FUSE Observations of the Dwarf Nova SW UMa During Quiescence

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**ABSTRACT**

We present spectroscopic observations of the short-period cataclysmic variable SW Ursa Majoris, obtained by the Far Ultraviolet Spectroscopic Explorer (FUSE) satellite while the system was in quiescence. The data include the resonance lines of O VI at 1031.91 and 1037.61 Å. These lines are present in emission, and they exhibit both narrow (\( \sim 150 \text{ km s}^{-1} \)) and broad (\( \sim 2000 \text{ km s}^{-1} \)) components. The narrow O VI emission lines exhibit unusual double-peaked and redshifted profiles. We attribute the source of this emission to a cooling flow onto the surface of the white dwarf primary. The broad O VI emission most likely originates in a thin, photoionized surface layer on the accretion disk. We searched for emission from H 2 at 1050 and 1100 Å, motivated by the expectation that the bulk of the quiescent accretion disk is in the form of cool, molecular gas. If H 2 is present, then our limits on the fluxes of the H 2 lines are consistent with the presence of a surface layer of atomic H that shields the interior of the disk. These results may indicate that accretion operates primarily in the surface layers of the disk in SW UMa. We also investigate the far-UV continuum of SW UMa and place an upper limit of 15,000 K on the effective temperature of the white dwarf.

**Subject headings:** stars: binaries — stars: dwarf novae — stars: individual (SW UMa) — ultraviolet: stars

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1. Introduction

Cataclysmic variables (CVs) are binary star systems in which the primary, a white dwarf (WD), accretes material from a Roche-lobe-filling secondary, usually a late-type main-sequence star. In the absence of a strong magnetic field from the WD, the stream flowing out from the secondary forms an accretion disk around the primary. Such accretion disks serve as reservoirs for the mass-transfer process; thermal and viscous instabilities cause the disk to switch to a high-temperature, mostly ionized state from a low-temperature, mostly neutral state. The transition from the high state back to the low state is accomplished by rapid disposal of disk matter onto the WD. This disk-instability mechanism is responsible for the periodic episodes of elevated rates of accretion onto the primary that are the origin of the outbursts commonly observed in dwarf novae (DNe), when the overall brightness of the system abruptly increases by several magnitudes (Warner 1995; Cannizzo 1993; Lasota 2001). During these eruptions, which can range from several days to a few weeks in duration, the majority of the luminosity of the system comes from the accretion disk and the associated hot spot (where the accretion stream from the secondary impacts the outer edge of the disk) and boundary layer (where material from the inner edge of the disk decelerates from its Keplerian velocity to meet the more slowly rotating surface of the WD). Historically, DNe have been classified on the basis of their lightcurves, and the classifications are named after an observational archetype. The U Gem stars are considered to be the typical DN systems. The lightcurves of SU UMa stars, an important subclass of U Gem stars, exhibit periodic “superoutbursts” that are $\sim 0.7$ mag brighter and $\sim 5$ times longer duration than usual.

The presence of a strong magnetic field alters the geometry of the mass-transfer process considerably. In AM Her systems, or “polars,” (see Cropper 1990 for a detailed review) the field is strong enough to prevent an accretion disk from forming altogether; instead, the primary rotates synchronously with the orbital period of the binary, and the accretion stream from the secondary is channeled along the field lines directly down to the WD. AM Her systems do not exhibit dwarf nova eruptions, although they do alternate between high and low accretion states. In systems where the magnetic field is weaker, only the inner portion of the disk is disrupted, and material may still collect in an outer disk or annulus before accreting onto the WD along the field lines. Such systems are called “intermediate polars” (IPs). The DQ Her stars are a subclass of the IPs, characterized by rapidly rotating primaries.

SW UMa is a DN of the SU UMa subclass, and has been characterized as a tremendous outburst amplitude dwarf nova (Robinson et al. 1987; Howell, Szkody, & Cannizzo 1995). It undergoes outbursts on a $\sim 460$-day cycle, jumping from a minimum apparent magnitude $M_V = 16.5$ during quiescence to a maximum brightness of $M_V = 10.8$. It is an ultrashort-
period binary with $P_{\text{orb}} = 81.8$ min (Shafter 1983; Shafter, Szkody, & Thorstensen 1986; hereafter SST86). SST86 observed a 15.9-minute periodicity in the optical photometry of SW UMa in quiescence and also marginally detected this periodicity in soft X-rays (0.05–2 keV) observed by EXOSAT. These findings suggest that magnetic accretion is taking place, and thus SW UMa may be an IP. This idea is supported by the fact that SW UMa is an unusually strong X-ray emitter for such a faint optical source. ROSAT observations of the soft X-ray (0.1–2.5 keV) emission from SW UMa in quiescence failed to detect the 15.9-minute period but could not rule out its presence (Rosen et al. 1994). No 15.9-minute period has been detected in either high-speed optical photometry (Robinson et al. 1987) or X-rays during superoutburst phases of SW UMa, but this could be due to the fact that, during outburst, the Alfvén radius might shrink to less than the WD radius (Szkody, Osborne, & Hassall 1988); in other words, the greatly enhanced mass-transfer from the disk swamps the magnetic field of the WD, and disk accretion then proceeds as in non-magnetic systems. Further searches for periodic behavior at the beat frequency between the presumed 15.9-minute rotational period of the WD and the 81.8-minute orbital period have failed to detect any periodicity (P. Szkody, private communication, 2004). If indeed SW UMa is an IP, it stands as one of the two shortest-period examples known, the other being EX Hya.

