NEW ULTRAVIOLET OBSERVATIONS OF AM CVn

RICHARD A. WADE, MICHAEL ERACLEOUS, AND HÉLÈNE M. L. G. FLOHIC

Department of Astronomy and Astrophysics, The Pennsylvania State University, University Park, PA 16802, USA; wade@astro.psu.edu, mce@astro.psu.edu, flohic@astro.psu.edu

ABSTRACT

We have obtained observations of the ultraviolet spectrum of AM CVn, an ultrashort-period helium cataclysmic variable, using the Space Telescope Imaging Spectrograph aboard the Hubble Space Telescope (HST). We obtained data in time-tag mode during two consecutive orbits of HST, covering 1600–3150 and 1140–1710 Å, respectively. The mean spectrum is approximately flat in $f_{\lambda}$. The absorption profiles of the strong lines of N v, Si iv, C iv, He ii, and N iv are blueshifted and in some cases asymmetric, evidencing a wind that is partly occulted by the accretion disk. There is weak redshifted emission from N v and He ii. The profiles of these lines vary mildly with time. The light curve shows a decline of $\sim 20\%$ over the span of the observations. There is also flickering and a 27 s (or 54 s) “dwarf nova oscillation,” revealed in a power-spectrum analysis. The amplitude of this oscillation is larger at shorter wavelengths. We assemble and illustrate the spectral energy distribution of AM CVn from the ultraviolet to the near-infrared. Modeling the accretion phenomenon in this binary system can in principle lead to a robust estimate of the mass accretion rate on to the central white dwarf, which is of great interest in characterizing the evolutionary history of the binary system. Inferences about the mass accretion rate depend strongly on the local radiative properties of the disk, as we illustrate. Uncertainty in the distance of AM CVn and other parameters of the binary system currently limit the ability to confidently infer the mass accretion rate.

Key words: accretion, accretion disks — binaries: close — novae, cataclysmic variables — stars: individual (AM Canum Venaticorum) — stars: winds, outflows

1. INTRODUCTION

AMCVn(HZ 29; $\alpha = 12^h34^m54.6^s$, $\delta = +37^\circ37'43''$ [J2000.0], $l = 140^\circ$, $b = +79^\circ$, $V \approx 14.1$) is the type star of the small class of helium cataclysmic variables (HeCVs). These are also called interacting binary white dwarfs, although the mass donor star which fills its Roche lobe and transfers mass via a gas stream and accretion disk to the mass-gaining white dwarf may not itself be fully degenerate. Hydrogen lines are absent from the spectra of these objects. A recent review of the class and a summary of possible evolutionary pathways leading to the AM CVn stars can be found in Nelemans (2005).

The orbital period of AM CVn is $P_{\text{orb}} = 1029$ s (Nelemans et al. 2001). A signal is found at this period in the power spectrum of time-series photometry, and a second signal is found near $P_{\text{sh}} = 1051$ s. This latter signal is thought to represent a “permanent superhump,” at the beat period between the orbital period and the precession period of a noncircular disk. From the fractional excess of $P_{\text{sh}}$ over $P_{\text{orb}}$, it is thought possible to estimate the mass ratio of the binary system, $q = M_2 / M_1$, where $M_2$ is the mass of the donor star (see § 3.4). A recent paper describes a kinematic measurement of $q$ (Roelofs et al. 2006).

The accretion disk in AM CVn appears always to be in a stable “high” state, consistent with the relatively high mass transfer rate that is expected of the HeCVs at the short end of the observed range of periods. (Smak 1983; Tsugawa & Osaki 1997; Deloye et al. 2005). Mass transfer is thought to be driven ultimately by gravitational wave radiation of orbital angular momentum, combined with the expansion of the donor star as mass is lost. In this model, the orbital period evolves to larger values with time, and the mass transfer rate to smaller values. A measurement of the mass accretion rate can help constrain the mass ratio and/or the donor star mass, from which it may be possible to reconstruct the prior history of the binary (Deloye et al. 2005). Inferring the mass transfer rate from observation involves measuring the distance of the system and estimating the bolometric flux, or accurately modeling the spectral energy distribution (SED) of the accretion disk, also taking into account light from the two stars. Either method involves measuring the emitted spectrum over a broad range of wavelengths.

