Spectral response of the pulsationally induced shocks in the atmosphere of BW Vulpeculae

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ABSTRACT

BW Vulpeculae (BW Vul) is remarkable for exciting an extremely strong radial pulsation mode which grows through its outer envelope and forms visible shock features in the atmosphere. Material propelled upwards by the shock returns violently to the lower photosphere where it creates a second shock just before the start of the next cycle. We have obtained three nights of echelle data for this star over about five pulsation cycles ($P = 0.201$ d) in 2000 September in order to investigate the effects of atmospheric shocks on important lines in the optical red spectrum. These lines include He I $\lambda$5875 and $\lambda$6678, C II $\lambda\lambda$6578–83 doublet, and other moderate and high excitation lines. To these data we have added 37 archival IUE/SWP echelle spectra obtained in 1994. We have investigated the equivalent widths and shapes of the optical lines for evidence of lag and have compared our results to the IUE fluxes extracted from the far-ultraviolet continuum, He II $\lambda$1640, and several resonance lines.

A comparison of He I $\lambda$5875 and $\lambda$6678 line profiles during the peak of the infall activity suggests that differences in the development of a second blue lobe in the profile at this time are due to heating and a short-lived formation of an optically thin layer above the region compressed by the infall. This discovery and the well-known decreases in equivalent widths of the C II doublet at the two shock phases further suggest that shock heating flattens the atmospheric temperature gradient.

Except for evidence of wind absorption in the far blue wings of the ultraviolet resonance lines, we find no evidence for a shock delay arriving at different photospheric strata (i.e., a ‘Van Hoof effect’). Line-to-line differences in the relative strengths of double lobes can be false indicators arising from varying degrees of desaturation of multiple lines, such as for the red He I lines.

Key words: line: formation – line: profiles – shock waves – stars: individual: BW Vul – stars: variables: other.

1 INTRODUCTION

The $\beta$ Cephei variable BW Vulpeculae (BW Vul; HR 8007, HD 199 140; B1 V to B2 III) is in kinematic terms the largest amplitude pulsator known in the Galaxy. Its fundamental radial pulsation mode (Stamford & Watson 1981; Aerts et al. 1995) is so strongly excited as to produce discontinuous ‘standstill’ features in the star’s light curve and, immediately following this, a longer standstill in the radial velocity curve as well. These features result from highly non-linear processes associated with upward propagating pulsation waves. These waves emerge into the photosphere as highly supersonic shocks. During the pulsation cycle, the optical line profiles remain in absorption but undergo extreme variations in shape and velocity. Equivalent width variations are also noticeable at certain phases. In the often-used convention that $\phi = 0$ occurs at light maximum (minimum radius), the radial velocity standstill becomes centred at $\phi = 0.98–1.00$. Line profiles exhibit double lobes at phases just before (centred at $\phi \approx 0.90$), and during some cycles just after ($\phi \approx 0.06$) the velocity standstill phase (e.g. Mathias et al. 1998). Adding to the complexity of description, the radial velocity curve is sensitive to the method of measurement, the spectral and temporal resolution of the observation, and especially to the momentary pulsational amplitude of the star, because the amplitudes of the pulsations fluctuate by several per cent from night to night (Crowe & Gillet 1989; Aerts et al. 1995; Mathias et al. 1998; Garnier

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et al. 2002). The equivalent widths of some metal lines vary with phases as a function of excitation potential (Furenlid et al. 1987). The finite signal-to-noise ratio and temporal sampling frequency of the International Ultraviolet Explorer (IUE) observations set practical limits on the otherwise considerable complementary ultraviolet (UV) information that they offer to optical spectra.

Historically, controversy has surrounded the interpretations of the profile and strength variations caused by shock waves moving through the atmosphere of BW Vul. One of these is the so-called ‘Van Hoof effect’, named after its primary discoverer (Van Hoof & Struwe 1953). This characteristic is the purported phase lag between the velocity curves extracted from lines formed at different atmospheric depths. This is thought to be the result of the finite travel time required for a pulsational shock wave to pass through the various line-formation strata. In a recent report, Mathias et al. (1998) reported that double line profiles of various lines observed near $\phi \approx 0.9$ and sometimes 0.1 can exhibit equal blue–red strengths at slightly different phases.

A related issue is the cause of the line doubling itself. Ogders (1955) and Goldberg, Walker & Ogders (1976) suggested that the doubling occurs from velocity discontinuities below and above a shock and suggested that this shock accelerates the line-forming regions of the atmosphere from the lower photosphere to create a density discontinuity. The semi-ejected ‘shell’ coasts to some maximum height and returns ballistically to these lower strata. In a contrasting interpretation, Young, Furenlid & Snowden (1981, hereafter YFS) suggested that turbulence and pressure effects are the chief causes of the profile doublings at these phases. In their picture, the standstills are caused by line formation in both a lower stationary atmospheric region as well as an infalling zone rendered transparent by its lower density. All these studies have pointed to the extended displacements of the line-formation region (several per cent of a stellar radius) and its virtual free fall from maximum to minimum radius.