In this paper we present observations of SW UMa obtained by the Far-Ultraviolet Spectroscopic Explorer (FUSE) while the system was in quiescence. The original aim of these observations was to search for emission from molecular hydrogen, which would serve as direct evidence that the accretion disk cools sufficiently during quiescence to allow the formation of molecules. This emission was not detected, but the detection limits leave open the possibility of layered accretion in the disk of SW UMa. We also looker for a faint far-UV continuum from this source, which would indicate thermal (blackbody) emission from the WD. The upper limits on this continuum can be used to constrain the post-outburst cooling of SW UMa. The only obvious features in the FUSE spectra of SW UMa are the O VI resonance lines at 1031.91 Å and 1037.61 Å, which exhibit both narrow and broad emission components. Broad emission of several blended transition of C III centered at 1176 Å is also detected. We examine the unusual features of these lines and explore possible physical mechanisms explaining their formation.

2. Observations

2.1. FUSE Observations of SW UMa

We obtained 10 exposures of SW UMa with FUSE on JD 2452220 (2001 November 6, between 00:42 and 15:31 UT). These observations are archived under FUSE guest investigator
program b074. The FUSE instrument is described in detail by Moos et al. (2000) and Sahnow et al. (2000). The four FUSE spectrographs cover the wavelength range of 905–1188 Å, with spectral channels denoted by combining the grating coating names (LiF and SiC) with the telescopes (1 and 2) and detectors (a and b). Three spectroscopic apertures are available (LWRS, MDRS, and HIRS), providing monochromatic resolving powers of 20,000–24,000 (±2000). SW UMa was observed through the LWRS aperture, which has a field of view that is 30″ square. The LWRS aperture center was placed at 129°.178958 azimuth and +53°.476972 declination (provided in the exposure file header information), which corresponds to SW UMa’s coordinates of \( \alpha_{2000} = 08^h 36^m 42.95^s, \delta_{2000} = +53^\circ 28' 37.1'' \) to within an angular distance of 1.7″. The position angle of the y-axis of the LWRS aperture was 7.9° East of North during the 10 FUSE science exposures of SW UMa. The photon events from SW UMa were accumulated by the detectors in the time-tag (TTAG) mode. Because of the low Earth orbit of FUSE (768 km), strong airglow emission lines (primarily those of O I, N I, and the Lyman series of H I) due to scattered sunlight are present in the astrophysical spectra observed with the large LWRS aperture during the daylight portion of the orbit.

We used the CalFUSE version 2.2.3 calibration software to recalibrate the archival spectra for each exposure of SW UMa. The 10 exposures were then summed for each of the separate spectral channels, yielding a single set of spectra representing 29,000 s of exposure time. The CalFUSE pipeline includes relative wavelength calibration for the detector segments in each channel, and this is believed to be accurate to within 2 pixels (0.012 Å). The absolute wavelength calibration is less reliable, so to correct for small pixel shifts between the subsequent exposures we cross-correlated the LiF1a and LiF2b exposures over the small wavelength range of 3 Å centered on the O VI 1031.9 Å line. As a further check on the absolute wavelength scale in the vicinity of the O VI emission lines, we measured the centers of the 5 nearby O I airglow lines, which lie in the geocentric frame of rest. All 5 lines were found to lie within 0.02 Å (6 km s\(^{-1}\)) of their rest wavelengths. We then transform the wavelength scale to heliocentric rest by correcting for the -23 km s\(^{-1}\) shift introduced by Earth’s orbital motion in the direction of SW UMa at the time of our observations. The flux calibration steps include flat-fielding, background subtraction, burst removal, and 1-D spectrum extraction for absolute flux conversion that corrects for optical (point-source) astigmatism in the cross-dispersion direction.

### 2.2. FUSE Sky-Background Observations Near SW UMa

Immediately prior to our observations of SW UMa, FUSE obtained three exposures with the telescope apertures pointed at a blank patch of sky ~1′ to one side of the target. These
observations, part of the S405 “sky-background” program, total 9800 s of exposure time and provide a valuable diagnostic of the ambient far-UV background spectrum in the immediate vicinity of SW UMa. We applied the same calibration steps to the sky-background data as to the SW UMa target data to ensure consistency between both datasets.

### 2.3. AAVSO lightcurves

The American Association of Variable Star Observers (AAVSO) maintains an extensive database of observations contributed by a global network of amateur astronomers. These data provide invaluable lightcurve coverage on countless variable stars. The AAVSO database contains nearly 25,000 observations of SW UMa, dating back to 1939. Using their online lightcurve generator,\(^1\) it is straightforward to track the brightness of a source, and hence the outburst cycle of a DN like SW UMa, over a specified period of time. At the time of the FUSE observations of SW UMa (JD 2452220), the visual magnitude of the system was \(M_V \approx 17\). The previous and subsequent eruptions, both marked by an increase in brightness to \(M_V \approx 10.5\), occurred 150 days before and 350 days after this date. We are therefore confident that FUSE did indeed observe SW UMa during its quiescent phase.

