACT. Biweekly ultraviolet observations of the red supergiant–hot dwarf binary VV Cephei during 1991, obtained near third quadrature, have revealed the existence of short-term continuum variations. We infer these are superposed on an underlying emission-line spectrum. The viewing geometry of this long-period system suggests we are seeing a process associated with nonuniform mass transfer to an accretion disk. This rapid variability can be related to global instabilities in the stellar wind and mass loss from the red supergiant.

1. INTRODUCTION

VV Cephei is a very long-period binary, comprised of an M2 Iab (supergiant) primary plus a hot companion (type B1–B2) orbiting within the extended atmosphere of the primary star. The eccentric orbit and the Hα disk around the B star, inferred by Wright (1977), suggests mass transfer. The orbit is sufficiently eccentric that the primary may fill its Roche lobe near periastron, triggering transient mass loss (Guinan et al. 1985). During a recent analysis of 12 years’ worth of ultraviolet spectroscopy of VV Cep, reported by Bauer et al. (1991, hereafter, referred to as BNS91), evidence for transient absorption features was detected. During 1991, the phase of the 20.3-yr binary placed the system near third quadrature, and we report here the results of a new series of regularly spaced IUE observations. The detection of systematic, rapid variations is relevant to both the study of the mass-loss physics of the evolved M supergiant, and the processes connected with mass transfer and accretion onto the B star companion. Section 2 discusses the observed variations. Section 3 explores a mass-transfer model. Section 4 summarizes our conclusions and suggests future observational efforts.

2. OBSERVED VARIATIONS

We made use of the International Ultraviolet Explorer (IUE) satellite (Boggess et al. 1978) to obtain low- and high-dispersion mid- and far-ultraviolet spectra of VV Cep every two weeks between 1991 early June through 1991 late October. Details of the high-dispersion observations are given in Table 1. Low-dispersion observations accompanied these, with 3-min SWP (1150–2000 Å) and 20-s LWP (2000–3200 Å) exposure times.

2.1 Continuum

Figure 1 illustrates the light variation extremes for low-dispersion spectra, as observed during 1991. Table 2 documents the integrated flux over the full wavelength range, and selected wavelength-continuum flux levels in the SWP and LWP low-dispersion spectra at each of the 11 dates those spectra were obtained. As Fig. 2 illustrates, the integrated ultraviolet light varies considerably on the 2-week time scales in which the observations were obtained. A semiperiodic alternation between minima and maxima is apparent on a 2–4-week time scale, although faster and slower variations cannot be ruled out. Integrated continuum changes as large as 88% were found in SWP spectra, and 53% in the LWP region.

We began our investigation of the detailed nature of these variations by selecting a series of continuum points throughout the SWP and LWP region, which were found by scanning the high-dispersion spectra at bright phases. These points are probably “pseudocontinuum points,” because the spectrum is rich with absorption and emission features (see figures in BNS91). These “continuum” points reflect spectral plateaus, typically 1–2 Å wide, selected because they were separated from strong lines and instrument defects. We initially assumed the variation is mostly due to additional absorption in the spectra rather than variable emission. Table 2 displays these high-dispersion continuum points as a function of time and wavelength, and it is clear that the shorter wavelengths are the more variable. By averaging four low-continuum-brightness spectra and five high-continuum-brightness spectra, we derived a continuum ratio as a function of wavelength (Fig. 3). This shows at least 70% variation of extinction in the SWP region, and less than 20% variation in the Fe II and Mg II line rich LWP region (2650–2800 Å). This relatively
flatter extinction curve longward of about 2400 Å is analogous to that deduced by Buss and Snow (1988) for red supergiant stars, assuming large, cold dust particles. However, a closer look at the spectra also reveals significant variation in the numerous spectral lines as well (see below).

As Table 2 indicates, the 1991 July 6 observation has the lowest integrated SWP flux value of the 11 observations. On the assumption that this represents the highest opacity period during our series of observations, we will subsequently reference other spectra to this one.

