The Far Ultraviolet Spectrum of Z Cam in Quiescence and Standstill\textsuperscript{1}

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ABSTRACT

We have obtained Far Ultraviolet Spectroscopic Explorer (905–1187Å) spectra of the non-magnetic cataclysmic variable Z Cam during a period of quiescence. The spectrum resembles that of a hot (57,000 K) metal-enriched white dwarf. A high effective temperature is consistent with the expectation that dwarf nova systems that show standstills, as Z Cam does, have higher than normal time-averaged mass accretion rates. It is also consistent with current estimates for the mass and distance to Z Cam. A white dwarf model in which 29\% of the surface has a temperature of 72,000 K and the rest of the surface is at 26,000 K also reproduces the spectral shape and the continuum flux level at the nominal distance and WD mass, and is a somewhat better statistical fit to the data. A second component could be due to a rotating accretion belt, a remnant of an outburst that ended eleven days prior to the \textit{FUSE} observation, or ongoing accretion. We favor the uniform temperature model for Z Cam, largely because
the data do not require anything more complicated. We have compared the quiescent spectrum with an archival spectrum of Z Cam in standstill, obtained with ORFEUS. The standstill spectrum is described well by a disk accreting at 
\[ \dot{M}_{\text{disk}} = 7^{+4}_{-2} \times 10^{16} \text{ g s}^{-1}, \]
where the errors depend on the assumed inclination.

The quiescent spectra cover a full orbital period and are time-resolved to \( \sim 500 \text{ s} \). No variability was observed in the continuum during the observation, but the depth of many of the absorption lines increased between orbital phases 0.65 and 0.81. We attribute this effect to absorption by material associated with the accretion stream, which is easier to understand if the inclination is near the maximum allowed value of 68°.

Subject headings: accretion, accretion disks — binaries:close — novae, cataclysmic variables — stars: individual (Z Cam) — ultraviolet: stars — white dwarfs

1. Introduction

Cataclysmic variables (CVs) are interacting binary systems in which a white dwarf (WD) accretes matter from a low-mass companion. In non-magnetic CVs, the in-falling matter forms a disk around the WD. Dwarf novae (DNe) are disk-accreting CVs that undergo sharp rises in luminosity, during which the optical brightness typically increases by 2 to 5 mag. The outbursts occur when a sudden increase in the gas viscosity (due to a change in the ionization state of the gas) allows matter to flow more rapidly through the disk, causing an increase in the accretion luminosity.

In most DNe, outbursts last for a day to a few weeks. In the subclass of DNe known as U Gem systems, outbursts end with a steady decline to minimum that has a typical timescale of a day. However, in Z Cam systems, the decline from outburst occasionally stalls about 1 mag below the peak. Such ‘standstills’ can last for days to, in a few cases, years. Other non-magnetic CVs (nova-like variables) appear to remain persistently in the outburst state. The Z Cam standstill state is comparable to that of a nova-like variable, i.e. a steady, high state, but somewhat lower in luminosity than the peak of a dwarf nova outburst.

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The difference in outburst behavior between U Gem, Z Cam and nova-like systems is thought to reflect a difference in the rate of mass flow from the secondary ($\dot{M}_2$). In DNe, $\dot{M}_2$ is below the upper stability boundary ($\dot{M}_{\text{crit}}$) for which DN outbursts can occur, whereas in nova-like systems $\dot{M}_2 > \dot{M}_{\text{crit}}$. In Z Cam-type stars $\dot{M}_2$ lies very near, but below $\dot{M}_{\text{crit}}$ most of the time. Standstill phases are triggered when an increase in $\dot{M}_2$ (King & Cannizzo 1998) is accompanied by a decrease in $\dot{M}_{\text{crit}}$ as a response to heating of the outer edge of the accretion disk by the increased mass transfer (Buat-Ménard, Hameury, & Lasota 2001; Stehle, King & Rudge 2001). Thus, $\dot{M}_2$ becomes greater than $\dot{M}_{\text{crit}}$ and the disk assumes a stable high state (like a nova-like variable). It has been difficult to measure mass transfer rates in CVs observationally, and as a result reliable empirical determinations of $\dot{M}_2$ and $\dot{M}_{\text{crit}}$ are lacking. On theoretical grounds, $\dot{M}_{\text{crit}}$ is thought to be about $3 \times 10^{17}$ g s$^{-1}$ when heating of the mass transfer stream is taken into account (Schreiber & Gänsicke 2002).

Z Cam is the brightest (in outburst) and most extensively studied object of its class. It has an orbital period $P_{\text{orb}} = 0.289$ d, which implies that it, like other standstill systems, is above the period gap. (A complete list of system parameters is presented in Table 1.) The difference in the magnitude at outburst maximum ($m_v = 10.4$) and quiescence ($13$) is small for DNe in general, but typical of standstill systems. The standstill $m_v$ averages 11.5 (Oppenheimer, Kenyon & Mattei 1998). Far ultraviolet (FUV) spectra of Z Cam in outburst were obtained with the Hopkins Ultraviolet Telescope (HUT) (Long et al. 1991, 1993; Knigge et al. 1997). The outburst spectrum resembles that of a steady-state accretion disk with a mass accretion rate $\dot{M}_{\text{disk}} = 3 \times 10^{17}$ g s$^{-1}$, modified by resonant scattering by material in a wind (Knigge et al. 1997).

Here, we attempt to complete the picture of Z Cam by describing FUV spectra of Z Cam in the quiescent and standstill states. We utilize spectra of Z Cam in quiescence that we have obtained using Far Ultraviolet Spectroscopic Explorer (FUSE), and a spectrum of Z Cam in standstill obtained with ORFEUS telescope that we retrieved from the MAST archive. Our discussion of the effort to understand the two datasets is organized as follows: In Section 2, we describe the FUSE data reduction and the mean spectrum of Z Cam in quiescence. In Section 3, we attempt to fit the spectrum of Z Cam in quiescence, while in Section 4 we analyze the time variability of the spectral lines. In Section 5, we describe the ORFEUS spectrum of Z Cam in standstill as well as our attempts to model that spectrum. Finally, in Section 6, we evaluate the available spectral models and compare the properties of Z Cam in its different luminosity states.
2. Observations and Qualitative Description of the FUSE Data

FUSE provides a resolving power of $\sim$20,000, in the 905–1187 Å range (Moos et al. 2000; Sahnow et al. 2000). Z Cam was observed with FUSE on 2002 February 9, from 13:19:54 UT to 21:06:12 UT. As indicated in Fig. 1, the observations took place about eleven days after the return to quiescence from a short outburst and five days before the next outburst. The observations were made through the LWRS (30″ × 30″) aperture. The data were obtained in the histogram mode, because Z Cam can (in outburst) exceed the brightness limit for the high-time-resolution mode. A total of 24,436 s of useful data was obtained. This comprised 43 separate exposures, ranging in length from 534 s to 584 s.

The raw data were extracted and calibrated with version 2.2 of the CALFUSE pipeline and version 12 of the CALFUSE calibration files. The spectrum from each FUSE channel was examined separately to ensure that the flux calibration was consistent enough for the spectra to be spliced together. Some data at the edges of each detector segment where the flux calibration is often uncertain were masked out, as was the ‘worm’ feature that is present in the LiF1b channel. The spectra from the SiC1a channel indicated anomalously higher fluxes in the range 1000-1065 Å and so this region was excluded. The remaining data from the four channels were combined to create spectra at 0.1Å binning. Our process for combining the data consists of summing all the data points that fall within a given wavelength bin, weighting each according to the detector pixel sensitivity.

A time-averaged spectrum was created by summing the individual spectra, weighted according to exposure time. This is shown in Fig. 2. The interstellar lines have measured widths of $\sim$0.1 Å (about the expected spectral resolution), indicating that the four channels remained well-aligned over the course of the observation. This is supported by the flux levels of the overlap regions between spectral channels.

The quiescent spectrum has a fairly flat continuum with peak flux lying near 1000 Å, at a flux level of $2.2 \times 10^{-13} \text{erg s}^{-1} \text{cm}^{-2} \text{Å}^{-1}$. The continuum flux falls by only $\sim$ 25% from its peak level before Lyman line blanketing sets in at 912Å. Table 2 lists the spectral lines observed in the FUSE spectrum of Z Cam. The equivalent width (EW) measurements are made from the time-averaged spectrum, except for those lines that are seen to be obscured by airglow in Fig. 2; in this case the measurements are made from a mean spectrum constructed from exposures that were recorded during spacecraft night (as indicated in the image header). The night-time exposures make up about 30% of the total observing time and are relatively free of distortion by airglow lines. Of absorption lines intrinsic to Z Cam, we see the Lyman series up to at least $n = 6$, and a range of metals, including CII–III, NII–IV, OVI, SIII–VI and SiIII–IV. The absorption lines are smooth and are fit well by Gaussian profiles with FWHM of $< 1000 \text{km s}^{-1}$. Some of the absorption lines cut into broad emission profiles.
These include the lower ionization lines of $\text{C}\,\text{III}\,\lambda\,977$ and $\text{C}\,\text{III}\,\lambda\,1176$, $\text{S}\,\text{IV}\,\lambda\lambda\,1062,1073$ and $\text{Si}\,\text{III}\,\lambda\,1108$–$1113$ and the higher ionization $\text{O}\,\text{V}\,\lambda\lambda\,1032,1038$ lines. None of the absorption lines fall to zero flux at the line core: the deepest absorption lines are $\text{O}\,\text{VI}$ and $\text{C}\,\text{III}$, which have absorption minimum flux levels of, respectively, 30 and 40% of the continuum.