SW UMa was first observed in the UV by the International Ultraviolet Explorer (IUE) satellite on JD 2450057 (1995 5 December), and while it is clear from the AAVSO lightcurves that the system was in quiescence at that time, it is uncertain when exactly the previous DN eruption took place. The light curves show that the system was in outburst on JD 2449200, more than 800 days prior to the IUE observations. The subsequent confirmed eruption of SW UMa began on JD 2450200, and the gap between this date and that of the previous confirmed outburst corresponds closely to twice the typical 460-day outburst cycle. It is conceivable that SW UMa skipped an outburst, but there also appear to be gaps in the coverage provided by the AAVSO that could be large enough to miss an outburst if one had occurred in the meantime. We can, however, state with confidence that SW UMa did not erupt within the timeframe extending 350 days prior to the IUE observations. SW UMa has also been observed in quiescence by the Hubble Space Telescope Imaging Spectrograph (HST/STIS), an instrument with spectral coverage similar to that of IUE SWP. The STIS data have not yet been made public, but preview spectra are available.

\(^1\)http://www.aavso.org/data/lcg
3. Discussion

When analyzing spectra in the far-UV, interstellar reddening is always a concern. Szkody, Osborne, & Hassall (1988) estimate a negligible reddening of \( E(B-V) = 0 \) for SW UMa, with an upper limit of \( E(B-V) = 0.02 \) that translates into an interstellar hydrogen column density of \( N_H = 1 \times 10^{20} \text{ cm}^{-3} \). We will therefore neglect the effects of reddening in the analysis below, with the following caveat: Even a small \( E(B-V) \) can be significant at these wavelengths. In the limiting case of \( E(B-V) = 0.02 \), the fluxes observed by FUSE would be underestimates by a factor of 1.4 (Cardelli, Clayton, & Mathis 1989).

3.1. Molecular Hydrogen

One theory for dwarf nova outbursts is that the Magneto-Rotational instability of Balbus & Hawley (1991) does not operate in quiescent CV disks because of a very low ionization state, in which case the viscosity will be extremely low. Gammie & Menou (1998) investigated this idea, and found that the required ionization fraction is extremely small, \( \sim 10^{-6} \). Further studies have essentially confirmed this ionization requirement (Fleming, Stone, & Hawley 2000; Menou 2000), even if including the previously neglected effects of non-ideal MHD Hall terms changes the ionization threshold somewhat (Sano & Stone 2003 and references therein). In the presence of X-rays at the observed levels, such a low ionization state cannot be maintained by radiative recombination in atomic gas (\( \alpha \sim 10^{-13} \text{ cm}^3 \text{ s}^{-1} \)). However, dissociative recombination of molecular hydrogen ions (\( \alpha \sim 10^{-8} \text{ cm}^3 \text{ s}^{-1} \)) can provide the low neutral fraction needed. Thus, the theory that CV low states result from a shutdown of the Magneto-Rotational instability leads to an expectation that the disk of a low state CV should be molecular. Howell, Harrison, & Szkody (2004) have recently reported detection of \( \text{H}_2 \) and CO infrared emission from WZ Sge in its low state. SW UMa, like WZ Sge, has a very low accretion rate in its low state.

Pumping of \( \text{H}_2 \) by \( \text{Ly}_\alpha \) produces \( \text{H}_2 \) emission lines in the UV in a wide range of astrophysical systems, ranging from sunspots (Jordan et al. 1978) to T Tauri star accretion disks (Saucedo et al. 2003; Herczeg et al. 2002) and Mira (Wood, Karovska, & Raymond 2002). The bands connected to the ground vibrational level fall in the FUSE bandpass, with the strongest features expected at about 1050 and 1100 Å (Raymond, Blair, & Long 1997). These features are not detected in our FUSE data, and the spectra yield upper (3\( \sigma \)) limits of \( 3.6 \times 10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1} \) and \( 2.8 \times 10^{-15} \text{ erg cm}^{-2} \text{ s}^{-1} \), respectively, for their fluxes. The C IV flux observed in the archival IUE data is \( f_{\text{CIV}} \approx 2 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1} \) and the H\( \alpha \) flux is \( f_{\text{H}\alpha} \approx 1.5 \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1} \) (SST86). Considering a ratio \( f_{\text{Ly}_\alpha}/f_{\text{H}\alpha} \approx 15 \) or a ratio \( f_{\text{Ly}_\alpha}/f_{\text{CIV}} \approx 2 \) based on the X-ray-illuminated accretion disk models of Raymond (1993), the
intrinsic Lyα flux from SW UMa before interstellar absorption ought to be about $2\times10^{-13}$ erg cm$^{-2}$ s$^{-1}$. The emission should arise from the disk surface, and half of it should be directed downward if the emitting region is a simple slab. A detailed model would be needed to predict the fraction of that emission that excites H$_2$, but for a local Lyα line width of 0.5 Å (excluding Keplerian velocity shifts), approximately 10% of the flux is resonant with the $1 - 2P(5)$ and $1 - 2R(6)$ transitions of H$_2$, and about 20% of the photons absorbed should be converted to the bands in the FUSE wavelength range (see Wood, Karovska, & Raymond 2002). Thus a rough prediction for the fluxes would be $4\times10^{-15}$ erg cm$^{-2}$ s$^{-1}$. This is not far above the upper limits quoted above. We also note that the preview STIS spectra of SW UMa do not show the H$_2$ bands (e.g., those near 1610 and 1670 Å) seen in other H$_2$ fluorescent spectra. The STIS spectra have higher signal-to-noise than the FUSE spectra, but it is also difficult to predict the intensity of the longer wavelength bands.

If the disk is indeed molecular, as indicated by the WZ Sge detections, the lack of fluorescent emission might be attributed to a surface layer of atomic gas that shields the disk from Lyα photons. Such a layer could be a small fraction of the disk mass, but it would have an ionization fraction much larger than the limit given by Gammie & Menou (1998). It is possible that accretion proceeds in this surface layer, as has been proposed for T Tauri stars by Gammie (1996) and developed for quiescent DNe by Menou (2002).

