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OBSERVATIONS OF THE WHITE DWARF IN THE U GEMINORUM SYSTEM WITH THE HOPKINS ULTRAVIOLET TELESCOPE

KNOX S. LONG
Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218
WILLIAM P. BLAIR, CHARLES W. BOWERS, ARTHUR F. DAVIDSEN, AND GERARD A. KRISS
Center for Astrophysical Sciences, Department of Physics and Astronomy, The Johns Hopkins University,
Charles and 34th Streets, Baltimore, MD 21218
EDWARD M. SION
Department of Astronomy and Astrophysics, Villanova University, Villanova, PA 19085
AND
IVAN HUBENY
NASA/Goddard Space Flight Center, Greenbelt, MD 20771
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ABSTRACT

We have used the Hopkins Ultraviolet Telescope to obtain a far-ultraviolet (830–1860 Å) spectrum of the dwarf nova U Geminorum. The spectrum, which was obtained 10 days after U Gem had returned to the low state following a normal outburst, shows prominent absorption features due to the Lyman series of hydrogen and the Balmer lines of He II, as well as weaker absorption lines due to metals, including C III λ977, C III λ1176, N V $\lambda\lambda$1239, 1243, Si IV $\lambda\lambda$1394, 1403, C IV $\lambda\lambda$1548, 1551, and possibly O VI $\lambda\lambda$1032, 1038. The continuum, which extends to the Lyman limit but not beyond, is dominated by emission from the white dwarf. The average surface temperature appears to have been ~38,000 K if all the UV light comes from the white dwarf. This temperature is higher than the temperature derived from previous measurements with *IUE* obtained further from outburst. There is evidence for a hot (~57,000 K) component in the continuum which may be due to the boundary-layer region of the white dwarf photosphere. There is no obvious evidence of UV emission from the accretion disk. A preliminary analysis of the strength of the absorption lines suggests that most of the lines, but not those from ions with the highest ionization potential, arise in the photosphere of the white dwarf, which has nearly solar surface composition due to accretion from the secondary companion.

Subject headings: novae, cataclysmic variables — stars: individual (U Geminorum) — ultraviolet: stars — white dwarfs

1. INTRODUCTION

Cataclysmic variables (CVs) are highly variable, mass-exchanging binary star systems containing a white dwarf (WD) and a normal late-type dwarf star. U Gem is the prototype for those CVs known as dwarf novae, which undergo quasi-periodic outbursts of up to 6 mag at optical wavelengths. The outbursts are due to changes in the temperature and structure of the accretion disk that funnels material from the normal star onto the nonmagnetic WD. In U Gem, the interval between outbursts is ~118 days, and a typical outburst ($\Delta m_v = 5$) lasts from 7 to 14 days (Warner & Nather 1971). The individual stars have been identified as a 0.8–1.1 $M_\odot$ WD and 0.56 $M_\odot$ M5 V star that orbit each other with a period of 250 minutes (Eason & Worden 1983).

Because U Gem is nearby (78 pc; Bailey 1981) and bright ($m_v = 14$), it has been the subject of several UV investigations (Fabbiano et al. 1981; Panek & Holm 1984, hereafter PH; Kiplinger, Sion, & Szkody 1991, hereafter KSS). Extinction along the line of sight is low. On the basis of the appearance of the 2200 Å bump, PH estimate $E(B-V) = 0.03 \pm 0.01$, while Verbunt (1987) gives $E(B-V) = 0.03$ as an upper limit. In the outburst of U Gem studied by PH, the UV flux rose by a factor of 100, the strongest absorption line was N V λ1240, and no P Cygni profiles were seen, all of which is consistent with the standard picture in which the UV light from dwarf novae is dominated by an optically thick accretion disk. In contrast, the quiescent UV spectrum of U Gem appears to be dominated by the UV flux from the WD. PH derive a temperature of 30,000 K based on analysis of the Lyman-α absorption profile. The *IUE* spectra also show metal absorption lines during quiescence, some of which both PH and KSS suggested could be associated with the WD photosphere, the inner accretion disk, or a boundary layer.

Here we report far-UV observations of U Gem obtained with the Hopkins Ultraviolet Telescope on NASA's Astro-1 shuttle mission in 1990 December (Davidsen et al. 1992). This is the first observation of U Gem with sufficient sensitivity to explore the wavelength range between Lyman-α and the Lyman limit. Observations of dwarf novae in the region below Lyman-α are important to probe the inner regions of the accretion disk and to search for radiation from the boundary layer between the disk and the WD. In the case of U Gem, observations in this wavelength range are necessary to provide a more accurate determination of the temperature and properties of the WD in this system.

2. OBSERVATIONS

The Hopkins Ultraviolet Telescope (HUT) consists of a 0.9 m diameter iridium-coated primary mirror feeding a 0.4 m Rowland spectrograph that diffracts light (830–1860 Å in first order) onto a CsI-coated, microchannel-plate–intensified, photon-counting detector (Davidsen et al. 1992). U Gem was observed through a 30″ diameter aperture beginning at 5:10 GMT on 1990 December 9 for 1580 s. The observation took place almost entirely in orbital night when airglow emissions (with the exception of Lyman-α) are weak. For the analysis described here we have considered those data obtained during the 1100 s period centered on orbital midnight (5:17–5:35 GMT) when Lyman-α was weakest. The mean count rate from U Gem was ~75 counts s^{-1}. The pointing was stable throughout the observation, with rms pointing jitter of only 1″.1. As a result, the intrinsic resolution of the spectrum is ~3 Å.

The flux-calibrated spectrum of U Gem is shown in Figure 1. The raw spectrum was corrected for dark counts and grating-scattered light based on the count rate, 6.4×10^{-4} counts s^{-1} $diode^{-1}$, measured below 912 Å, and reduced to absolute fluxes as described by Davidsen et al. (1992). The continuum level at 1450 Å, 1.7×10^{-13} ergs cm^{-2} s^{-1} Å^{-1}, is very close to the level observed with *IUE* when U Gem is in quiescence (PH). The most prominent absorption features in the spectrum are in the spectral region below Lyman-α. The Lyman lines are observed through at least Lyman-δ. In addition to the Lyman series, a number of other absorption lines are seen. Below Lyman-α these include C III λ977, He II λ992 + N III λ991, He II λ1085 + N III λ1085, and C III λ1176. There is also a strong feature blended with Lyman-β, which could be either C II λ1037, O VI $\lambda\lambda$1032, 1038, or a combination of the two. The line identifications, the observed line centers, and estimates of the equivalent widths of the stronger and better isolated lines, as measured using the IRAF[1] SPLOT utility, are listed in Table 1. In the region above Lyman-α, the equivalent widths we measure are similar to those measured by KSS from *IUE* spectra. All of the lines intrinsic to U Gem, including the Lyman lines, are blueshifted by ~2.5 Å, but the airglow lines are not shifted. This is most likely due to a displacement of U Gem by about 7″ from the center of the 30″ diameter aperture.

As part of a program to support the Astro-1 mission, the American Association of Variable Star Observers (AAVSO) monitored U Gem in the time period surrounding our observation of U Gem. The visual light curve is shown in Figure 2. U Gem displayed an outburst which began about 25 days prior to the HUT observation. The visible light output returned to its quiescent level about 10 days prior to our UV observation.

3. ANALYSIS

3.1. *WD Models and Model Fitting*

PH concluded that quiescent emission in U Gem is dominated by emission from the WD in the system. This was based

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[1] IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy (AURA), Inc., under cooperative agreement with the National Science Foundation.