A careful inspection of the mean spectrum indicates that the flux below the Lyman limit is not zero, but averages $4 \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$. Judging from earlier FUV observations (Knigge et al. 1997, also Section 5) and given the hydrogen column density ($N_H = 3 \times 10^{19}$ cm$^{-2}$) to Z Cam (Mauche 1995, private communication as quoted by Knigge et al. 1997), we expect to see no flux from Z Cam in this region. Calibration of $\text{FUSE}$ spectra involves a background subtraction step and for histogram data a time-averaged background is used. If the average background during the observation were higher, then the extra background will appear as extra flux after the $\text{FUSE}$ pipeline processing. The background is a combination of scattered light and internal detector background and does not follow the effective area curve of $\text{FUSE}$ for valid photons. As a result, the effect of poor background subtraction is most severe when the effective area is smallest (or at the short wavelength end of the detector).

The scattered-light portion of the background is much higher in the spacecraft daytime. Therefore, we checked the mean spectrum from the full observation against one constructed from night-time only exposures. For the night-time spectrum, the flux below the Lyman limit averages $1 \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$ (one quarter that of the mean spectrum). At wavelengths longer than 915 Å the discrepancy is significantly smaller, with the night-time continuum being on average $\sim 5\%$ less than in the mean spectrum, although in the two spectra the depth of the interstellar Lyman lines differs by about the same amount as the flux level below 915 Å. At the minima of absorption lines intrinsic to Z Cam (excluding those filled in by airglow in the mean spectrum) the day-time flux is, at worst 15% less than the night-time flux level, with the effect being greatest in lines lying below 1000 Å.

Given that the flux offsets are small we are confident that the background subtraction problem does not affect the spectrum significantly at most wavelengths and does not prevent an accurate qualitative assessment of the spectrum. However, in applying spectral model fits (in Section 3) we use only the night-time data. This is primarily because the absence of many of the strong airglow lines that are seen in the mean spectrum allows more data points to be included in the model fits, but also because we are more confident that the flux level of the night-time only data is closer to the true observed flux.
3. Analysis of the Quiescent Continuum

A comparison of model flux levels with the observed fluxes calls for a reliable measurement of the distance to Z Cam. This has been estimated variously at > 190 pc (Berriman, Szkody, & Capps 1985) and < 390 pc (Kiplinger 1980), based on the fraction of infrared and optical luminosity that can be attributed to the secondary star. A recent parallax measurement, combined with proper motions and absolute magnitude constraints, puts the distance somewhat closer at 163$^{+68}_{-38}$ pc (Thorstensen 2003); we shall use this last distance in this paper.

3.1. White Dwarf Model Fits

WD model spectra were generated using TLUSTY and SYNSPEC software (Hubeny 1988; Hubeny et al. 1994; Hubeny & Lanz 1995). The model spectra covered effective temperatures from 13,000 K to 100,000 K and rotation rates of 0 to 1200 km s$^{-1}$. We adopted $N_H = 3.0 \times 10^{19}$ cm$^{-2}$ (Mauche 1995, private communication as quoted by Knigge et al. 1997), E(B-V)=0.0, and log $g$ = 8.5 (strictly log $g$ = 8.6 is expected for a 1$M_\odot$ WD). The parameters of all the model fits are listed in Table 3.

We first fit non-rotating DA models to the mean night-time spectrum, after masking all of spectral lines other than those associated with hydrogen. The models were fit by $\chi^2$ minimization. The best-fit DA model has $T_{WD} = 51,200$ K. As shown in Fig. 7, the model is a reasonably good match to the continuum slope and the peak of the continuum at $\sim$1000 Å. The best-fitting DA model falls below the data from the Lyman limit to about 950 Å; at the limit the model flux lies at about $\sim$ 60% of the observed flux. Varying the interstellar $N_H$ about its modest value has a negligible effect on the appearance of the best-fit model spectrum. Increasing the interstellar reddening from zero to E(B-V) = 0.03 (the upper limit given by Verbunt 1987) increases the best-fit temperature marginally, and also lowers the model peak flux level slightly, to better match the observed level.

Assuming the entire WD is visible, the normalization of a model is a measure of the solid angle of the WD and can be combined with the distance to give the WD radius. For the best-fit DA model we arrive at $R_{WD} = 4.7^{+0.8}_{-0.3} \times 10^8$ cm, where the errors correspond to the upper and lower distance limits. Adopting the WD mass-radius relation of Anderson (1988) and $M_{WD} = 0.99 \pm 0.15 M_\odot$ (Shafter 1983, quoted in Knigge et al. 1997), the expected $R_{WD}$ for Z Cam is $5.8^{+1.1}_{-1.2} \times 10^8$ cm. The value $R_{WD}$ (and hence the mass) determined from the fit is therefore consistent with the value of $R_{WD}$ predicted from Shafter’s mass estimate and the normal WD mass-radius relation.
The DA model spectrum does not fit the higher order Lyman lines particularly well. They are broader and deeper in the model spectrum than the observed lines. Increasing $T_{\text{WD}}$, or decreasing the surface gravity of the model narrows the predicted profiles, but not enough to bring the models and the data into good agreement. Changing these parameters also causes the spectral slope to become steeper, worsening the model fit to the continuum. One possibility is that there is an emission component, possibly from the disk, that contributes to the narrowness of the observed lines. The H$\text{I}$ emission is illustrated most effectively by the difference spectrum in Fig. 7. The emission components around other lines (as noted in Section 2) can also be made out in the difference spectrum, although they appear to be weaker than the H$\text{I}$ emission. We contrast this to the result of Gänsicke et al. (1998), who find that the lack of strong Lyman absorption in the UV spectrum of AM Her in the high state can be explained by irradiation of the WD surface by a hot spot that radiates as a blackbody, without noticeable emission or absorption features.

We next considered WD with metal-enriched photospheres. Solar abundance models were created for a range of temperatures from 13,000 K to 100,000 K and WD rotational velocities from 0 to 1200 km s$^{-1}$. Before fitting the spectrum, the O$\text{VI}$ $\lambda \lambda 1031,1039$, S$\text{VI}$ $\lambda \lambda 933,944$ and N$\text{IV}$ $\lambda 924$ lines were masked out, as WD surface temperatures are not typically high enough to form these high-ionization lines.

The best-fit solar-abundance WD model is shown in Fig. 4. It has $R_{\text{WD}} = 4.4 \times 10^8$ cm, $T_{\text{WD}} = 57,200$ K and $v \sin (i) = 330$ km s$^{-1}$. The peak in the continuum at 1000 Å and the slope of the continuum are a good match to the data. However, like the DA model the solar abundance model underestimates the flux at the long- and short-wavelength ends of the spectrum. The effect is slightly less in the solar abundance case, because the hotter WD does a better job reproducing the short-wavelength emission. As was the case with the DA model fits, the best fit parameters indicate that the WD is at somewhat greater distance than 163 pc and/or has some what greater mass than 0.99 $M_\odot$. However, given the error bars, the various estimates are self-consistent.

The solar abundance WD model does a good job of reproducing some of the stronger absorption lines, e.g. C$\text{III} \lambda 977$, N$\text{II} \lambda 1085$, Si$\text{IV} \lambda \lambda 1122,1128$ and C$\text{III} \lambda 1176$. In the model the N$\text{IV} \lambda 924$, N$\text{III} \lambda 989$, S$\text{III} \lambda 1012-1021$ and S$\text{IV} \lambda \lambda 1062,1073$, S$\text{III} \lambda 1077$ and Si$\text{III} \lambda 1108-1113$ lines are significantly weaker then in the data, whereas the Si$\text{IV} \lambda 1066$ line is much stronger.

In other quiescent CV, two-temperature (2T) WD model fits have been known to give a significant improvement over the single-temperature models (e.g. Long et al. 1993; Gänsicke & Beuermann 1996; Szkody et al. 2002a). In non-magnetic CVs, the second component is attributed to matter arriving onto the surface of the WD from the accretion disk. The
accreted matter is hotter than the WD and travels at the Keplerian rotational velocity, and so the high-temperature, rapidly-rotating gas can form an ‘accretion belt’ on the WD surface (Kippenhahn & Thomas 1978).