3.2. Far-UV Continuum

The effective temperature ($T_{\text{eff}}$) of the WD in SW UMa was first measured by Gänsicke & Koester (1999; hereafter GK99). They fit model atmosphere spectra to IUE SWP spectra ($\lambda = 1200$–1900 Å) obtained during quiescence. Assuming a WD with surface gravity $\log g = 8$ ($M_{\text{WD}} = 0.6$ M$_\odot$), they derive a best-fit effective temperature of $T_{\text{eff}} = 16,000 \pm 1500$ K and estimate a distance $d = 182$ pc for SW UMa. Applying a similar approach to the STIS spectra of SW UMa, Szkody, Sion, Gänsicke, & Howell (2002; hereafter SSGH02) derive $T_{\text{eff}} = 14,000 K$ and $d = 159$ pc.

These values for the quiescent $T_{\text{eff}}$ of the WD in SW UMa can be compared to that of WZ Sge, another short-period DN. Following an eruption in 2001 July, the WD in WZ Sge was observed to cool from 23,400 K in 2001 October to 15,900 K 17 months later (Long et al. 2004). This eruption of WZ Sge was the first such outburst in 22 years, a timescale that is clearly much longer than the typical outburst period of SW UMa, and so it is reasonable to expect a disparity between the cooling timescales of the two systems. The WD in WZ Sge, with $M_{\text{WD}} = 0.9$ M$_\odot$ (Long et al. 2003), is more massive than the WD in SW UMa, so this may partially account for the fact that the cooling time for WZ Sge exceeds the typical
outburst period of SW UMa. Given the obvious disparities between these two CVs, it is intriguing that they seem to exhibit very similar $T_{\text{eff}}$ in quiescence.

Our FUSE observations of SW UMa were taken on JD 2452220 (2001 6 November). The AAVSO lightcurves clearly indicate that an outburst was in progress on JD 2452070, 150 days earlier. We are therefore in a position to place a constraint on the post-outburst temperature of the WD by investigating the far-UV continuum emission in the region just shortward of the IUE SWP spectral coverage. Due to the extreme faintness of the source, the expected continuum level of the 16,000 K WD ($f_{\text{cont}} \sim 5 \times 10^{-15} \text{ erg cm}^{-2} \text{s}^{-1} \text{Å}^{-1}$ for $\lambda = 1100$–1150 Å) of GK99 is close to the detection threshold of FUSE, which is nominally 30% of the typical detector background levels, or $\sim 2 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$ in the LiF channels. In order to attempt such a sensitive measurement, we took advantage of the FUSE “sky background” observation (§2.2). We performed a detailed inspection of all of the FUSE raw exposures from both datasets in the wavelength regions of 1120–1130 Å and 1155–1165 Å of the LiF1b and LiF2a detector segments, where the continuum is predicted to be strongest, and no strong airglow lines are present. The count rates in the SW UMa target exposures were significantly higher, by a factor of $\sim 1.5$, than the count rates in the sky-background exposures. This seems to suggest that the elevated count rates are due to photons from SW UMa. However, continuum emission from a point source should produce a measureable peak in the count density in the cross-dispersion direction of the detector, but we do not detect any enhancement in the count density resembling a continuum in the raw exposures. A broad component to the O VI emission is evident upon careful examination of the raw exposures between 1030 and 1040 Å in the LiF1a and LiF2b channels of the SW UMa target data (§3.3 below), and these counts yield a peak flux of $4 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$ in the calibrated spectra. The fact that we can see the broad O VI in the raw data but cannot detect a continuum at similar flux levels prevents us from making a firm measurement of the far-UV continuum in SW UMa. Instead, we will place conservative upper limits on the continuum levels across the FUSE spectral bandpass.

Working with the calibrated, fully-extracted and summed data from the CalFUSE pipeline, we subtracted the 9800-s sky-background spectra from the 29,000-s SW UMa spectra. This reduces potential systematic errors introduced by the FUSE background subtraction, but at the cost of increased noise. Imperfections in the background subtraction are pronounced in regions of the spectra that lie close to a detector edge, hence we do not use these regions when attempting to characterize the continuum. We further process the data by removing all prominent airglow features and coarsely resampling the spectra in 10 Å bins. We then take the average of the two LiF channels covering each spectral bandpass between 1060 and 1180 Å. We adopt twice these average values as our upper limits on the continuum, or else we set the upper limits to $3 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$, the flux level of the
significantly detected broad O VI emission, whichever is greater. It must be stressed that there is no way to place a meaningful statistical upper limit on the continuum, because the dominant sources of error are uncertainties in the background subtraction. But given that the flux levels in the rebinned spectra from the independently calibrated LiF1b and LiF2a channels agree with each other to better than 50%, and that we observe the broad O VI emission at a comparable flux level, we are confident that our upper limits are at least 3 times greater than the level of the systematic errors.

These upper limits, along with the IUE SWP spectrum, are compared to a grid of WD model spectra provided by the authors of GK99. These models are based on a log \( g = 8 \) WD with a pure hydrogen/helium atmosphere, whereas the models used in GK99 are for a WD with solar abundances. This disparity causes us to adopt slightly different scale factors when comparing the models to the data. The scale factor used determines the ratio of the WD radius \( R_{\text{WD}} \) to the distance \( d \), according to the relation

\[
 f_{\text{scale}} \equiv \frac{f}{F} = \frac{\pi R_{\text{WD}}^2}{(3.086 \times 10^{18} d)^2},
\]

where \( f \) is the observed flux and \( F \) is the model flux. We test models for \( T_{\text{eff}} \) in the range of 12,000–18,000 K (in increments of 1,000 K). We calculate \( f_{\text{scale}} \) by matching the model flux to the IUE flux within the region of 1250–1500 Å, accepting as plausible values of \( f_{\text{scale}} \) that give 84 pc \( \leq d \leq 243 \) pc for a log \( g = 8 \) WD.