In the most recent kinematical description, Mathias et al. (1998) and Garnier et al. (2002) have summarized the present consensus that there are two shocks per cycle. The first, ‘pulsation’, shock is the result of the evolution of the upward-propagating wave which grows in amplitude from the envelope where it is excited. As it emerges into the atmosphere at $\phi = 0.1$, this shock has a moderately high Mach (5–7) number, as referenced by the velocity ‘discontinuity’ just prior to the velocity standstill. A subsequent, ‘infall’, shock, occurring 0.8 cycles after the first, is due to the extreme compression of the upper atmospheric strata as they fall back and catch up to the more slowly returning layers of the lower photosphere. In this picture, the line profiles exhibit double lobes during the main (and often infall) shock because of the velocity jump associated with it. Mathias et al. (1998) also note that because the density of the atmosphere decreases monotonically outwards, the infalling region cannot be described as a disconnected shell. In addition, they suggest that shock progresses inward in terms of absolute (Eulerian; radius from star centre) coordinates even as it moves outwards in mass. Thus, their description reconciles the idea expressed by several previous authors that two outward-moving shocks per cycle propagate up through the atmosphere. In this study, we adopt this view of Mathias et al. (1998) that this shock is a natural consequence of infall.

The elusiveness of even a qualitative interpretation of the shocks in BW Vul has slowed the necessary development of self-consistent radiative hydrodynamical models. Early on, Stamford & Watson (1978) posited that a large-amplitude velocity piston at the base of the atmosphere developed into a thin, isothermal shock as it progressed through the line-formation region. Using this dynamical model atmosphere, they constructed line profiles of $\text{Si~}^\text{III} \lambda 4552$ at several key phases in the cycle. Profiles at phases we now call the infall shock exhibited line doubling (albeit over only a brief interval). In subsequent work, Stamford & Watson (1981) placed a large, adiabatic sinusoidal velocity variation at the base of a grey model atmosphere and demonstrated that an isothermal shock developed in the line-formation region. Recently, Owocchi & Crammer (2002) have developed hydrodynamic models that roughly simulate the velocity and light variations of the pulsating star. Their models assume strong outgoing shocks in realistic atmospheres. The shocks begin in the envelope as a large-amplitude pulsation wave, break into a small-amplitude shock in the lower photosphere, and evolve into an isothermal, large-amplitude ($60 \times$ in density) shock in the wind. The results of Owocchi & Crammer (2002) show that the shock has the effect of flattening the atmospheric density gradient well out into the wind, thereby explaining the large range in phase over which the shock can be traced in the UV resonance lines. As these waves emerge into the wind, they can impact slower flows, causing reverse shocks and the formation of discrete absorption components (DACs) in the far blue wings, indeed as observed in the $\text{Si~IV}$ and $\text{C~IV}$ lines (Burger et al. 1982; Blomme & Hensberge 1985; Massa 1994).

The present paper was motivated partially by our impression that an understanding of the shock wave properties has been hampered by uncertainties in spectroscopic measurements and interpretation. For example, YFS and Crowe & Gillet (1989) found widely different average equivalent widths for the important $\text{C~II} \lambda \lambda 6578$–82 lines. Yet the ‘large’ values found by YFS during the distension phases formed the basis of their conclusion that line doubling and strengthening is caused by changes in atmospheric continuous opacity. This suggestion, though oft-quoted, has gone untested. We also realized in planning our programme that the existence of a Van Hoof effect could be tested by comparing the responses of the red $\text{He~I} \lambda 5875$ (triplet) and $\lambda 6678$ (singlet) lines, which probe different column lengths through their gf difference, and also volume densities because of the triplet line’s mild sensitivity to density through the partial metastability of its lower level. Other significant lines in the red region are the $\text{Si~II} \lambda \lambda 6371$ and $\text{Si~III} \lambda 5740$ features, which together provide a measure of variations in the atmosphere’s ionization equilibrium. The echelle data we have obtained sample formation conditions of many lines at the same time and thus can provide accurate phasing information from this variable-amplitude pulsator. This simultaneity permits us to remove past ambiguities in correlating behaviours of various lines at different epochs. A second reason for undertaking this study is the availability of IUE data, which permits a comparison of the behaviours of the wind and photospheric lines.

2 OBSERVATIONS

2.1 Observations and reduction details

The optical data for this study were obtained on the nights of 2000 September 19–21 with the Sandiford echelle spectrograph (McCarthy et al. 1993) attached by fiber optics to the Cassegrain focus of the Struve 2.1-m telescope at McDonald Observatory. 60 observations were obtained during the interval JD 245 1805.574–581, 61 during JD 245 1806.560–856 and 48 during 245 1807.568–916. The cross-dispersing prism in the spectrograph was rotated to select a central wavelength of 6120 Å and to include a nearly continuous wavelength range (22 orders) of $\lambda \lambda 5510$–6735 on
a CCD detector. This configuration resulted in a spectral resolution of 45 000 and a pixel spacing of 2.8 km s$^{-1}$ pix$^{-1}$. Signal-to-noise ratios of 200–300 were typically attained in integration times of 5–6 min. The mid-observation times for the three nights are shown in Table 1, while a line list of identified features in our spectra is given in Table 2. The wavelengths and excitation potentials listed are obtained from the Kurucz line library (Kurucz 1990).

The spectra were kindly reduced (background-subtracted, extracted, and flat-fielded) by Dr Chris Johns-Krull using computer codes described by Hinkle et al. (2000) and Piskunov & Valenti (2002). Wavelengths were determined by an interactive graphics package that allowed a solution simultaneously in the echelle and cross-dispersion axes (J. A. Valenti, private communication). Solutions were obtained by minimizing residuals between laboratory and observed Th and Ar line wavelengths and iteratively rejecting outliers. Corrections for terrestrial orbital and rotational velocities were made. Rectification of echelle orders was performed by an interactive polynomial fitting procedure. Orders were then spliced at wavelengths for which flux contributions of adjoining orders were equal. We measured the radial velocities of strong lines by cross-correlating the lines against a reference line profile observed near $\phi = 0.2$. Profiles at this phase are approximately symmetric and exhibit an approximately mean width and thus lend themselves to comparison with profiles of extrema phases. We determined true equivalent widths of these lines and other analysed features in the McDonald spectra by an interactive computer algorithm tailored for this application. The program uses input wavelength ranges over which both the continuum and the line’s absorption profile are to be extracted. The continuum level is then fixed by a specified ‘nth percentile brightest flux’ among candidate fluxes in the continuum window. The value of $N$, typically $\approx 80$ per cent, can depend on the presence of non-stellar features but is well suited to modification interactively when such unwanted features appear as telluric lines, cosmic rays, or fringing.