The visible spectrum of AM CVn has been studied extensively, and the visible SED has been modeled on the assumption that it is dominated by the accretion disk (e.g., El-Khoury & Wickramasinghe 2000; Nesser et al. 2001; Nagel et al. 2004). A reasonable degree of success has been achieved in these studies in accounting for the profiles of the He i absorption lines, although different authors have inferred (or imposed!) different properties of the disk such as the mass transfer rate, the disk size, and the disk inclination. The ultraviolet (UV) spectrum and the overall SED have received less attention in recent years but offer the possibility, when used together with the He i lines, of more powerfully constraining the parameters of the disk model.

With the above considerations in mind, we obtained observations of the UV spectrum of AM CVn using the Space Telescope Imaging Spectrograph (STIS) aboard the Hubble Space Telescope (HST). One goal was to model the UV absorption line spectrum of the accretion disk in some detail and thus infer the mass transfer rate $dM/dt$ and inclination angle $i$ of the disk rather directly. We also hoped to learn more about the chemical composition of the material being transferred. Instead of showing an absorption spectrum that arises purely from a steady disk in local hydrostatic equilibrium, however, the STIS observations show evidence of a disk wind, which obliterates many of the stronger diagnostic lines and blends that are key to such an analysis. Moreover, the
existence of a wind calls into question some of the standard assumptions underlying models of accretion disk atmospheres.

The STIS data greatly exceed, in quality, reliability, spectral resolution, and time resolution, most of the UV observations of AM CVn that were made with the International Ultraviolet Explorer (IUE) in the period 1978–1991 (which nevertheless hinted at the presence of wind line profiles). The STIS data exceed in wavelength coverage some earlier HST observations of AM CVn, made using the Goddard High Resolution Spectrograph (GRHS). They have revealed some behavior not previously reported, including oscillations in light level with a period of $\sim 27$ s.

We defer a detailed modeling effort and in this contribution focus on describing the UV spectrum and its behavior and on presenting the overall SED of AM CVn. We describe the STIS observations and the major features of the spectrum, emphasizing the wind line profiles, their variation with time, and the time variation and power spectrum of the measured fluxes. We assemble the UV-visible-infrared SED of AM CVn, which forms one basis for modeling the accretion process in this binary. We briefly discuss some practicalities and uncertainties of such modeling, which lead to uncertainties in the inferred mass accretion rate. In particular, we illustrate the critical role played by the radiative properties of the gas in the accretion disk. We also emphasize the importance of an accurate knowledge of the binary mass ratio and distance to AM CVn, as they relate to inferring $\dot{M}$.

The paper is organized as follows. In §2 we describe the observations with STIS, then present our findings concerning mean and time-dependent behavior of the flux level and line profiles. In §3 we discuss the apparent variation in UV flux level, identify the 27 s oscillations as “dwarf nova oscillations,” compare the “wind” line profiles with theoretical expectations and observations of other systems, and present and discuss the SED of AM CVn. We briefly summarize our findings and discussion in §4.

2. OBSERVATIONS AND FINDINGS

We observed AM CVn with STIS on 2002 February 21, during two consecutive orbits of the HST. The target was observed in time-tag mode, in the first orbit with the NUV-MAMA and grating G230L for 32 minutes, and in the second orbit with the FUV-MAMA and grating G140L for 40 minutes. Thus, we have complete orbital coverage of the binary star with each detector/disperser setup, but we do not have coverage of the 13.4 hr precessional period of the eccentric disk which gives rise to a 1051 s superhump period (Patterson et al. 1993).