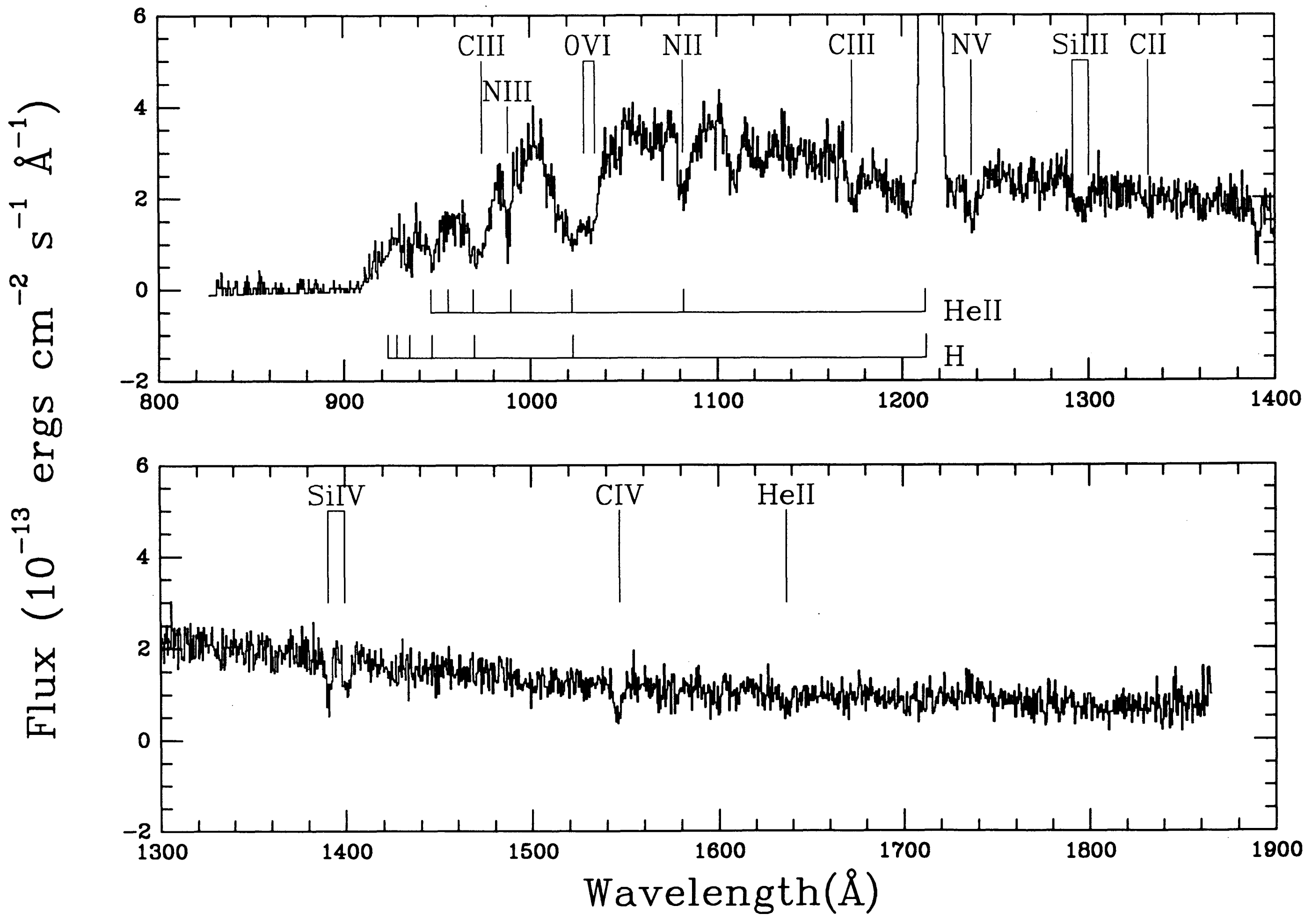

FIG. 1.—Spectrum of U Gem as observed with HUT. Prominent absorption lines are marked. Individual bins are 0.51 Å wide.

TABLE 1

SUMMARY OF ABSORPTION LINES IN U GEM

Ion	$\lambda_{\rm obs}$[a] (Å)	EW (Å)	FWHM (Å)
Lyδ + He II	947.7	2.3	4.6
Lyγ + C III	972.3	7.8	11.3
He II + N III	988.3	2.0	3.7
Lyβ + C II + O VI	1025.3	17.3	23.5
He II + N II	1083.0	3.5	8.2
Si III	1109.2	2.3	6.5
Si IV	1123.3	1.7	9.0
C III	1173.9	1.5	4.9
N V	1237.9	2.5	6.7
Si II	1265.7	0.7	3.2
Si III	1296.1	3.2	10.0
Si IV	1390.7	1.8	3.8
Si IV	1400.6	1.7	3.8
C IV	1545.8	2.9	4.8
He II	1636.6	1.8	5.3

[a] As discussed in the text, all of the observed wavelengths are shifted by about 2.5 Å, which we believe is due to the position of U Gem in the HUT aperture. However, no correction to $\lambda_{\rm obs}$ has been made for this effect in the table.

on (*a*) the fact that the quiescent UV spectrum is similar to that of a normal B0.5 star ($f_\lambda \propto \lambda^{-3.3}$) rather than the flatter (λ^{-2}) spectrum which is typical of disk-dominated CVs; (*b*) the existence of a broad absorption line at Lyman-α resembling the profile expected from a 30,000 K WD; and (*c*) the agreement between the observed flux and the flux expected from a 30,000 K WD at the distance of U Gem. We observe the same slope ($f_\lambda \propto \lambda^{-3.3}$) longward of 1250 Å, corroborating that part of the argument. In addition, the detection of broad, higher order Lyman lines with HUT and the fact that U Gem has a rich absorption-line spectrum in the far-ultraviolet (FUV) (rather than the emission-line spectra seen in most other dwarf novae in quiescence) support the hypothesis that the WD dominates the quiescent UV spectrum in U Gem.

Assuming that this is true, then some if not all of the absorption lines can be explained as arising from the photosphere of the WD. The WD in U Gem accretes material at an average rate of $\sim 10^{-10}\ M_\odot\ {\rm yr}^{-1}$ (Patterson 1984). The mass of a WD atmosphere is quite small ($\ll 10^{-12}\ M_\odot$), and therefore the accretion or replacement time scale is short, and the abundances in the photosphere should be those of the companion M star, which we assume to be nearly solar. Diffusion is unlikely to be important because the time scale associated with settling of metal ions into the interior is ~1–3 yr (cf. Vauclair, Vauclair, & Greenstein 1979; Michaud 1987).

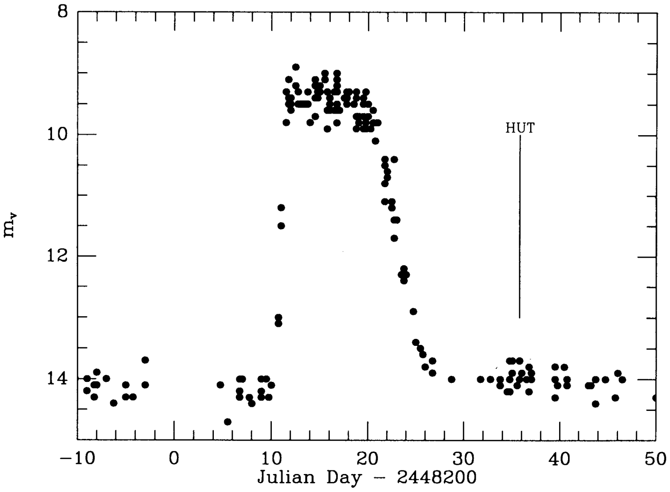

FIG. 2.—Optical light curve of U Gem in the period surrounding the HUT observation as observed by the AAVSO. The HUT observation occurred 25 days after the beginning of an outburst and 10 days after the system had returned to its quiescent visual magnitude.