### 2.2 IUE spectra

In order to avoid uncertainties in the absolute calibration of fluxes, we made use of 38 high-dispersion echellograms obtained with the SWP camera through the large aperture during monitoring campaigns on the star in 1994 October and November. ‘NEWSIPS’ extractions were downloaded from the MAST$^1$ web-based archives. We emphasize that our NEWSIPS-processed spectral fluxes are extracted by different algorithms than those used by Stickland & Lloyd (2002), although the results are gratifyingly similar. Absorption line strength indices (LSIs) were then calculated by ratioing the total net (uncorrected for ripple distortion) flux in a narrow band centred at line centre to the total net flux in the parent echelle order. Such indices are not true equivalent widths, but they are directly proportional to them and increase with absorption strength. Because these indices are insensitive to continuum placement, and (as defined herein) independent of errors in blaze function (‘ripple’) correction, they are unambiguous measures of the absorption for prescribed velocity limits, and they are particularly accurate differential measures of line strength differences for an IUE time series.

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1 Multi-Mission Archive at Space Telescope Science Institute, under contract to NASA.
Table 2. Summary of atomic data for lines in McDonald spectra.

| Wavelength | Ion  | \( \chi \) (eV) | \( \log gf \) |
|------------|------|-----------------|-------------|
| 5606.09    | Si   | 13.8            | 0.16        |
| 5639.980   | Si   | 14.1            | 0.33        |
| 5640.314   | Si   | 13.8            | 0.15        |
| 5646.979   | Si   | 14.1            | 0.11        |
| 5648.070   | C ii | 20.8            | -0.45       |
| 5639.980   | Si   | 14.1            | 0.33        |
| 5640.314   | Si   | 13.8            | 0.15        |
| 5659.956   | Si   | 13.7            | -0.07       |
| 5662.460   | C ii | 20.8            | -0.27       |
| 5666.629   | N ii | 18.5            | 0.01        |
| 5676.017   | N ii | 18.5            | -0.34       |
| 5679.558   | N ii | 18.6            | 0.28        |
| 5686.213   | N ii | 18.6            | -0.47       |
| 5696.603   | Al iii| 15.7            | 0.23        |
| 5710.766   | N ii | 18.6            | -0.47       |
| 5722.730   | Al iii| 15.7            | -0.07       |
| 5739.734   | Si ii| 19.8            | -0.160      |
| 5747.300   | N ii | 18.6            | -1.020      |
| 5833.938   | Fe iii| 18.6            | 0.616       |
| 5875.615   | He i | 21.0            | 0.73        |
| 6247.178   | Al ii| 16.6            | -0.20       |
| 6346.859   | N ii | 23.3            | -0.86       |
| 6371.371   | Si ii| 8.2             | 0.00        |
| 6379.617   | N ii | 18.5            | -0.92       |
| 6528.01    | H i  | 10.2            | -0.69       |
| 6578.052   | C ii | 14.5            | 0.12        |
| 6582.882   | C ii | 14.5            | -0.18       |
| 6678.154   | He i | 21.2            | 0.33        |

2.3 Radial velocity ephemeris

Although there is unanimity that BW Vul is monoperiodic (with \( P \approx 0.201 \pm 0.043 \)), some controversy has surrounded the ‘drifting’ of its pulsation period derived from data sets of different epochs. Various authors have suggested ephemeris corrections for a quasi-evolutionary lengthening, light travel time across a binary, and both random and discontinuous changes for unspecified reasons. In past years, support has built for the binarity solution with an orbital period near 34 yr (Pigulski 1993; Odell 1994; Horvath, Gherga & Farkas 1998), although it appears possible that small random changes can also alter the phase zero-points from time to time (Sterken 1993). We have adopted the binary+secular-lengthening solution of Horvath et al. for the light minimum phases. Light minimum is the recommended new benchmark because it can be determined with greater precision (Sterken 1993). To these calculated phases, we have added 0.48 cycles (Furenlid et al. 1987; Stickland & Lloyd 2002) to reference them to the traditional zero at optical light maximum. This is also the approximate mid-point of the radial velocity standoff. This ephemeris agrees to within 0.015 (±0.02) cycles of the mid-point occurrence of the standstill in our McDonald data. The relative phases of the 1995 IUE epoch did not match as well, giving a difference of 0.09 cycles from this ephemeris relative to the standstill occurrence found by Stickland & Lloyd. We have referred our \( \phi = 0 \) fiducial to the Stickland & Lloyd phase \( \phi = 0.10 \), which takes into account that the latter authors tied their zero-point to radial velocity maximum instead of the usual velocity standstill criterion.2

2Note that the photometric standstill occurs just before the onset of velocity standstill and is much shorter. These respective standstills last about 0.05 and 0.15 cycles (see e.g. Furenlid et al. 1987).