The NUV observation started at 09:16:57 UT and lasted for 1920 s, with wavelength coverage 1577–3161 Å. The FUV observation started at 10:35:48 UT and lasted for 2400 s, thus ending almost 2 hr after the start of the NUV exposure. The FUV wavelength coverage was 1121–1717 Å, overlapping the NUV coverage. The “52X0.1” aperture (0.1 wide, long slit) was used. An acquisition/peak-up sequence of exposures was done prior to the NUV observations to center the star accurately in the slit. During the spectrum exposures, the rms jitter of HST on the V2 and V3 axes was less than about 8.5 mas, with no recenterings and no losses of lock.

2.1. Trend of Flux Level with Time

The light curve of AM CVn (1650–1700 Å integrated flux) during the HST observation is shown in Figure 1. This wavelength range was observed using both instrument setups and does not include any strong lines. There is an apparent, more-or-less steady decline in flux, which corresponds to a change of 0.21 mag over the course of 2 hr.

![Figure 1](image)

**Fig. 1.** Light curve of AM CVn showing the 1650–1700 Å integrated flux during the HST observation. Each point represents a 30 s time interval. Data collection lasted for 2 hr, with a gap owing to Earth occultation of the line of sight between the NUV and FUV observations. An apparent steady decline in flux level is evident, corresponding to a change of 0.21 mag over the course of 2 hr.

A portion of the apparent decline can possibly be accounted for in terms of a small inconsistency of calibration between the NUV/G230L and FUV/G140L observing modes. Three active galactic nuclei (AGNs), observed by one of the authors with STIS using these same modes in the same back-to-back fashion (albeit with the 52X0.2 aperture rather than the 52X0.1 aperture) are suitable as a test of this, since their UV fluxes do not vary significantly over the course of a day. The 1650–1700 Å fluxes differ by about 6%–7%, in the same sense as observed for AM CVn. For AM CVn, the change in the mean NUV/G130L 1650–1700 Å flux to the mean FUV/G140L flux is 15%.

Within each observation (NUV or FUV), a declining straight-line fit to the full-band fluxes binned in 30 s intervals gives a much smaller $\chi^2$ statistic compared with a constant-flux fit, the slopes being $\sim 0.1%$ minute$^{-1}$ in each case. Taking the 1650–1700 Å fluxes at face value, and considering the NUV and FUV data as a single series gives an average decline of 0.17% minute$^{-1}$. Presumptively “correcting” the FUV flux relative to the NUV flux by $\sim 7\%$, as suggested by the AGN data, would give an average rate of decline for the combined data sets of $\sim 0.09%$ minute$^{-1}$, similar to the individually estimated slopes. There is, of course, structure in the light curves on top of straight-line behavior (discussed in §2.3 below), so these exercises are only suggestive, not probative.

We have considered whether there is a likely artificial origin for the apparent decline in flux, and find nothing plausible. Thus, we regard the apparent decline as probably real, perhaps modified by a $\sim 7\%$ correction to the relative calibration of the FUV and NUV data. (We do not apply any such correction further in this paper, however.) In §3.1 we discuss other published observations of AM CVn, as they bear on possible similar flux variations in UV or visible light.

2.2. The Mean Ultraviolet Spectrum

The mean short-wavelength (FUV-MAMA, G140L) spectrum of AM CVn is shown in Figure 2. The spectrum covers 1150–1715 Å with a resolution of 1.4 Å ($\approx 300$ km s$^{-1}$ at midrange),

---

3 See [http://www.stsci.edu/hst/stis/](http://www.stsci.edu/hst/stis/) for the STIS Instrument Handbook.
Fig. 2.—Mean short-wavelength (FUV-MAMA and G140L) spectrum of AM CVn. The spectrum covers 1150–1715 Å with a resolution of 1.4 Å. The strongest absorption features are marked and labeled below the spectrum; the tick marks are shifted to align with the troughs of these features. (See Table 1 for laboratory wavelengths; see Fig. 4 for individual profiles.) Sharp, interstellar lines are indicated with unshifted tick marks above the spectrum (see Table 2). The Ly \( \alpha \) laboratory transition at 1215.15 Å is probably a blend of H \( \alpha \) and He \( \alpha \) from the AM CVn core and red side of the line; if the extended blue wing is included, the EW is 4.26 Å. Given the low resolution offered by the G140L grating, we do not attempt to decompose this feature or derive a H \( \alpha \) interstellar column density.