In order to understand both the observed line strengths and the FUV energy distribution within the context of an accreting hot WD, we have fitted the data with a series of model spectra calculated assuming high-gravity ($\log g = 8$) atmospheres. There are many absorption features apparent in the HUT data, especially below Lyman-α. We therefore wanted to compare results for metal-enriched as well as pure hydrogen atmospheres. Since a readily available grid of spectra from such atmospheres does not exist, we have created one.

We first calculated a grid of model atmospheres (25,000 K < T < 115,000 K) using the program TLUSTY (Hubeny 1988), which has recently been upgraded to incorporate an accelerated algorithm for complete linearization (Hubeny & Lanz 1992). For the calculations of the structure of the atmosphere we assumed that the composition was either pure hydrogen or hydrogen and helium in their cosmic abundance ratio. (At the temperatures and gravities of interest here, metals do not affect the opacity of the atmosphere significantly.) We adopted the occupation probability description of the Lyman and Balmer series (Hummer & Mihalas 1988), and non-LTE (NLTE) opacity distribution functions (Hubeny, Hummer, & Lanz 1992) to describe the complicated opacity in the region of line merging longward of the Lyman and Balmer limits. As expected, trial calculations demonstrated that NLTE effects had a negligible effect on the structure of the atmospheres; therefore, the grid of models was calculated assuming LTE.

Once the model atmospheres had been constructed, we produced synthetic spectra for the HUT spectral range using a separate program SYNSPEC (I. Hubeny 1992, unpublished). Source functions were calculated using second-order escape probability theory (Hummer & Rybicki 1982) for the resonance lines of the first 20 elements (hydrogen through calcium) and assuming an LTE source function for all other transitions. (As was the case for the structure calculations, NLTE effects are not very significant in the radiative transfer calculations in these hot, high-gravity atmospheres.) The intrinsic line profiles have the form of a Voigt function and account for the effects of natural, Stark, van der Waals, and thermal Doppler broadening. For Stark broadening of the He II λ1640 line the recent results by Schoening & Butler (1989) were used. The *gf*-values and the broadening parameters of the other lines were taken from Kurucz's (1990) line list. This line list contains approximately 120,000 spectral lines in the HUT wavelength region. The spectrum was calculated initially on a very fine grid ($\delta\lambda \leq 0.015$ Å) and then convolved with a Gaussian (FWHM = 3 Å) and resampled to match the HUT bin size and spectral resolution.

The pure hydrogen spectra agree reasonably well with a set of spectra constructed for $\log g = 8$ LTE atmospheres kindly provided to us by Vennes (1991). At 30,000 K, for example, the differences are less than 20% at all wavelengths. As one might expect, the differences are largest below 1050 Å. The differences are even smaller at higher temperatures. Although detailed spectra of WDs with normal or nearly normal abundances have not been published, Henry, Shipman, & Wesemael (1985) have calculated equivalent widths of some of the prominent UV absorption lines. As in our calculations, they started with a model for the structure calculated for LTE and pure hydrogen. They argue that the calculated equivalent widths (EWs) should be accurate to within a factor of 2 or 3 over the range of temperatures 15,000–100,000 K. We have compared the EWs we derive with theirs and find they usually agree within a factor of 2.

To compare the models with the data, we have used the IRAF task SPECFIT, a nonlinear χ^2 minimization routine which is part of the HUT analysis package. HUT is a photon-counting instrument, and it is straightforward to establish and propagate statistical errors for HUT spectra. In all the fits we have allowed for reddening using Seaton's (1979) mean Galactic extinction curve, assuming it to be valid to 912 Å as is indicated by Longo et al.'s (1989) analysis of *Voyager* observations. The amount of neutral hydrogen along the line of sight to U Gem is small. Mauche (1991) estimates that $N_{\rm H}$ is 3.1×10^{19} cm^{-2} based on an analysis of curves of growth of low-excitation lines in high-resolution spectra of U Gem in outburst. This column is sufficient to eliminate any second-order extreme ultraviolet (EUV) radiation, and has a negligible effect on the first-order HUT spectrum except within a few angstroms of the Lyman limit. We have fixed $N_{\rm H}$ at this value in the fits described below. The results of the models are summarized in Table 2.

3.2. *Single-Temperature Models with Pure Hydrogen Atmospheres*

PH and KSS used pure hydrogen, log $g = 8$ atmospheres for their determination of the temperature of the WD. To provide a basis for our further discussion, we first fitted the HUT data to a set of models created assuming pure hydrogen. We fitted the overall continuum, excluding only the region dominated by Lyman-α airglow. These model fits have three free parameters: the temperature of the WD, a normalization, and the amount of extinction. The best fit ($\chi^2 = 3389$ for 1810 data points and three free parameters) was obtained with a temperature of 38,600 K and $E(B-V) = 0.06$. A comparison of this model with the data is shown in Figure 3 as a solid line. The model fits the overall shape of the spectrum reasonably well, but the large χ^2 indicates that the fit is unsatisfactory. The largest differences between the model and the data are locations where there are easily identifiable absorption lines and in the region below 970 Å. The best-fit value of the reddening [$E(B-V) = 0.06$] is somewhat higher than the value inferred by PH from analyzing the 2200 Å feature in the spectrum. The best pure hydrogen model with $T = 30{,}000$ K (the value obtained by PH) and $E(B-V)$ allowed to vary (but constrained to be greater than 0.0) is shown by the dashed line in Figure 3; it has $E(B-V) = 0.0$, does not account at all for the flux observed below 970 Å, and has a significantly worse χ^2 (see Table 2).

PH's estimate of the temperature of the WD in the U Gem system was based on the shape of the Lyman-α profile of U Gem in quiescence as observed through *IUE*'s small aperture, using models of pure hydrogen WD atmospheres calculated by Wesemael et al. (1980). To assure ourselves that the difference in the temperature we measure is not due to the models we have employed, we obtained the small-aperture spectrum (SWP 15086) described by PH from the *IUE* archive. Figure 4*a* shows two fits of the Lyman-α region of this *IUE* spectrum using our models. Since *IUE* is not a photon-counting instrument, establishing the allowable ranges for the temperature is less straightforward than for the HUT data. However, the 30,000 K model (Fig. 4*a*, *dashed curve*) provides a much better fit than the 38,600 K (*solid curve*).

For comparison we have fitted the Lyman-α portion of the HUT data in the same manner. This comparison is shown in Figure 4*b*. In this case we modeled the wavelength range 1165–1205 Å and 1227–1260 Å using a pure H, WD atmosphere and Gaussian absorption lines at C III λ1176, and N V λ1240. The best fit ($\chi^2 = 173$ for 142 data points and seven free parameters) was obtained for a temperature of 36,300 K. If T is fixed at 30,000 K and the other parameters are allowed to vary, $\chi^2 = 221$. The statistically allowed range is approximately 32,000–43,000 K (which in this case corresponds to the 90% [$\chi^2_{\rm min} + 12.0$] confidence limit). The statistical errors are large because the more temperature-sensitive portions of the Lyman-α region are obscured in the HUT spectra by geocoronal Lyman-α. Nevertheless, fits of the Lyman-α region also suggest that the temperature was higher than 30,000 K during our observation.