3 RESULTS

3.1 Radial velocities

A large number of radial velocity curves have been discussed for BW Vul from as many optical data sets. We decided to focus on the velocities of the red helium lines both to check our phase zero-points and to search for cycle–amplitude differences during our observations. Our mean nightly heliocentric radial velocities are \(-7.7, -10.3\) and \(-11.4 \text{ km s}^{-1}\). The resulting mean of \(-9.7 \text{ km s}^{-1}\) is in excellent agreement the mean of \(-9.2 \text{ km s}^{-1}\) given by Mathias et al. (1998). In Fig. 1 the radial velocities are shown for He i \( \lambda 5875 \) for all three nights. It was possible to measure the equivalent widths of the lines arising from highly excited atomic levels, but these often were both weakened and broadened to invisibility during the critical shock passage phases. Radial velocities are also given in Fig. 1 for Si iii \( \lambda 5740 \) and Si ii \( \lambda 6371 \) (the latter can reliably be measured only in the phase range \( 0.1 < \phi < 0.85 \)). The silicon lines have velocity amplitudes 5–10 per cent larger than the helium line curves and even more striking discontinuities at the beginning of the end of the standstill. The He i velocity curve (not shown) has even a slightly smaller amplitude and less steep ‘discontinuities’ than the He i line curves do. We believe that these are effects of the far wings of the helium and hydrogen lines, which tend to broaden the cross-correlation function and produce artificially small velocity differences for the line core.

In the upper halves of the Fig. 1 panels we exhibit the equivalent widths of the Si ii \( \lambda 6371 \) line over those phases outside the shock intervals – these are the times when the line was strong enough that reliable centroid positions could be measured. On nights 2 and 3 we see that the phases of velocity maximum extend slightly longer in the Si ii feature than in the He i line, causing a slight delay in the onset of the standstill for the He i line curves. This delay seems to be an artefact of a relatively ‘late’ desaturation of the blue lobe of the weaker Si ii line, causing the line’s centroid velocities to remain at negative velocities for a longer time and to later phase than the other lines measured (see Section 4.4).
3.2 Behaviour of the excited optical lines

3.2.1 The red He I lines

The accurate measurement of equivalent widths of lines in the BW Vul spectrum is challenging because the positions, widths and core depths vary dramatically over the cycle. We began our study by investigating equivalent widths for the $\lambda\lambda$5875 and $\lambda\lambda$6678 lines. These He I transitions are, respectively, analogue triplet and singlet 2P–3D transitions, and each has excitation potentials of 21 eV. Although variations of the neutral helium line have not yet been studied in this star, their importance cannot be overstated because of the sensitivity of the lines to atmospheric heating. Furenlid et al. (1987) reported unambiguous evidence for a temperature rise from increases in the ratio of a pair of O II and Fe III lines during the velocity-standstill phase. Fig. 2 shows the variation of the true equivalent widths for the He I $\lambda\lambda$5875 and He I $\lambda\lambda$6678 lines for all three nights. These plots exhibit generally two maxima, the stronger of the two centred at the occurrence of the infall shock at $\phi \approx 0.90$–0.95. The equivalent width ratio of these lines is 1.13 $\pm$ 0.03 outside the ‘windows’ of the two shock intervals. Because the ratio of their atomic $gf$s is 2.5, the observed ratio indicates that the features are very optically thick. The ratio is virtually the same during the passage of two shocks.

3.2.2 C II $\lambda\lambda$6578, 6583 doublet and high-excitation lines

The C II $\lambda\lambda$6578, 6583 doublet is located close to the H$\alpha$ line and arises from a similarly excited level of 14.4 eV. Thus, it has long served as a conveniently accessible temperature probe for atmospheres of variable B stars. We measured the true equivalent widths of each of these lines in the same manner as the He I lines. These are exhibited in Fig. 3, where we have represented the two lines by different symbols and rescaled the equivalent widths of $\lambda6583$ to the slightly larger ones of $\lambda6578$. Some of the scatter at like phases arises from measurements at adjacent pulsation cycles. The $gf$ ratio of the components is 2. The observed ratios do not show evidence of variations during the cycle, and their nightly means, 1.28, 1.14 and 1.16, show clearly that even though the lines are comparatively weak they are quite optically thick.

Our C II doublet curves in Fig. 3 exhibit well-defined minima that coincide in phase with the broad minimum found by Crowe & Gillet (1989), except that the latter authors’ data do not hint at a separation in phase between the two individual shocks. The C II curves are also very similar to those shown for the residual intensity of the H$\alpha$ core discussed by Crowe & Gillet (1989). We have confirmed this behaviour for the core of this line in our data and we have also found that the equivalent widths extracted from small wavelength windows centred on the core exhibit a similar behaviour. The effect rapidly disappears and even inverts as we include more and more contribution of the H$\alpha$ wings in the window. These results confirm that the variations are produced by localized atmospheric strata. Other moderate to high excitation lines such as N II $\lambda5750$ ($\chi = 18.5$ eV) and S II $\lambda5640$ (13.8 eV) produce variations similar to the C II doublet, but the intrashock maxima for them are not always so clearly separated in phase. For phases outside the two shock intervals, many of the lines in our sample broaden and fade to below our detection threshold.