The results of this analysis of the UV continuum of SW UMa are shown in Fig. 1. We find that a model with \( T_{\text{eff}} \leq 15,000 \) K for a 0.6 M\( \odot \) WD at \( d = 173 \) pc best matches the IUE spectrum while falling within the upper limits on the far-UV continuum imposed by FUSE. Hence, the effective temperature of the WD does not exceed 15,000 K at the time of the FUSE observations, 150 days post-outburst. This result agrees well with the findings of SSGH02 and with the lower end of the temperature range derived by GK99 from the IUE spectrum, 350 days post-outburst (§2.3 above), but the flux in their 16,000 K model significantly exceeds our conservative upper limits in the far-UV.

3.3. On the Origin of the O VI Emission Lines

The narrow O VI lines at 1031.91 and 1037.61 Å, with integrated fluxes of \( 1.8 \times 10^{-14} \) erg cm\(^{-2}\) s\(^{-1}\) and \( 8.9 \times 10^{-15} \) erg cm\(^{-2}\) s\(^{-1}\), respectively, are the most strongly detected emission lines in the FUSE spectra of SW UMa (Fig. 2). These lines are nevertheless far too faint to allow phase-sampling of the 81.2-minute binary orbital period with only 29,000 s of FUSE exposure time. Thus, the observed profiles represent an integration over multiple orbits. As
such, these lines are puzzling in several respects. They are very narrow, with FWHM of 150 km s\(^{-1}\). They exhibit unusual, double-peaked shapes that are slightly asymmetric. And they appear to be redshifted by \(\sim 80\) km s\(^{-1}\) with respect to heliocentric rest. In order to investigate the possible sources of the O\(\text{VI}\) emission in SW UMa, we consider the plausibility of an origin in each of the three main components of this binary system; the primary, the secondary, and the disk/accretion stream.

*The secondary.* The companion star in the SW UMa system is believed to be a very low-mass, late-type (0.1 M\(_{\odot}\), \(B-V = 1.7\)) main-sequence star (SST86). It is almost certainly too faint in the UV to be observable by FUSE. To quantify this, we assume that the companion has \(L_{\text{bol}} \sim 10^{-3} L_\odot\) and is at a distance of \(d = 182\) pc. The observed bolometric luminosity at Earth will thus be \(l_{\text{bol}} = 9.64 \times 10^{-13}\) erg cm\(^{-2}\) s\(^{-1}\). Given that the luminosity in O\(\text{VI}\) should be only a tiny fraction (\(\sim 10^{-5}\)) of the bolometric luminosity, it is extremely unlikely that the secondary contributes to the observed O\(\text{VI}\) lines. Furthermore, the most plausible orbital parameters for the system, when integrated over the orbital period of the system, would yield spectral lines approximately twice as wide as those observed here.

*The disk/accretion stream.* Based on observations of other CVs, it is entirely reasonable to expect that O\(\text{VI}\) emission could originate in the disk, a hotspot in the disk, or even in the accretion stream flowing from the secondary. Disk emission almost certainly dominates the O\(\text{VI}\) line profiles during outburst, as seen in WZ Sge (Long et al. 2003), but to date there have been no FUSE observations of SW UMa during an outburst phase. A very broad C\(\text{IV}\) 1550 Å emission feature dominates the archival IUE SWP quiescent spectra of SW UMa, with a flux \(f_{\text{CIV}} \approx 2 \times 10^{-13}\) erg cm\(^{-2}\) s\(^{-1}\) and a line width of \(\sim 2000\) km s\(^{-1}\) that is comparable to that of the H\(\alpha\) emission line observed by SST86. The H\(\alpha\) profiles show a doubled-peaked shape characteristic of an origin in a rotating Keplerian disk, but this level of detail in the C\(\text{IV}\) profile is not resolved by IUE (in any case, the C\(\text{IV}\) feature is a blend). In contrast, the narrow O\(\text{VI}\) lines observed by FUSE, although exhibiting a double-peaked shape, are only 150 km s\(^{-1}\) wide, a value that is an order of magnitude smaller than the typical Keplerian orbital velocities in the disk. As noted in §3.2, the data do show a faint, broad component to the O\(\text{VI}\) emission at 1032 Å, \(\sim 2000\) km s\(^{-1}\) wide, with an integrated flux of \(f_{\text{broad}} = 2 \times 10^{-14}\) erg cm\(^{-2}\) s\(^{-1}\) ±40%. The large error on this value is primarily due to the presence of the strong airglow lines of O I and Ly\(\beta\) that bracket the broad O\(\text{VI}\) emission (see Fig. 2). While most of the airglow emission can be removed from the spectrum, residual contamination from the line wings still prevents an accurate measurement of the true zero-flux level on either side of the broad O\(\text{VI}\). Nevertheless, the ratio of the broad O\(\text{VI}\) to C\(\text{IV}\) emission is small, with \(f_{\text{broad}}/f_{\text{CIV}} \sim 1/10\). The C\(\text{III}\) emission at 1176 Å is similarly broad and comparably bright, with an integrated flux of \(f_{\text{CIII}} = 2.5 \times 10^{-14}\) erg cm\(^{-2}\) s\(^{-1}\) ±20%. This suggests that the C\(\text{IV}\) and C\(\text{III}\) emission from the disk originates...
in relatively cool, quite likely photoionized gas (Ko et al. 1996; Mauche, Lee, & Kallman 1997).