To see whether model fits of this type provide a better representation of the spectrum, we fit the data to models consisting of two different temperatures, allowing the normalization and rotational velocity of each to vary independently. The best fit has one component with temperature $T_1$ of 26,300 K covering 71% and a second component with $T_2$ of 71,700 K covering 29% of the surface. Statistically, the more complex model with $\chi^2_\nu$ of 9.4 is better than the single-temperature fit with $\chi^2_\nu$ of 10.1, but qualitatively there is little difference between the fits and neither is “statistically acceptable” in the sense that $\chi^2_\nu$ is still considerably greater than one. Therefore physical arguments will ultimately guide the interpretation.) For the 2T fit, the dominant contribution to the emission is due to the higher temperature component. At 1100 Å, 78% of the flux is from the high temperature component and shortward of 1000 Å essentially all of the flux is from the hot component. The 2T fit does result in a larger radius of $6.0 \times 10^8$ cm for the WD, which is typically the case when 1T and 2T models are compared. A value of $6.0 \times 10^8$ cm (at the nominal distance for Z Cam) is close to the value of $5.8^{+1.1}_{-1.2} \times 10^8$ cm predicted from the estimated mass.

We have performed tests to see how the temperature and contribution of the hot component ($T_2$) varies as a function of the temperature of the low temperature ($T_1$) is adjusted. For $T_1$ between 23,000 and 37,500 K, it is possible to fit a two-component WD model with a radius in the range allowed by the error limits on the WD mass (Table 1). As the temperature of the low-T component increases, the fraction of the surface covered by the hot component also increases. At $T_1 = 23,000$ K, the hot component has $T_2 = 70,000$ K and covers 27% of the surface, whereas at 37,500 K the hot component has $T_2 = 75,000$ K and covers 41% of the surface. Statistically, there is little difference between the goodness of these 2T fits. They all have $\chi^2_\nu$ in the range 9.4 to 9.9.

The values of the rotation velocity $v \sin(i)$ for our best-fit 2T model are 170 and 320 km s$^{-1}$ for the low and high temperature components, respectively. There is no real (positive) evidence that the second component, if it exists, is rotating rapidly, and hence there is no “smoking gun” for a rapidly rotating accretion belt. This is not entirely surprising though, given the fraction of the flux contributed by the high temperature component.

Z Cam was extensively observed with the International Ultraviolet Explorer (IUE) between 1979 and 1991, although only twice during quiescence. The flux level at the long wavelength end of the FUSE spectrum provides an excellent overlap with the short-wavelength end of the Z Cam quiescent IUE spectrum SWP18844 (as presented in Szkody & Mateo 1986) and SWP37155. We rebinned the FUSE spectrum to the 1.7 Å to match the wavelength
spacing of the LOWRES IUE dataset and merged it with SWP18844. We then created model spectra to match the coarser spectra resolution of IUE. At this resolution, there is little sensitivity to $v \sin (i)$ and so all of the models were constructed with $v \sin (i)$ of 300 km s$^{-1}$. A solar abundance model fit to the combined FUSE and IUE spectrum (Fig. 5) has $T_{\text{WD}} = 46,600$ K and $R_{\text{WD}} = 6.0 \times 10^8$ cm. At $\lambda \gtrsim 1500$ Å the model flux level is somewhat lower than is observed and at around 1000 Å the model continuum level lies slightly above that of the observed spectrum. The larger value of $R_{\text{WD}}$ is a direct result of the lower temperature in these fits.

In Fig. 5, we also plot the best 2T WD fit to the combined spectrum. In this case, $T_1$ is 17,600 K and this component covers 97% of the surface, while $T_2$ is 82,000K and covers only 3% of the surface. In terms of flux, the low T component contributes 27% at 1100 Å and 46% at 1500 Å. There is a significant improvement in the statistical quality of the fit from $\chi^2$ of 8.2 to 4.9. The 1T model has difficulties at the short and long wavelength ends of the spectrum; the 2T model (predictably) addresses these difficulties since the high T component provides flux near the Lyman limit while the low T component provides flux at the long wavelength portion of the spectrum. However, $R_{\text{WD}}$ is now larger than desired. If one constrains the normalization to place the system at the nominal distance and radius ranges, tests show that larger $T_1$ and lower $T_2$ are required. As was the case for when only the FUSE data were fitted, there is a locus of values for $T_1$ and $T_2$ that provide qualitatively similar fits to the data.

### 3.2. Accretion Disk Model Fits

Given that Z Cam was observed in the quiescent state, we do not expect that steady-state accretion disk models would provide a good description of the FUSE spectra. Nevertheless, it is important to check that this is not the case. Therefore, we constructed model disk spectra from summed, area-weighted, Doppler-broadened spectra of stellar atmospheres of the appropriate temperature and gravity for each disk annulus. As for the WD models, we adopted $E(B - V) = 0$ and $N_{\text{H}} = 3.0 \times 10^{19}$ cm$^{-2}$. Disk spectra were created for a range of $\dot{M}_{\text{disk}}$ from $10^{14}$ to $10^{19}$ g s$^{-1}$, and normalized to a distance of 163 pc. Since the inclination for Z Cam is not tightly constrained ($57 \pm 11^\circ$), we created model spectra for inclinations of 46°, 57°, and 68°. We then fit the data using the same wavelength intervals as the solar abundance WD fits. Unless otherwise indicated, these fits have one variable $\dot{M}_{\text{disk}}$, since in most cases we did not allow the normalization (or alternatively the distance) to be a free parameter.

Fig. 6 shows the best-fit disk spectrum with $\dot{M}_{\text{disk}} = 9.1 \times 10^{15}$ g s$^{-1}$. This model matches
the slope and level of the continuum between 1050 and 1185Å, but bluewards of Ly β the model flux declines steeply to zero. As expected from a Keplerian disk, the rotational velocities are too high to fit the narrow absorption lines. Since we are not allowing the normalization to vary in these fits, the exact values of \( \dot{M}_{\text{disk}} \) that we derive are dependent both on the distance to Z Cam and on the inclination. The inclination of Z Cam cannot be very much larger than 68° or eclipses would be observed. If we assume this inclination, then we obtain \( \dot{M}_{\text{disk}} \) of \( 1.3 \times 10^{16} \text{ g s}^{-1} \) and a slightly better fit in terms of \( \chi^2_{\nu} \). This apparent improvement in the fit is due to the fact that higher \( \dot{M}_{\text{disk}} \) model has a flatter continuum slope at shorter wavelengths. This said, the fits are considerably worse than both the uniform T and two-T WD models.

Better fits would be obtained if the normalization of the spectra were not fixed. Indeed the best fit to the spectral shape would suggest \( \dot{M}_{\text{disk}} \) of \( 1.8 \times 10^{17} \text{ g s}^{-1} \), a physically implausible value for a quiescent system, and an equally implausible distance of 710 pc.

We also combined an accretion disk component with the WD models. We fit two-component models wherein the first component was a WD with \( \log g = 8.5 \) and the second component was an accretion disk of \( i = 57^\circ \) (the resultant spectrum was essentially unchanged when the disk inclination was varied to 68°). In the combined disk and WD model the WD is at 62,000 K, with \( R_{\text{WD}} = 4.0 \times 10^8 \text{ cm} \) and the disk has \( \dot{M}_{\text{disk}} = 1.7 \times 10^{15} \text{ g s}^{-1} \). The resultant model differs negligibly from the WD model fits (see Fig. 4); \( \chi^2_{\nu} \) is 9.8, slightly worse than produced in the 2T WD fits (9.4). The WD component dominates the model spectrum, while the disk component acts basically only to flatten the continuum slope, by providing a small flux contribution at long-wavelengths. Since in quiescence, one does not necessarily expect the spectrum to mimic that produced by steady state disk models, we also experimented with models in which the disk contribution was assumed to be a power law \( (f_\nu \propto \nu^{-\alpha}) \). These models produce similar fits statistically \( (\chi^2_{\nu} = 8.7) \) to fits using a WD and a steady state disk built from stellar spectra. The power law contributes about 33% of the flux at 1100 Å and has a slope \( \alpha \) of 1.6. The WD contributes the bulk of the flux, and has a temperature of 44,900 K, \( R_{\text{WD}} \) of \( 4.3 \times 10^8 \text{ cm} \), and \( v \sin (i) \) of 210 km s\(^{-1}\).

For completeness, we carried out the same disk model analysis for the combined \textit{IUE} and \textit{FUSE} data. The results are almost identical to that of the \textit{FUSE} data alone. A careful inspection of Fig. 7, where the results are shown, indicates that the main observational disagreement between disk and WD models for Z Cam is in the \textit{FUSE} wavelength range. We note in passing that \( \chi^2_{\nu} \) for the combined WD and disk fit (5.0 for 57°) is better than for simple 1T WD or disk models, and almost identical to that obtained for 2T WD models (4.9). The inferred WD radius for the combined WD and disk model fit suggests a very massive WD, in excess of \( 1.35 M_\odot \) and much greater than estimated by Shafter (1983). One
way to lower the mass would be to allow the distance to be larger. But much more probably, the result is an artifact of our limited knowledge of the spectrum of a quiescent disk, which we, in the absence of any fully-calculated alternative, have represented as that expected from a steady-state optically-thick disk.