3.3. *Single-Temperature Models with Solar Abundances*

We next attempted to model the data in terms of WD photospheres with solar abundances. The best-fitting model is shown in Figure 5. It has a temperature of 37,700 K, $E(B-V) = 0.035$,

TABLE 2

SUMMARY OF MODEL FITS TO HUT SPECTRUM OF U GEM

Model	χ^2	Degrees of Freedom	Temperature (K)	$E(B-V)$[a]
Single-T, pure H	3389	1806	38,600	0.06
	4385	1807	30,000[b]	0.00
Lyα region only	173	134	36,300	0.00[b]
	221	135	30,000[b]	0.00[b]
Single-T, solar abundances	2789	1806	37,700	0.035
	2921	1807	34,700	0.00[b]
Two-T, solar abundances	2595	1804	30,000 56,600	0.02

[a] $E(B-V)$ was constrained to be greater than or equal to 0.00 in all fits in which the reddening was allowed to vary.

[b] Parameter was fixed at this value for fit.

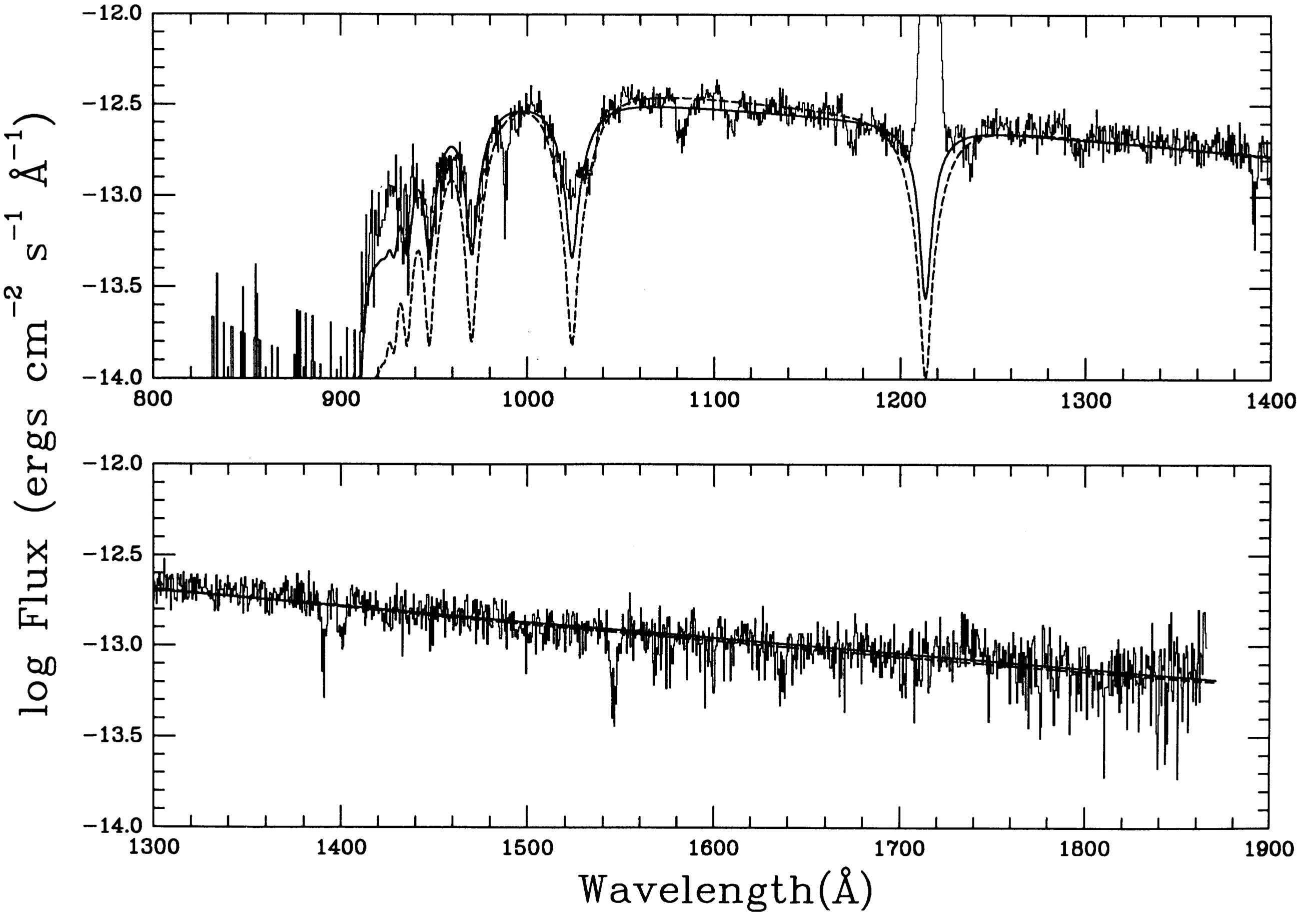

FIG. 3.—WD model fits to the HUT data. The solid curve, which is the best-fit single-temperature pure hydrogen WD model, is for a temperature of 38,600 K. The dashed curve is the best fit when the WD temperature has been constrained to be 30,000 K, the value deduced by PH far from outburst.

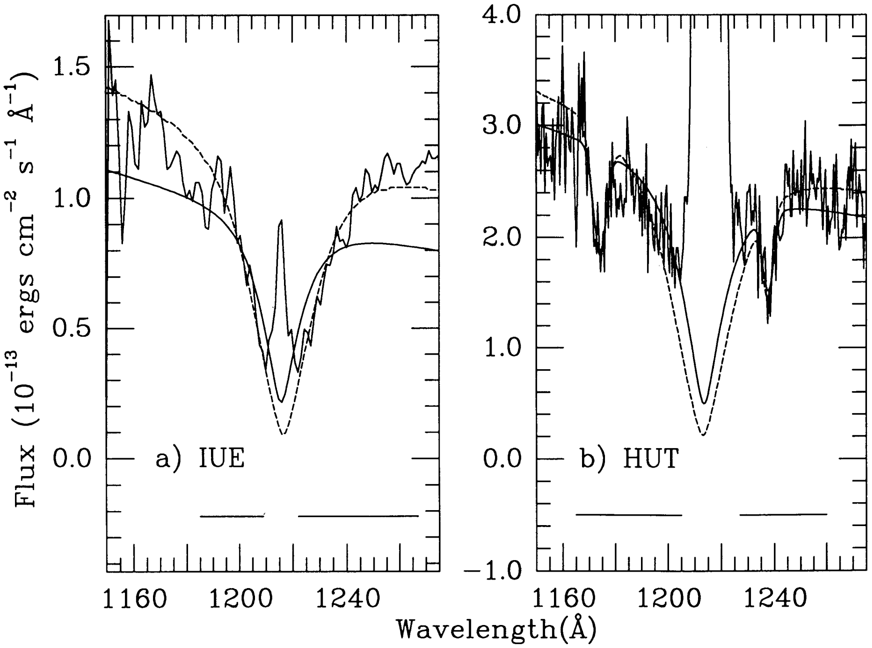

FIG. 4.—(*a*) WD model fits to the Lyman-α portion of the *IUE* spectrum analyzed by PH. The conventions are the same as in Fig. 3, except that here the 30,000 K spectrum is the best-fit spectrum. Not all the light gets through *IUE*'s small aperture, and so the vertical scale of this figure has been adjusted so that it has effectively the same "stretch" as (*b*). The broken horizontal line shows the regions which were included in the fit. (*b*) WD model fits to the Lyman-α portion of the HUT data. The solid curve is the best-fit WD model with a temperature of 36,300 K. The dashed curve is the best fit when the WD temperature is constrained to 30,000 K. As before, the broken horizontal line shows the regions which were fitted.

