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HOPKINS ULTRAVIOLET TELESCOPE OBSERVATIONS OF U GEMINORUM FAR FROM OUTBURST

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ABSTRACT

The Hopkins Ultraviolet Telescope was used during the Astro-2 Space Shuttle mission to obtain a far-ultraviolet (820–1840 Å) spectrum of the dwarf nova U Geminorum in its low state. At the time of the observation, U Gem had been at optical minimum for 185 days. The HUT spectrum is dominated by the white dwarf star, and shows (among other things) very strong, broad hydrogen Lyman absorption lines. A comparison with solar abundance white dwarf models indicates a temperature near ~30,000 K. Comparison to a similar spectrum obtained during the Astro-1 mission in 1990, only 10 days after U Gem had returned to the low state following a normal outburst, confirms that the average temperature of the white dwarf in U Gem drops substantially between outbursts. Furthermore, differences between the models and the data at the shortest wavelengths in both spectra support the hypothesis that the surface temperature is nonuniform and that a decrease in the relative importance of a hot region, possibly a belt, on the surface of the white dwarf causes the observed 30% decline in flux at 1450 Å far from outburst.

Subject headings: stars: binaries: close — stars: individual (U Geminorum) — stars: novae, cataclysmic variables — ultraviolet: stars

1. INTRODUCTION

U Geminorum lies at a distance of about 90 pc (Marsh et al. 1990) and is the prototypical dwarf nova, undergoing quasi-periodic outbursts ($\Delta t \sim 118$ days; $\Delta m_v \sim 5$) lasting typically 7–14 days (Szkody & Mattei 1984). It is thought to consist of a $1 \pm 0.25\ M_\odot$ white dwarf (WD) and a $0.36 \pm 0.10\ M_\odot$ M5 star exchanging matter by means of a viscous accretion disk (Wade 1981). The binary orbital period is 4.25 hr.

U Gem was observed with the Hopkins Ultraviolet Telescope (HUT) during the Astro-1 Space Shuttle mission in 1990 December, just 10 days after the system had returned to optical quiescence following a normal outburst (Long et al. 1993). The 830–1860 Å spectrum that was obtained with HUT showed a "blue" continuum with strong absorption features due to the Lyman series of hydrogen and weaker metal absorption lines. The HUT observation provided compelling proof that the quiescent UV spectrum of U Gem is dominated by emission from the WD, as Panek & Holm (1984) had argued from *IUE* spectra, and showed that the abundances in the atmosphere of the WD were approximately solar. Model fits to the Astro-1 observations implied an average WD temperature of ~38,000 K, which is higher than the temperature derived from *IUE* observations far from outburst. This suggested that the WD in U Gem is heated during outburst and then cools between outbursts, consistent with evidence for a decline in the UV flux with time from outburst (Kiplinger, Sion, & Szkody 1991). The Astro-1 data could also be fitted to a two-T model for the WD in which 85% of the surface had a temperature of 30,000 K and 15% had a temperature of 57,000 K, which Long et al. (1993) suggested might arise from a viscously heated differentially rotating atmosphere produced by the outburst. Subsequently, Long et al. (1994) obtained 1150–1650 Å spectra with the Faint Object Spectrograph FOS on the *Hubble Space Telescope* ~13 and 70 days after outburst; comparison of these spectra with solar abundance models showed a temperature drop from 39,400 to 32,100 K. Because the FOS spectra do not extend to wavelengths less than 1160 Å they are relatively insensitive to departures from a uniform temperature distribution.

In this Letter, we report a second observation with the Hopkins Ultraviolet Telescope of U Gem in quiescence, an observation obtained on the Astro-2 space shuttle mission in 1995 March at a time when U Gem had been at optical minimum for 185 days.

2. OBSERVATIONS

HUT is an instrument designed for use as an attached payload on the Space Shuttle. It consists of a 0.9 m primary mirror, a prime focus Rowland spectrograph, and a CsI-coated microchannel-plate-intensified photon-counting detector (Davidsen et al. 1992). For Astro-2, the spectrograph covered the wavelength range 820–1840 Å and had a resolution that varied slightly with wavelength but was typically 3 Å. Improvements to the telescope and the performance of the instrument on Astro-2 are documented by Kruk et al. (1995).

