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HIGH-VELOCITY WINDS FROM A DWARF NOVA DURING OUTBURST

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ABSTRACT

An ultraviolet spectrum of the dwarf nova TW Vir during an optical outburst shows shortward-shifted absorption features with edge velocities as high as 4800 km s^{-1}, about the escape velocity of a white dwarf. A comparison of this spectrum with the UV spectra of other cataclysmic variables suggests that mass loss is evident only for systems with relatively high luminosities ($\gtrsim 10\ L_\odot$) and low inclination angles with respect to the observer's line of sight. The mass loss rate for cataclysmic variables is of order $10^{-11}\ M_\odot\ yr^{-1}$; this is from $\sim 10^{-2}$ to $\sim 10^{-3}$ of the mass accretion rate onto the compact star in the binary. The mass loss may occur by a mechanism similar to that invoked for early-type stars, i.e., radiation absorbed in the lines accelerates the accreting gas to the high velocities observed.

Subject headings: stars: dwarf novae — stars: individual — stars: mass loss — stars: winds

I. INTRODUCTION

As part of a series of ultraviolet observations of cataclysmic variable (CV) stars, which are disk-accreting close binary systems, we observed several dwarf novae in various luminosity states. Here we report evidence for a high-velocity wind from TW Virginis during an optical outburst. The C IV λ1549 line shows a marked "P Cygni" feature characteristic of an expanding atmosphere; several other UV lines show shortward-shifted absorption profiles. We estimate the mass loss rate by fitting the line profiles to theoretical models and attempt to specify the conditions under which mass loss from CVs in general is likely to be observed.

II. THE OBSERVATIONS

The object TW Vir was found to be brighter than its quiescent-state visual magnitude of 15.8 on 1981 January 2, by one of us (F. A. C.) and J. Middleditch using the Lick Observatory Anna Nickel 1 m telescope. The optical spectrum (λ = 3600–6000 Å) taken at that time (of uncertain photometric quality) shows a ~15 Å emission feature at Hβ λ4861 with an equivalent width of 3 Å; this line appears to be superposed on a shallow absorption feature more than 100 Å wide. There may also be shallow absorption about 80 Å wide at Hγ.

The only optical spectrum published for TW Vir of which the authors are aware was taken almost 40 years ago during a low state (near 15th magnitude) and shows an emission-line spectrum consisting of six hydrogen lines, He I λ4471, and possibly the K line of Ca II λ3933 (Elvey and Babcock 1943). Hard X-rays ($kT \geq 2$ keV) with a flux of 2×10^{-12} ergs cm^{-2} s^{-1} have been detected from TW Vir during what was probably a quiescent state (Córdova and Mason 1982).

A 60 minute ultraviolet exposure of TW Vir was taken by one of us (K. O. M.) on the night following the optical observation, 1981 January 3, beginning at 06:47:37 UT, with the low-resolution (~6 Å), short-wavelength (λ = 1150–1950 Å), wide-aperture (10″× 20″) camera on the *International Ultraviolet Explorer* satellite (*IUE*). The Fine Error Sensor (FES), a visual photometer on *IUE*, gave $V = 13.9 \pm 0.1$ for the star, indicating that it was still in an outburst state. Owing to poor weather at Lick Observatory during the *IUE* observations, simultaneous optical data were not acquired. No AAVSO light curves of the outburst were made, and thus it is not known at what part of the outburst cycle the *IUE* spectrum was taken.

III. RESULTS

a) The Continuum Distribution

The broad-band continuum *IUE* fluxes are plotted as a function of wavelength in Figure 1; also plotted at 5400 Å is the FES flux. Several models which have the same spectral shape as the UV data are shown in Figure 1: the steady state, optically thick disk model in which

[1]Guest Observer, *IUE* satellite.

