ORFEUS II FAR-ULTRAVIOLET SPECTROSCOPY OF AM HERCULIS

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ABSTRACT

Six high-resolution ($\lambda/\Delta\lambda \approx 3000$) far-UV ($\lambda \lambda = 910$–1210 Å) spectra of the magnetic cataclysmic variable AM Herculis were acquired in 1996 November during the flight of the ORFEUS-SPAS II mission. AM Her was in a high optical state at the time of the observations, and the spectra reveal emission lines of O VI $\lambda \lambda 1032, 1038, C$ III $\lambda \lambda 977, 1176$, and He II $\lambda 1085$ superposed on a nearly flat continuum. Continuum flux variations can be described as per Gänzicke et al. by $L \approx 20$ K white dwarf with $n \approx 37$ K hot spot covering a fraction $f \approx 0.15$ of the surface of the white dwarf, but we caution that the expected Lyman absorption lines are not detected. The O VI emission lines have a broad and narrow component structure similar to that of the optical emission lines, the C III and He II emission lines are dominated by the broad component, and the radial velocities of these lines are consistent with an origin of the narrow and broad components in the irradiated face of the secondary and the accretion funnel, respectively. The density of the narrow- and broad-line regions is $n_{nfr} \approx 3 \times 10^{10}$ cm$^{-3}$ and $n_{bdl} \approx 1 \times 10^{12}$ cm$^{-3}$, respectively, yet the narrow-line region is optically thick in the O VI line and the broad-line region is optically thin; apparently, the velocity shear in the broad-line region allows the O VI photons to escape, rendering the gas effectively optically thin. The orbital phase variations of the emission-line fluxes are unexplained.

Subject headings: binaries: close — stars: individual (AM Herculis) — stars: magnetic fields — ultraviolet: stars — white dwarfs

1. INTRODUCTION

AM Herculis is the prototype of a class of strongly magnetic ($B \approx 10$–100 MG) cataclysmic variables (see Cropper 1990 for a review and the volume by Buckley & Warner 1995 for recent results). The strong field locks the white dwarf into corotation and the accreting matter is channeled along the field lines for most of its trajectory from the secondary’s inner Lagrangian point to the white dwarf magnetic pole. A strong shock forms in the stream of freely falling matter close to the white dwarf surface, thermalizing a significant fraction of its kinetic energy and raising its temperature to a few tens of keV. The accretion region is therefore a source of hard X-rays, but soft X-rays are also produced by reprocessing of the hard X-rays in the white dwarf photosphere and by (with a tip of the hat to Dr. Bengue) “deep heating” of the white dwarf photosphere by blobs of material that penetrate to large optical depths before thermalizing their kinetic energy (Kuijpers & Pringle 1982). The dominant source of the UV continuum is the white dwarf photosphere, while the optical continuum is produced by free-free and bound-free emission from the funnel above the accretion shock and possibly the irradiated face of the secondary (Schachter et al. 1991). Sources of IR through far-UV (FUV) emission lines include the irradiated face of the secondary, the accretion stream, and the accretion funnel. The contribution of each of these emission regions to the net spectrum can be distinguished by the phasing and radial velocity amplitudes of the emission lines and the phasing and amplitude of continuum flux variations. Because of the small size and high X-ray luminosities of these binaries, photoionization of all of these emission regions is likely to be important, with ionization parameters $\xi \equiv L/nr^2 = 100L_{33}/n_{13}r_{13}$, where $L_{33}$ is the X-ray luminosity in units of $10^{33}$ ergs s$^{-1}$, $n_{13}$ is the particle density in units of $10^{13}$ cm$^{-3}$, and $r_{13}$ is the distance from the X-ray emission region in units of $10^{10}$ cm.

