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SPECTROSCOPY OF Z CAMELOPARDALIS IN OUTBURST WITH THE HOPKINS ULTRAVIOLET TELESCOPE

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ABSTRACT

The Hopkins Ultraviolet Telescope on board the Astro-1 shuttle mission was used to observe the 830–1850 Å spectrum of the cataclysmic variable Z Camelopardalis near the peak of a normal outburst. The observation reveals a rich absorption-line and continuum spectrum which peaks near 1050 Å at a flux of 5×10^{-12} ergs cm^{-2} s^{-1} Å^{-1}. In the sub-Lyα region, some of the stronger absorption lines include S VI $\lambda\lambda$933, 945, C III λ977, N III λ991, O VI $\lambda\lambda$1032, 1038, He II λ1085, P V $\lambda\lambda$1118, 1128, and C III λ1176. No emission is observed below the Lyman limit. The continuum spectrum resembles that of an optically thick accretion disk where the integrated spectrum is constructed by summing stellar model atmospheres. Similar models using summed blackbody spectra fail to approximate the observed continuum.

Subject headings: stars: accretion — stars: binaries — stars: dwarf novae — stars: individual (Z Camelopardalis) — ultraviolet: spectra

1. INTRODUCTION

Dwarf novae are low-mass binary systems in which matter is transferred from a normal red dwarf star overflowing its Roche lobe to an accretion disk around a white dwarf star. During frequent outbursts where the visible light increases by 3–5 mag, the accretion disk dominates the total luminosity of the system. The outbursts are thought to be due to an increase in the mass flow in the inner accretion disk, triggered most likely by a thermal instability in the disk (Smak 1984; Hassall, Pringle, & Verbunt 1985). Sub-Lyα UV observations of dwarf novae in outburst are important because they probe the structure of the high-temperature, inner portions of the accretion disk and may provide information on the boundary layer between the disk and the white dwarf. The only previous observations of cataclysmic variables (CVs) in this wavelength range have been carried out with the *Voyager* Ultraviolet Spectrometers (Polidan, Mauche, & Wade 1990; Polidan & Holberg 1987; Polidan & Carone 1987). These observations show evidence of absorption features near 980 and 1030 Å and indicate a change in the continuum slope below 1200 Å. However, the limited resolution of the *Voyager* spectrographs (18 Å) has made detailed interpretation of these spectra difficult.

Z Cam, one of the brightest dwarf novae, is the prototype of a subclass which sometimes exhibits halts or "standstills" in their decline from outburst. During normal periods, Z Cam undergoes outbursts of $\Delta m_V \sim 3.4$ about once a month (Verbunt 1987). Z Cam has a 6.96 hr period, and, like most dwarf novae, its distance is not well known; estimates range from 200 pc (Szkody & Wade 1981) to as large as 390 pc (Kiplinger 1980). No eclipses are observed, and the inclination angle is estimated to be near 57° (Shafter 1983). Z Cam has been the subject of several UV investigations with *IUE* (Szkody 1981; Klare et al. 1982; Szkody & Mateo 1986). In the high state—outburst or standstill—the *IUE* studies show a continuum slope with a power-law index $\alpha = -2$. There are strong absorption features associated with He II λ1640, C IV $\lambda\lambda$1548, 1551, N V $\lambda\lambda$1239, 1243, Si III $\lambda\lambda$1295–1303, and Si IV $\lambda\lambda$1394, 1403. The C IV and He II features exhibit P Cygni profiles. The reddening to Z Cam is low; Klare et al. (1982) give $E(B-V) = 0.02 \pm 0.01$ based on fits to the 2200 Å bump.

In this *Letter* we describe an observation of Z Cam at the peak of a normal outburst obtained with the Hopkins Ultraviolet Telescope (HUT) on shuttle mission Astro-1. Since HUT is optimized for the 900–1200 Å wavelength range, observations of CVs (and in particular of a dwarf nova in outburst) were a high priority for the HUT observing program.