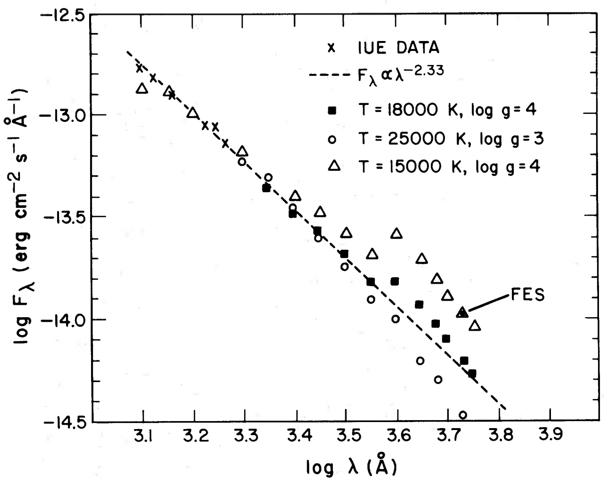

FIG. 1.—The continuous flux distribution of TW Vir showing the *IUE* data and FES data point at 5400 Å. Also shown are four theoretical models: the steady state, optically thick disk model ($\lambda^{-2.33}$); and three model atmospheres computed by Kurucz (1979). The two hottest Kurucz models are not plotted for $\lambda < 1500$ Å since they overlap each other, the *IUE* data, and the disk spectrum.

$F_\lambda \propto \lambda^{-2.33}$ (Lynden-Bell 1969); and model atmospheres (Kurucz 1979) with effective temperatures and gravities $T = 18{,}000$ K, $\log g = 4$, and $T = 25{,}000$ K, $\log g = 3$. It is interesting to note that these models agree with each other in spectral shape all the way from the far-ultraviolet (1250 Å) to the start of the optical band (3100 Å), demonstrating the need to extend the measurements to longer wavelengths if these models are to be distinguished. None of the model spectra predict enough emission in the optical band to account for the observed flux at 5400 Å. If a lower-temperature atmosphere, $T = 15{,}000$ K, $\log g = 4$, is assumed, the overall spectrum will be flatter, and the ratio of the flux at 1450 Å to the flux at 5400 Å will more nearly represent the data (see Fig. 1). Such a distribution, however, falls below the observed far-UV flux ($\lambda < 1400$ Å). Thus neither the single temperature and gravity model atmospheres calculated by Kurucz (1979) nor the steady, optically thick disk distribution fit the entire observed spectrum.

b) *The Line Spectrum*

The UV spectrum, illustrated in Figure 2, shows two kinds of line profiles: a P Cygni feature consisting of shortward-shifted absorption and emission near the rest wavelength at C IV λ1549; and shortward-shifted absorption with little or no emission at N V λ1240, O IV λ1342, Si IV λ1397, C III λ1176, and at the Si III/O I/Si II blend ~λ1300. Some of these spectral features are shown in more detail in Figure 3. The edge velocity of each line (where the short wavelength edge of the absorption component crosses the continuum) is listed in Table 1. Assuming that the lines are formed in outflowing material, the edge velocity represents a lower limit to the terminal velocity of the wind, v_∞. The largest de-

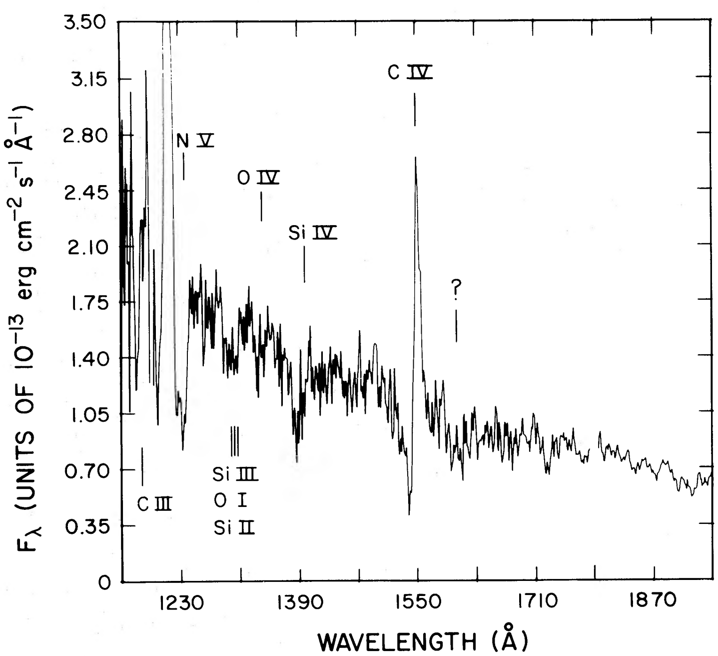

FIG. 2.—The *IUE* spectrum from the file SWP 10951, taken with the low-resolution (~6 Å), short-wavelength camera through the large aperture. The pronounced emission feature at 1215 Å is geocoronal Lyα; the gaps at 1191 Å and 1790 Å are the locations of camera reseaux. The broad dip from about 1590 Å to 1614 Å may be Al III, Fe III, or possibly [Ne IV].