3.2.3 Si II $\lambda6371$ and Si III $\lambda5740$ lines

The Si II $\lambda6371$ and Si III $\lambda5740$ lines are important because they arise from atomic levels having the largest combined excitation and ionization potentials of all the lines in our optical coverage, except for the He I lines. In addition, their combined responses furnish information on changes in the ionization equilibrium in this atmosphere during the pulsation cycle. In investigating the strengths of these lines, we found first that the Si III $\lambda5740$ line shows only mild increases of $\sim$10–50 per cent in equivalent width from night to night during shock passage. This is because the ionization equilibrium of silicon is roughly balanced between Si$^{+1}$ and Si$^{+2}$. However, as the dashed lines at the top of each of the panels in Fig. 1 show (the reciprocals of the line strength are plotted), the response of the Si II $\lambda6371$ line can be quite pronounced. During the passage of the second (pulsation) shock, the $\lambda6371$ broadens and weakens so much that its velocity centroid cannot be reliably measured. As indicated in Fig. 1, the phases of maximum weakening do not coincide with the shock passage but rather are delayed by 0.10 cycles after the end of the standstill phase, when the strengths of the excited lines are slowly decreasing.

Fig. 3 indicates that there are variations in shock heating and of the inequality of amounts of heating between the two shocks. We can see this, first, in the amplitude variations in the shocks (as judged

![Figure 2](https://example.com/figure2.png) Equivalent widths of He I $\lambda6678$ with phase for the three nights of study; offsets of $-0.3$ Å and $-0.6$ Å are introduced for visual clarity. Approximate error bars are indicated.

![Figure 3](https://example.com/figure3.png) C II $\lambda\lambda6578$, 6583 equivalent width curves for the three nights in this study. The values for $\lambda6583$ are scaled by factors of 1.3, 1.1 and 1.2 for the three nights, respectively, to match the $\lambda6578$ data.
by the sharpnesses and depths of the C II minima) and, secondly, in the variation of the strengths of the Si II line and other moderate excitation lines, e.g. S II λ5640. These diagnostics generally imply that the temperature increase associated with the pulsational wave is the stronger of the two shocks. This is contrary to the inequality of the shock jumps (Fig. 1; see also Mathias et al. 1998). We also note that the phase of equivalent width minimum is delayed by 0.07–0.08, both with respect to the line’s radial velocity minimum (Fig. 1) and relative to the C II equivalent width minimum at φ = 0.1.

3.3 Ultraviolet lines

Except for the He II 1640-Å line (‘helium Hz’, \(\chi_{exc} = 41\) eV), the UV lines used in this analysis are all resonance lines. To varying degrees, the latter lines have components formed both in the static line-forming region (upper photosphere) and the accelerating wind. We will treat these lines in order of likely formation depth, starting from the He II feature, and work our way up through ionization potential out into the wind.

3.3.1 He II λ1640

Fig. 4 depicts the extracted UV continuum (UVC; representing λλ 1800–1905) light curves from the 37 available large-aperture IUE/SWP spectra obtained in 1994, together with the extracted line strength index created from ratios of fluxes within about ±1.6 Å of the He II line centre to all the other net (ripple uncorrected) fluxes in the echelle order containing the line. The detailed shape of the UVC curve is in excellent agreement with the two plots constructed by Stickland & Lloyd (2002) from essentially the same data. The curve shows a broad, asymmetric maximum which may be an unresolved rendition of two peaks apparent in the line strength curves at φ = 0.9 and 0.1. This double-peaked structure is completely unresolved in optical light curves (cf. figure 3 of Stickland & Lloyd 2002). Note also that the scatter is small and does not seem to reflect the obvious cycle-to-cycle differences at some phases in the radial velocity curves. The He II λ1640 absorption curve is morphologically very similar to the UVC curve. The curves extracted from the blue and red halves of the profile are in turn identical to one another. A slight kink is visible in the He II curve at φ = 0.05–0.25 and is also reproduced in the UVC curve (Fig. 4). For clarification we overplot two curves in Fig. 4. The first is a simple sine curve (dashed line), and the second (solid line) is a sine curve that has been compressed/stretched in the first and second quadrants. No matter how we choose a fitted curve to the observed values (from three different pulsation cycles) the dip and bump features fall outside the error limits. Because these features are also visible in the two UVC curves of Stickland & Lloyd, these are undoubtedly real.

3.3.2 Resonance lines of moderately excited ions: Al III, Si III and Si IV

Fig. 5 depicts the UVC and absorption curves for the lines Al III λ1855, Si III λ1206 and Si IV λ1394 resonance lines. The line strengths are obtained from the central profile within about ±0.8 Å of the line centre and refer to the strength of the continuum. In the case of Si III and Al III the indices are inverted because the line responds oppositely from the other features. Error bars are indicated.

Figure 4. UVC fluxes at ~λ1850 (diamonds) and line strength index for He II λ1640 (crosses). The latter, denoted LSI, is defined in Section 2.2. UVC fluxes are plotted relative to the mean, but 0.7 units are subtracted from the He II LSI to separate the curves. Symbols for data above φ = 1.0 are repeated and rendered small. The dashed line through the He II curve is a reference sinusoid; the solid line is a compressed/stretched curve around the sinusoid (see text). Note the slight kink in the descending He II curve in the φ range 0.05–0.25.

Figure 5. UVC fluxes at ~λ1850 (diamonds) and line strength indices for the Al III λ1855, Si III λ1206 and Si IV λ1394 resonance lines. The line strengths are obtained from the central profile within about ±0.8 Å of the line centre and refer to the strength of the continuum. In the case of Si III and Al III the indices are inverted because the line responds oppositely from the other features. Error bars are indicated.
is cooler and more tenuous than the shock interface (Liberman & Velikovich 1986). A strong post-shock rarefaction is clearly visible in the hydrodynamic simulations of Owocki & Cranmer (2002) and indicates a rough ‘half-wavelength’ of ~0.25 cycles. From this result we might anticipate the effects of a rebound shock having approximately this delay. Altogether, we can speculate that the marginally visible kinks in the UVC and He II strength curves at $\phi \approx 0.23$ are produced by a small temperature enhancement due to the rebound. In this picture the abrupt appearing end of the UVC maximum would be the result of particles entering the cooled post-shock flow.