2. OBSERVATIONS AND REDUCTION

Z Cam was one of ~10 bright dwarf novae monitored by the American Association of Variable Star Observers for Astro-1. The beginning of an outburst from Z Cam was observed from the ground on 1990 December 6. The HUT observation of Z Cam was performed at the peak of the outburst when $m_V \sim 10.6$. The outburst appears to have been rather typical; Z Cam decayed back to its quiescent level of ~13.1 in about 11 days (Mattei 1991).

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The HUT instrument is described by Davidsen et al. (1991). Important features of HUT include coverage from 830 to 1850 Å with ~3 Å resolution, a photon-counting detector, and high time resolution. HUT also has EUV sensitivity in the 415–950 Å range using the second order of the grating. The observation was carried out in 2 s time-resolved mode using a 30″ diameter aperture. It began on 1990 December 9 at 14:02:02 GMT and lasted for 1870 s. It took place almost entirely in orbital night. The count rate from Z Cam was ~1500 counts s^{-1}.

The spectral resolution was not affected significantly by the 2″ (FWHM) image size of a point source in the 30″ aperture, but the resolution can be degraded by pointing jitter. Pointing errors derived from the motion of guide stars in the HUT TV camera indicate an RMS pointing jitter during the Z Cam observation of ±1″.25; such errors degrade the resolution of the spectrograph by less than 1 Å. Analysis of video frames indicate that Z Cam was well centered in the aperture and comparison of the placement of the interstellar cutoff at 912 Å in Z Cam with a number of other objects observed by HUT indicates the wavelengths are consistent to within 1 Å.

There were some ~10% fluctuations in the count rate of Z Cam. Most of these fluctuations occurred either near the beginning of the observation when the pointing was being adjusted or during the last 400 s of the observation when astronauts were exercising on a treadmill. There is no change in the continuum slope during times when the count rate is low nor is there a significant change in the line-to-continuum ratio. Although flickering at the few percent level cannot be ruled out, Z Cam was not a highly variable FUV source during these observations on time scales from 2 s to 20 minutes.

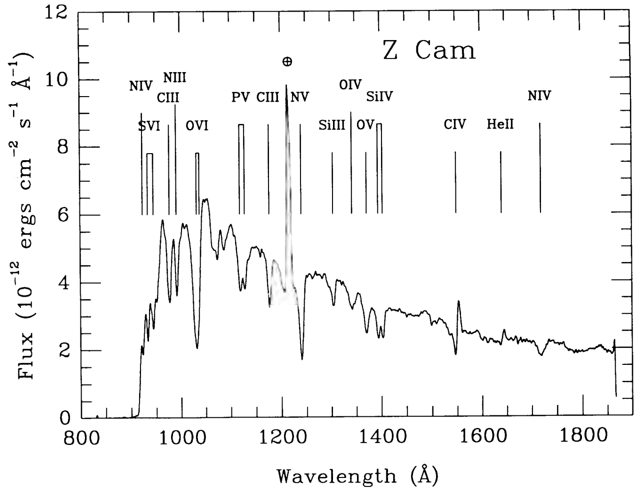

FIG. 1.—The flux-calibrated spectrum of Z Cam as observed with HUT. For the figure, the raw spectrum was smoothed with a Gaussian filter ($\sigma = 1$ Å). Numerous broad absorption lines are seen against a complex continuum which appears to turn over below 1050 Å. The only airglow line in the spectrum is due to Lyα.