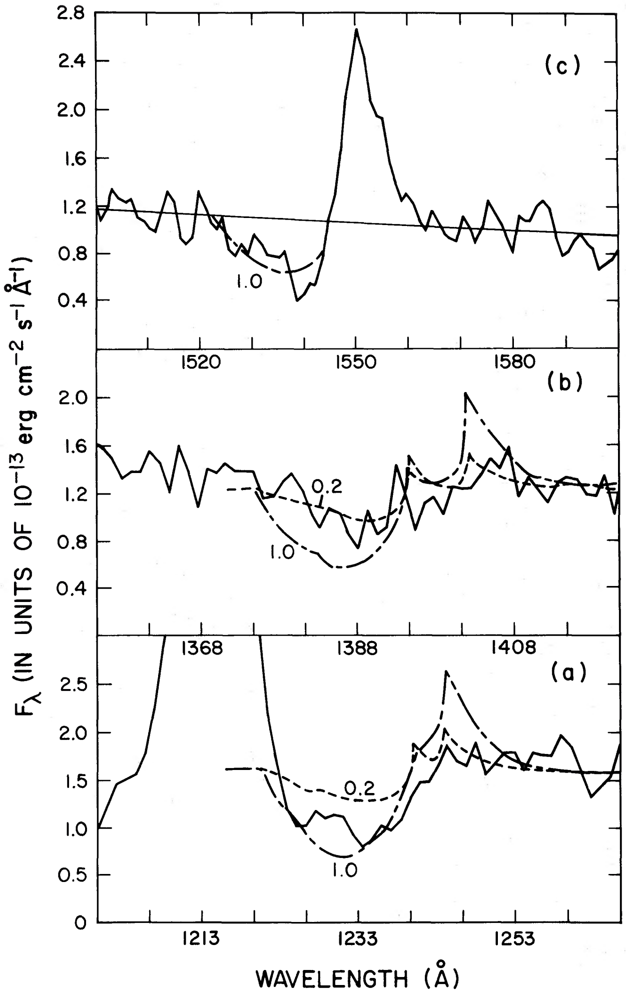

FIG. 3.—Enlargements of various portions of Fig. 2 to show the detail in the line profiles: (*a*) N V λλ1239, 1243 and theoretical profiles for doublet resonant lines from Fig. 5*a* of Olson (1982*a*); (*b*) Si IV λλ1394, 1403 and profiles from Fig. 5*b* of Olson; (*c*) C IV λλ1548, 1551 and the absorption part of a profile from Fig. 7*b* of Castor and Lamers (1979). The thin solid line in (*c*) is the estimate of the background we used to calculate the equivalent widths of the absorption and emission components of C IV. The fits to the profiles are labeled with a parameter, T_B, related to the optical depth of the shortward (absorption) component.

TABLE 1
TW VIRGINIS LINES

Line	λ_0 (Å)	v_{edge}	Comments
C IV	1548, 1551	−4800, +2200	P Cygni profile, $EW_{abs} = 7.1$ Å, $EW_{emis} = 12.7$ Å.
Si IV	1394, 1403	−3000	P Cygni profile in which shortward-shifted absorption dominates small emission component.
N V	1239, 1243	< −4300	Shortward-shifted absorption contaminated by Lyα.
O IV	1338, 1343, 1344	−2400	Shortward-shifted absorption.
C III	1176	−2300	Shortward-shifted absorption.
Si III, O I, Si II	1298, 1304, 1309	−2800	Shortward-shifted absorption.

tected edge velocity is observed for C IV, where $v_{\rm edge} \sim -4800$ km s^{-1}. This is about the escape velocity of a white dwarf, $v_{\rm esc} = (2GM/r)^{1/2} \approx 5000(M/M_{\odot})^{1/2} (R/10^9 \text{ cm})^{-1/2}$ km s^{-1}, indicating that the wind could emanate from close to the compact star. The central depth of the C IV absorption component occurs at a wavelength corresponding to $v_{\rm cen} \sim -2100$ km s^{-1}. The sum of the equivalent widths of the emission and absorption components of the C IV line is 19.8 Å; the ratio of the equivalent width of the emission to that of the absorption, W_R/W_B, is 1.8. The background level used for the equivalent width measurement is shown as a thin line in Figure 3*c*. This level may be an underestimate of the true background if the apparently noisy features in the spectrum are actually a myriad of closely spaced absorption lines; in the case when the continuum is drawn through the peak of the fluctuations, the value for W_R/W_B may be as low as 1.0. The equivalent widths of the other lines are even more difficult to measure: N V is contaminated by geocoronal emission at Lyα, and the other lines are doublets or triplets (see Table 1) in which the components are only partially resolved.