AM Her has been observed in the UV numerous times with IUE (Raymond et al. 1979; Heise & Verbunt 1988; Gänzicke, Beuermann, & de Martino 1995; Silber et al. 1996; Gänzicke 1998) but on only two previous occasions in the FUV: once in 1993 September during the flight of the Orbiting and Retrievable Far and Extreme Ultraviolet Spectrograph–Shuttle Pallet Satellite (ORFEUS-SPAS) I mission (Raymond et al. 1995) and once in 1995 March during the Astro-2 mission (Greeley et al. 1996). We here discuss six FUV spectra of AM Her acquired in 1996 November during the ORFEUS-SPAS II mission. These observations are superior to those of ORFEUS I because of the extensive phase coverage and, thanks to the $\approx 100\%$ improvement in the effective area (Hurwitz & Bowyer 1996; Hurwitz et al. 1998), the higher signal-to-noise ratio of the individual spectra. Combined with the results from recent EUV and X-ray observations of AM Her, the ORFEUS II spectra allow a detailed picture to be drawn of the locations of, and physical conditions in, the various FUV emission regions of this compact magnetic binary.

2. OBSERVATIONS

The FUV spectra were acquired with the Berkeley spectrograph in the ORFEUS telescope during the flight of the ORFEUS-SPAS II mission in 1996 November–
December. The general design of the spectrograph is discussed by Hurwitz & Bowyer (1986, 1996), while calibration and performance of the ORFEUS-SPAS II mission are described by Hurwitz et al. (1998); for the present purposes, it sufficient to note that spectra cover the range $\lambda \lambda = 910$–$1210$ Å and that the mean instrument profile FWHM $\approx 0.33$ Å, hence $\lambda / \Delta \lambda \approx 3000$. Because the orbital period of ORFEUS-SPAS (91 minutes) was very nearly half of the binary orbital period of AM Her (186 minutes), to obtain full phase coverage it was necessary to observe the source in pairs of consecutive orbits over an interval of 2 days or 17 binary orbits. Specifics of the observations are collected in Table 1: the HJD of the start of the exposures, the length of the exposures, and the range of binary phases assuming Tapia’s linear polarization ephemeris (Heise & Verbunt 1988). AAVSO measurements near the time of 1988). these exposures confirm that AM Her was in a high state, at an optical magnitude of 13.1 $\pm$ 0.2 (J. A. Mattei, Observations from the AAVSO International Database 1997, private communication).

### Table 1

| Start Date (HJD – 2,450,000) | Exposure (s) | Phase (\(\phi\)) |
|-----------------------------|-------------|------------------|
| 413.67401                   | 1876        | 0.332–0.501      |
| 413.73574                   | 1951        | 0.811–0.986      |
| 414.68375                   | 1953        | 8.164–8.339      |
| 414.74966                   | 1772        | 8.675–8.834      |
| 415.82732                   | 1990        | 17.034–17.213    |
| 415.89073                   | 2007        | 17.526–17.706    |

Figure 1 shows the background-subtracted and flux-calibrated spectra binned to a resolution of 0.1 Å and smoothed with a five point triangular filter. Relatively strong residual geocoronal emission lines of H I $\lambda 1025.7$ (Ly{$\beta$}), He I $\lambda 584.3$ (at 1168.7 Å in second order), N I $\lambda\lambda 1134, 1200$, and O I $\lambda 988.7$ have been subtracted from these spectra by fitting Gaussians in the neighborhood ($\pm 5$ Å) of each line. The remaining geocoronal emission lines are all very weak and contaminate only a limited number of discrete (FWHM $\approx 0.8$ Å) portions of the spectra. These FUV spectra are generally consistent with the two spectra acquired during the ORFEUS I mission in 1993 September (Raymond et al. 1995), with emission lines of O VI $\lambda 1032$, 1038, C III $\lambda 977, 1176$, and He II $\lambda 1085$ superposed on a nearly flat continuum. The broad and variable emission feature at $\lambda \approx 990$ Å may be N III, but the flux and position of this feature are uncertain because it coincides with a strong increase in the background at $\lambda \approx 1000$ Å, which renders noisy the short-wavelength end of these spectra.