TABLE 1

| Ion               | \( \lambda_{\text{obs}} \)  | \( \lambda_{\text{k}} \) |
|------------------|-----------------------------|--------------------------|
| H \( \alpha \) Ly\( \alpha \), He \( \alpha \) | 1215.67, 1215.15 | ... |
| N \( \nu \)       | 1238.82, 1242.80            | 1240.8                   |
| Si \( \nu \)      | 1393.76, 1402.77            | 1398.3                   |
| C \( \nu \)       | 1548.20, 1550.77            | 1549.5                   |
| He \( \nu \)      | 1640.38                     | ... |
| N \( \nu \)       | 1718.55                     | ... |

" Vacuum (heliocentric) wavelengths are used throughout. Observed wavelengths of line cores are often shifted from the laboratory values; see Fig. 4.

" Adopted “zero-velocity” wavelength for profiles shown in Fig. 4, in the case of doublets.

" Probable blend of H \( \alpha \) (interstellar) and He \( \alpha \) from the AM CVn system, possibly with a blueshifted wind component.

which in this hydrogen-deficient object is likely the He \( \alpha \) (2–4) transition at 1215.15 Å. Like the other strong absorption lines, this feature is asymmetric, with the blue absorption wing being broader than the red wing. This feature is included in Table 2; the tabulated equivalent width is derived from a Gaussian fit to the core and red side of the line; if the extended blue wing is included, the EW is 4.26 Å. Given the low resolution offered by the G140L grating, we do not attempt to decompose this feature or derive a H \( \alpha \) interstellar column density.

Fig. 3.—Mean long-wavelength (NUV-MAMA and G230L) spectrum of AM CVn. The spectrum covers 1600–3150 Å with a resolution of 2.8 Å. Absorption features from He \( \alpha \) and N \( \nu \) are marked and labeled (see Table 1 for laboratory wavelengths; see Fig. 4 for the N \( \nu \) profile). Sharp, interstellar lines are indicated with tick marks above the spectrum (see Table 2). Note the expanded vertical scale.
The mean long-wavelength (NUV-MAMA, G230L) spectrum of AM CVn is shown in Figure 3. The spectrum covers 1600–3150 Å with a resolution of 2.8 Å/cm (or 1.6 Å/pixel at midrange), sampled at ≈1.6 Å/pixel. This spectral region is also characterized by a roughly flat continuum. Interstellar lines (see Table 2) are marked above the spectrum as before; the intrinsic lines of He II and N IV (see Table 1) are marked and labeled. (The He II line sits in the overlap region common to both the G140L and G230L spectra.)

The local flux minimum in the 1800–2000 Å region (Fig. 3) is not of interstellar origin. The pattern of flux variation here is similar to that seen in the spectra of early B stars (B0.5–B3, especially luminosity classes II and I; cf. Wu et al. 1991). Important contributors likely include Al iii and Fe iii (see the atlases by Rountree & Sonneborn 1993 and Walborn et al. 1995).

Mean profiles of the strong absorption lines from N v, Si iv, C iv, He ii, and N iv are shown in detail in Figure 4, on a common velocity scale. The velocity zero point in each panel is set at the nominal (rest) wavelength of the line, or the average wavelength in the case of doublets. The pattern of flux variation here is similar to that seen in the spectra of early B stars (B0.5–B3, especially luminosity classes II and I; cf. Wu et al. 1991). Important contributors likely include Al iii and Fe iii (see the atlases by Rountree & Sonneborn 1993 and Walborn et al. 1995).