### 3.3. The Quiescent Line Emission

It has been suggested that in quiescent CV the accretion disk is truncated at its inner edge, due to irradiation by the white dwarf (e.g. King 1997). If we assume that the emission components seen around some of the absorption lines are formed in a Keplerian disk, and hence are Doppler broadened by the disk rotation, we can estimate the smallest radius at which the emission is formed.

Using the Starlink software **dipso**, we fit the $\text{Si} IV \lambda 1063,1072$, $\text{Si} III \lambda 1108-1113$ and $\text{C} III \lambda 1175$ lines after first normalizing the continuum flux. We fit a Gaussian absorption and emission line to each component of the multiplet (except in the case of $\text{C} III \lambda 1175$, which is fit as a single line). These are shown in Fig. 8. After subtracting the multiplet splitting, the emission components all have widths of about $\sim 4000 \text{ km s}^{-1}$ (FWZI). This translates to a rotational velocity of $2400 \text{ km s}^{-1}$, or a Keplerian disk radius of $2.3 \times 10^9 \text{ cm}$, which is $\sim (1-5) R_{\text{WD}}$ (King 1997, for example, predicts that the quiescent disk truncation radius is $\sim (1-5) R_{\text{WD}}$). This suggests that the emission lines could be formed by material rotating with the quiescent accretion disk.

At present we have only a poor idea of exactly what observational signatures from a cold optically-thin disk would be detectable in the FUV. However, there is substantive evidence that there is an additional component to the quiescent continuum and some attempts have been made to model the structure of this as a coronal layer above the quiescent disk (e.g. Meyer & Meyer-Hofmeister 1994; Liu, Meyer, & Meyer-Hofmeister 1995). There currently exist no quantitative UV spectral models for such a corona, so in order to get some idea of what these properties might be, we constructed TLUSTY models of an optically thin plasma veil, at various temperatures and densities, which were then rotated as a solid body, to mimic the disk rotation. We then took a simple optically thin emission prescription for the emitted flux ($F_\nu = B_\nu(1-e^{-\tau_\nu})$). The optically thin plasma was able to reproduce the relative strengths of the emission components seen around some absorption lines. However, there was some degeneracy between various H column densities, electron densities and temperatures. Hence, we found it impossible to estimate, from these models, a possible physical structure for the corona.
4. Variability on the orbital timescale

The 43 histogram exposures cover just over one orbital period of Z Cam from 0.94 to 0.06, with a phase uncertainty of 0.015 (using the spectroscopic ephemeris of Thorstensen & Ringwald, 1995). The phase coverage is continuous, apart from gaps at phases 0.57–0.63 and 0.81–0.88. We are thus confident that the mean spectrum is representative of the average over the full orbital period, rather than a reflection of some orbital phase-dependent characteristic.

We created a continuum light curve by summing the flux over selected spectral windows. For the light curve we used only data from the LiF1 channel. FUSE is guided on this channel and so it should be less susceptible than the others to channel misalignment. To measure flux variation across the entire LiF1 range, we first excluded regions contaminated by airglow and the worm region (see Section 2) and summed the flux over the ranges 996–1024, 1029–1038, 1046–1081, 1095–1103 and 1170–1185 Å. Continuum flux varied by up to \( \sim 15\% \) either side of the mean. However, given the noted discrepancy between the day and the night-time flux levels (see Section 2), we found no evidence of variability in the continuum flux level in excess of that which could be associated with the periodic transition of the spacecraft from day to night time.

The spectroscopic ephemeris of Thorstensen & Ringwald (1995) is accurate enough to radial-velocity correct each exposure onto the WD rest frame, with errors of about 25 km s\(^{-1}\). The spectra presented in this section are plotted after this correction has been applied. Fig. 9 shows the 1005–1045 Å region plotted in phase bins of 0.1 \( P_{\text{orb}} \). The 1100–1133 Å spectral range encompasses the \( \text{C}\,\text{II}\,\lambda\,1010 \), \( \text{S}\,\text{III}\,\lambda\,1012–1021 \), \( \text{Ly} \beta \) and \( \text{O}\,\text{VI}\,\lambda\,\lambda\,1032,1037 \) lines and gives a good representative sample of the line variability seen across the spectrum.

In the time-averaged spectrum the flux minima of the absorption lines are all centered at between 100 and 200 km s\(^{-1}\) redwards of the transition rest velocity. Throughout the observation there is almost no shift in the position of this feature, except for during phase 0.5 to 0.7 where the entire line profile shifts bluewards by about 100–200 km s\(^{-1}\) (i.e. back to closer agreement with the rest velocity, see Fig. 9). That the mean line profiles are centered redwards of the rest-velocity could well be an artifact of the radial velocity correction. We take the zero-phase ephemeris from the inferior conjunction of red star emission lines, rather than using the \( \text{H}\alpha \) emission line ephemeris, as the latter may be formed in an extended outflow (see Thorstensen & Ringwald 1995). This therefore, does not take into account gravitational redshifting, which is 76 km s\(^{-1}\) if \( M_{\text{WD}} = 0.99 \) (or 108 km s\(^{-1}\) if \( M_{\text{WD}} = 1.14 \)). If the absorption lines are formed on the surface of the WD, then this accounts for a portion of the redshift of the mean line profile centroids.
There is little variability in the strength and width of the absorption lines, except between phases 0.65 and 0.81 (Fig. 10). Then there is a sharp increase in the strength of most of the absorption lines and we clearly see some lines that are barely apparent in the mean spectrum, e.g. \( \text{P} \text{vi} \lambda \lambda 1118,1128 \) and the \( \text{Si} \text{iii} \lambda \lambda 994–997 \) triplet. At the same time there is no sign of an increase or decrease in continuum flux. The FWHM of the lines increases by no more than a few tens of \( \text{km} \, \text{s}^{-1} \). The additional absorption mainly affects the depth of the line absorption. There is no shift bluewards or redwards from the mean line profile.

The increased absorption is seen across the full range of atomic species and ionization stages, for example \( \text{S} \text{iii} \lambda \lambda 1012–1021 \), \( \text{S} \text{iv} \lambda \lambda 1062,1073 \) and \( \text{S} \text{vi} \lambda \lambda 933,944 \). The higher ionization \( \text{S} \text{iv} \) and \( \text{S} \text{vi} \) lines increase in EW by around 30%. On average, the increase in line EW at phase 0.65–0.81 is also \( \sim 30 \)%. The \( \text{Si} \text{ii} \) triplet shows increased absorption by up to 300% in the mean EW of the \( \text{S} \text{iii} \lambda 1013 \) component, but only 40% in the \( \text{S} \text{iii} \lambda 1021 \) component. Some lines, such as \( \text{Si} \text{ii} \lambda 1108–1113 \), show a smaller variation (\( \sim 10 \)%); others, such as \( \text{Si} \text{ii} \lambda 997 \) and \( \text{P} \text{v} \lambda 1118 \), increase their EW by two or three times; and others, such as \( \text{Si} \text{ii} \lambda \lambda 994,995 \), appear only during the period of enhanced absorption. There are a few lines, most notably \( \text{N} \text{iv} \lambda 924 \), \( \text{O} \text{vi} \lambda \lambda 1032,1038 \), and \( \text{C} \text{iii} \lambda \lambda 977,1176 \) that do not increase in EW at phase 0.65–0.81. As the lines that show increased absorption cover a range of excitation energies we can rule out any obvious temperature-dependence. An increase in the absorption line strength could stem either from an increase in the column density of absorbing ions, or from an increase in their covering factor against the continuum background (or a combination of the two). Given that, at the time of the increased absorption, we see no evidence of an accompanying alteration of the ionization balance, it seems most likely that we are seeing a shift of material into the line of sight and/or an increase in the continuum covering fraction of absorbing ions. We are unable to say whether the narrow absorption endures beyond phase 0.81 as there is a gap in the data from phase 0.81 to 0.88. However, when the coverage picks up again at phase 0.88, the additional absorption has disappeared.

5. The FUV spectrum of Z Cam in standstill

Z Cam entered standstill on 1992 September 23. Z Cam was observed with the Berkeley Extreme and Far-UV Spectrometer (BEFS), on board the \textit{ORFEUS} telescope (Hurwitz et al. 1998), on 1993 September 18. A single 1477s spectrum was obtained. The system remained in standstill for a further 100 days, before declining to quiescence (see the lightcurve in Oppenheimer, Kenyon & Mattei 1998). During the standstill the system brightness can fluctuate by about 0.3 mag either side of the average magnitude of 11.5, but the timing of
this observation so far into the standstill assures us that ORFEUS captured Z Cam in a true standstill phase.