U Gem was observed through a 20″ diameter circular aperture on 1995 March 8 beginning at 14:51 GMT (JD 2449785.11865) for 1960 s. The observation was during orbital night, which minimized airglow contamination, and the total source counting rate was ~100 counts s^{-1}. U Gem had been at

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[1] Astro-2 Guest Investigator.

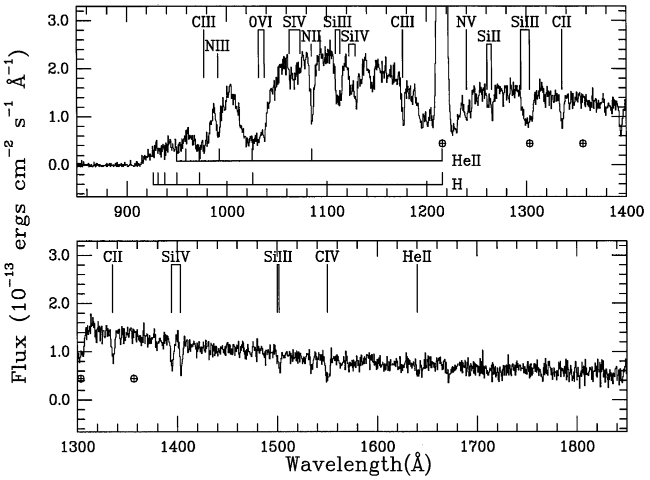

FIG. 1.—Flux-calibrated spectrum of U Gem as observed on Astro-2. In addition to broad absorption lines due to the Lyman series of hydrogen, numerous metal absorption features can be seen.

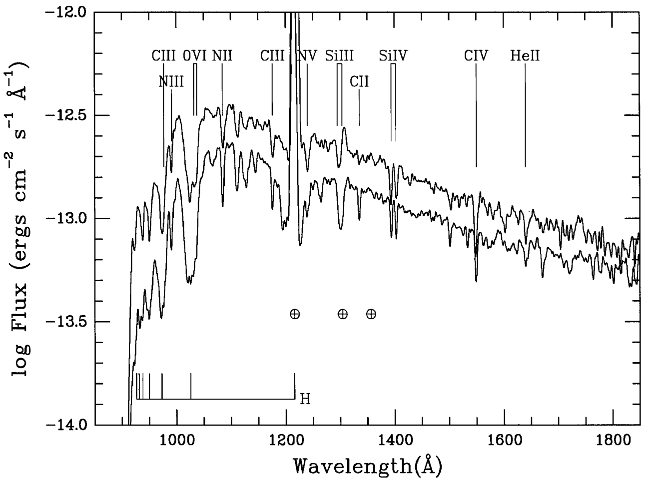

FIG. 2.—Comparison between the spectra obtained on Astro-1 (*upper curve*) and Astro-2 (*lower curve*). The flux on Astro-2 was about 30% less than on Astro-1 at 1450 Å. The Lyman lines are broader on Astro-2 and the flux decline is greatest at the shortest wavelengths, indicating a lower temperature. On Astro-1, there is evidence for O VI λλ1032,1038 on the red wing of Lyman-β. The data for both spectra have been smoothed with a Gaussian (3 Å FWHM).

optical minimum since the previous "wide" outburst had ended on JD 2,449,600, 185 days before the HUT observation. The next outburst, also a "wide" outburst, began on JD 2449810, 24 days later. The time from the beginning of the previous outburst to the next outburst was 237 days, the longest interval between outbursts in the AAVSO records since 1943 (J. Mattei 1995, private communication). Hence, the HUT spectrum of U Gem reflects the system a very long time from outburst.

The flux-calibrated spectrum of U Gem is shown in Figure 1. It was obtained using a calibration procedure that corrects the count rate spectrum for dark count and grating-scattered light (using the count rate below 912 Å), for doubly counted photons (arising from persistence in the phosphor of the HUT detector) and for second-order photons (affecting the spectrum at wavelengths longer than 1824 Å) and then multiplies the corrected count rate spectrum by a time-dependent sensitivity function. The systematic uncertainty in the flux calibration is less than 5% (Kruk et al. 1995).