We have run a similar photoionization model (Raymond 1993) using the X-ray luminosity of SW UMa for an annulus near the outer edge of the disk ($r = 10^{10}$ cm). It predicts $f_{\text{broad}}/f_{\text{CIV}} = 1/40$, in keeping with the small value observed. The C III 977 Å intensity is predicted to be 8 times the O VI intensity, and C III 1176 is predicted to be twice as bright as O VI. While these numbers are consistent with the observed fluxes only at the factor of 2 level, the model code, which was designed for low mass X-ray binaries, is pushing the range of its validity, and the model parameters are uncertain. No general model of UV emission from a magnetically heated disc atmosphere is available, but the solar transition region shows an O VI to C IV ratio of about 1/3 to 1/2, while the ratios of O VI to C III 977 Å and C III 1176 Å are about 2/3 and 3/2, respectively (Woods & Rottman 2002).

The possibility remains that the narrow O VI emission comes from a localized area in the disk or accretion stream. The most likely source of such emission would be the hot spot where the accretion stream joins the outer edge of the disk. We have modeled the line profile by assuming that the emitting source orbits the center-of-mass of the binary system at a velocity typical of the outer edge of the accretion disk, and that the emission is anisotropic, visible to FUSE only during the redshifted phase of the orbit. This can reproduce the observed redshift and line width, but not the double-peaked shape. The anisotropy could potentially arise if the hot spot were obscured by the disk or accretion stream at viewing angles corresponding to the blueshifted orbital phase. There are problems with this interpretation, however. The condition that the emission be visible only during certain convenient orbital phases is arbitrary, and the orbital velocity chosen is poorly constrained. Worse, the observed brightness of the narrow O VI lines is very difficult to explain in terms of a hotspot in a quiescent DN. The interaction of the accretion stream with the disk edge is highly unlikely to produce a shock strong enough to emit O VI at the observed levels. An alternative is that the O VI comes from photoionized gas. But because the narrow and broad components of the O VI emission exhibit similar total fluxes, photoionization would require that the hotspot or small region of the accretion stream emitting the narrow O VI component present a solid angle to the WD comparable to that of the entire accretion disk. This condition seems implausible at best. We thus conclude that while the broad O VI emission comes from the disk, the narrow O VI emission probably originates elsewhere.

The primary. The remaining plausible source of the O VI emission is the white dwarf itself. Chandra X-ray spectra of non-magnetic CVs with low accretion rates and also of the intermediate polar WX Hya are matched reasonably well by models of gas cooling from a temperature around 20 keV (Szkody et al. 2002; Mukai et al. 2003; Perna et al. 2003; Homer
et al. 2004). Barring an implausible termination of the cooling at a temperature above $10^6$ K, such cooling flows must also produce O VI. The cooling flow is essentially identical to the cooling behind a shock front, so an extended version of the shock models of Raymond (1979) can be used to predict the X-ray and UV emission spectrum. A model for a 4250 km s$^{-1}$ shock (peak temperature $T = 20$ keV) with a preshock density of $n = 10^{10}$ cm$^{-3}$, matches the X-ray spectrum of V426 Oph (Homer et al. 2004) and predicts an O VI flux of $2.3 \times 10^8$ erg cm$^{-2}$ s$^{-1}$ out the front of the shock. For a WD of radius $R_{\text{WD}} = 8.9 \times 10^8$ cm at a distance of 182 pc (GK99), this implies a flux at the Earth of $5.7 \times 10^{-16}$ erg cm$^{-2}$ s$^{-1}$ and an accretion rate of $7.0 \times 10^{13}$ g s$^{-1}$. The O VI flux is directly proportional to the preshock density and thus to the accretion rate. The observed flux of $2.7 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ in the narrow O VI component indicates an accretion rate of $3.0 \times 10^{15}$ g s$^{-1}$.

The shock model also predicts that the ratio of the X-ray to the O VI luminosity will be $L_X/L_{\text{OVI}} = 1.7 \times 10^3$ for $T = 20$ keV. SST86 use their EXOSAT Channel Multiplier Array observations of SW UMa to derive soft (0.05–2 keV) X-ray fluxes that range from $3.2 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ for a 0.07 K blackbody model to $5 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ for a 0.21 keV thermal bremsstrahlung source. SW UMa was also marginally (2σ) detected by the the EXOSAT medium energy detector in the range of 2–6 keV, with a limit of $7 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ placed on the flux for a 10 keV thermal bremsstrahlung spectrum. Taken together, the EXOSAT X-ray fluxes, when compared to the FUSE O VI fluxes, suggest that $L_X/L_{\text{OVI}} \sim 300$. If instead we assume a 20 keV bremsstrahlung, as in the V426 Oph model, the X-ray flux is doubled while the flux in O VI remains constant, and the ratio of luminosities becomes $L_X/L_{\text{OVI}} \sim 600$. Rosen et al. (1994) provide a further check on the soft X-ray luminosity of SW UMa. They derive a flux of $2.7 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ in the 0.1–2.5 keV range by fitting a two-component Raymond & Smith (1977) model to a ROSAT spectrum obtained over a period of 25 days beginning 4 days after the cessation of an outburst. Given the inconsistencies between the various models fit to the EXOSAT data by SST86, the unknown attenuation of the observed X-rays by interstellar material, and the indisputable variability of the source, the error on these estimates is undoubtedly large, a factor of 2 or more. Within the boundaries of these uncertainties, however, the O VI emission observed by FUSE appears to be consistent with a cooling flow onto the surface of the WD.