### 4.2 Blue wing strengthenings (moderate velocities)

To gain some insight into the cause of the equivalent width variations of the red He I lines exhibited in Fig. 2, we examined the shapes of the two lines as a function of phase. Fig. 7 illustrates that the cause of the equivalent width maximum of $\lambda 5875$ at $\phi = 0.9$ on each night is a strengthening of the blue wing. In these plots we exhibit this fact by multiplying the depth of $\lambda 6678$ on the blue wing (and also extreme red wing) by a factor of 1.4 to 1.8. Fig. 7 shows that blue wings of $\lambda 6678$ scaled by these factors indeed replicate the $\lambda 5875$ absorptions at this phase. We see this phenomenon over a total range of 0.08–0.10 cycles centred on radial velocity maximum ($\phi \approx 0.91$) on each of the three nights. In these various examples, the limiting line-depth scaling factor appears to be about 2.0. As this is also the $g/f$ ratio of the lines, it is likely that these extra absorptions are due to the medium at negative velocities being optically thin to He I line radiation. An alternative possibility, that the excess arises from metastability of $\lambda 5875$, is implausible because no such excess absorption is present in this line during the distension (low-density) phases at $\phi \sim 0.5$.

If temperature variations cause the changes in the blue wings of the He I lines, there should be a similar response in the inner blue wing of the C IV doublet members – the cores of the Si IV lines are too

### Figure 7.

Profile for the red $\lambda 5876$ (dashed) and $\lambda 6678$ (solid) He I lines, which have an atomic $g/f$ ratio of 2.5:1, at a phase near $\phi = 0.90$ on each of three nights. This ratio is ameliorated slightly by a wavelength dependence of continuous opacity. Thus, we have also depicted the $\lambda 6678$ feature scaled by a factor of 2 (dotted line), as well as this same feature (thick dot-dashed) scaled by the indicated scale factor given next to the solid dot. This figure suggests that the ‘excess absorption’ of the blue segment of both lines is due to optical thinness of the line at negative velocities. The lines seem to be strictly optically thin (ratio of 2) up to about $-30$ km s$^{-1}$ on ‘night 3’ (September 21).

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broad to demonstrate this. Fig. 8 implies that the absorption-scaling argument is likely to be valid, i.e. that an excess absorption at about $-100$ km s$^{-1}$ of the line centre is caused by an optically thin column at these shifted wavelengths. (By ‘excess’, as for the He I lines in the previous figure, we refer to the absorption in the blue wing of the stronger $\lambda 1548$ line relative to $\lambda 1550$.) The grey-scales of Massa (1994, see Fig. 3) exhibit this same effect – as a low-velocity ‘spur’ occurring $\sim0.1$ cycles before the wind acceleration manifests itself at more negative velocities.

### 4.3 C II line strength variations

The reader will recall that YSF first drew attention to C II variations during the cycle of BW Vul and posited that the C II variations were the result of the lines growing anomalously strong outside the shock phases. To test this assertion, we have synthesized the C II doublet with the Hubeny SYNSPEC (Hubeny, Lanz & Jeffery 1994) line synthesis code using Kurucz (static!) model atmospheres.

For an atmosphere having $T_{\text{eff}}=23,000$ K, $\log g=4$, and $\xi_t=5$ km s$^{-1}$, we found an equivalent width of 0.22 Å, for $\lambda 6578$ and a $\lambda 6578/\lambda 6583$ ratio of 1.14. We obtain nearly identical results for $\log g=3$. These values compare well with our mean observed $\lambda 6578$ equivalent width value of 0.235 $\pm$ 0.015 Å for phases outside the shocks and with the corresponding mean observed ratio of 1.19. Our modelling also shows that the strengths of these lines are quite insensitive to changes in temperature in the domain 20 000–25 000 K. The models do not confirm the speculation by YSF that changes in atmospheric density play a strong role in determining the line strength changes during the cycle. Of course, the line strengths will increase appreciably with any microturbulence that might accompany the shocks, so this would not explain the decrease during these phases. The upshot of these calculations is that the decreases in C II strengths observed at shock phases cannot be due to simple changes in atmospheric temperature or density. Thus, our results suggest that the question to pose is not ‘why are the C II strengths large during the non-shock phases?’, but rather ‘why do the C II strengths decrease to smaller values than they should have during shock phases?’

The question is critical to a discussion of the shocks in BW Vul’s atmosphere because the effects of temperature increases are obvious for other lines but lead to a contradiction for the response of the C II features. Adding additional turbulence from a shock would make the disagreement worse by forcing the predicted absorptions to be larger.

#### 4.4 Physical effect of the shocks on the He I and C IV lines

If enhancements of neither temperature nor turbulence can explain the line weakening, let us consider instead the effect of a flattening of the temperature gradient with atmospheric depth, particularly in the construct of a local thermodynamic equilibrium (LTE) Milne–Eddington atmosphere. In this formulation the strengths of weak lines should simply be proportional to the gradient $dT/dr$. To interpret the enhanced absorptions in the blue wings of the He I lines (and possibly C IV) at $\phi=0.9$, we should also consider the heating effects from infall of material above where a line is being formed.