In Figure 1 we show a flux-calibrated spectrum of Z Cam, using 1270 s of data from the middle of the observation when pointing errors were low and airglow emissions were weakest. The flux calibration is based on in-flight observations of the DA white dwarf G191-B2B and preflight laboratory data (Davidsen et al. 1991). The spectrum is quite complex, showing a bright continuum with numerous absorption features. The slope of the continuum longward of Lyα is similar to that which has been observed previously with *IUE*. However, below Lyα the continuum peaks near 1050 Å at a flux of 5×10^{-12} ergs cm^{-2} s^{-1} $Å^{-1}$ and falls to 3×10^{-12} ergs

TABLE 1

LINES IN THE HUT SPECTRUM OF Z CAMELOPARDALIS

λ_{obs} (Å)	EW (Å)	FWHM (Å)	Identification	Comments
923.2......	1.1	3.5	N IV λ923.0	
933.5......	1.4	3.6	S VI λ933.4	
944.7......	1.2	3.6	S VI λ944.6	
976.7......	3.2	7.5	C III λ977.0	
991.2......	2.1	5.6	N III λ991.0	
1031.5......	10.8	14.6	O VI & Lyβ	Fit as single line
1023.6......	2.1	9.2	Lyβ	Deblended
1029.8......	4.1	9.2	O VI λ1031.9	Deblended
1035.5......	4.5	9.2	O VI λ1037.6	Deblended
1069.3......	4.2	17.3	S IV λλ1062.7, 1073.0	Fit as a single line
1063.3......	1.7	8.4	S IV λ1062.7	Deblended
1073.8......	1.7	8.4	S IV λλ1073.0, 1073.5	Deblended
1085.8......	1.5:	9.2:	He II λ1085.0	Continuum placement uncertain
1118.4......	2.7	8.9	P V λ1118.0	
1128.4......	2.4	8.9	P V λ1128.0	
1176.3......	2.4	7.1	C III λ1175.8	
1216.5......	7.5:	35.0:	Lyα	Broad absorption; after deblending airglow emission and N V absorption
1239.8......	5.6	9.0	N V λλ1238.8, 1242.8	Fit as a single line
1295.2......	0.6	6.6	Si III λλ1294.5–1303.3	Large multiplet fit as doublet
1304.1......	1.4	6.6	Si III λλ1294.5–1303.3	Large multiplet fit as doublet
1343.2......	1.2	11.2	O IV λλ1338.6, 1343.0, 1343.5	Fits as a single line
1370.2......	2.7	9.5	O V λ1371.3	
1393.9......	2.0	6.3	Si IV λ1398.8	
1402.9......	1.9	6.3	Si IV λ1402.8	
1564.4......	3.0	7.0	C IV λλ1548.1, 1550.8	λ_{obs} is peak absorption
1553.2......	2.2	5.5	C IV λλ1548.1, 1550.8	Emission
1636.9......	1.0:	17.9:	He II λ1640.5	λ_{obs} is peak absorption
1643.8......	4.8	4.8	He II λ1640.5	Emission
1718.4......	3.0	15.2	N IV λ1718.6	

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cm^{-2} s^{-1} Å^{-1} at 950 Å. There is a sharp cutoff in the spectrum at the Lyman limit, and there is no evidence of any flux shortward of 912 Å.

We have identified many of the absorption lines with permitted transitions of ions that are expected in dense plasmas with temperatures in the range of 20,000–100,000 K. Table 1 presents a summary of the identifications, equivalent widths, and line widths of the features. The prominent features include the $1s$–$2p$ transitions of the Li-like ions of O VI λλ1032, 1038, N V λλ1239, 1243, and C IV λλ1548, 1551 and the Na-like ions of S VI λλ933, 945, P V λλ1118, 1128, and Si IV λλ1394, 1403. All of the lines except P V come from abundant ions. P V λλ1118, 1128 appears to be the only reasonable identification for the two lines whose observed wavelengths are 1118.4 and 1128.4 Å in our spectrum. With the exception of a few luminous hot stars observed with *Copernicus* (e.g., Morton & Underhill 1977), this is the first time most of the transitions shortward of Lyα have been observed in an extrasolar target.

The equivalent widths of the lines were established using the "splot" task in IRAF. Many of the lines are blends, while in other cases it is quite difficult to determine the level of the underlying continuum. Therefore, the results presented in Table 1 are only estimates. Equivalent widths of blended features have been estimated by fixing the separation between lines at their laboratory values and assuming all lines in a blend have the same shape.