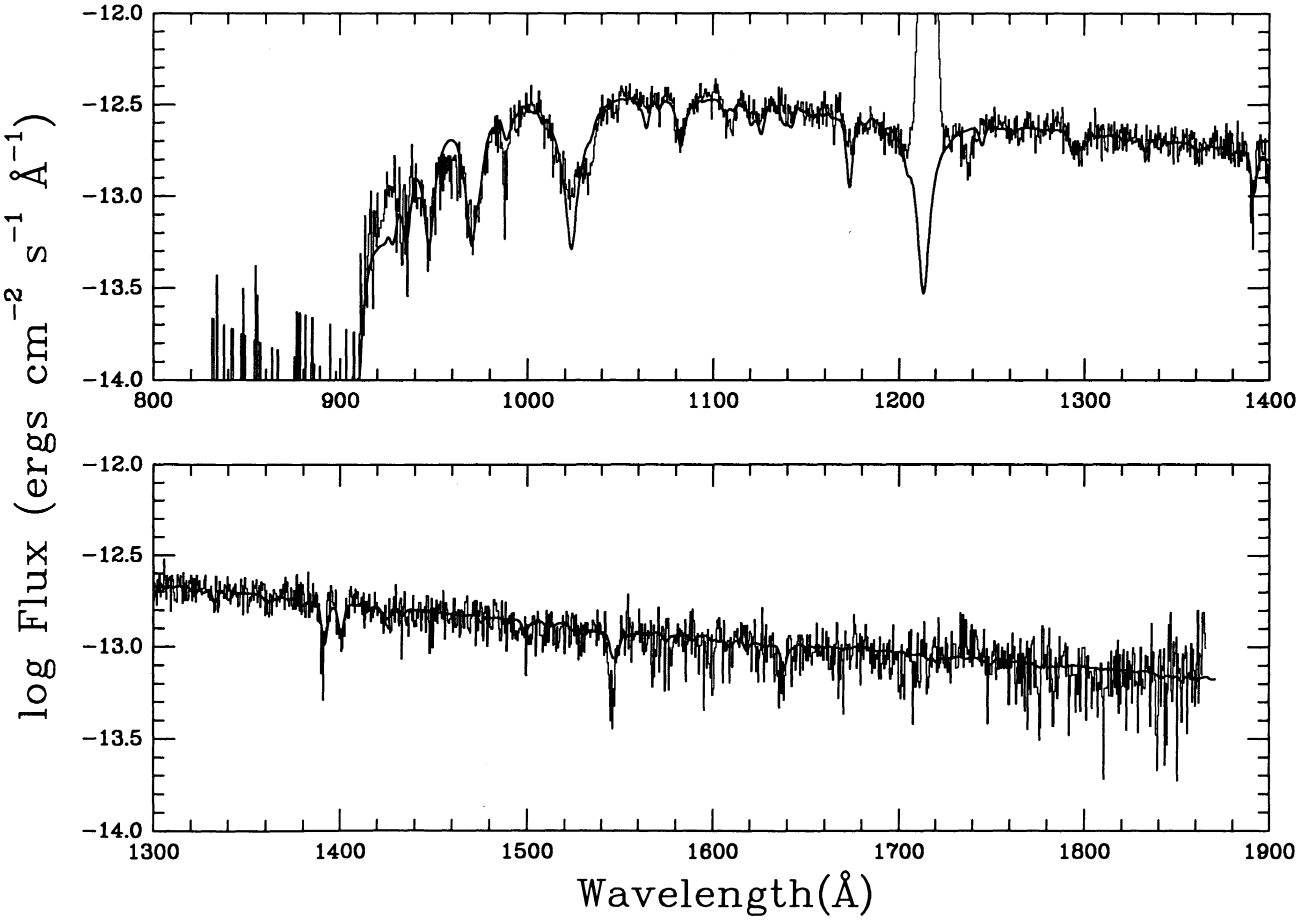

FIG. 5.—WD models with solar abundances compared with the HUT data. The solid curve is the best-fitting single-temperature model. As described in the test, it has a temperature of 37,700 K.

and $\chi^2 = 2789$ for 1810 data points and three free parameters. This model provides a much better fit than any of the pure hydrogen models. The improvement in χ^2 is basically due to the inclusion of more absorption lines. Indeed, most of the features in the observed spectrum can also be seen in the model atmosphere, and in most cases the absorption depths agree to within a factor of 2. If we assume that this basic model is correct, then the 99% confidence contour ($\chi^2_{\rm min} + 14.1$) allows temperatures between 36,400 and 39,100 K and $E(B-V)$ between 0.024 and 0.047. [As is the case in all the single-temperature models, there is some correlation between the derived value of $E(B-V)$ and the temperature. Lower temperatures correspond to lower values of $E(B-V)$.] Even if $E(B-V)$ is set to 0.0, the best-fitting temperature, 34,700 K exceeds 30,000 K, and χ^2 rises to 2921.

There is no obvious pattern of changes in metal abundances which would improve the fits, since some lines are too strong and others too weak. We have experimented with constructing models in which abundances are all adjusted simultaneously, and in some cases they do improve the fits slightly, although the derived temperatures do not change significantly. For example, the best fit using metal abundances which are one-third solar yields a temperature of 37,400 K and a χ^2 of 2742 instead of the 2789 we obtained with normal abundances.

The basic shortcomings of the model are that it still does not fit the region below 970 Å very well and that the model does not reproduce the absorption line at 1240 Å or the line on the red wing of Lyman-β satisfactorily. The feature at 1240 Å is surely due to N V $\lambda\lambda$1239, 1243, which should not be created in the photosphere of the WD until the temperature reaches ~90,000 K. The feature at about 1035 Å that is present in the ~38,000 K models is due to C II λ1037. However, unlike most of the other features in the spectrum, the model shows a feature that is not as deep as the observed feature. An alternative possibility, discussed in § 3.5, is O VI $\lambda\lambda$1032, 1038, but this doublet requires an even higher temperature than N V.

3.4. *Two-Temperature Models with Solar Abundances*

The difference between the temperature we observe and the temperature derived by PH is intriguing. Our observation occurred only 10 days after the end of an optical outburst. KSS have examined a number of *IUE* spectra of U Gem throughout quiescence. They agree with PH that the spectrum far from outburst resembles that of a WD with a temperature of 30,000 K, but they also find that the UV flux level at 1620 Å decreases by about 20% between 22 and 100 days past maximum. They argue that the Lyman-α profile evolves during the quiescent period and that it is well fitted by a 30,000 K WD only toward the middle or end of the quiescent interval. They suggest that the changes in flux can be understood in terms of a hot component that decays away slowly during quiescence.

Assuming this to be the case, a possibility that can be ruled out immediately is that the entire surface of the WD cools from

~38,000 to 30,000 K, because then the UV flux from U Gem would decline by a factor of 2. The flux we observe at 1620 Å is 1.0×10^{-13} ergs cm^{-2} s^{-1} Å^{-1} (which corresponds to a dereddened value of 1.2×10^{-13} ergs cm^{-2} s^{-1} Å^{-1}, assuming $E(B-V) = 0.03$). This is very close to the dereddened flux of 1.1×10^{-13} ergs cm^{-2} s^{-1} Å^{-1} reported by KSS 22 days after maximum and ~20% higher than the flux at the end of the quiescent interval. This suggests that the hot component of the photosphere, if it exists, comprises a relatively small portion of the WD photosphere.