We retrieved the BEFS spectrum, pre-calibrated, from the MAST archive. The spectrum covers the range 700–1175Å at a spectral resolution of about 0.2Å in the two longer-wavelength channels of the spectrometer. However, no flux was detected below 912Å, so we have used only data from the longest-wavelength channel (900–1175Å).

In Fig. 11 we have plotted the BEFS and the FUSE spectra together. Despite the order-of-magnitude difference in continuum flux, the two spectral shapes are very similar. The standstill spectrum peaks at \( \sim 1060 \text{Å} \), at \( \sim 2 \times 10^{-12} \text{erg s}^{-1} \text{cm}^{-2} \text{Å}^{-1} \). This is to the red of the peak in the quiescent spectrum (at \( \sim 1000 \text{Å} \)). On the longer-wavelength side of the peak, both have similar continuum slopes. Both spectra show significant flux down to the Lyman limit, although the continuum between 912Å and the peak flux is slightly flatter in the quiescent spectrum than in standstill.

Most of the absorption lines seen in the standstill spectrum as we are also seen in quiescence (see Table 4). In the BEFS spectrum the absorption equivalent widths are generally 30-60\% greater in the higher-ionization lines (e.g. O iv, S iv and S vi) than in the FUSE spectrum, whereas the lower-ionization lines (e.g. S iii) are weaker by a factor of at least 2. Note also the appearance of the P v \( \lambda \lambda 1118,1128 \) lines at standstill (which are only seen at phase 0.65–0.81 in quiescence). This is indicative of a general move upward in the ionization state between quiescence and standstill. The standstill line widths (FWHM) are generally about 100–200 km s\(^{-1}\) narrower than the quiescent lines, with the exception of C iii, N iii and O vi. In standstill, there is no sign of the broad line emission that is seen in quiescence. Nor for that matter are there indications of the wind that is observed in outburst in Z Cam, e.g. P-Cygni-like profiles or even blue-shifted absorption features.

We repeated the model-fitting exercise that was carried out on the quiescent spectrum, beginning with solar abundance WD models (as for Section 3). In order not to bias a comparison to the FUSE data, we excluded the same regions of the spectra as were used for the FUSE analysis. In general, the best-fit values of \( \chi^2 \) were lower for the ORFEUS than the FUSE data, a fact that is directly attributable to the statistical quality of the two datasets.

The best-fit WD model is shown in Fig. 12. The WD model spectrum matches fairly well to the observed continuum, although the model flux peaks at around 1000 Å, bluewards of the observed flux peak at 1060 Å. The best fit has a temperature of 59,700K and \( v \sin (i) \) of 240 km s\(^{-1}\), not very different from that in the FUSE quiescent spectrum. In common with the quiescent WD model fits, the model Lyman lines are broader than the observed. However, the normalization at 163 pc gives \( R_{WD} = 12.5 \times 10^8 \text{cm} \), which would imply an unacceptably
We then fit model accretion disk spectra, as in Section 3.2. We find that the standstill continuum emission is reproduced well by an accretion disk model with $\dot{M}_{\text{disk}} = 6.9 \times 10^{16} \, \text{g s}^{-1}$ at an inclination of $57^\circ$ and $\dot{M}_{\text{disk}} = 1.1 \times 10^{17} \, \text{g s}^{-1}$ at $68^\circ$ (see Fig. 12). The disk models are a good fit to the continuum (the higher-inclination model is slightly better), although they are unable to reproduce the absorption lines. The disk model falls off steeply towards the Lyman limit, whereas the data (and to a certain extent the WD models) level off before dropping steeply to zero.

6. Discussion

6.1. The continuum emission in Quiescence, Standstill and Outburst

In quiescence, we find that the FUV continuum of Z Cam as observed by *FUSE* is qualitatively well-described in terms of emission from a hot metal-enriched WD atmosphere. For log $g=8.5$, the best fit single temperature models has a $T_{\text{WD}}$ of 57,200 K and $R_{\text{WD}}$ of $4.4 \times 10^8 \, (d/163\text{pc}) \, \text{cm}$. The mass of the WD in Z Cam is estimated to be $0.99 \pm 0.15 \, M_{\odot}$, which suggests $R_{\text{WD}}$ of $5.8^{+1.2}_{-1.8} \times 10^8 \, \text{cm}$. Thus the two measurements of $R_{\text{WD}}$ can be reconciled if the distance to Z Cam is $214^{+41}_{-44} \, \text{pc}$, where the errors here are calculated from the uncertainty in the mass. This is slightly larger than, but wholly consistent with the astrometric distance of $163^{+68}_{-38} \, \text{pc}$.

If this interpretation is correct, then the WD in Z Cam is hot when compared to the WDs in other CVs. A recent compilation of reliably determined WD temperatures in CVs by Araujo-Betancor et al. (2005) contains 34 objects (other than Z Cam) ranging in temperature from 9,500 K in the polar EF Eri to 50,000 K in the nova-like variable and SW Sex star DW UMa. A temperature of 57,200 K would make Z Cam the hottest WD in a CV, excepting only V1500 Cyg, which is still cooling from its nova outburst in 1975 and for which there is a crude blackbody temperature estimate of 70,000 to 120,000 K for the WD (Schmidt, Liebert, & Stockman 1995).

Is this reasonable? The surface temperatures of WDs in CVs are thought to be primarily determined by the accretion history of the WD (Sion 1985). This is because although the WDs in CVs emerge from the common envelope phase as very hot WDs, the WDs cool to temperatures of 4,500-6000 K in the 3-4 Gyr required to reach the mass-exchanging stage. Accretion reheats the surface layers of the WD on the time scales of outbursts (weeks), as is evidenced from observations of temperature changes in WDs in CVs such as U Gem (Long et al. 1993) and VW Hyi (Gänsicke & Beuermann 1996). More importantly, accretion reheats
the entire WD over longer time scales \((10^8 \text{ years})\), as the envelope and core adjust to the increase in mass of the WD, an effect known as compressional heating, and through nuclear burning of the accreted material (Sion 1995; Townsley & Bildsten 2002). Recently, Townsley & Bildsten (2003) have determined the relationship between time-averaged accretion rate and WD temperature. For a temperature of 57,000 K, the required rate is \(\sim 10^{18} \text{ g s}^{-1}\) (with uncertainties of perhaps a factor of two). (A somewhat lower value of \(4 \times 10^{17} \text{ g s}^{-1}\) is obtained for 45,000 K, the temperature derived from the combined \(FUSE + IUE\) spectrum.) Thus the accretion rate required is high, although it may be consistent with the fact that Z Cam is commonly in (or near) the high state. Indeed, of the four systems with WD temperatures greater than 40,000 K, MV Lyr, TT Ari, RU Peg, and DW UMa, all but RU Peg are nova-like variables and hence, like Z Cam, are systems where there are other indications of high time-averaged accretion rates. Given this, we believe a temperature of 57,000 K is reasonable.

An alternative interpretation of the \(FUSE\) quiescent spectrum is that the surface temperature of the WD in Z Cam is not uniform. Our analysis shows that a somewhat better, but still not statistically acceptable fit to the \(FUSE\) data can be obtained if 2T models are considered. Our best fit had a low temperature component with \(T_1\) of 26,300 K covering 71% of the surface and a high temperature component with \(T_2\) of 71,700 K covering 29%. If the low temperature component represents energy loss from the interior of the WD while the high temperature component is due to recent or ongoing accretion, then 94% of the luminosity of the WD is due to recent accretion. Is this reasonable?

If the excess emission is due to ongoing accretion, then the observed luminosity is \(f GM_{\text{WD}} \dot{M}/R_{\text{WD}}\), where \(f\) is the fraction of gravitational energy available that is radiated. For the best 2T parameters, the excess luminosity is \(1.9 \times 10^{33} \text{ erg s}^{-1}\), and the implied value of \(\dot{M}\) is \(8.3 \times 10^{15} \text{ g s}^{-1}/f\). This is a fairly large value for a disk in quiescence, especially since \(f \leq 0.5\), but is hard to rule out because of our lack of good models for emission from quiescent disks and the brightness of the WD itself.