The doublets of the Na-like ions S VI λλ933, 945, P V λλ1118, 1128, and Si IV λλ1394, 1403 are resolved; the equivalent widths of the lines are not in the ratio of their statistical weights, indicating that they are saturated. Several of the absorption lines do not involve ground-state transitions as expected if the absorption arises within a relatively dense atmosphere. These include C III λ1176, N IV λ923, N IV λ1719, and He II λ1640. Multiple ionization states of many elements are present. The line spectra clearly merit a detailed analysis that is beyond the scope of this brief *Letter*.

There also appears to be a broad absorption feature centered on Lyα which is partially filled in by the Lyα in the airglow. (The airglow would also obscure any narrow core to the line.) The analysis of this feature is further complicated by the presence of strong N V absorption near 1240 Å. Nevertheless, after fitting and removing the airglow line and N V, we estimate this absorption feature has an equivalent width of 7.5 Å and a FWHM of 35 Å. There does not appear to be a comparable feature associated with Lyβ.

3. ANALYSIS AND DISCUSSION

In an attempt to describe the continuum spectrum of Z Cam, we have constructed, following the prescription of Wade (1984, 1988), model spectra of a steady state accretion disk by summing blackbody spectra and stellar Kurucz (1979, 1991) model atmospheres. All of the models have a white dwarf mass of 1 $M_\odot$, close to the value inferred (0.99 $M_\odot$; Shafter 1983), an inner accretion radius of 5×10^8 cm (i.e., the accretion disk extends down to the white dwarf surface), and an outer radius of 30 $R_{\rm WD}$ (which is sufficiently large that the predicted spectrum in our wavelength range is insensitive to the outer radius). Models for a range of mass accretion rates have been calculated and scaled to match the observed flux at 1425 Å.

For the blackbody models (Fig. 2), the slope of the continuum matches that observed longward of 1200 Å for mass accretion rates of $\sim 10^{18}$ g s^{-1}, but the blackbody models do not turn down at the shorter wavelengths like the observed spectrum. A better approximation to the observed continuum is obtained with the Kurucz models. Specifically, we find that the continuum shape is well matched with a mass accretion rate of $\sim 10^{16.5}$ g s^{-1}, as shown in Figure 2. The sharpness in the turnover of the continuum below 1050 Å is tracked by these models, providing strong evidence that line blanketing in the atmosphere of the disk at these wavelengths is responsible for the turnover. For this accretion rate the maximum temperature in the disk model is ~40,000 K. The spectral shape of the Kurucz models is not extremely sensitive to the mass accretion rate (because the accretion disk temperatures vary as $\dot{M}^{1/4}$). Nevertheless, models based on Kurucz atmospheres with much higher accretion rates ($>10^{17}$ g s^{-1}) tend to produce too much emission near the Lyman limit; models with lower rates ($<10^{16}$ g s^{-1}) produce too little emission there.