2.2 Spectral Lines

We examined the high-dispersion spectra to determine the behavior of individual absorption and emission lines in an effort to ascertain whether they vary with the continuum. After noting the presence of what appear to be emission lines around 2750 Å (see below), we decided to reexamine the spectra recorded near first quadrature (BNS91). In comparing the Fe II lines in the newer observations (circa phase 0.7), with earlier spectra (circa phases 0.2-0.3), we find that the newer data can be interpreted as an ensemble of emission lines above a faint continuum, while the older phases appear to have a generally stronger continuum plus absorption lines. The emission lines appear doubled and asymmetric in ways interpretable as atmospheric flow patterns, as we will discuss.

2.2.1 Low Excitation: Mg II and Fe II Lines

The Mg II lines during 1991 only show small variations at the level of ~5%. However, compared to spectra shown by BNS91, the ratio between the emission peaks of this doubly reversed profile is more like the egress phases (0.0-0.1) than any of the later, first-quadrature phases (0.2-0.3). We attribute this changing appearance to disk-stream view angle changes, analogous to Hα (see Wright 1977, and below).

Examination of the UV multiplets 62 and 63 of Fe II, in the 2750 Å range, indicates that the spectra at these phases...
Fig. 3—The ratio of the average of brightest monochromatic continuum flux levels at selected UV wavelengths in high-dispersion spectra, with the average of lowest levels, revealing the absorption’s dependence upon wavelength. Five brightest and four faintest continuum dates (Table 2) were averaged to produce the ratio.

is quite different from those reported by BNS91 for earlier phases. We interpret the spectrum shown in Fig. 4 to be comprised of a series of double peaked emission features atop a weak continuum. The deep, narrow absorption cores of the upper spectrum (following first quadrature) have an almost one-to-one correspondence with the central reversal of the doubled emission lines in the lower spectrum taken near third quadrature in 1991. The major difference between spectra near 0.25 phase and 0.7 phase is that the continuum appears eroded in the later phases, which we interpret as due to intervening material in the line of sight (e.g., a stream) at the later times. This assumption is consistent with geometrical expectation for the relative positioning of stars and a trailing stream obscuring the continuum source when viewed near third quadrature. The “residual” emission is probably nebular material excited by the hot star, quite possibly the disk itself.

In a study of excitation mechanisms for different lines of Fe II in the spectra of cool giant stars, Judge et al. (1992) concluded that UV multiplets 1, 2, 32, 33, and 60 are excited by electron collisions, while UV multiplets 3-6, 34-36, and 61-64 are excited primarily by electron excitation of metastable quartet terms below ~4 eV, followed by photoexcitation due to lines at optical wavelengths by photospheric radiation. We examined the spectra of VV Cep to look for qualitative differences in the variation behaviors of these multiplets, to determine if they might arise from different parts of the binary. It appears that the asymmetry, during 1991, in the doubly reversed lines that are excited by electron collisions [e.g., UV60 lines at 2953 and 2970 Å—Fig. 5(a)] is more extreme than those excited radiatively [e.g., UV62 lines at 2749 and 2755 Å—Fig. 5(b)]. Judge et al. interpret these lines in terms of high electron density where the electron collision excitation occurs. The asymmetric emission favoring the long-wave side of the profile of these lines [e.g., Fe II multiplets UV1, UV2, UV60—Fig. 5(a)] suggests optically thick, blueshifted overlying absorption eroding the short-wavelength side of the emission feature and could indicate expansion of either the M supergiant chromosphere itself, or the impact/expansion site of a stream hitting the accretion disk around the B star. We favor the latter interpretation, because the emission fluxes are orders of magnitude brighter than chromospheric levels for single M supergiants (cf. Stencel and Chapman 1981).