At this phase, upper strata are returning toward the surface at nearly free-fall velocities (Furenlid et al. 1987). Strata just below them fall slightly more slowly, and so on, down to the fully-braked stationary layers. These combined decelerations produce compression over a broad range of layers. The result of this pile up is a conversion of differential flow velocity to local heating. Indeed, this effect can be observed as the first maximum of the UVC and He II line strength curves at $\phi=0.85$–0.1 (i.e. at velocity maximum) and by the disappearance of the cool-gas diagnostic, Si II $\lambda 6371$, at the same times. Heating will increase the number of atoms in excited states and thus should permit new optically thin absorption to appear in the excited He I lines. This absorption is formed in a still-falling column which is still high enough in the atmosphere to be optically thin to an external observer. Most of the initial column density will be concentrated near the shock, so the lobe will appear at near-rest velocities. As this pile up proceeds, the threshold column density needed for visibility will recede (moving upward, in Eulerian coordinates), permitting the optically thin absorption in the profile to grow toward positive velocities until it runs into and merges with the optically thick red lobe. The process ceases when the deepest layers essentially at rest become optically thick to the observer. At this point, just after phase 0.0, the entire profile becomes optically thick over a broad distribution of line velocities, both from the still-falling column and the strata at rest at the bottom. The standstill phase ends quickly as the material in the falling column is suddenly exhausted – the optical depth turns thin and to zero very quickly at wavelengths in the red lobe of the profile.

During the infall phase, the velocity gradient can be expected to increase among the superficial, cooler layers, causing proportionally more heating there. Thus, the weakening of the C III doublet (first dip in Fig. 3) is consistent with a flattening of the gradient of the atmospheric temperature and line source functions. Indeed, in the expectation of accompanying increased turbulence, it seems difficult to understand how the weakening could arise in any other way. The second dip of the C III curve features coinciding with the passage of the pulsation shock can be explained by a more fundamental characteristic: the shock has a tendency to be more nearly isothermal than in the pre-shock atmosphere.

The above picture is sketched qualitatively in Fig. 9. This illustration depicts the evolution of the stellar radius (top) and the absorption profiles (bottom) during five phases ($\phi$), including one just before and one just following the primary shock passage interval. These line shapes may be compared to those in Fig. 7 or figure 1 of Mathias et al. (1998) and are additionally indicated as having blueshifted, redshifted and/or stationary components. The five central panels

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3 A fact which may bear on this discussion is that to reproduce UV spectrophotometric signatures from line aggregates in BW Vul’s IUE/SPW camera spectra, Smith (2001) found it necessary to impose arbitrarily an artificial steepening of the temperature gradient for a simulated model atmosphere at minimum light phase. This is equivalent to imposing a flattening of the gradient in the maximum light phase, as suggested from this optical study.
Schematic illustration of the formation of the He I λ5876 line profile as it evolves through radius minimum. The top panel suggests the overall behaviour of the stellar radius. The five bottom panels approximate the apparent line profile (F(λ)) at five specific phases (φ). The centre of each panel corresponds to the rest wavelength of the line (tick marks). The composite line profiles (solid lines) are decomposed into blueshifted (black rectangle) and redshifted (red shading) and optically thick components, and the unshifted optically thin component (× shading). The five vertical panels in the centre illustrate (i) the relative positions (z horizontal lines) and (ii) motions (vectors) of six specific Lagrangian zones in the atmospheres, (iii) the position relative to these layers where the monochromatic optical depth τλ ≈ 1 (black dotted line), and (iv) the location where each component of line absorption is likely to be strongest (shaded rectangles). Thus, for φ = 0.86, the optically thin stationary component (∝ shading) is formed below the optically thick redshifted component (∝ shading). These profiles should be compared with those in Fig. 7, and also with fig. 1 of Mathias et al. (1998). This figure is available in colour in the online version of the journal on Synergy. In the online version of the figure, the redshifted components (∝ shading) are coloured red, the unshifted components (∝ shading) are coloured green and the blueshifted component (solid) is coloured blue.

Figure 9.

show a representation of several notional ‘layers’. From left to right, these are shown to be falling inwards (arrows), and then arrested and reversed by material moving upwards from beneath. Compression gives rise to heating and a flattening of the temperature gradient. In turn, this gives rise to absorption in optically thin layers (φ = 0.86), represented by a shaded rectangle (∝). Other line components are also represented, displaced according to whether they are formed in outflowing (blueshifted, solid), stationary (no shift, × shaded) or infalling (redshifted, / shaded) material. The zero velocity reference position or, equivalently, the rest wavelength for the absorption line is marked at the bottom of each panel. On the basis of observations presented here, a dashed line indicates where the atmosphere becomes optically thick across the line profile (τλ = 1). Whether absorption lines are formed in optically thick or thin layers is suggested by their proximity to this curve. In any case, while admitting the omission of critical details of transfer of photons across the profile as the line as it turns optically thick, it appears possible that we can understand the formation of the excess optically thick absorption in the blue wing of the He I lines as well as the weakening of the temperature-sensitive C II and Si II lines.

Suffice it to say that in contrast to the infall shock the heating associated with the infall shock in our picture will extend over a broader range of strata in the atmosphere at any given moment than heating from the primary shock. If the UVC and He II and Si II line curves are to be taken as diagnostics of atmospheric heating, the pulsation shock is more impulsive and liberates more heat per unit time than the infall shock. In contrast, according to the equivalent width curves of Si II λ6371, the heating from the infall shock not only lasts longer, but by differing amounts from cycle to cycle. This suggests that the details of this heating are driven by the strength of the earlier pulsation wave. Also, as noted in Section 3.2.3, the velocity jump criterion leads to the opposite inequality of apparent shock strengths, with the radial velocity jump to the standstill (infall shock) being typically larger than the jump at the end of the standstill (primary shock). Because the velocity and equivalent width variations measure different types of shock properties, this apparent disagreement of the inequalities need not be a contradiction to the model.