IV. DISCUSSION

a) *Comparison with Other Observations of Mass Loss*

Velocity-shifted spectral features of the kind observed in TW Vir are common among O and Of-type stars, OB supergiants, Be stars, and Wolf-Rayet stars, among others (Conti 1978). The characteristic P Cygni profile in these stars is believed to be produced in an expanding extended atmosphere or wind: the shortward component is caused by Doppler-shifted absorption in the line of sight; the longward component is formed by emission from that part of the wind receding from the observer; and the emission near the rest wavelength of the line is from material expanding at right angles to the line of sight.

The driving mechanism for the wind in many of these stars is believed to be radiation pressure. Lucy and Solomon (1970) have noted that the phenomenon is self-amplifying in that radiation absorbed by the lines transfers momentum from the photons to the ions, resulting in an outward velocity which shifts the effective absorption energy to shorter wavelengths in the continuum, where the ions can be further accelerated. Castor, Abbott, and Klein (1975) show that the radiation force may act on a very large number of lines in addition to the resonance lines considered by Lucy and Solomon. The model of Castor *et al.* predicts that the terminal velocity will be proportional to the luminosity and to the escape velocity from the photosphere.

A line-driven mechanism may give rise to mass loss in CVs, too, if the acceleration due to radiation from the central star and inner disk exceeds that due to gravity. In TW Vir, the edge velocities of the absorption wings are of the magnitude of the escape velocity from the surface of the accreting white dwarf; this is similar to the case of late B supergiants, where $v_\infty \sim v_{\rm esc}$ (Cassinelli and Abbott 1981). Hence the innermost region of the disk, where the gravitational field is strongest, may be responsible for the high velocities in the observed wind. Regions of the disk farther away from the center may contribute to lower-velocity wind ejecta through both radiative and evaporative processes. A conically shaped wind region, centered on the rotation axes of the disk, would be expected because of the planar nature of the disk. Thus high-velocity winds may be observable only in systems with high luminosities and low inclinations.

P Cygni lines are evident in the UV spectra of a number of CVs, and there does appear to be some support for a relationship between the observability of a high-velocity wind and the orbital inclination of the system. For the CV systems with the highest disk luminosities, the velocity-shifted absorption component is much more pronounced than the emission component if the inclination angle is low ($i \leq 45°$) (e.g., the erupting dwarf nova SS Cyg [Heap *et al.* 1978]; the nova-like "disk" stars TT Ari [Guinan and Sion 1981*a*], V3885 Sgr [Guinan and Sion 1981*b*], and RW Sex [Greenstein and Oke 1982]; and the former nova HR Del [Hutchings 1980]). The dwarf nova SY Cnc (thought to be at low inclination because of the lack of an eclipse in its visual light curve) also exhibits predominantly shortward-shifted absorption during outburst (cf. Fig. 2 in Szkody 1981). Other dwarf novae in outburst exhibiting P Cygni profiles, but with the emission component much more dominant, are RX And (Szkody 1982), AH Her (our own unpublished spectrum; and Szkody 1981), and TW Vir (this work). All of these objects are probably of relatively low inclination because, as in SY Cnc, no eclipses have been detected. An object with extremely weak velocity-shifted absorption, but relatively strong emission, is the dwarf nova EM Cyg, on the decline from an outburst (cf. Fig. 1 in Szkody 1981); its inclination angle is somewhat larger ($\sim 67°$) than the above-mentioned objects. In two nova-like variables with high inclinations, UX UMa ($i \sim 75°$) and RW Tri ($i \sim 82°$), the emission is asymmetric with the long-wavelength side stronger, i.e., only a hint of a P Cygni feature (Holm, Panek, and Schiffer 1982; our own unpublished spectra of RW Tri). In the former nova DQ Her ($i \sim 90°$) the UV lines appear to be in emission at the rest wavelengths (Lambert and Slovak 1981). Thus it seems that the more edge-on a system is, the more its spectral lines will appear at the rest wavelengths because the effects of the wind absorption component are not observable.