The luminosity emitted in the Fe II lines is of interest. Using the 855 pc distance listed by Humphreys (1978), and noting the average flux for multiplet UV63 lines of about $8 \times 10^{-12}$ ergs cm$^{-2}$ s$^{-1}$ Å$^{-1}$ over ~2 Å intervals, roughly 100 Fe II emission lines would produce about $10^{33}$
2.2.2 Origin of the Doubled Fe II Emissions

like material. peaked emission lines, perhaps as though it is the approaching side of the cores are blue-shifted from the lab frame with $-55 \text{ km s}^{-1}$ velocity. Note $\pi$ (UV62 and UV63), and that the taken between phases 0.680 and 0.700. The small arrows indicate the rest

Fig. 6—A combination plot of smoothed spectra for all 11 observations taken between phases 0.680 and 0.700. The small arrows indicate the rest wavelengths for selected lines of Fe II (UV62 and UV63), and that the cores are blue-shifted from the lab frame with $-55 \text{ km s}^{-1}$ velocity. Note the strongest variation appears on the short-wave side of the double peaked emission lines, perhaps as though it is the approaching side of the disk emission that it being variably obscured by the intervening stream-like material.

2.2.2.2 Origin of the Doubled Fe II Emissions

Figure 6 shows time variations in the doubly reversed emission lines arising from photoexcited multiplets UV62 and UV63. Comparing the 11 different observations in mid-1991 reveals that the centroid of the emission-line envelope is blue-shifted with respect to the central absorption. The central absorption appears relatively stationary, at $-55 \text{ km s}^{-1}$ (e.g., the line at 2739 Å, Fig. 6). The line splitting is comparable to twice the disk orbital velocity (see below). The high-velocity, shortest-wavelength side of the emission feature changes the most during the 1991 observations.

We suggest that these characteristics are a result of the viewing geometry of the system, in which the discontinuous stream, when seen near third quadrature, enters the disk in a direction which variably obstructs our view of the continuum from the B star and modulates the emission from the accretion disk. In other words, we observe a rotationally split emission feature, with the short-wavelength emission brighter and more variable than the long-wavelength side of these photoexcited Fe II lines. This high-velocity material is the blue-shifted, optically thin “spray/splash” of “hot-spot” material driven away from the stream-disk impact site. The absorption reversal longward of the emission centroid is the infalling stream material, red-shifted at third quadrature.

To test this model, we examined observations from earlier phases (0.224 and 0.292) when the B star was on the opposite side of the M star and with its orbital direction coming toward us. Because the stream must enter the disk on the side trailing the B star, it would have entered the disk on the side opposite of that which was observed at the later phases and not occulted the B star continuum. We found that the earlier phases feature less eroded continuum levels and do not exhibit the absorption characteristics of the phases in which we observed (see figures in BNS91). This supports the geometric model just described.

2.2.3 High Excitation: C IV and Si IV Lines

BNS91 classified the companion as an early B star based on the strengths of the Si IV and C IV resonance lines in the spectrum of VV Cep. The complexity of the spectra and limited signal-to-noise make it difficult to judge, but it appears that any variation that might be occurring is dominated by changes in the continuum rather than in the shape of these lines. Equivalent width measures appear constant over time, within the errors. Thus, we tend to concur with the opinion that these are due to the underlying hot-star photosphere.

3. STREAM AND DISK INTERACTION MODEL

We base our analysis on the model developed by Wright (1977) and hypothesize that the M supergiant does not fill its Roche lobe completely, except at near- and slightly post-periastron times when temporary Roche lobe overflow drives a stream which forms an accretion disk around the B star. Wright (1977) estimated this disk to have an outer radius of 650 $R_{\odot}$ based on eclipse behavior of the Hα profile. We hypothesize that the matter escaping from the M star does so noncontinuously due to intrinsic variations of the M supergiant and sporadic overflow of its Roche lobe near periastron passage (Guinan et al. 1985).