In many ways, the Astro-2 spectrum of U Gem resembles that obtained during Astro-1 (see Fig. 2). The Lyman series of hydrogen is observed through at least Lyman-δ, and there are a large number of metal lines which can be identified with either He II or metal ions (see Fig. 1). U Gem was fainter when observed on Astro-2. Near 1450 Å, the Astro-2 flux is ~70% of the Astro-1 flux. This should be compared with the 28% decline measured by Long et al. (1994) from FOS spectra obtained 10 and 70 days from an outburst. For the Astro-2 observation the color temperature is also lower and Lyman-α, Lyman-β, Lyman-γ, and Lyman-δ all have larger equivalent widths in the Astro-2 data, consistent with emission from a lower temperature WD.

3. ANALYSIS

We have analyzed the Astro-2 spectrum of U Gem with the same grid of white dwarf model spectra use to interpret the Astro-1 and *HST* spectra of U Gem (Long et al. 1993, 1994). Each of the model spectra were constructed using the pair of programs TLUSTY and SYNSPEC (Hubeny, Lanz, & Jeffery 1995; Hubeny & Lanz 1995). We have fitted the models to the Astro-2 data using the IRAF task SPECFIT (Kriss 1994), a nonlinear χ^2 minimizing routine, assuming that the only errors in the HUT data are due to counting statistics. Our model fits also allow us to vary the amount of reddening using the mean Galactic extinction curve of Longo et al. (1989). We have allowed for the effects of neutral hydrogen, $N_{\rm H}$, along the line of sight, fixing the quantity at 3.1×10^{19} cm^{-2}, as measured from absorption lines in high-resolution *IUE* spectra of U Gem by C. Mauche (1995, private communication).

We first fit the entire HUT spectrum (920–1840 Å), omitting the region within 10 Å of Lyman-α that is contaminated by airglow. The best-fit model has a temperature of 29,700 K and $E(B-V)$ of 0.03. The overall normalization implies a WD radius of 5.4×10^8 (D/90 pc) cm, consistent with a WD mass of 1.05 $M_\odot$. This radius is very close to the radius 5.1×10^8 (D/90 pc) cm inferred from similar fits to the Astro-1 data. As

TABLE 1

SUMMARY OF MODEL FITS TO HUT SPECTRA OF U GEMINORUM

Model Description	Wavelengths Used	χ^2	DOF	T(K)	$E(B-V)$
One-T, solar abundances	920–1205, 1226–1840	3437	1767	29,700	0.032
One-T, solar abundances	1226–1840	1390	1175	29,900	0.029
Lyman-α region only	1165–1205, 1227–1260	384	132	28,000	···
Two-T, solar abundances	920–1205, 1226–1840	2919	1765	28,600 102,100	0.033
Astro-1, One-T	920–1205, 1226–1840	2789	1806	37,700	0.035
Difference	920–1205, 1226–1840	1983	1709	53,000	0.032

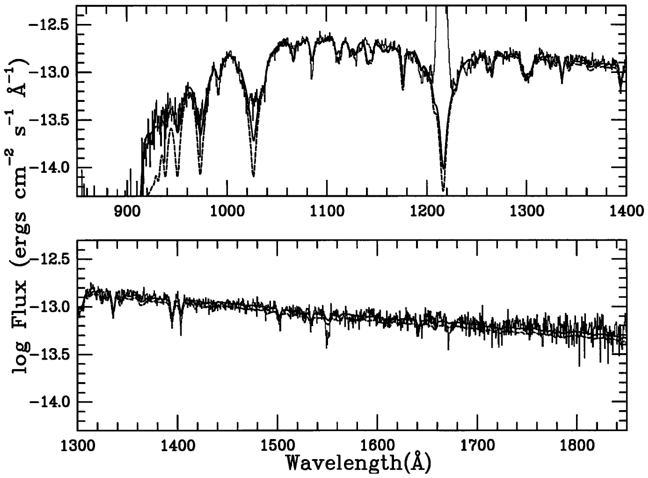

FIG. 3.—Comparison between the Astro-2 spectrum of U Gem and the best-fitting single-temperature and two-temperature WD models (see Table 1). The best-fitting single-temperature model, shown as the dashed line, has $T = 29{,}700$ K and has too little flux at the shortest wavelengths and deeper Lyman line profiles than the HUT data. The two-temperature model, shown as the solid line, fits the data near the Lyman limit substantially better than the single-temperature model. The effective temperature of the second component is about 102,000 K.

indicated in Table 1, fits limited to the Lyman-α region also indicate a lower temperature for Astro-2, although in this case the best fit is 28,000 K.