To test the possibility that a higher temperature component is present in the HUT data, we have fitted the spectrum with the sum of two normal-abundance, $\log g = 8$ atmospheres. These fits have five free parameters: a normalization (essentially a solid angle) and a temperature associated with each component, and the interstellar absorption which affects both. The best fit has a low-temperature component $T_1 = 30{,}000$ K, a high-temperature component $T_2 = 56{,}600$ K, $E(B-V) = 0.02$, and $\chi^2 = 2595$, which is (statistically at least) an improvement over the single-temperature fit described above.[2] (The formal 90% confidence error bars are quite small: 29,100 K < T_1 < 31,400 K and 54,000 K < T_2 < 58,000 K.) The improvement in χ^2 is primarily due to the better fit below 970 Å. A comparison between the best single-temperature fit and the best two-temperature fit to the data for the region below 1100 Å is shown in Figure 6. The lower ionization lines are also somewhat weaker than was the case for the one-temperature fits, owing to the fact that the high-temperature component dilutes their effect on the overall spectrum. The two-temperature fits do not explain N v λλ1239, 1243 or the red wing of Lyman-β (assuming this to be O VI λλ1032, 1038) because the temperatures are still not hot enough to produce these ions in the photosphere.

If the high temperature is due to a hot component on the surface of the WD, the fits suggest that the hot component occupies ~15% of the visible surface. The total luminosity of the hot component (for an assumed distance of 78 pc) is 2.7×10^{32} ergs s^{-1} compared with 1.2×10^{32} ergs s^{-1} for the cool component. However, the hot component radiates primarily in the region below 1200 Å. The high-temperature component contributes 81% of the flux at 950 Å, but only 33% of the flux at 1620 Å. If the hot component cooled back to 30,000 K then the 1620 Å flux would decline by about 22%, which is consistent with the 20% decline reported between outbursts (KSS). At optical wavelengths the disk dominates emission from the U Gem system; the WD contributes only about 18% of the flux. Therefore, given the intrinsic variability of the disk, it is not surprising that the decline in the flux from the WD, which would be only 4% of the total flux, is not observed at visual wavelengths.

3.5. *High-Ionization Lines*

The models we have described fit the overall shape of the HUT spectrum of U Gem fairly well. There are a number of discrepancies, however, and some of the more glaring problems are associated with the absorption features at the position of O VI λλ1032, 1038, N v λλ1239, 1243, and (to a lesser degree) C IV λλ1548, 1551, which are the highest ionization permitted transitions in the HUT spectral range. There is no doubt about the identification of N v λλ1239, 1243, which has been observed previously with *IUE*, since there are no other transitions which are likely to be strong at this wavelength. The reason our models do not account for N v is also easy to understand. N v λλ1239, 1243 is not a strong feature in our WD models or those of Henry et al. (1985) until the photospheric temperature reaches about ~100,000 K. This led KSS to suggest that U

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[2] We also carried out fits in which the second component was a blackbody or a power law. The reductions in χ^2 were about half as large as was the case when the second component was a WD atmosphere.

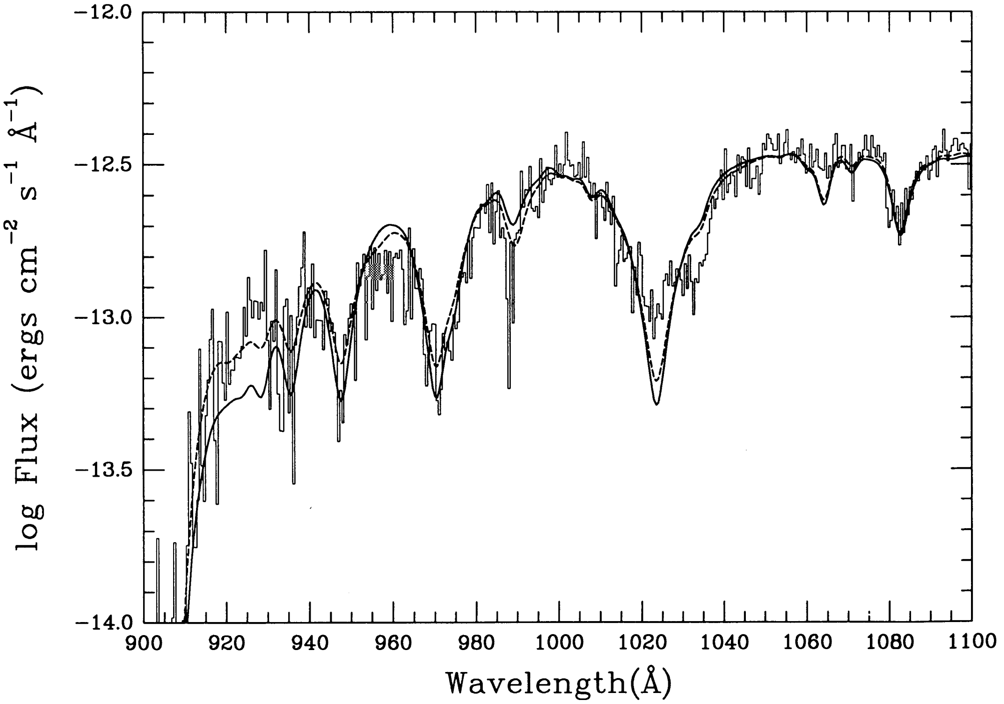

FIG. 6.—Best single-temperature and two-temperature models compared with the HUT data below 1100 Å. The solid curve is the best single-temperature fit which was shown for the full wavelength range in Fig. 5. The dashed curve is the best two-temperature fit to the data. The high-temperature component contributes 81% of the light at 950 Å but only 33% of the flux at 1620 Å. The fits are almost indistinguishable at longer wavelengths.

Gem in quiescence has an optically thin corona above the WD surface.

The situation with regard to the red wing of Lyman-β is more complex than the case of N V because this region contains a low-ionization line, C II λ1037, as well as O VI $\lambda\lambda$1032, 1038. In addition, there may be a small amount of Lyman-β emission near 1026 Å due to airglow. As a result, it is not obvious that the two components of O VI would be readily apparent, even though they are separated by 5.7 Å and are normally well resolved in HUT data. Therefore, we have carried out a series of detailed fits to the region between 1000 and 1050 Å. For these fits we assumed that the overall continuum was determined from a single-temperature white dwarf model and have added various lines, all of which were assumed to have Gaussian shapes. To account for possible weak Lyman-β airglow emission, we included a component at the position of Lyman-β whose width was fixed at 10 Å to match that observed from Lyman-α. (This is the expected width for the large aperture used in this observation.) For O VI and C II the line widths were fixed at 3.5 Å (in accord with other single absorption lines measured elsewhere in the spectrum). We carried out fits assuming both solar abundances and pure H for the white dwarf atmospheres. (The results using solar abundance atmospheres produced slightly higher values of χ^2 but were otherwise similar to the fits obtained with pure hydrogen atmospheres.)

We first fitted the data with a pure H model with Lyman-β and C II. The best fit we obtained had $\chi^2 = 113.9$ for 97 data points and four free parameters. We then added O VI to the fits, assuming either the optically thick or the optically thin limit for the ratio of the two lines. In both cases, χ^2 improved substantially, with somewhat better results obtained for the optically thin case, which yielded $\chi^2 = 99.4$ for 97 data points and five free parameters. For the best fit, the EW of the O VI lines is about 2 Å, which is similar to that for C II. However, in view of the difficulty in the local placement of the continuum level, these values should be regarded as very approximate. Nevertheless, the fits certainly suggest that O VI contributes significantly to the absorption feature in our spectrum.