On the other hand, the accretion belt hypothesis is that some of the kinetic energy of material that reaches the boundary layer between the disk and WD is stored in a rapidly rotating belt and released slowly during the interoutburst period. In standard accretion disk theory, half of the gravitational energy of material accreted by the WD is radiated by the disk and half remains as kinetic energy when it enters the boundary layer. For Z Cam, with a disk accretion rate of \(3 \times 10^{17} \text{ g s}^{-1}\), the disk luminosity is \(1.8 \times 10^{34} \text{ erg s}^{-1}\). For the outburst that preceded the \(FUSE\) observation, Z Cam remained within 1 mag. of outburst maximum for about 4 days (see Fig. 1), and hence the total energy release was about \(2.4 \times 10^{40} \text{ ergs}\). The \(FUSE\) observation occurred about 11 days from the return to quiescence and, as noted
previously, the belt luminosity in the context of this hypothesis was still $1.9 \times 10^{33}$ erg s$^{-1}$. We do not have the coverage to determine the time decay of the second component, but a conservative lower limit is obtained by assuming constant luminosity until the observation and zero from then on. By this argument the energy stored in the rotating layer was at least $1.8 \times 10^{39}$ ergs, or 8% of the energy of the outburst. If one assumes an exponential decay, then the energy release is $L(t)e^{(t/\tau)}\tau$, where $t$ is the time from outburst, $L(t)$ the luminosity at the time of our observation, and $\tau$ the decay time constant. If $\tau$ was 11 days, then the total energy released would be $2.7\times$ greater, or 20% of the total outburst energy. In either case, the energy that must be stored in the belt is large, though not energetically disallowed.

If the hot component is produced by short-term effects of accretion, then the low T component reflects the long-term average of accretion. For a temperature of 26,300, this requires an accretion rate of $1.2 \times 10^{17}$ g s$^{-1}$. This is lower than the number inferred from 1T fits, but still substantial.

So how does one decide between the two models we have explored for Z Cam in quiescence? The data are not definitive. The model parameters that result from both models are substantially in agreement with other known parameters of the system. $\chi^2_\nu$ is somewhat better for the 2T model than the uniform temperature model. But $\chi^2_\nu$ is much greater than 1 per degree of freedom in the 2T model, showing that it is at best a step toward a correct model of Z Cam in quiescence, and the systematic errors in the FUSE spectrum are difficult to quantify. The differences in the two model spectra are quite small; there is no characteristic of the spectrum that one can point to that requires a second component. Evidence that $v\sin(i)$ for the high temperature component is high compared to the low T component is lacking. In U Gem (Long et al. 1993; Froning et al. 2001), single temperature models lead to a physically implausible result, namely that the WD grows in radius during quiescence. Since we do not have multiple observations of Z Cam through a quiescent period, we do not know whether single T models lead to a similar problem in Z Cam. There are other well-observed systems, e.g. VW Hyi (Gänsicke & Beuermann 1996) and WZ Sge (Long, Sion, Gänsicke, & Szkody 2004), which do not exhibit “radius growth” in the context of one temperature models, and so one cannot use that as a guide. There is also no consensus theoretically. While Meyer & Meyer-Hofmeister (1994) have argued that mass transfer from the disk is higher immediately after outburst in order to explain UV delays in DNe, the expected X-ray evidence of a gradual decline in hard X-ray emission following outbursts is lacking. Furthermore the X-ray data that exist indicates that the X-ray plasma that exists in quiescence is not rotating rapidly (Szkody et al. 2002b; Mauche et al. 2004), and therefore it is hard to understand how it could produce a heated annular region around the surface. While Kippenhahn & Thomas (1978) postulated the existence of accretion belts and described an instability that might release energy in an accretion belt, there are to our knowledge no detailed calculations of
expected properties of the emitting region and no attempt to calculate the luminosity of the rotating component with time. Given these considerations, our answer to the question of which model is most likely correct is to appeal to Occam’s Razor and assert that the simpler 1T model provide a good physical description of the data and is therefore is the best-bet physical model to pursue.

In outburst, Knigge et al. (1997) showed that the shape of the FUV (900–1800 Å) continuum of Z Cam could be modeled as an accretion disk with \( \dot{M}_{\text{disk}} \approx 3 \times 10^{17} \text{ g s}^{-1} \) at an inclination of 57° and distance of 170 pc (very close to the best astrometric distance of 163 pc). In the high state, the fits are self-consistent. In standstill we find \( \dot{M}_{\text{disk}} \approx 7^{+3}_{-2} \times 10^{16} \text{ g s}^{-1} \). Approximately, then, there appears to be at least an order of magnitude increase in \( \dot{M} \) from quiescence to standstill, while \( \dot{M}_{\text{outburst}} \) is an order of magnitude higher still. Our derived \( \dot{M}_{\text{standstill}} \) gives an upper limit on \( \dot{M}_{\text{crit}} \), as it is a reasonable assumption that \( \dot{M}_{\text{standstill}} \) is also the rate of mass flow from the secondary at that time, which must be greater than \( \dot{M}_{\text{crit}} \). Buat-Ménard, Hameury, & Lasota (2001) calculate \( \dot{M}_{\text{crit}} = 3 \times 10^{17} \text{ g s}^{-1} \), using the formula of Hameury et al. (1998) and taking into account heating by the stream–disk impact (or \( 2 \times 10^{17} \text{ g s}^{-1} \) if tidal dissipation is also included). Our upper limit of \( \dot{M}_{\text{crit}} \lesssim 2 \times 10^{17} \text{ g s}^{-1} \) is just consistent with this and with the upper limit of \( \dot{M}_{\text{crit}} \lesssim 3.2 \times 10^{17} \text{ g s}^{-1} \) derived by Baraffe & Kolb (2000).

The comparison of the BEFS standstill spectrum and the FUSE spectrum of Z Cam in quiescence illustrates the problem of separating a WD spectrum from that of a disk. Except for the flux level the qualitative differences between the BEFS spectrum and the FUSE spectrum are relatively small. In both states, the continuum slope is almost the same and, other than a slight increase in ionization temperature, their line spectra are very similar. Yet, we find that in quiescence a WD alone can make up the continuum flux, whereas in standstill an accretion disk is the best model for the continuum flux. Ultimately, the key model parameter that has enabled us to fit one model and reject others is the normalization required to match the observed and the modeled flux levels, which in turn depends on the WD mass and the distance from the sun. Without a reasonably accurate knowledge of these parameters it would be impossible to judge between a wide range of models that reproduce the continuum slope and line spectrum equally well.

6.2. Phase-dependent variability of the spectral lines

In the time-resolved spectra of Z Cam in quiescence, we have seen enhanced line absorption between phase 0.65 and 0.81, which covers the full range of atomic species and excitation levels. The enhanced absorption is very well centered on the mean line profile, which, in
turn, is centered 100–200 km s$^{-1}$ to the red of the transition rest velocity. The change in absorption width is greatest in those lines that are weak or absent from the mean spectrum, but also encompasses lines which are thought to be optically thick in the mean spectrum, leaving only the N$\text{ iv} \lambda 924$, O$\text{ vi} \lambda \lambda 1032,1038$ and C$\text{ iii} \lambda 977$ and 1176 lines unchanged.

Flux variations at around phase 0.5–0.8 are seen in a selection of disk-accreting systems, in phenomena such as dips in the UV (Mason, Drew, & Knigge 1997) and X-ray (Hellier, Garlick, & Mason 1993) light curve of low-mass X-ray binaries and CV, and humps in the optical light curves of CV (e.g. Wood et al. 1989). This is typically attributed the interaction of the accretion stream from the secondary with the outer edge of the accretion disk. This can result in a luminous ‘bright spot’ at the outer edge of the disk, which is thought to be responsible for the optical light curve modulation. Also, the shock of the in-falling stream can cause the disk to bulge outwards at smaller radii or cause the stream to be deflected upward and arc over the surface of the accretion disk (e.g. Armitage & Livio 1998). This can cause phase dependent absorption as colder material in the accretion stream moves in front of the continuum source.

The additional absorption seen in Z Cam is qualitatively compatible with some sort of stream-disk interaction. The enhanced absorption is narrow and centered on the mean line profile, indicative of matter that is moving across, rather than parallel to the line of sight. There is no corresponding change in the ionization state and the increase in absorption affects those transitions that appear to be optically thick in the mean spectrum. This is consistent with a disk bulge or stream temporarily moving to occult a larger area of the continuum source, or to place a greater column density of absorbing ions into the line of sight. Also, the 0.65–0.81 phasing is in the phase range that stream-overflow effects are thought to be seen. In these respects Z Cam compares well with the FUSE spectrum of U Gem in outburst (Froning et al. 2001), which was observed to show strong enhanced absorption at phase 0.53 to 0.79. The line variability in U Gem is of a similar strength to that seen in Z Cam, i.e. residual line core flux reducing to as little as 40% of its mean value in some lines, with the O$\text{ vi}$ lines being the least affected, although the N$\text{ iv} \lambda 924$, C$\text{ iii} \lambda 1176$ and other weak lines participate in the variation in U Gem.

Smooth particle hydrodynamical models of the disk-stream interaction are now being produced (e.g. Armitage & Livio 1996, 1998; Kunze, Speith, & Hessman 2001). These models make predictions of the observational qualities which we are now able to set against the evidence for stream-related variability seen in the spectrum of Z Cam. The models are generally in agreement that stream overflow can occur at low mass-accretion rates, i.e. quiescent disks. Armitage & Livio (1998) predict that efficient cooling of the hot-spot region can occur in systems with low mass-accretion rates ($\dot{M} \lesssim 10^{-9} M_\odot \, yr^{-1}$, or $\lesssim 10^{16} \, g \, s^{-1}$), allowing
material to overflow the inner disk in a coherent stream, whereas, in higher-$\dot{M}$ systems the stream impact region tends to push the disk into a bulging shape. Using a different method, Hessman (1999) concurs with Armitage & Livio that up to $\sim 10\%$ of the matter in the accretion stream from the secondary is able to overflow the disk.