The time-resolved UV observations of the eclipsing system UX UMa (Holm, Panek, and Schiffer 1982) are particularly interesting in trying to locate the line-producing region. The emission lines (when present) in this highly inclined star are not observed to be eclipsed (unlike the UV and optical continuum). A similar result if found in a preliminary analysis of data on RW Tri by the authors. The implication is that the emission component of the lines is produced in a region that is large compared to the inner (eclipsed portion of the) disk.

The above-mentioned systems are of relatively high luminosity. Low-luminosity CVs such as the dwarf novae during quiescence exhibit only unshifted lines (usually in emission). The present data are too scant to uncouple the effects of inclination and luminosity (mass accretion rate) on the depth of the shortward component or the strength of the emission component. The dependence of the line profiles on the luminosity might be assessed by observations of changes in the P Cygni features of a dwarf nova as an outburst progresses.

b) *The Mass Loss Rate*

Theoretical P Cygni profiles assuming resonance scattering in a spherically symmetric wind have been calculated by Castor and Lamers (1979, hereafter CL; see also Olson 1978) and, for overlapping doublets, by Olson (1982*a*). The models are specified by the radial optical depth as a function of the flow velocity, $\tau(v)$, and the velocity law of the envelope, $v(r)$, where r is the distance from the center of the star.

If we compare the C IV profile of TW Vir with the profiles of CL, we find that W_R/W_B may be much larger (1.8) than any of the calculated profiles (see their Fig. 12). In contrast, in RW Sex, Greenstein and Oke (1982) have found that this ratio is too low (0.16) for the total optical depth implied by inspection of the short-wavelength wing alone. These discrepancies are probably caused by the poor approximation of a CV wind to a spherically symmetric geometry and/or the presence of other components such as an emission component from the entire disk or photospheric absorption at the rest wavelength. The effects of turbulence or rotation would also severely modify the profiles.

Since the short-wavelength wing of the profile is least affected by the addition of another component at λ_0, we compare only this part of the line with the theoretical profiles. The short-wavelength wing is also fairly insensitive to the adopted velocity law, so that we can attempt to derive qualitative information about the radial optical depth. If we compare the C IV short-wavelength wing in TW Vir with the profiles in Figure 4 of CL (or Figs. 1 and 2 of Olson 1978), we find that the optical depth decreases with increasing velocity (or increasing radius).

All of the UV resonance lines observed in the spectrum of TW Vir are doublets. For C IV, the doublet separation is small enough that we can compare the observed profiles to the theoretical profiles for singlets (CL). For an optical depth law in which $\tau(v/v_\infty) \propto (1-v/v_\infty)^\gamma$, a good correspondence is found with $T_B \approx 0.75$, if $\gamma = 1$; or $T_B \approx 1.5$, if $\gamma = 2$ (cf. Fig. 7 of CL). The variable T_B is a parameter used by Olson (1982*a*) which is related to the total optical depth derived from the shortward component. The optical depth is similar to that derived for the short-wavelength wing of the C IV profile of HR Del by Krautter *et al.* (1981), but is about 10 times less than the value derived for RW Sex by Greenstein and Oke (1982).

For the more widely separated doublets of N V and Si IV, we use the theoretical profiles for doublet resonance lines calculated by Olson (1982*a*). If γ is assumed to be unity, the observed N V profile compares favorably to the computed profile for $T_B \approx 0.8 \pm 0.2$; and the observed Si IV profile, to $T_B \approx 0.4 \pm 0.2$ (cf. Fig. 5 of Olson 1982*a*).

The mass loss rates are then given in units of 10^{-12} $M_\odot$ yr^{-1} by (eqs. [37]–[39], Olson 1982*a*)

$$g(C^{+3})\dot{m}_{-12} = 6\left(\frac{R_*}{R_\odot}\right)\left(\frac{v_\infty}{1000}\right)^2 T_B(\text{C IV})(1+\gamma)0.5^\gamma$$

$$= 5\left(\frac{R_*}{0.05R_\odot}\right),$$

$$g(N^{+4})\dot{m}_{-12} = 35\left(\frac{R_*}{R_\odot}\right)\left(\frac{v_\infty}{1000}\right)^2 T_B(\text{N V})(1+\gamma)0.5^\gamma$$