The spectra of many CVs in outburst show P Cygni profiles which are usually interpreted as evidence of a wind in the inner portion of the accretion disk (Mauche & Raymond 1987; Drew 1987). This interpretation is supported by UV observations of eclipsing systems (Holm, Panek, & Schiffer 1982; King et al. 1983; Cordova & Mason 1985), including, most recently, the HUT observations of the nova-like variable UX UMa, which show that the accretion disk is eclipsed but that the O VI (!), N V, and C IV emission-line–producing regions are not (Long et al. 1991a). There is not statistically significant evidence for a red emission wing on any of the resonance lines in the HUT spectrum of U Gem, although it is interesting that the apparent blueshift of the C IV absorption line is somewhat larger (3.3 Å) than that of most of the other lines (e.g., Si IV, which is shifted by 2.6 Å), which may indicate some mass loss is occurring. In quiescence, the *IUE* spectra of most dwarf novae show N V and C IV in emission; usually, this emission is assumed to arise from the accretion disk itself. In U Gem, as in a number of other CVs, hard X-ray emission is observed in quiescence (Cordova & Mason 1984). This is often interpreted in terms of a cloud of 10^7–10^8 K gas which might be expected to form around the WD when the accretion rate is low (see, e.g., Pringle 1977; Tylenda 1981). This gas could aid in the formation of O VI and the other high-ionization ions in several ways. First, photoionization of the residual wind and the outer atmosphere of the WD by X-rays from the hot plasma would tend to produce O VI. Second, the transition/cooling zone between the hot gas and the photosphere of the WD could produce the column densities of order 10^{15} cm^{-2} needed to produce the equivalent widths observed in U Gem.

4. DISCUSSION

The evidence that FUV emission from U Gem is dominated by emission from the WD is now very compelling. Better observations are needed to characterize fully the decline in flux between outbursts and its relationship to the second component of the emission that we find in the HUT data. Nevertheless, it is very tempting to associate the second component with the decay of the flux as observed with *IUE*.

Two other dwarf novae—WX Hyi (Hassall, Pringle, & Verbunt 1985) and VW Hyi (Verbunt et al. 1987)—have UV fluxes which decrease during their quiescent intervals. In both of these systems, outbursts are separated by 10–25 days, much less than is observed for U Gem. In WX Hyi the flux decreases with an *e*-folding time of about 6 days. In VW Hyi the flux decrease between outbursts is 20%–30%, similar to that observed in U Gem. The quiescent spectrum of VW Hyi appears to contain a broad Lyman-α absorption line which Mateo & Szkody (1984) interpret as direct evidence of a WD photosphere with $T = 18{,}000 \pm 2000$ K. The only emission line in VW Hyi is C IV $\lambda\lambda$1548, 1551, which may also indicate that the disk is weak in quiescence. The evidence that the WD dominates is weaker in WX Hyi. Its spectrum does not show Lyman-α in absorption, and metal lines in the system remain in emission throughout quiescence.

It is important to understand the cause of the flux decline in all of these systems. If it reflects a decreasing accretion rate, then the decline in the flux poses a direct challenge to disk instability models of dwarf nova outbursts. These models predict that the flux should increase slowly between outbursts (see Mineshige & Wood 1989 and references therein). On the other hand, if the WD dominates, then the decline in UV emission may be revealing something about the response of the WD to the outburst.

4.1. *Prompt Radiation due to Ongoing Accretion*

If the 57,000 K component we observe in U Gem is due to ongoing accretion, then the emission could arise either from the accretion disk itself or from the boundary layer between the accretion disk and the WD surface. However, emission from the accretion disk itself appears unlikely, since very high accretion rates ($>10^{18}$ g s^{-1}) are required to produce an optically thick disk with temperatures this high. If the emission from the disk resembles typical steady state accretion disk models (see, e.g., Wade 1984), such accretion rates would produce much more UV and optical emission than is observed from U Gem in quiescence.

Prompt emission from the boundary layer is more difficult to exclude. In the standard picture of CVs, the kinetic energy associated with the Keplerian motion of matter at the inner edge of the accretion disk represents half the total accretion energy (Lynden-Bell & Pringle 1974). If this energy is radiated promptly, then the bolometric luminosity of the boundary layer can equal the disk luminosity, or $L_b = (GM\dot{m})/(2R)$. Simple arguments based on the scale height and density of the emitting region suggest (Pringle 1977), and numerical calculations appear to confirm (Kley 1989), that if the accretion rate is high, the boundary layer will be optically thick and radiate approximately as a blackbody. Furthermore, because the effective area of the boundary layer is smaller than the area of the disk, the boundary-layer temperature T_b should be higher (200,000–500,000 K) than the effective temperature of the disk (20,000–50,000 K). Thus, the boundary layer will radiate primarily at EUV and soft X-ray wavelengths, while the disk dominates at UV and optical wavelengths. Conversely, if the accretion rate is low, the boundary layer will be optically thin and most of the energy will be radiated as hard (1–20 keV) X-rays.

U Gem exhibits large soft X-ray enhancements ($T_b \leq$ 300,000 K) during optical outbursts and a much harder X-ray spectrum during quiescence (Cordova & Mason 1984). It is, in fact, one of the few CVs that appears to provide direct confirmation for the standard model. If this picture is really correct for U Gem, then the second component in U Gem is not prompt emission from the boundary layer, because in the standard model the characteristic temperature associated with boundary-layer emission at low accretion rates is much higher than 57,000 K.

However, an alternative not excluded by the X-ray observations is that the boundary-layer temperature drops in U Gem when the accretion rate drops, since in that case interstellar absorption would hide the very soft X-rays and EUV photons that would dominate the boundary-layer emission. The hard X-rays that are observed might arise from a coronal region that exists in both outburst and quiescence. After all, the hard component does not disappear in outburst. It is simply that the hard X-ray flux rises much less than the soft X-ray flux.

If the 57,000 K component in the HUT spectrum arises from an optically thick (portion) of the boundary layer and if the distance to U Gem is 78 pc, then our observations imply that $L_b = 2.7 \times 10^{32}$ ergs s^{-1}, $R = 4.9 \times 10^8$ cm, and the boundary-layer region occupies ~15% of the WD surface (see § 3.4). If the boundary layer was powered by ongoing accretion during our observations and if the mass M of the WD is 1 $M_\odot$, then the accretion rate $\dot{m}$ must have been (at least) 1.7×10^{15} g s^{-1}. (In quiescence the X-ray luminosity of U Gem is only 2.2×10^{30} ergs s^{-1} [Cordova & Mason 1984], and so including this as part of the boundary-layer luminosity would not alter $\dot{m}$ significantly.)