The best-fitting single-temperature model is shown as the dashed line in Figure 3. The model provides a reasonable characterization of the data, especially longward of Lyman-α. Fits restricted to this wavelength range yield almost identical values of temperature and $E(B-V)$ (see Table 1). Longward of Lyman-α, the only real discrepancies are the depths of a few lines, most notably N V $\lambda\lambda1239$, 1243 and C IV $\lambda\lambda1548$, 1551. Shortward of Lyman-α, the main problem is that the models underestimate the flux near the Lyman limit and have deeper Lyman line profiles than is observed. The magnitude of the error is substantial, a factor of 4 at 925 Å. In addition there are some differences in absorption line profiles evident in the wavelength range 1080–1160 Å.

In an attempt to determine whether our WD model spectra are sensitive to the input physics, we have experimented with a limited grid of non-LTE models with temperatures near 30,000 K, a separate set of models in which cosmically abundant elements were incorporated into the atmospheric structure and spectral calculations, and a group of models in which the gravity was varied from $\log g = 6$ to $\log g = 9$. None of these changes improved the fits significantly, although relatively low-gravity ($\log g = 6$) models tend to have more flux at the shortest wavelengths due to the fact that the higher order Lyman lines are less blended. However, our estimate of mass and radius above suggests $\log g \sim 8.6$, not 6. We have also compared the Astro-2 spectrum of U Gem to the HUT spectrum of GD 71, a 32,400 K DA WD. The Lyman line profiles of GD 71 are not "filled in" compared to the models, and the GD 71 spectrum falls more rapidly between 950 Å and the Lyman limit than the U Gem spectrum. As a result of these considerations, we believe there must be real departures in the spectrum of U Gem from that of a "simple" WD.

From the Astro-1 data, using single-temperature, normal abundance models, we derived a higher temperature of 37,700 K and an almost identical $E(B-V)$ of 0.035. The main shortcomings of the model fits for the Astro-1 data were that the models underestimated the flux below 970 Å, underestimated N V $\lambda\lambda1239$, 1243 and C IV $\lambda\lambda1548$, 1551 equivalent widths, and did not produce the red wing of Lyman-β. N V $\lambda\lambda1239$, 1243 and C IV $\lambda\lambda1548$, 1551 were considerably stronger during Astro-1, and Long et al. (1993) argued that the structure on the red wing of Lyman-β was due to the presence of O VI $\lambda\lambda1032$, 1038 absorption in an accretion disk corona or wind. Therefore, the difficulties we have in fitting the Astro-2 data near the Lyman limit are similar to problems with the Astro-1 data, but the failure to model the depth of the Lyman line profiles is new.

In the earlier analysis of the Astro-1 U Gem spectrum, we investigated the possibility that part, but not all, of the WD surface had been heated by the previous outburst. There were three observational rationales for investigating such a possibility: (1) the discrepancy between the best-fit single-temperature model and the data, (2) the proximity of the observations to an outburst, and (3) the fact that the observed decline in UV flux far from outburst (Kiplinger et al. 1991) was less than expected for a 37,700 K WD cooling to 30,000 K. We found that the Astro-1 data and the decline in the UV flux could be modeled in terms of a WD in which 85% of the WD surface was at a temperature of 30,000 K and in which the remainder was at ~57,000 K.

Two temperature fits also improve the match to the Astro-2 spectrum (see Table 1). The best fit is obtained with 99% of the WD surface at 28,600 K and the remaining 1% at 102,100 K (close to the maximum temperature model in our grid). The best fit, shown as the solid line in Figure 3, is a better match to the shortest wavelength portion of the data, consistent with the hypothesis that the "extra" emission arises from the surface of the WD. Although we regard the improvement in χ^2 as suggestive, we note that models consisting of a uniform temperature WD and a power law produce very similar improvements in χ^2, reflecting the fact that the departures from a single-temperature WD are confined to a very small region of the spectrum. Thus we cannot rule out the possibility that the "extra" component in the Astro-2 data arises from some other source, e.g., the disk.

To explore the change between the spectrum of U Gem just after the return to quiescence and far from outburst, we have subtracted the Astro-2 spectrum from the Astro-1 spectrum. As shown in Figure 4, the difference spectrum looks like a WD, which lends credence to the hypothesis that the temperature of the WD surface was nonuniform during the Astro-1 observation. Model fits to this difference spectrum indicate a temperature of ~53,000 K. The difference spectrum does not resemble the HUT spectra of any other systems—SS Cyg, YZ Cnc, or WX Hyi—which appear to be dominated by the disk in quiescence.