#### 3. Results and Analysis

The extensive phase coverage of these observations allows studies of the phase variability of the FUV continuum and emission lines that were not possible with the limited amount of ORFEUS I data. To quantify the continuum flux density variations, we measured the mean flux density at $\lambda = 1010 \pm 5$ Å. This choice for the continuum bandpass is somewhat arbitrary, but it avoids the noisy portion of the spectra shortward of $\lambda \approx 1000$ Å, and it is a local minimum in the spectra. Ordered by relative orbital

![Fig. 1. ORFEUS spectra of AM Her ordered by binary phase. Each successive spectrum is offset by 1.5 flux density units. Two-component (20 + 37 kK) blackbody models are shown by the light-colored nearly straight curves.](image-url)
phase, the mean flux density in this bandpass is \( f_\lambda(1010 \text{ Å}) = 0.126, 0.181, 0.309, 0.403, 0.423, \) and \( 0.233 \times 10^{-12} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1} \). As shown in Figure 2, these flux density variations are reasonably well fitted \((\chi^2/\text{dof} = 8.9/3 \text{ assuming } 5\% \text{ errors in the flux densities})\) by \( f_\lambda(1010 \text{ Å}) = A + B \sin 2\pi(\phi - \phi_0) \) with \( A = 0.274(\pm 0.006) \times 10^{-12} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1}, B = 0.148(\pm 0.007) \times 10^{-12} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1}, \) and \( \phi_0 = 0.368 \pm 0.008 \). Since the \textit{ORFEUS} bandpass is too narrow to constrain the effective temperature meaningfully, it is not possible to determine uniquely the cause of these continuum flux density variations; they could be due to variations in the effective temperature, variations in the effective size of the emission region, or some combination of these. Assuming \( M_{\text{wd}} = 0.75 \, M_\odot \) \((R_{\text{wd}} = 7.4 \times 10^8 \text{ cm}), d = 75 \text{ pc}, \) and that the entire white dwarf surface radiates with a blackbody spectrum, the effective temperature varies with phase according to \( T_{\text{eff}}(\text{kK}) = 28.8 + 3.4 \sin 2\pi(\phi - 0.368). \) Gänside et al. (1995) modeled \textit{IUE} spectra of AM Her in a high state with white dwarf model atmosphere spectra and found that the observed variations of the flux and shape of the UV spectra could be described by a white dwarf of temperature \( T_{\text{wd}} \approx 20 \text{ kK} \) and a hot spot of temperature \( T_{\text{spot}} \approx 37 \text{ kK} \) with a relative area \( f = A_{\text{spot}}/\pi R_{\text{wd}}^2 \approx 0.08. \) If we similarly assume that we are seeing a 20 kK white dwarf with a 37 kK spot, the apparent projected area of the spot varies with binary phase according to \( f = 0.090 + 0.059 \sin 2\pi(\phi - 0.368). \) To demonstrate that such two-temperature blackbody models do a good job of matching the \textit{ORFEUS} spectra, we show in Figure 1 a series of 20 + 37 kK blackbody models superposed on the data. While the absolute normalization (effective area) of these fits differs somewhat from that of Gänside et al. because of the different assumed white dwarf radius, distance, and the use of blackbodies rather than white dwarf model atmosphere spectra, the trend is the same, with maximum FUV continuum flux, and hence maximum project spot area, occurring at \( \phi \approx 0.6. \)

While the spot model of the continuum flux variations of AM Her is simple and appealing, there is an inconsistency with observations in that there is no evidence in any of the \textit{ORFEUS} spectra of the Lyman absorption lines expected in the spectrum of a high-temperature, high-gravity stellar atmosphere. This problem of missing photospheric absorption features is not restricted to the FUV: the Lyz absorption line is weak in \textit{HST GHRS} spectra (Gänside 1998); the O vi 2s, 2p absorption edges expected in the photosphere of the soft X-ray emission region are not detected in the \textit{Extreme-Ultraviolet Explorer (EUV}) short wavelength spectra (Paerels et al. 1996); and the Ne vii 2s2p and 2s2p2 absorption edges tentatively identified in \textit{EUV} short wavelength spectra acquired in 1993 September (Mauche, Paerels, & Raymond 1995; Paerels et al. 1996) are subtle at best in the higher signal-to-noise ratio spectra acquired in 1995 March (Mauche, Liedahl, & Paerels 1998). The standard explanation for the lack of absorption features—a shallow photospheric temperature gradient caused by irradiation by the hot, post shock gas (van Teeseling, Heise, & Paerels 1994)—is not entirely satisfactory for two reasons. First, the run of effective temperature with optical depth must be fine-tuned so that emission lines are not produced. Second, “deep heating” of the photosphere by blobby accretion diminishes the fraction of the accretion luminosity in hard X-rays and hence decreases the importance of irradiation. Detailed work on the irradiation model is required to determine the severity of these concerns.