There is an accretion disk in U Gem during quiescence which is observed at optical wavelengths (see, e.g., Marsh et al. 1990). To see whether this disk is consistent with an accretion rate of 1.7×10^{15} g s^{-1}, we have constructed steady state accretion disk models for U Gem based on the prescription defined by Wade (1984) and discussed in the context of the HUT spectrum of Z Cam by Long et al. (1991b). Assuming the values of M, $\dot{m}$, and R from above, and a distance of 78 pc, the model yields an isotropically averaged flux of $\sim 10^{-13}$ ergs cm^{-2} s^{-1} Å^{-1} at 1400 Å. This corresponds to about one-half the flux we observe from U Gem at this wavelength. Had the contribution from the disk actually been this large, it would be surprising that it did not have a more obvious signature in the HUT spectrum. The model also yields a flux of 1.7×10^{14} ergs cm^{-2} s^{-1} Å^{-1} at 5700 Å, or $m_v = 13.3$, which is brighter than the value of $m_v = 14$ that was reported by the AAVSO at the time of our observation. Furthermore, both the hot spot where matter from the secondary hits the disk, and the WD, contribute significantly to the optical light from U Gem in quiescence. The hot spot in U Gem is eclipsed by the secondary star, and U Gem fades by ~0.9 mag when this happens (Krzeminski 1965); therefore, the white dwarf and the disk are no brighter than $m_v = 14.9$, or 5×10^{-15} ergs cm^{-2} s^{-1} Å^{-1}. A 30,000–40,000 K WD with a flux of 2×10^{-13} ergs cm^{-2} s^{-1} Å^{-1} at 1300 Å will have a visual magnitude of $m_v = 15.6$, or a flux of 2×10^{-15} ergs cm^{-2} s^{-1} Å^{-1} at 5700 Å. Therefore, the disk alone should have $m_v = 15.2$, or a flux of 3×10^{-15} ergs cm^{-2} s^{-1} Å^{-1} at 5700 Å, more than a factor of 5 fainter than the model prediction for the disk flux. These comparisons suggest that the accretion rate was too low at the time of our observation to explain the 57,000 K component as prompt radiation from an optically thick boundary layer.

4.2. *Boundary-Layer Cooling between Outbursts*

An alternative possibility is that the second component is a hot accretion belt created (or at least rejuvenated) in outburst which cools slowly between outbursts to account for the decline in the UV flux. The physical basis for the evolution of such belts might be either (*a*) deep radiative heating of the outer layers of the WD by the boundary layer during outburst and the slow diffusion of that heat out of the WD between outbursts (Pringle 1988) or (*b*) spin-up of the surface layers of the WD during outburst and the slow conversion of kinetic energy to heat as a result of viscous heating in the differentially rotating atmosphere (cf. Kippenhahn & Thomas 1978; Kutter & Sparks 1987, 1989).

As noted earlier, in the standard model of CV outbursts, up to half the accretion energy is released in an optically thick boundary layer. A portion of this energy will be absorbed by the WD atmosphere. Pringle (1988) has attempted to calculate the amount of energy that could be stored in the WD atmosphere during outburst and reradiated when the dwarf nova returned to quiesence. He found that the flux decline in VW Hyi could be explained if the boundary-layer temperature T_b reached 10^6 K. Kley's (1989) boundary-layer models indicate that temperatures at the surface of the WD in the equatorial plane do reach 10^6 K. The time constant in U Gem is much longer than in VW Hyi, but the thermal time scale and the total amount of energy deposited in the photosphere both scale as $T_b^{21/4}$. Therefore, relatively modest changes in T_b (and the fact that the WD in U Gem may be intrinsically hotter) would be needed to account for the differences between U Gem and VW Hyi.

However, measured boundary-layer temperatures appear to be lower than required. For example, in U Gem, the observed X-ray temperature is $\lesssim$300,000 K (Cordova & Mason 1984). More generally, the fact that only a few CVs exhibit the large soft X-ray enhancements suggests that temperatures are not as high as 10^6 K unless there is substantial absorption within the CV which prevents the X-ray radiation from escaping. Furthermore, Hoare & Drew (1991) have used a Zanstra analysis of He II emission in CV outbursts to argue that boundary-layer temperatures are actually between 50,000 and 100,000 K in most CVs. If these lower temperatures are representative, then the heated region of the WD atmosphere will not be sufficiently massive to keep the boundary layer hot between outbursts.

Another way to store part of the accretion energy from the outburst phase is to assume that the surface layers of the WD spin up during outburst.[3] In this case, the rate at which the energy is released will be determined by the effective viscosity of the differentially rotating WD atmosphere. The classical viscosity is quite low, and so, in the absence of magnetic fields which could pin the interior to the surface layers, the dominant source of viscosity is not completely understood. Kippenhahn & Thomas (1978) argue that an instability known as shear

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[3] This also might help explain why observations of several CVs, including VW Hyi (Mauche et al. 1991), suggest that boundary-layer luminosities are far less than disk luminosities.

mixing should dominate. They and Kutter & Sparks (1987, 1989) have carried out several calculations of continuous accretion onto differentially rotating WD atmospheres in an attempt to understand the time scale to thermonuclear runaway in classical novae and find substantial boundary-layer luminosities. If they are correct, shear mixing should be important for WDs in CVs as well (Sion 1985).

Recently, Sparks et al. (1992) attempted to model the temperature decline of the WD in the unusual dwarf nova WZ Sge in terms of shear mixing. Since its last outburst in 1978, the effective temperature of the WD in this system has dropped from 30,000 to 12,500 K (La Dous 1990). In their numerical simulation, Sparks et al. deposited a total kinetic energy of 1×10^{40} ergs on the surface of a 0.9 $M_\odot$ WD in 3 days. This simulation yielded a heated layer with a mass of 4×10^{-10} $M_\odot$ and a postoutburst luminosity of 1.2×10^{33} ergs s^{-1}, somewhat larger than is observed in U Gem. This luminosity implies a decay time of order 100 days, about that observed in U Gem. The surface layer, which covered a broad belt with a full width of 40° during the brief shear-mixing episode, had a belt luminosity corresponding to a temperature of 75,000–100,000 K. The penetration of the accreted material will be deepest at the equator, and hence the thermal time scale of the heated layer should be longer there than at higher latitudes (cf. Sion & Szkody 1990). Therefore, it is probably not significant that we observe a region which is significantly smaller ($\sim$17°) than the full zone in which shear mixing occurs. Thus, differential rotation of the surface layers of the WD and shear mixing appear to be a promising possibility for explaining both the existence and the subsequent decay of a heated accretion belt on the surface of U Gem.

5. SUMMARY AND CONCLUSIONS

We have used the Hopkins Ultraviolet Telescope to obtain an FUV spectrum of U Gem about 10 days after the end of an outburst. Most of the FUV emission from U Gem appears to rise from the WD in the system. The average temperature of the photosphere during our observation was about 38,000 K, which is higher than was deduced by Panek & Holm (1984) based on observations of U Gem during quiescence with *IUE*. The strengths of many, but not all, of the absorption lines in U Gem can be explained if abundances in the photosphere of the WD in U Gem are approximately solar. However, single-temperature models do not fit the spectral shape below 970 Å particularly well. Two-temperature models in which $\sim$85% of the WD surface has a temperature of 30,000 K and $\sim$15% has a temperature of $\sim$57,000 K fit the region below 970 Å better.

We have explored various possibilities to explain the hot component in our spectrum. It is most likely due to radiation from the boundary-layer region of the WD surface rather than from the accretion disk which exists in U Gem in quiescence. If the standard picture of boundary-layer emission is correct, then the hot component is not due to ongoing accretion onto the WD because the temperature we observe is too low. Furthermore, if the emission were due to an optically thick boundary layer powered by ongoing accretion, the associated disk would be brighter than observed. A more promising explanation appears to be delayed emission from a viscously heated, differentially rotating atmosphere. This accounts naturally for the existence of the 57,000 K component and the decay of the UV flux from U Gem during quiescence. Clearly, additional observations of U Gem at different times during the outburst cycle (preferably with an instrument which can observe down to the Lyman limit) are needed to characterize better both the spectrum of the hot component and its decline during the outburst cycle and to provide more exacting constraints on possible models for this system.

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