4. DISCUSSION

The Astro-2 observations of U Gem far from outburst clearly show that the average temperature of the WD in the U Gem system cools between outbursts, solidifying the picture of the system developed with *IUE* (Kiplinger et al. 1991), Astro-1 (Long et al. 1993), and *HST* (Long et al. 1994). The second HUT observation makes this conclusion far more robust than before because we can now compare two spectra obtained with the same instrument which include the higher order Lyman lines and the Lyman limit. Furthermore, the *HST*

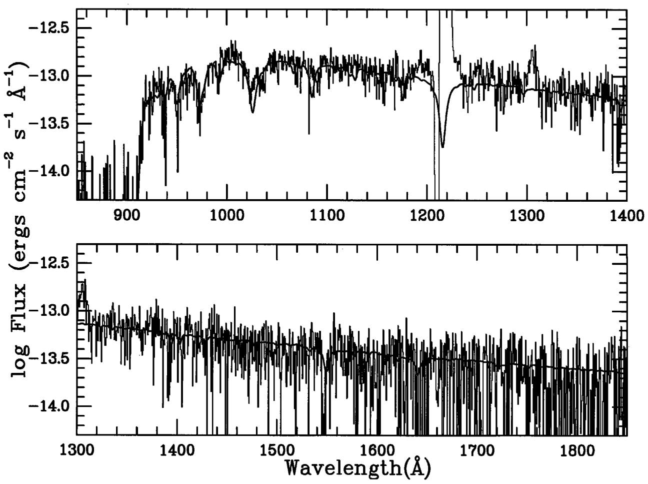

FIG. 4.—Spectrum obtained by subtracting the Astro-2 spectrum from the Astro-1 spectrum. The solid curve is the best-fitting WD model to the difference spectrum. It has a temperature of 53,000 K. The difference spectrum does not resemble any of the dwarf novae observed in quiescence with HUT whose UV light appears to be dominated by the disk.

and Astro data, taken together, suggest that most of the cooling takes place within the first 70 days after outburst.

A number of explanations have been advanced to explain cooling of the WD in a dwarf nova in the interoutburst interval. Pringle (1988) suggested that heat diffusing into the atmosphere during the outburst and back out of the atmosphere in quiescence might account for the WD observed in VW Hyi. However, in U Gem at least, the *EUVE* observations (Long et al. 1995) suggest a boundary layer temperature near 135,000 K, which is not high enough to produce the desired effect. Meyer & Meyer-Hofmeister (1994) suggested that self-sustaining coronal flows exist in dwarf novae after outburst which evaporate material from the inner accretion disk and deposit it onto the WD. The accretion rate declines with time, which would account for the cooling of the WD. Sion (1995) proposed that compressional heating, the heat produced by the weight of accreted material on the atmosphere, results in heating of 5000–10,000 K. Sion's spherically symmetric modeling of compressional heating also indicated cooling timescales of several months, which may be appropriate for U Gem. In our analysis of the Astro-1 data, we proposed that spin-up of the surface layers of an accretion belt on the WD during outburst and the slow conversion of rotational kinetic energy to heat in the differentially rotating atmosphere might explain the cooling of the white dwarf (Long et al. 1993). This picture leads naturally to a multitemperature WD. If a hot rotating accretion belt exists, then it may be observable as a Doppler-broadened component of the absorption lines in the WD atmosphere. Recent GHRS spectra of Si IV λλ1394, 1403 in U Gem obtained shortly after an outburst show that most of the WD is slowly rotating ($v \sin i < 100$ km s^{-1}); searches for a rapidly rotating component were unsuccessful (Sion et al. 1994). More observations, especially multiple observations that include the region below Lyman-α of a single quiescence interval, are needed to resolve which of these mechanisms causes the decline in flux with time from outburst from the WDs in U Gem and other dwarf novae.

The Astro-2 observations of U Gem and other cataclysmic variables would not have been possible without the dedicated support of Janet Mattei and the observers of the AAVSO, our colleagues on the HUT team, and the NASA Shuttle mission operations and support crew. This work is supported by NASA contract NAS 5-27000 to the Johns Hopkins University.

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