### 3.2. Emission Lines

Accompanying the continuum flux variations are variations in the flux and radial velocity of the emission lines. In what follows, we concentrate on the emission lines longward of \( \lambda = 1000 \text{ Å} \) where the spectra and hence the line fluxes and positions are not adversely affected by the high background and consequently low signal-to-noise ratio. To determine the parameters of the O vi \( \lambda \lambda 1032, 1038 \) doublet, we fitted the spectra in the neighborhood of the line \( \lambda = 1035 \pm 10 \text{ Å} \) with a linear continuum plus four Gaussians corresponding to the broad and narrow components of each member of the doublet, with the separations of the doublets constrained to the known wavelength difference, and the widths of each component constrained to be the same (10 free parameters). The C iii \( \lambda \lambda 1176 \) and He ii \( \lambda 1085 \) lines could be and hence were fitted with a linear continuum plus a single Gaussian (five free parameters).

Figure 3 shows the fits of the O vi lines, with both the data and the model binned to a resolution of 0.1 Å and smoothed with a five-point triangular filter. The figure demonstrates that a Gaussian parameterization of the O vi emission-line components is adequate for most of the spectra, and that, thanks to the high spectral resolution of the Berkeley spectrograph, reasonably unique decompositions can be made of these complex line profiles. The fitting parameters for the broad and narrow components of the O vi lines have been converted into physical quantities (flux, velocity, FWHM) and are listed in Table 2. The velocities of the broad and narrow components of the line are shown in Figure 4 and have been fitted to a sinusoidal function \( v = \gamma + K \sin 2\pi(\phi - \phi_0) \) with the parameters shown in Table 3. Figure 4 demonstrates that the fit to the radial velocities of the narrow component of the line is not good \((\chi^2/\text{dof} = 89/3)\), possibly because of residual variations in the zero point of the wavelength scale of the spectrograph, but that at \( K \approx 60 \text{ km s}^{-1} \) its radial velocity amplitude is on the low side of, but consistent with, the range of \( K = 60–150 \text{ km s}^{-1} \) for the narrow IR and optical emission lines measured on previous occasions (Greenstein et al. 1977; Young & Schneider 1979; Crosa et al. 1981). On the other hand, the radial velocity amplitude of the broad component of the line is \( K \approx 400 \text{ km s}^{-1} \), which is high compared to the range of \( K = 150–310 \text{ km s}^{-1} \) for the broad IR and optical emission lines. The similar amplitude and phase of the radial velocity variations of the C iii and

![Figure 2](imageurl)  
**Figure 2.** Mean flux density at \( \lambda = 1010 \pm 5 \text{ Å} \) in units of \( 10^{-12} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1} \) as a function of binary phase.
broad O VI emission lines argue that these lines originate in the same stream of gas within the binary. In contrast, the He II radial velocity is quite different: compared to the C III and broad O VI lines, the He II line has a similar phase offset but a large $\gamma$-velocity and half the radial velocity amplitude. The He II radial velocity behaves as if the stream of gas responsible for this emission line is hidden from view when it is directed toward the observer.