This overflow results in a stream through the inner Lagrangian point to the accretion disk around the B star. The irregular UV variations near third quadrature suggest that this stream is likely to consist of a series of clumps of matter with nonuniform densities and separation. As these clumps move away from the M star, they cool. On their way to the B star, we observe these cool clumps to absorb the B star’s continuum as they pass through our line of sight to the B star. The amount of obscuration depends on the internal density of the clumps, their temperature, and our orientation with the stream in relation to the B star. Because each of these change, the amount of absorption we observe changes radically as well. We will apply this model to explain the transient absorption previously described, as well as the observed red-shifted emission of electron-collision excited Fe II lines. The latter is presumed to arise from local heating and expansion due to the impact of the infalling matter with orbiting matter already in an accretion disk (Livio 1992). Particularly energetic expansion events could account for the high-velocity blue-shift events reported by BNS91.

The 2-week time scale for strong variations in the continuum light, plus the estimated gravitational infall speed for matter in the stream, 113 km s$^{-1}$ (computed below), allows us to roughly constrain the maximum dimension of putative clumps in the stream to $<1.4 \times 10^6$ km (200 $R_{\odot}$). Alternately, if the biweekly variations were produced by clumpy matter inside the accretion disk itself, the clumps in the outer disk would be moving at 77-km s$^{-1}$ orbital speed at 650 $R_{\odot}$ and would transit the 15 $R_{\odot}$ B star disk in approximately one day. We examined the only
pair of such closely spaced high-dispersion spectra we have, namely SWP 42585 and SWP 42587, taken about 3 h apart on 1991 October 1, and find small but possibly real-line variations. In terms of flux differentials (upper two curves, Fig. 7), the variations appear more pronounced in the 1400–1500 Å region, and are qualitatively similar to those seen during 2-week variations, but on a smaller scale. These observations deserve to be repeated to verify short-term variations mimicking the longer variations, but at a lower level.

3.1 Radiation Output due to Collisions

Is the emission-line spectrum seen during 1991 the signature of the accretion disk? Previous analyses have shown that the emission-line output in the related ζ Aurigae binaries greatly exceed that for single cool stars (cf. Stencel and Chapman 1981), where the excess was interpreted to be due to large-scale wind–wind collisional shocks in the binary system. VV Cep would require significantly longer IUE exposures if it were simply a fainter single red supergiant. In VV Cep, however, rather than wind–wind shocks, the Hα evidence suggests a large accretion disk occurs in the system, perhaps due to the high mass-loss rate from the M star. We argue that only the B star could ultimately help produce the solar luminosity worth of Fe II line emission from this system, previously noted.

By comparing estimated velocities of infalling and orbiting matter, we can estimate the energy available to produce the observed ionization and compare these with the variation observed in atoms with different levels of excitation. First, the velocity of particles in the infalling stream \( v_{in} \) toward the B star, at a radius \( r \), is the same as the escape velocity from that radius with the opposite sign, assuming a negligible initial velocity from the M star, and \( M_B = 20 M_\odot \). Then we calculate the orbital velocity of the matter already in the disk \( v_{orb} \), which is \( \sqrt{2} \) less than the velocity of the infalling matter. At the derived radius of the accretion disk, namely 650 \( R_\odot \) (Wright 1977), \( v_{orb} = 77 \) km s\(^{-1}\) and \( v_{in} = 113 \) km s\(^{-1}\).

To obtain a minimum value of the energy transfer possible between any orbiting particle and an infalling particle, we assume that the infalling matter is coming into the disk nearly parallel to the tangential velocity of the orbiting matter. Too steep an angle of collision would disrupt the disk. These assumptions would imply that the excess velocity of the infalling matter compared with the orbiting matter, at a given radius, would translate into an energy which would have to be expelled from the system in some way. Otherwise, if the extra energy went into accelerating the orbiting particles, the radius of the accretion disk would increase. These assumptions imply a maximum available energy \( E_{coll} \) per infalling particle of mass \( m \):

\[
E_{coll} = m/2[v_{orb}(v^2-1)]^2. \tag{1}
\]