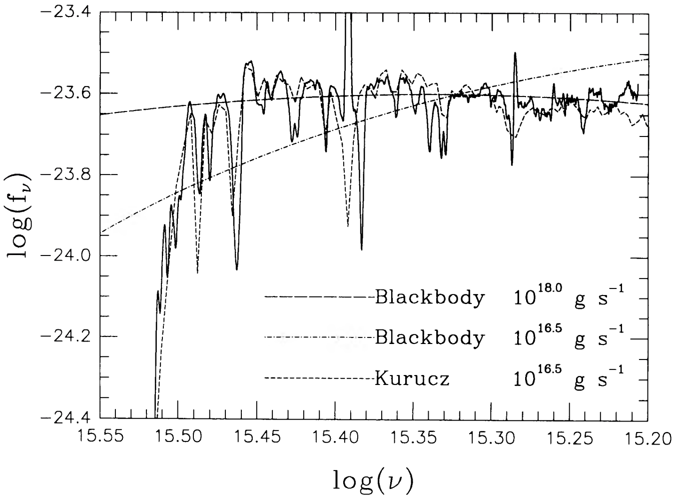

FIG. 2.—A comparison of the Z Cam spectrum and model spectra generated by assuming that the disk has a temperature profile given by standard accretion disk theory. All of the models are normalized to the observed flux of Z Cam at 1425 Å which has been corrected for the modest amount of absorption [$E(B-V) = 0.02 \pm 0.01$] reported by *IUE* (Klare et al. 1982). Blackbody models with $\dot{M} \sim 10^{18}$ g s^{-1} match the continuum above 1050 Å reasonably well, but fail at shorter wavelengths. A model based on Kurucz's (1991) stellar atmospheres and $\dot{M} = 10^{16.5}$ g s^{-1} is qualitatively similar to the continuum of Z Cam. A blackbody model with $\dot{M} = 10^{16.5}$ g s^{-1} is shown for comparison.

On the other hand, the 1400 Å flux produced by a Kurucz model disk is a factor of 11 less than that observed for an accretion rate of $10^{16.5}$ g s^{-1} if the distance to Z Cam is 200 pc. (This comparison assumes that the specific intensity of the disk varies as the cosine of the inclination angle.) To match the flux at 1400 Å, $\dot{M}$ would need to be increased by roughly a factor of 20, or alternatively the UV-emitting portion of the disk would have to be ~3.3 times larger than predicted by standard accretion disk models. Wade (1988) has identified a similar problem in a sample of nova-like variables observed with *IUE*; specifically he found that the accretion rates required to match the *IUE* color indices [$\log(f_{\lambda 1460}/f_{\lambda 1800})$ versus $\log(f_{\lambda 1800}/f_{\lambda 2800})$] were too low to account of their luminosities.

Models of accretion disks based on stellar atmospheres provide a coarse approximation to the continuum emission expected from dwarf novae in outburst. However, high-quality data such as those presented here clearly merit calculations which model the physical conditions expected in the disks of dwarf novae, including both line and continuum opacities. One of the few attempts to model the spectra of dwarf novae in this manner was carried out by la Dous (1989), who synthesized, assuming LTE conditions, optically thick accretion disk spectra in which noninteracting annuli have effective temperatures and gravities that are essentially the same as those used in the simplified models discussed above. The model described most fully by la Dous (1989) is one in which $M_{\rm WD} = 1\ M_{\odot}$, $\dot{M} = 7 \times 10^{16}$ g s^{-1}, $R_{\rm in} = 1.6 \times 10^{9}$ cm, and $R_{\rm out} = 25R_{\rm in}$. The continuum spectrum from this model looks rather similar to what we observed in Z Cam, providing hope that detailed calculations of this sort can be used to model such spectra. However, Z Cam has more emission near 1000 Å, and higher ionization absorption lines are much more prominent in the data than in the model. Conversely, lines of low ionization states such as C II and Si II which are prominent in la Dous's model are absent from our spectra. The broad Lyα feature is also much more prominent in the model spectrum. All of these effects suggest a greater contribution from higher temperature material in Z Cam. Because la Dous did not calculate a large grid of models, it is unclear whether the differences between the model and the observed spectrum are due primarily to choices of the parameters, such as $\dot{M}$, or to incompleteness of her model, which is not a self-consistent treatment of energy dissipation and radiative transfer in the disk. Attempts to incorporate more physics into disk models have been carried out (e.g., Hubeny 1989) but have not yet resulted in model spectra with enough spectral resolution for detailed comparison with the HUT data.