If the phase-dependent absorption is a result of stream-overflow, it may have implications for the estimated inclination of the system. Logically, for absorption by the stream, the absorption strength should have a strong correlation with inclination angle. At higher inclinations, material above the disk plane presents a higher column density to the bright continuum regions, i.e. the WD and inner disk. Kunze, Speith, & Hessman (2001) estimate that in outburst, enhanced absorption can be seen in systems of inclinations down to $65^\circ$, based on the maximum scale height above the disk attained by material in the accretion stream. However, they predict that, at low $\dot{M}$, material is not as strongly deflected upward as for high $\dot{M}$ and that an inclination angle of at least $75^\circ$ is needed before the overflowing stream can cause accretion dips. At an inclination of only $57 \pm 11^\circ$ (as taken from Shafter 1983), Z Cam would fall below this lower limit. Furthermore, an inclination above the current upper limit of $68^\circ$ for Z Cam would produce observable eclipses and therefore can be ruled out. However, given the similarity of the time-dependent absorption to that seen in U Gem ($i = 67 \pm 3^\circ$), an inclination angle near $68^\circ$ seems far more plausible than the opposite extreme of $48^\circ$.

7. Conclusions

We have obtained observations with the FUSE satellite of the dwarf nova, Z Cam, during a period of quiescence. The spectrum is characterized by a fairly flat continuum, with a peak in the flux at 1000Å. The line spectrum covers a broad range of atomic species and ionization stages and is dominated by absorption lines of FWHM $< 1000 \text{ km s}^{-1}$. Qualitatively, the spectrum can be self-consistently described in terms of emission from the WD with a temperature of 57,000 K. Modest improvements in the fits are obtained with 2T models in which most of the emission comes from a small fraction (29%) of the surface heated to 71,700 K. The remainder is at 26,300 K. We favor the uniform temperature model for Z Cam, largely because the data do not require anything more complicated. There are emission lines (e.g. $\text{C}III \lambda 1176$) that do not come from the WD. The widths of these lines are consistent with a disk origin.

In the phase-resolved quiescent spectrum we have observed transient enhanced line absorption. From the 0.65–0.81 phasing of this absorption and its effect on a wide range of ionization species, we attribute it to material raised from the disk plane into the LOS, due
to interaction of the accretion stream with the disk, or the stream itself moving over the
disk. Such effects may be easier to understand if inclination of Z Cam is close to the upper
limit of 68°.

The standstill continuum is best described by an optically-thick disk accreting at a rate
of $7^{+4}_{-2} \times 10^{16}$ g s$^{-1}$, depending on the actual inclination of Z Cam. The continuum slope
and the line absorption spectra differ little between quiescence and standstill, despite that,
during standstill, an accretion disk creates (most of) the continuum flux. The qualitative
similarity of the two spectra highlights the difficulty of separating WD from disk signatures
without detailed model fitting and, also, underlines the reliance of the model fits on an secure
knowledge of the distance and the WD mass.

The high temperature of the WD in Z Cam and the estimates of mass accretion rate in
standstill and outburst are all consistent with a mass transfer rate from the secondary star
that is higher than in normal DNe. Additional FUV observations of Z Cam in the period
following a normal outburst are highly desirable both to better understand the physics of
standstill systems and to cleanly distinguish between single and multi-temperature models
of the WD in Z Cam.

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Fig. 1.— V-magnitude light curve of Z Cam from 2001 December 16 to 2002 March 6 (AAVSO, Mattei J. A., 2002, Observations from the AAVSO international database, private communication). The date of our FUSE observation (February 9 2002, MJD 52314.25) is marked with a vertical line.

Fig. 2.— Mean FUSE spectrum of Z Cam created from the exposure time-weighted mean of all 43 exposures.

Fig. 3.— DA WD model fit to the night-only mean quiescent spectrum of Z Cam. The upper panel plots the observed spectrum and best-fit model (in red); the lower panel plots the residual spectrum after the model has been subtracted and $1\sigma$ errors in the observed spectra (in blue). Only metal-line free portions of the spectrum were included in the DA model fits, the excluded regions plotted in grey. Model parameters are given in Table 3.

Fig. 4.— Solar abundance model WD fits to the mean FUSE spectrum of Z Cam. In the upper panel the solid (red) line plots the best statistical-fit single temperature model and the dashed (blue) line plots our two-temperature model. The lower panel plots the difference spectrum of the observed and single-temperature model flux, with (1-$\sigma$) errors in blue. The grey portions of the plotted spectrum were not considered in fitting the data. Model parameters are given in Table 3.

Fig. 5.— Solar abundance WD model fits to the merged FUSE and IUE spectra of Z Cam. In the upper panel the solid line plots the best statistical-fit single temperature model and the dashed (blue) line plots our two-temperature model. The lower panel plots the difference spectrum of the observed and single-temperature model flux, with errors in blue. The grey portions of the spectrum that have been masked out from the fits. Model parameters are given in Table 3.

Fig. 6.— The best-fit accretion disk models compared to the quiescent spectrum of Z Cam. The solid (red) line indicates the 57$^\circ$ model and the long-dashed (blue) line indicates the 68$^\circ$ model with the distance fixed at 163 pc. The dashed (black) line is the best fit when the normalization (or equivalently the distance) is a free parameter. Model parameters are given in Table 3.

Fig. 7.— Disk fits to the merged FUSE and IUE spectra of Z-Cam. The solid (red) curve is the best fit when the distance is constrained to be 163 pc and the inclination is 57$^\circ$. The long-dashed (blue) curve is similar but for an inclination of 68$^\circ$. The dashed (black) curve is the best fit when the normalization (or equivalently the distance) is a free parameter. As previously, the lower panel is difference between the best 57$^\circ$ model and the data.
Fig. 8.— Line profile fits to the \( \text{Si}^{\text{IV}} \lambda\lambda 1063,1072, \text{Si}^{\text{III}} \lambda 1108–1113 \) and \( \text{C}^{\text{III}} \lambda 1175 \) lines, after the continuum has been normalized. The lines are fit using Gaussian emission and absorption line profiles using the DIPSO software. When the multiple components of a line, e.g. \( \text{Si}^{\text{IV}} \lambda 1063 \) and \( \text{Si}^{\text{IV}} \lambda 1072 \) can be separated, one Gaussian absorption and one Gaussian emission profile has been used for each component.

Fig. 9.— A phase-resolved segment of Z Cam FUV spectrum showing in the range 1005–1045Å. The main features are due \( \text{C}^{\text{III}} \lambda 1010, \text{Si}^{\text{III}} \lambda 1012–1021, \text{Ly} \beta \) and \( \text{O}^{\text{VI}} \lambda\lambda 1032,1037 \) lines. The phased spectra are created by summing those exposures which, all or mostly, fall inside the given phase range. The grey line is the time-averaged spectrum from all 43 radial-velocity corrected exposures.

Fig. 10.— Selected regions of the Z Cam spectra, showing the mean spectrum between phases 0.65 and 0.81, over-plotted on the mean spectrum from the full observation (gray line). The spectra are summed from the individual exposures, after they have been radial velocity corrected according to the ephemeris of Thorstensen & Ringwald (1995).

Fig. 11.— Time-averaged spectrum of Z Cam in standstill as observed by the BEFS on-board the ORFEUS satellite, plotted with the quiescent \textit{FUSE} spectrum (from those exposures recorded mostly during spacecraft night). The flux scale is \( 10^{-13} \text{erg s}^{-1} \text{cm}^{-2} \text{Å}^{-1} \) for the \textit{FUSE} spectrum and \( 10^{-12} \text{erg s}^{-1} \text{cm}^{-2} \text{Å}^{-1} \) for the BEFS spectrum, the latter is also offset upward by \( 2 \times 10^{-12} \text{erg s}^{-1} \text{cm}^{-2} \text{Å}^{-1} \), so that the standstill spectrum lies above the quiescent spectrum. In the lower panel is plotted the ratio of the standstill flux to the quiescent flux.

Fig. 12.— Solar abundance WD model fits to the BEFS spectrum of Z Cam in standstill. In the upper panel, the solid (red) line plots the best-fit model. Model parameters are given in Table 3.