One caveat to this interpretation must be mentioned. SSGH02 give a rotational velocity of $v \sin i = 200 \pm 50$ km s$^{-1}$ for the WD in SW UMa. This value is based on a model atmosphere spectrum that fits several metallic absorption lines in the STIS spectra of SW UMa. The value of 200 km s$^{-1}$ is not very different from the widths of the narrow O VI components, but if of the intrinsic O VI emission line is actually rotationally broadened by 200 km s$^{-1}$, then the emission profile observed by FUSE, as the integration over many orbits, cannot present a two-peaked shape, as explained in §3.4 below. Hence, if both the
If the high rotational velocity for the WD and the double-peaked line shape are correct, then we would expect that the accretion from the cooling flow might not be uniformly distributed over the surface of the WD, but could instead be concentrated at the magnetic poles at intermediate latitudes.

### 3.4. Details of the O VI Emission Line Profiles

The redshifted line centroid and the double-peaked, asymmetric line profiles remain difficult to explain. In the shock model, the gas has slowed to a few km s\(^{-1}\) by the time it reaches the temperature range of \(10^5\) to \(10^6\) K where O VI is formed. However, the cooling flow in the shocked gas becomes violently thermally unstable in this temperature range. This can lead to larger downflow speeds due to lack of pressure support and to random motions at the level of tens of km s\(^{-1}\) (e.g. Innes 1992). This may or may not be able to produce the \(\sim 80\) km s\(^{-1}\) redshift observed in the O VI lines. The instability also affects the predicted emission line fluxes, but probably only by about a factor of 2 when averaged over space and time. In any case, it is unclear how the heliocentric redshift of \(\sim 80\) km s\(^{-1}\) translates into the rest frame of the center-of-mass of the SW UMa system, because the proper motion of the system is not very well constrained.\(^2\) It may be that the redshifts of the narrow O VI lines themselves are indicative of a high proper motion for the system, but we cannot make this claim solely on the basis of two relatively faint lines from a single species of ion in the FUSE spectra.

We have further investigated the double-peaked structure of the O VI lines by refining the CalFUSE extraction procedure. Both O VI lines are observed over small regions on the LiF1a detector with enhanced number density of pixel counts compared to scattered light (or “background” counts). The number density of O VI counts over these regions exhibits a significant peak in the cross-dispersion direction. We can therefore decrease the height of the spectral box used by CalFUSE v2.2.3 to extract the 1-D spectrum. This limits small background contributions in the cross-dispersion direction and further increases the signal-to-noise (S/N) around the O VI emission lines. The procedure is equivalent to limiting the height of the LWRS aperture to screen out scattered light contributions from areas against the sky that are not filled by the point source as its spectrum is focused on the detector. To determine a mean noise level in the emission lines, we construct a histogram of the difference.

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\(^2\)The currently accepted value for the heliocentric radial velocity of SW UMa is \(-20\) km s\(^{-1}\). This value appears to have been taken from the systemic velocity parameter used in fits to the wings of the broad H\(\alpha\) line profiles performed by SST86.
between the extracted spectrum and the same spectrum smoothed by convolution with a gaussian of 0.09 Å HWHM. The resulting flux distribution provides a 1-σ (rms) noise value of $7.6 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$ in LiF1a. Since we observe that the central depths in the smoothed spectrum of the O VI lines exceed $1 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$ with respect to their flux maxima, we conclude that these central depressions are statistically significant. The rms value of the spectral noise is also smaller than the difference between the smoothed peak flux in the red and violet emission component of O VI 1031.9 Å, signaling an asymmetric line profile. Our advanced recalibration procedure of the LiF1a channel yields somewhat smaller noise levels for the central depression of the O VI 1031.9 Å emission line, thereby confirming the double-peaked, asymmetric shape of the line profile.

A double-peaked shape is a signature of emission lines formed in a rotating disk or annulus. In such cases, the separation of the two peaks corresponds to the Keplerian velocity at the outer edge of the disk, while the overall width and shape of the profile are governed by the velocity of the inner edge of the disk and the thermal/turbulent velocities within the emitting material. Although the O VI lines in SW UMa are too narrow, with the peaks too close together, to have their origin in the disk, in general an orbiting/revolving emitting region can produce a similar profile, provided that the integration time spent observing the line exceeds the period of revolution, and that the thermal/turbulent velocities present in the emitting material do not exceed the bulk velocity due to the revolution. We have simulated an emission line profile produced by a gaussian emitter moving in a circular orbit with a radial velocity semiamplitude of $v \sin i = 50$ km s$^{-1}$, the value derived by SST86 for the WD in SW UMa. This model is symmetric, so it cannot reproduce the asymmetry observed in the profiles, and the redshift ($v_{\text{cent}} = 80$ km s$^{-1}$) is forced to match the centroid of the observed lines. The model is scaled so that the simulated line profile has the same integrated flux as the observed line profile, as shown in Fig. 3. We find that this approach reproduces the overall width of the line and the separation of the peaks reasonably well, but overestimates the flux in the line center while underestimating the flux in the line wings.