The accretion disk models described above consider only half of the accretion energy. The standard theory predicts that half of the accretion energy should be released in a boundary layer between the inner edge of the accretion disk and the white dwarf as the kinetic energy of the inflowing material is thermalized. Assuming the energy is radiated promptly, models suggest that this boundary layer will radiate thermal EUV/soft X-ray emission, or perhaps a harder spectrum if it is optically thin. No such emission is observed in most CVs, which has led to suggestions (e.g., Kallman & Jensen 1985) that the boundary layer emissions are absorbed at soft X-ray wavelengths by winds in CVs. Such a wind might not be opaque longward of 912 Å. However, the HUT data do not show obvious evidence for a boundary layer. Specifically, the higher order Lyman lines, which should be a signature of emission from a hot high-gravity component in the spectrum of Z Cam, are weak or absent. However, in the absence of detailed and believable disk models, it is difficult to place hard limits on the boundary layer emission if it exists.

The existence of P Cygni emission features in C IV and He II, which have been observed previously with *IUE* (Szkody & Mateo 1986), are direct evidence of the existence of a wind in Z Cam during outburst. None of the other lines in our spectrum show evidence for an emission-line component or a classical P Cygni profile despite the higher signal-to-noise ratio and higher spectral resolution of HUT data compared with *IUE* spectra. We estimate the blue wing of C IV to have a velocity of ~5000 km s^{-1} (1525 Å). The P Cygni profile for He II is not as well defined as for C IV, especially for the absorption component. It is not clear whether dips at 1600 and 1611 Å are part of the P Cygni absorption system or not. Without these absorption dips, the blue wing of the absorption extends at least to 4000 km s^{-1} (1618 Å). If the dips mentioned above are part of the He II absorption and not separate absorption features, the blue wing extends to ~8500 km s^{-1} (1594 Å).

The absence of emission-line components in the other lines does not preclude their formation in a wind. Plausible models for the winds in CVs lead to P Cygni profiles without emission components (Drew 1987; Mauche & Raymond 1987). Often the emission component simply fills in part of the absorption profile causing the center of the absorption line to be blueshifted. Szkody & Mateo (1986) concluded that N V and Si IV were most likely formed in the wind in Z Cam because these lines were blueshifted by ~5 Å. Our observations of N V and Si IV show *no blueshift*, although the appearance of C IV is similar in the two observations. Furthermore, there is no evidence of a significant blueshift in any other absorption feature in the spectrum. Since the accretion disk dominates the continuum emission in outburst, the absorption lines may be largely associated with the disk itself.

4. CONCLUSIONS

Using HUT on Astro-1, we have obtained the first high signal-to-noise ratio spectrum of a dwarf nova with sufficient spectral resolution to resolve individual absorption lines in the wavelength range shortward of Lyα. These data clearly show the importance of spectral coverage to the Lyman limit for CVs, since models that fit the continuum longward of 1200 Å vary dramatically in the region below 1200 Å. To the extent that Z Cam is typical of dwarf novae in outburst, the HUT observations confirm the result first obtained with *Voyager* that the spectra of CVs peak in the 900–1200 Å region considerably longward of the Lyman limit (cf. Polidan & Holberg 1987). The HUT spectra show many absorption lines below Lyα; the strongest feature is dominated by O VI λλ1032, 1038 rather than Lyβ. The HUT spectrum of Z Cam demonstrates that standard disk models employing summed blackbodies or Kurucz model atmospheres are inadequate, although the Kurucz models give a much better approximation to the spectral shape. Our preliminary analysis clearly demonstrates the need for detailed modeling using realistic physics in order to understand the far-UV emission of CVs.

A list of the names of the people who made this observation possible would dwarf the length of this *Letter*. Here we acknowledge John-David Bartoe and Ken Nordsieck, who played key roles in reorganizing the Astro-1 mission to allow commanding from the ground when hardware failures made it impossible for the astronauts to control the instruments. We also thank Robert Kurucz for providing his most recent models and the American Association of Variable Star Observers for supporting all of Astro's many launch attempts. The HUT project was funded by NASA contract NAG 5-27000 to The Johns Hopkins University.

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