Fig. 13.— Disk model fits to the BEFS spectrum of Z Cam in standstill. In the upper panel, the solid (red) line plots the best fit accretion disk model spectrum at 57° and the long-dashed (blue) lines plots our best disk model at 68°. The dashed (black) line is the best fit when the normalization is not constrained. Model parameters are given in Table 3.
Table 1. Adopted system parameters for Z Cam.

| Parameter     | Value                | Reference |
|---------------|----------------------|-----------|
| $P_{\text{orb}}$ (d) | 0.2898406(2)          | 1         |
| $K_1$ (km s$^{-1}$) | 135 ± 9               | 1         |
| $i$ (°)       | 57 ± 11               | 2         |
| $M_1$ ($M_\odot$) | 0.99 ± 0.15           | 2         |
| $M_2/M_1$     | 0.71 ± 0.10           | 2         |
| $d$ (pc)      | 163$^{+68}_{-38}$     | 3         |

References. — (1) Thorstensen & Ringwald 1995 (2) Shafter 1983 (3) Thorstensen 2003
Table 2. Spectral lines identified in the *FUSE* spectrum of Z Cam in quiescence.

| Ion        | $\lambda_{lab}$ (Å) | EW (Å) | FWHM (km s$^{-1}$) |
|------------|---------------------|--------|-------------------|
| N iv* + H i... | 922–924; 923.2 | 2.02±0.10 | 1030±65           |
| H i...     | 930.748             | 0.6±0.1  | 570±75            |
| S vi...    | 933.4               | 0.79±0.06 | 565±30            |
| H i...     | 937.8               | 1.1±0.1  | 545±45            |
| S vi...    | 944.5               | 0.82±0.06 | 470±20            |
| H i+ P iv... | 949.7; 950.7 | 1.80±0.1  | 900±60            |
| H i...     | 972.5               | 1.09±0.08 | 600±50            |
| C iii...   | 977.0               | 1.14±0.06 | 590±40            |
| He ii* + N iii... | 989.8; 992.3 | 2.88±0.09 | 1150±40           |
| Si iii*... | 997.4               | 0.17±0.02 | 300±20            |
| C ii*...   | 1010.0              | 0.20±0.04 | 420±90            |
| S iii...   | 1012.5              | 0.09±0.02 | 240±60            |
| S iii...   | 1015.5              | 0.40±0.02 | 410±30            |
| S iii...   | 1021.1              | 0.56±0.03 | 500±30            |
| Ly $\beta$... | 1025.7       | 1.0±0.2  | 470±90            |
| O vi...    | 1031.9              | 1.57±0.03 | 610±20            |
| O vi...    | 1037.6              | 1.88±0.03 | 700±20            |
| S iv...    | 1062.7              | 0.75±0.07 | 480±30            |
| S iv...    | 1073.0              | 0.73±0.05 | 480±30            |
| S iii*...  | 1077.2              | 0.11±0.02 | 280±61            |
| He ii* + N ii... | 1084.9; 1085.0 | 1.9±0.2  | 1020±80           |
| Si iii*... | 1108.4; 1110.0     | 1.65±0.03 | 890±20            |
| Si iii*... | 1113.2              | 0.98±0.02 | 500±20            |
| P v...     | 1118.0              | < 0.1    | < 500             |
| Si iv*...  | 1122.5              | 0.6±0.1  | 730±50            |
| P v+ Si iv*... | 1128.0; 1128.3 | 0.8±0.1  | 850±80            |
| C iii*...  | 1175.3              | 3.28±0.06 | 940±30            |
Table 3. Model Fits to Z Cam in quiescence and standstill

| Model type | $R_{\text{WD}}$($10^8$ cm) | $T_{\text{WD}}$ (K) | $v \sin(i)$ (km s$^{-1}$) | $\dot{M}_{\text{disk}}$($10^{15}$ g s$^{-1}$) | D$^a$ (pc) | $\chi^2_{\nu}$ | N |
|------------|------------------|-----------------|-----------------|------------------|----------|----------------|---|
| **QUIESCENTE (FUSE)** | | | | | | | |
| DA         | 4.3              | 58,100          | -               | -                | 163      | 6.7            | 672 |
| WD         | 4.4              | 57,200          | 330             | -                | 163      | 10.1           | 1146|
| 2WD        | 6.0 (71%/29%)    | 26,300/71,700   | 170/370         | -                | 163      | 9.4            | 1146|
| Disk (46°) | -                | -               | -               | 6.6              | 163      | 32.1           | 1146|
| Disk (57°) | -                | -               | -               | 9.1              | 163      | 27.1           | 1146|
| Disk (68°) | -                | -               | -               | 12.9             | 163      | 22.0           | 1146|
| Disk (57°) | -                | -               | -               | 180.0            | 710      | 11.9           | 1146|
| Disk (46°) & WD | 4.0       | 62,000          | 306             | 1.2              | 163      | 9.8            | 1146|
| Disk (57°) & WD | 4.0       | 62,000          | 295             | 1.7              | 163      | 9.8            | 1146|
| Disk (68°) & WD | 3.9       | 62,000          | 293             | 2.5              | 163      | 9.8            | 1146|
| **QUIESCENTE (FUSE & IUE)** | | | | | | | |
| WD         | 6.0              | 44,600          | -               | -                | 163      | 8.2            | 471 |
| 2WD        | 18.4 (97%/3%)    | 17,600/82,400   | -               | -                | 163      | 4.9            | 471 |
| Disk (46°) | -                | -               | -               | 6.0              | 163      | 11.1           | 471 |
| Disk (57°) | -                | -               | -               | 8.7              | 163      | 9.6            | 471 |
| Disk (68°) | -                | -               | -               | 12.9             | 163      | 8.1            | 471 |
| Disk (57°) | -                | -               | -               | 182.0            | 710      | 5.8            | 471 |
| Disk (46°) & WD | 3.0       | 82,000          | -               | 3.0              | 163      | 4.7            | 471 |
| Disk (57°) & WD | 3.0       | 81,000          | -               | 4.0              | 163      | 5.0            | 471 |
| Disk (68°) & WD | 3.0       | 81,000          | -               | 6.3              | 163      | 5.4            | 471 |
| **STANDSTILL (ORFEUS)** | | | | | | | |
| WD         | 12.5             | 59,700          | 240             | -                | 163      | 2.6            | 1505|
| Disk (46°) | -                | -               | -               | 43.0             | 163      | 2.7            | 1505|
| Disk (57°) | -                | -               | -               | 69.0             | 163      | 2.6            | 1505|
| Disk (68°) | -                | -               | -               | 112.0            | 163      | 2.5            | 1505|
| Disk (57°) | -                | -               | -               | 195.0            | 270      | 2.4            | 1505|

$^a$A value of 163 pc implies the distance was fixed at this value.
Table 4. Spectral lines identified in the BEFS spectrum of Z Cam in standstill.

| Ion              | $\lambda_{\text{lab}}$ (Å) | EW (Å)     | FWHM (km s$^{-1}$) |
|------------------|----------------------------|------------|---------------------|
| H i...           | 930.748                    | 0.68 ± 0.09| 220 ± 30            |
| S vi...          | 933.4                      | 1.20 ± 0.19| 460 ± 100           |
| H i...           | 937.8                      | 0.81 ± 0.13| 590 ± 120           |
| S vi...          | 944.5                      | 1.35 ± 0.11| 750 ± 130           |
| H i + P vi...    | 949.7                      | 1.68 ± 0.12| 730 ± 60            |
| H i...           | 972.5                      | 1.12 ± 0.07| 490 ± 40            |
| C iii...         | 977.0                      | 1.84 ± 0.08| 760 ± 40            |
| N iii + Si iii* | 989.8; 993.5               | 2.13 ± 0.10| 1380 ± 100          |
| Si iii*...       | 994.8                      | < 0.2      | < 300               |
| Si iii*...       | 997.4                      | 0.24 ± 0.03| 310 ± 50            |
| S iii...         | 1012.5                     | < 0.1      | < 300               |
| S iii...         | 1015.5                     | < 0.1      | < 300               |
| S iii...         | 1021.1                     | 0.22 ± 0.04| 320 ± 70            |
| Ly $\beta$...   | 1025.7                     | 0.76 ± 0.07| 320 ± 40            |
| O vi...          | 1031.9                     | 2.07 ± 0.09| 1000 ± 50           |
| O vi...          | 1037.6                     | 2.40 ± 0.10| 745 ± 40            |
| S iv...          | 1062.7                     | 0.98 ± 0.45| 700 ± 40            |
| S iv...          | 1073.0                     | 0.94 ± 0.45| 460 ± 30            |
| He ii* + N ii... | 1084.9; 1085.0             | 0.58 ± 0.08| 1110 ± 150          |
| Si iii*...       | 1108.4; 1110.0             | 0.50 ± 0.04| 420 ± 40            |
| Si iii*...       | 1113.2                     | 0.56 ± 0.06| 380 ± 60            |
| P v...           | 1118.0                     | 0.92 ± 0.05| 580 ± 40            |
| Si iv*...        | 1122.5                     | 0.53 ± 0.07| 660 ± 90            |
| P v + Si iv*...  | 1128.0; 1128.3             | 0.76 ± 0.07| 740 ± 70            |