Using the above equation an individual silicon atom dropped in from infinity would acquire 147.5 eV when it reached the outer radius of the accretion disk. A carbon atom would have 62.6 eV, and hydrogen 5.3 eV. To obtain a value of the total energy of an average clump, we assume the clump to be an essentially pure hydrogen cloud. The total energy that the infalling clump would have to give up to maintain the orbital radius of the accretion disk, where \( M_c \) is the mass of the clump, would be

\[
E_{tot} = E_{coll} M_c / m_{H}. \tag{2}
\]

This gives the maximum total luminosity output in every direction of radiation, due to collisions and maintained for a 2-week period, of between \( 2 \times 10^{26} \) and \( 2 \times 10^{28} \) ergs s\(^{-1}\). To derive this value, we assumed a spherical clump of hydrogen gas at the maximum possible clump radius (given above) with a density ranging from \( 10^5 \) to \( 10^9 \) particles per cm\(^3\). These densities are consistent with those deduced for inner winds of red supergiants (cf. Stencel et al. 1981). With the B star’s luminosity estimated to be \( 1.2 \times 10^{38} \) erg s\(^{-1}\), the emission resulting from the collisions becomes insignificant to the overall continuum appearance. It also appears inadequate to power the estimated solar luminosity worth of Fe II emission estimated previously. The line emission, which we ascribe to the disk, must arise mostly from reradiation of hot star energy rather than solely collisional input. This large accretion system offers an unique environment for the study of energy transport that produces this line luminosity. For the emission-line luminosity to be collision-energy powered, clump densities in excess of \( 10^{10} \) cm\(^{-3}\) would be required. In principle, we should not dismiss this possibility, because similar densities are inferred or maser clumps around late-type giants and supergiants (Alcock and Ross 1986). These can be generated by thermal instabilities operating over scale sizes a few percent of the red supergiant star radius, transforming stellar plasma into molecules and dust (Stencel 1992). The latter could account for the variable broadband extinction we observe, if the VV Cep clumps were similarly cool, molecular material.
4. DISCUSSION

A series of biweekly ultraviolet spectra of VV Cep obtained over several months near third quadrature, in mid-1991, have established variability in the UV continuum. The persistence of emission-line profiles is consistent with viewing the hot star and its disk being irregularly occulted by clumpy material, which constitutes the mass-transfer stream in this long-period binary. The sampling enables us to place an upper size limit to these clumps which is no larger than 200 $R_\odot$. This size limit is nearly 1/16th the diameter of the M supergiant itself and provides an interesting limit for the size of coherent mass ejections from such stars. Such ejections could be powered by either oscillatory/pulsational phenomena, or magnetic effects (e.g., eruptive prominences). Either way, the rapidity of such ejections which become part of the mass-transfer stream suggest a lower limit to the mass-transfer/mass-loss rate of $10^{-11} M_\odot$ yr$^{-1}$, along the line of sight to the hot star, assuming the clumps are as dense as the inner wind of similar red supergiants. We deduce this from the volume of a 200 $R_\odot$ sphere with a mean density of $10^6$ cm$^{-3}$, which yields $10^{-12} M_\odot$ transiting the B star line of sight each $10^6$ s. Given a projected orbital separation during 1991 of about 5000 $R_\odot$, comparing this cross-sectional area with the 15 $R_\odot$ line-of-sight column to the B star, would boost the mass-loss rate by about $10^5$, if clumps were being ejected isotropically from the M supergiant star. The implied mass-loss rate of a few times $10^{-6} M_\odot$ yr$^{-1}$ is consistent with previous estimates for this and related objects. For the future, more closely spaced observations will be needed to better constrain the detailed mass-transfer clump size.

In addition, we may be recognizing in VV Cep at these phases, the first evidence for the spectrum of an accretion disk, as seen in the emission-line profiles of the Fe II lines described above. One motivation for study of this and other very widely separated systems, is that the enormity of the accretion disk may permit dissection of its physical processes in ways not possible in far more compact interacting binaries, where the development of large disks is truncated by tidal limits.

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