5 CONCLUSIONS

Our primary results may be summarized as follows. From optical radial velocities we find:

(i) The cycle-to-cycle change of radial velocity amplitudes is confirmed in our data (Section 3.1). These variations may explain occasional differences in standstill attributes (e.g. their mean radial velocity).

(ii) At φ ≈ 0.9, the anomalously strong blue lobes in the He I λ5876 and λ6678 lines produce departures of the velocity curve relative to curves extracted from weaker lines which suggest that the differences in onset of the first velocity discontinuity are attributable to this profile peculiarity (Section 3.1).

From UV data we conclude:

(iii) UVC flux and He II line strength curves track each other and the red halves of various resonance lines well. There seems to be no systematic phase difference between them, suggesting that for practical purposes they are formed at nearly the same atmospheric depth (Section 3.3; Fig. 4).

(iv) These same two curves with phase depart from sinusoidal form, in particular showing a kink just after the passage of the primary shock (Fig. 4).

From optical line strengths we find:

(v) The C II doublet and Si II λ6371 weaken during shocks, i.e. they do not become anomalously strong at other phases (Section 3.2.1, Fig. 3).

(vi) The C II doublet strength ratio remains strongly optically-thick-like during shock passage; the lines do not desaturate (Section 3.2.2).

(vii) The blue lobes of the He I lines grow during the infall shock phases (Fig. 7). This is consistent with their being in an optically thin column, even though these atoms are at rest velocity and are likely at the deeper layers of the infall process (cf. Fig. 9).

(viii) The C IV and Si IV lines seem to show similar blue-lobe effects at these phases (Section 4.4).

(ix) Transient blue lobes clearly can form in some lines more strongly than others, whether for reasons of temperature sensitivity or line strength. This can masquerade as a phase-delay through atmospheric strata (a ‘Van Hoof effect’).

Points (v)–(vii) suggest that both infall heating and differential velocities through the atmosphere are critical in producing the
double lobes during shock passages. [Our explanation has some commonality and differences with both the models of YFS and Mathias et al. (1998)]. The heating during the infall shock is likely to be distributed across a range of atmospheric layers, which would produce the shallow temperature slope (relative to the slope in a static B star atmosphere) required to explain simultaneously the weakening of the C II doublet lines and the strengthening of the blue lobes of the He I lines. The quantitatively similar heating implied by the C II and Si II lines weakenings likewise suggests a tendency of the temperature gradient to become shallow as well. We hope to carry out future work to evaluate what temperature gradients are needed to fit the C II and He I line/lobe strengths and to learn what is required of ab initio hydrodynamic atmospheric models.

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REFERENCES

Aerts C., Mathias P., Van Hoolst T., De Mey K., Sterken C., Gillet D., 1995, A&A, 301, 781
Blomme R., Hensberge H., 1985, A&A, 148, 97
Burger M., de Jager C., van den Oord G. H., Sato N., 1982, A&A, 107, 320
Crowe R., Gillet D., 1989, A&A, 211, 365
Furenlid I., Young A., Meylan T., Haag C., Crinklaw G., 1987, ApJ, 319, 264
Garnier D., Nardetto N., Mathias P., Gillet D., Fokin A. B., in Aerts C., Bedding T., Christensen-Dalsgaard J., eds, ASP Conf. Ser. Vol. 259, Radial & Nonradial Pulsations as Probes of Stellar Physics. Astron. Soc. Pac., San Francisco, p. 206
Goldberg B. A., Walker G. A. H., Odgers G. J., 1976, AJ, 81, 433
Hinkle K., Wallace L., Valenti J., Harmer D., eds, 2000, Visible & Near-Infrared Atlas of the Arcturus Spectrum. Astron. Soc. Pac., San Francisco
Horvath A., Ghezegha O., Farkas L., 1998, Rom. A. J., 8, 89
Hubeny I., Lanz T., Jeffery S., 1994, Newslett. Anal. Astron. Spectra, 20, 30
Kurucz R. L., 1990, Trans. IAU, 20B, 169
Liberman M. A., Velikovich A. L., 1986, Physics of Shock Waves in Gases and Plasmas. Springer-Verlag, Berlin
Massa D., 1994, Ap&SS, 221, 113
Mathias P., Gillet D., Fokin A. B., Cambon T., 1998, A&A, 339, 525
McCarty J. K., Sandiford B. A., Boyd D., Booth J., 1993, PASP, 105, 881
Odell A. P., 1994, Inf. Bull. Variable Stars, 4138
Odgers G. J., 1955, Pub. Dom. Ap. Obs., 10, 215
Owocki S. P., Cranmer S. R., 2002, in Aerts C., Bedding T., Christensen-Dalsgaard J., eds, ASP Conf. Ser. Vol. 259, Radial and Nonradial Pulsations as Probes of Stellar Physics. Astron. Soc. Pac., San Francisco, p. 512
Pigulski A., 1993, A&A, 274, 269
Piskunov N. E., Valenti J. A., 2002, A&A, 385, 1095
Smith M. A., 2001, ApJ, 562, 998
Stamford P. A., Watson R. D., 1978, Publ. Astron. Soc. Aust., 3, 273
Stamford P. A., Watson R. D., 1981, Proc. Astron. Soc. Aust., 4, 210
Sterken C., 1993, A&A, 270, 259
Stickland D., Lloyd C., 2002, Observatory, 122, 33
Van Hoof A., Struve O., 1953, PASP, 65, 158
Young A., Furenlid I., Snowden M. S., 1981, ApJ, 245, 998 (YFS)

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