4. INTERPRETATION

To understand the above results, it is necessary to establish the phasing of the secondary and white dwarf and the relative orientation of the X-ray emission region (these and other aspects of the binary are summarized in Fig. 5). The phasing of the secondary is determined relative to the magnetic ephemeris by the radial velocity of the star’s IR absorption lines. Leaving aside uncertain corrections for the asymmetric irradiation of the inner face of the secondary by the X-ray emission region, inferior conjunction of the secondary (blue to red zero crossing of the absorption lines) occurs at $\phi \approx 0.65$ (Young & Schneider 1979; Southwell et al. 1995). The geometry of the X-ray emission region is determined by quasi-simultaneous EUVE, ROSAT, and ASCA observations of AM Her in 1995 March (Mauche et al. 1998; see also Paerels et al. 1996 and Ishida et al. 1997). At hard X-ray energies ($E \approx 4$–10 keV) where the hard “thermal bremsstrahlung” component dominates the X-ray spectrum, the X-ray light curves are single peaked, with a

Fig. 3.—Regions of the spectra containing the O VI doublet showing Gaussian fits to the broad and narrow components. Panels are ordered by relative binary phase. Units of flux density are $15^{12}$ ergs cm$^{-2}$ s$^{-1}$ Å$^{-1}$.

Fig. 4.—Radial velocity of the broad (squares) and narrow (crosses) components of the O VI doublet as a function of binary phase.

Fig. 5.—Schematic diagram of AM Her showing the velocity vectors and inferred locations of the FUV broad- and narrow-line regions and the phases of the X-ray eclipse, EUV flux deficit, maximum FUV and hard X-ray continuum flux, maximum O VI broad-line flux, and maximum blue-shift of the He II and broad O VI lines.
| $\phi$         | Narrow Component | Broad Component |
|---------------|------------------|-----------------|
|               |      $f(1032 \, \AA)$ |      $f(1038 \, \AA)$ |       Velocity |       FWHM$^*$ |       Velocity |       FWHM$^*$ |
|               |        (10$^{-12}$ ergs cm$^{-2}$ s$^{-1}$) |        (10$^{-12}$ ergs cm$^{-2}$ s$^{-1}$) |       (km s$^{-1}$) |       (km s$^{-1}$) |       (km s$^{-1}$) |       (km s$^{-1}$) |
| 0.034–0.213   |      0.46 ± 0.05 |      0.40 ± 0.05 |       −27 ± 5 |         174 ± 13 |      1.9 ± 0.1 |     0.9 ± 0.1 |      −456 ± 27 |     1051 ± 49 |
| 0.164–0.339   |      0.42 ± 0.06 |      0.46 ± 0.06 |       −82 ± 4 |         133 ± 11 |      2.1 ± 0.1 |     1.1 ± 0.1 |      −149 ± 13 |     825 ± 36 |
| 0.332–0.501   |      0.80 ± 0.07 |      0.55 ± 0.05 |       −4 ± 3 |         127 ± 7 |      1.1 ± 0.1 |     1.2 ± 0.1 |       +204 ± 23 |      831 ± 47 |
| 0.526–0.706   |      0.83 ± 0.07 |      0.68 ± 0.06 |       −80 ± 3 |         161 ± 8 |      0.6 ± 0.1 |     0.4 ± 0.1 |       +360 ± 44 |     694 ± 100 |
| 0.675–0.834   |      0.50 ± 0.06 |      0.62 ± 0.07 |       −58 ± 4 |         153 ± 11 |      0.9 ± 0.2 |     0.3 ± 0.1 |       +57 ± 35 |      749 ± 86 |
| 0.811–0.986   |      0.94 ± 0.06 |      0.82 ± 0.06 |       +114 ± 3 |        157 ± 6 |      1.1 ± 0.2 |     0.7 ± 0.1 |       −204 ± 94 |     1503 ± 164 |

$^a$ Instrumental profile FWHM $\approx$ 95 km s$^{-1}$. 
broad, flat maximum centered at $\phi \approx 0.6$ and an eclipse (of the X-ray emission region by the body of the white dwarf) centered at $\phi \approx 0.11$. At soft X-ray energies ($E \lesssim 1$ keV) where the soft “blackbody” component dominates the X-ray spectrum, the light curves are more complex, with a “bright” phase from $\phi \approx 0.3$–0.6, a “dim” phase from $\phi \approx 0.6$–1.0, and the same eclipse observed at higher energies. The ROSAT HRI ($E \approx 0.1$–2.0 keV) light curve tracks the EUV deep survey and short wavelength ($E \approx 0.1$–0.2 keV) light curves over most binary phases, but from $\phi \approx 0.3$–0.6, excess absorption is indicated by a deficit of EUV flux.