4. Conclusions

SW UMa has presented a challenge for observers and theorists of DNe alike. It is a faint target and seems to exhibit some unusual characteristics that complicate its classification within the standard CV taxonomy. The observations and analyses presented here represent a first look at SW UMa in the far-UV wavebands covered by FUSE. The most interesting features in the FUSE spectra are the emission lines of O VI at 1031.9 and 1037.6 Å. These lines possess both narrow and broad components.
The broad O VI and C III 1176 Å emission suggest a thin, photoionized layer on the surface of the accretion disk in SW UMa, which is exposed to X-ray radiation from the WD. The upper limits on the H$_2$ emission are consistent with a layer of atomic H immediately below the O VI emitting region that can shield the bulk of the disk, which could consist of cooler, molecular gas. Indeed, the presence of atomic H is a necessary condition to enable the mechanism of layered accretion in DNe (see Menou 2002). Given that H$_2$ has been detected in IR spectroscopy of WZ Sge (Howell, Harrison, & Szkody 2004), a search for H$_2$ emission from SW UMa in the IR could explore the disk structure in more detail.

The measured fluxes of the narrow O VI emission profiles are consistent with formation in a cooling flow onto the surface of the WD and suggest a quiescent accretion rate for the system of $\sim 3 \times 10^{15}$ g s$^{-1}$. The double-peaked nature of the line profiles can be accounted for, at least partially, by the orbital motion and geometry of the WD, but the asymmetries and redshifts in the line profiles remain difficult to explain. We cannot rule out an origin of the narrow O VI in either the hot spot or some other localized area of the disk or accretion stream, but find this interpretation less compelling than that of a cooling flow onto the WD. Either phase-resolved far-UV spectroscopy of SW UMa or a reliable determination of the systemic velocity could help settle these outstanding questions.

It is also a bit puzzling that we do not detect the C III emission line at 977 Å, given the presence of the C III emission around 1176 Å. We searched for evidence of this line in the spectra from the SiC1b and SiC2a channels of FUSE, but found no significant emission at 977 Å in SiC2a and only a weak profile in SiC1b. The latter is due to a known contamination from scattered solar C III 977 Å in that channel. The SiC channels of FUSE are generally more vulnerable to scattered light contamination than are the LiF channels, and the sensitivity in the region of 977 Å, covered only by the SiC channels, is down by a factor of 2 from the sensitivity of the LiF channels in the vicinity of 1032 Å. Hence, the non-detection emission from C III 977 Å and other, weaker resonance lines in the FUSE spectra of SW UMa is a function of the extreme faintness of the source coupled with the variation in detector sensitivity with spectral channel, and does not exclude the possibility of an abundance of other ionic species in the SW UMa system.

The upper limits on the faint, far-UV continuum limit the temperature of the WD during the quiescent phase to less than 15,000 K. This result agrees well with the $T_{\text{eff}} = 14,000$ K of SSGH02 and places a downward constraint upon the estimate of $T_{\text{eff}} = 16,000 \pm 1500$ K derived by GK99 from the IUE spectrum of SW UMa.

It might be worthwhile to attempt a target-of-opportunity FUSE observation of SW UMa during or immediately following a DN eruption of the system. The high-state temperature of the system should yield a far-UV continuum level that would be easily observable.
by FUSE, allowing a measurement of the post-outburst cooling in SW UMa similar to that already carried out for WZ Sge (Long et al. 2003). In addition, such observations would enable a comparison of the O\textsc{vi} profiles during outburst with the quiescent profiles presented here, potentially leading to a more complete description of the physical mechanisms driving the accretion in this system over the course of the outburst cycle.

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Fig. 1.— Effective temperature of the white dwarf from the UV spectrum. The FUSE upper limits on the far-UV continuum in the range of 1060–1180 Å are shown by arrows; these, along with the IUE SWP spectrum of SW UMa for 1250–1500 Å, are compared to model spectra scaled to match the integrated flux from IUE. The models are calculated for a pure hydrogen–helium WD, and their most striking features are the extremely broad Lyα absorption at 1216 Å and sharp drop in flux shortwards of 1100 Å. The model that best agrees with both the FUSE upper limits and the IUE data is for $T_{\text{eff}} = 15,000$ K (solid line). Also shown are models for 14,000 K (dashed line), 16,000 K (dash-dotted line), and 17,000 K (dotted line).
Fig. 2.— Region of the FUSE LiF1a channel containing the O VI 1031.9 and 1037.6 Å emission features. The narrow emission lines exhibit redshifted, asymmetric, double-peaked profiles. The O VI region is surrounded by strong airglow lines of O I and Lyβ. A heavily smoothed spectrum with the airglow lines and the narrow O VI removed has been overplotted (heavy line) to highlight the underlying broad component of the O VI 1031.9 emission; a broad component of O VI 1037.6 is also suggested but is excluded from the analysis because of its extreme faintness and proximity to the O I 1039.2 Å airglow line.
Fig. 3.— Comparison of a simulated line profile based on orbital geometry and dynamics with the narrow component of the O VI 1031.9 Å emission from the FUSE LiF1a data. The broad O VI component has been subtracted from the spectrum. We assume that a gaussian emission line of width $v_{br} = 45$ km s$^{-1}$ (a value which incorporates plausible values for thermal and rotational broadening) originates from a WD in a binary orbit with radial velocity semiamplitude $v \sin i = 50$ km s$^{-1}$. If the line is integrated through at least one orbital period, the result is a double-peaked profile. The simulated profile is scaled to match the observed flux and given a redshift $v_{cent} = 80$ km s$^{-1}$, the velocity of the observed displacement of the line centroid with respect to heliocentric rest.