$$= 30\left(\frac{R_*}{0.05R_\odot}\right),$$

$$g(Si^{+3})\dot{m}_{-12} = 24\left(\frac{R_*}{R_\odot}\right)\left(\frac{v_\infty}{1000}\right)^2 T_B(\text{Si IV})(1+\gamma)0.5^\gamma$$

$$= 11\left(\frac{R_*}{0.05R_\odot}\right),$$

where the $g(i)$ are the ion fractions of ion i relative to its element, and V_∞ is taken to be 4800 km s^{-1}. Solar abundances are assumed. The radius (R_*) of the wind-emitting region is conservatively chosen to be $0.05R_\odot$ (3×10^9 cm) because the effective size of the disk at 1550 Å is smaller than the size of the disk in the optical ($\sim 10^{10}$ cm) but larger than the size of the white dwarf ($\sim 5\times10^8$ cm).

Since we do not know the effective temperature of the radiation field seen by the ions in TW Vir's wind, we can only roughly estimate the ion fraction and hence, the mass loss rate. In this context, it is of interest to compare the ratios of the ion fractions deduced for TW Vir with those of early-type stars since their spectra are similar (e.g., Guinan and Sion 1981*a*, *b*). Olson (1982*b*) has plotted the ion fractions of N V, Si IV, and C IV for O and B stars as a function of effective temperature, assuming solar abundances. The ratio $g(C^{+3})/g(Si^{+3})$ observed for TW Vir implies an effective temperature of 27,000 K, with $\log g(C^{+3}) = -1.75$ and $\log g(Si^{+3}) = -1.50$. At this temperature, however, $g(N^{+4})$ would be about 7 times smaller than observed. One possibility is that the material in the wind is not of solar abundance, i.e., the N V may be enhanced relative to the C IV and Si IV. We note, however, that there is some uncertainty in the fitted wind parameter T_B, and that Olson's plots contain some scatter. If we attempt to derive a temperature which gives the best fit (in a least-squares sense) to all three ion fractions, we find $T_{eff} = 30{,}000\text{–}35{,}000$ K.

If we adopt $T_{eff} = 27{,}000$ K, then $g(C^{+3}) = 0.018$ and $g(Si^{+3}) = 0.032$, and $\dot{m} \approx 3 \times 10^{-10} (R_*/0.05 R_\odot)$ $M_\odot$ yr^{-1}. This would be the mass loss rate if the wind were spherically symmetric. If we assume instead a conical shape for the wind, $\dot{m}$ is reduced by the factor $\Omega_w/4\pi$, where Ω_w is the solid angle into which the wind flows. For a cone half angle of $\sim 30°$ and assuming that the wind emanates from above and below the disk, $\dot{m} \approx 4 \times 10^{-11}$ $M_\odot$ yr^{-1}, or $\approx 3 \times 10^{15}$ gm s^{-1}. An effective temperature of 32,000 K gives lower ionization fractions for $g(C^{+3})$ and $g(Si^{+3})$, but a higher ionization fraction for $g(N^{+4})$. At this temperature, the mass loss rate averaged from all three ions gives a value for $\dot{m}$ four times higher than the above value. The error in $\dot{m}$ is, therefore, at least an order of magnitude, mainly because of uncertainties in R_* and the ion fractions.

This mass loss rate is from $\sim 10^{-2}$ to $\sim 10^{-3}$ of the accretion rate calculated for the more luminous CV systems under the assumption of steady state accretion through an optically thick disk (cf. Table 3 in Córdova and Mason 1982).

The momentum rate of the wind, $\dot{m}v_\infty$, is $\sim 1 \times 10^{24}$ $(R_*/0.05 R_\odot)$ $(\Omega_w/0.27\pi)$ ergs cm^{-1}. The momentum rate of the radiation, L/c, is 1×10^{23} $(L/L_\odot)$ ergs cm^{-1}. The luminosity of the average dwarf nova during outburst is $\sim 10\text{–}100$ $L_\odot$ (Córdova and Mason 1982; Greenstein and Oke 1982), although not all of this radiation will be seen by the wind. Thus radiation pressure may be sufficient to account for the observed winds. For comparison, in O and B stars, the ratio of the wind momentum to the radiation momentum is of order unity (from the tables presented by Garmany *et al.* 1981). If the wind momentum in CVs exceeds the radiation momentum, a source of mechanical energy (e.g., rotation or magnetic fields) may be required to start the wind. Radiation pressure in the lines could then complete the acceleration of the wind to high velocities.

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