Given that the FUV and hard X-ray light curves both peak at $\phi \approx 0.6$, it is apparent that the $\approx 37$ kK hot spot we invoked in §3 to describe the FUV continuum flux variations is associated with the X-ray emission region. The size of these emission regions depends sensitively on their effective temperatures, but for what seem to be reasonable assumptions the FUV emission region is significantly larger than the X-ray emission region. Specifically, blackbody fits to EUVE spectra yield $T = 240$–290 kK and $f_\nu(2–5) \times 10^{-3}$ for the soft X-ray emission region (Paerels et al. 1996), while fits to the IUE and ORFEUS spectra yield $T \approx 37$ kK and $f_\nu(5) \approx 0.1$ for the FUV emission region (§3 and Gänsicke et al. 1995). A larger FUV emission region is also consistent with the fact that the FUV continuum flux is never fully eclipsed by the body of the white dwarf, whereas the X-ray flux is. These emission regions are offset relative to the secondary by $\Delta \phi \approx 0.05$, which is consistent with the azimuth of the magnetic pole of the white dwarf [$\psi = 0.046 \pm 0.033$; Cropper 1988, but we have corrected a mistake therein ($\psi = \phi_s - \phi_c = 0.653 \pm 0.029 - 0.607 \pm 0.016 = 0.046 \pm 0.033$, not 0.087 $\pm 0.030$)]

Since the maximum redshift of the broad O vi, C iii, and He ii emission lines occurs at approximately the same phase as the maximum visibility of the FUV and X-ray emission regions, it is reasonable to conclude that these lines are produced in the funnel of gas directed toward and falling onto the FUV and X-ray–bright accretion region in the vicinity of the magnetic pole of the white dwarf. Half a binary orbital period later, the X-ray emission region is eclipsed by the body of the white dwarf, and the broad O vi, C iii, and He ii emission lines attain their maximum blueshifts. The pathological behavior of the radial velocities of the He ii emission line ($\approx 0$ km s$^{-1}$ maximum blueshift) suggests that the portion of the accretion funnel responsible for this emission line is eclipsed along with the X-ray emission region by the body of the white dwarf. The excess absorption from $\phi \approx 0.3$–0.6 is presumably due to the accretion stream and funnel that lie along the line of sight at these binary phases. On the other hand, the cause of the “bright” and “dim” phases of the EUV and soft X-ray light curves is a mystery deepened by the fact that in 1991 April (Gänsicke et al. 1995) the “dim” phase of the soft X-ray light curve preceded the “bright” phase, the reverse of what was observed in 1993 September (Paerels et al. 1996) and 1995 March (Mauche et al. 1998). The solution of this puzzle is left as an exercise to the reader.

The physical conditions of the FUV line-emitting gas are constrained by a number of pieces of information. In gas illuminated by a mixture of hard and soft X-rays, O vi exists over a range of ionization parameters $\xi \approx 30$–60 and temperatures $T \approx 20$–100 kK, peaking at $\xi \approx 35$ and $T \approx 20$ kK (Kallman & McCray 1982, model 5; pure soft X-ray illumination gives a similar result according to the code described by Raymond 1995). Support for the inferred temperature range is provided by the mean C iii $\lambda 977$/1176 line ratio of $\approx 2$, which requires $T \approx 50$ kK (Keenan, Feibelman, & Berrington 1992; F. P. Keenan, private communication). Over the inferred range of ionization parameters, helium makes the transition from He ii to He iii, with He iii dominant above $\xi \approx 35$. Similarly, the dominant ionization stage of carbon should be C iv–C viii, not C iii, but this is consistent with the fact that C iv $\lambda 1550$ in the UV is much brighter than C iii $\lambda 977$, 1176 in the FUV (Raymond et al. 1979; Heise & Verbunt 1988; Greeley et al. 1996). The density of the O vi narrow-line region is $n_{\text{abs}} = L/\xi r_{\text{abs}} \approx 3 \times 10^{10} L_{33.5}$ cm$^{-3}$, where $r_{\text{abs}} = 5.3 \times 10^{10}$ cm is the distance from the white dwarf to the face of the secondary and $L_{33.5}$ is the X-ray luminosity in units of $3 \times 10^{34}$ ergs s$^{-1}$ (Paerels et al. 1996). The density of the O vi broad-line region is uncertain because its distance from the white dwarf is uncertain, but at $r_{\text{blr}} \gtrsim 1 \times 10^{10}$ cm (where the free-fall velocity is $\approx 1300$ km s$^{-1}$, much higher than the O vi radial velocity amplitude), $n_{\text{blr}} \lesssim 1 \times 10^{12} L_{33.5}$ cm$^{-3}$.

Surprisingly, even though the O vi broad-line region is a factor of $\approx 30$ times denser than the O vi narrow-line region, the ratio $R$ of the O vi line intensities shown in Table 2 demonstrates that it is the narrow-line region ($R \approx 1$), not the broad-line region ($R \approx 2$), which is optically thick. If the broad-line region were fully optically thin, it would be equally bright when viewed from any orientation (i.e., any orbital phase); if optically thick and elongated, it would be bright twice per orbital period and dim twice per orbital period; in fact, the O vi broad-line flux varies sinusoidally, with a maximum flux at $\phi \approx 0.2$ and a minimum at $\phi \approx 0.7$ (Fig. 6). The cause of this variation is unknown. Puzzling too is the variation with phase of the O vi narrow-line flux. From our association of the O vi narrow-line region with the irradiated face of the secondary, one would expect minimum O vi narrow-line flux at inferior conjunction of the secondary at $\phi \approx 0.65$ and a broad maximum 180° later, but this is not the case.

We close by considering the relationship between the broad Balmer and O vi line-emitting gas. Stockman et al.

| Line        | Component | $\gamma$ (km$^{-1}$) | $K$ (km s$^{-1}$) | $\phi_0$ |
|-------------|-----------|---------------------|------------------|---------|
| O vi $\lambda$1032, 1038 | N         | $-22 \pm 6$         | $57 \pm 9$       | $0.700 \pm 0.022$ |
| O vi $\lambda$1032, 1038 | B         | $-49 \pm 14$        | $412 \pm 19$     | $0.297 \pm 0.007$ |
| He ii $\lambda$1085 | B         | $+176 \pm 18$       | $180 \pm 29$     | $0.391 \pm 0.018$ |
| C iii $\lambda$1176 | B         | $+6 \pm 19$         | $480 \pm 29$     | $0.284 \pm 0.008$ |

$^a v = \gamma + K \sin 2(\phi_0 - \phi).$
(1977) found that the Balmer lines arise in an optically thick region with a density of $10^{13} < n(\text{cm}^{-3}) < 2 \times 10^{14}$, which is a factor of $\geq 10$–200 times higher than the density of the O VI broad-line gas. That the Balmer and O VI emission-line regions are at least roughly cospatial is indicated by the similar amplitude and phasing of their radial velocity variations (Table 3; Priedhorsky 1977; Cowley & Crampton 1977). The ratio of the radial velocity amplitudes is $K_{\text{O VI}}/K_{\text{Balmer}} = 1.6 \pm 0.2$ and $\sim 1$ for the data of Priedhorsky (1977) and Cowley & Crampton (1977), respectively. Assuming that the gas is in free-fall onto the white dwarf, $K_{\text{O VI}}/K_{\text{Balmer}} < 2$ implies $r_{\text{Balmer}}/r_{\text{O VI}} < 4$. By mass conservation, $n_{\text{Balmer}}/n_{\text{O VI}}$ is less than 2 if the stream cross section is constant with radius, and is greater than 1/32 if the stream cross section scales like the dipolar field as $r^3$. The ionization parameter of the Balmer emission-line region is then $\xi \sim 1$, which does not allow H I to dominate over H II. Consequently, the accretion flow must be clumped for the O VI and Balmer emission lines to coexist, which is consistent with the idea of clumpy accretion as an explanation for the soft X-ray excess (Kuijpers & Pringle 1982) and for the variability observed in hard X-rays and at optical wavelengths (Beardmore & Osborne 1997).

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