We binned the time-tagged observations for both the FUV/G140L and NUV/G230L data sets, using both 30 and 3 s bins. From the 30 s binned data, we prepared trailed spectrograms for each region. Inspection of the trailed spectrograms (not illustrated) did not reveal any marked time-dependent behavior. There are, however, some subtle variations in the profiles of the wind lines, which became more evident when the mean spectrum was subtracted.
from the 30 s binned data. The pattern of variation comprises an interval of a few hundred seconds during which both red and blue “edges” of the wind absorption features are located at longer wavelengths than in the mean spectrum, followed by an interval of similar length in which the features are shifted to shorter than average wavelengths. The total displacement corresponds to a few hundred km s\(^{-1}\). The Ly\(^\alpha\) feature and other interstellar features do not show this variation. The pattern of redshift followed by blueshift is repeated about 900 s later, in the second half of the NUV/G230L observation set. This pattern is illustrated in Figure 5, where spectra averaged over two 480 s intervals are shown for the (mainly interstellar) Ly\(^\alpha\), N\(_{\text{v}}\), S\(_{\text{i}}\), C\(_{\text{iv}}\), and He\(_{\text{ii}}\) profiles. The two intervals are separated by a 120 s gap. (We did not attempt to optimize the size and spacing of the intervals chosen for illustration, so 480 s should not be interpreted as the duration of either the “red” or “blue” phase.) The wind from AM CVn thus seems to be mildly unsteady. Further interpretation of the wind lines is offered in § 3.3.

The 30 and 3 s binned light curves of AM CVn for the short-wavelength FUV/G140L data (1150–1715 Å) are shown in Figure 6. There is evident structure (flickering) in the light curve, which is also manifested as low-frequency noise in the power spectrum. The power spectrum of the G140L data is shown in Figure 7. The mean level was subtracted from the 3 s binned light curve, prior to computing the Fourier transform. The Nyquist period is 6 s, and the power spectrum is sampled at 513 frequencies. Each point in the spectrum is statistically independent of its neighbors, that is, a pure monochromatic signal would show power in a (centered) single bin. Normalized power spectra are shown. The significance of a signal is given in terms of the probability, \(N_{\text{exp}}(p/h_i)\), that an isolated peak of power \(p\) could arise by chance in a white-noise spectrum containing \(N\) bins with mean power \((h_i)\). See Eracleous et al. (1991) for further details.

In addition to the low-frequency noise, there is a peak at \(f = 37.0\) mHz (\(1/f = 27.0 \pm 0.3\) s). The peak is slightly broadened: a Gaussian fit shows the FWHM to be 0.61 mHz. The estimated coherence of this oscillation is thus \(Q \approx 60\), where \(Q\)
true period may be 54 rather than 27 s. Further discussion of the oscillations is presented in § 3.2.

3. DISCUSSION

3.1. The Ultraviolet Flux Level

We noted in § 2.1 the apparent decline in AM CVn’s UV flux level during our STIS observations. Our tentative conclusion is that this decline is larger than can easily be accounted for by instrumental or calibration effects, and should be regarded as real, especially as it seems to be at least marginally present within each of the FUV and NUV observations separately, as well as when they are considered together.

Noting that an excursion of similar amplitude was seen in 1981 March, but in the visible band and lasting only 500 s (Elsworth et al. 1982), we investigate whether other brightness changes of similar rate, duration, or amplitude have been observed in AM CVn before, in either visible or UV light.

R. K. Honeycutt has kindly communicated to us the results of synoptic monitoring of AM CVn in the $V$ band over the time period 1990 November to 1996 August. These observations were made using the Roboscope (Honeycutt et al. 1994). One to four magnitude measurements were made per night, with 506 measurements in total spread over 417 nights. On nights with multiple observations (usually separated by a few hours) the intranight variations in brightness are consistent with the measured errors of observation, which are typically at or below the 1% level. On a few occasions brightness changes of a few percent from one night to the next are noted, although they are of marginal statistical significance. Slow drifts in the average $V$ magnitude of a similar amplitude are also noted over the course of an observing season. No “outbursts” are seen, nor any rapid and persistent changes in brightness such as those seen in the STIS data of Figure 1. The median magnitude is $V = 14.11$.

Skillman et al. (1999) also report from high-speed photometry that the visual brightness of AM CVn is quite robust, always between $V = 14.10$ and 14.20 and never varying more than 0.07 mag during a night.

Taking the various calibrated fluxes at face value, we find the UV flux from AM CVn to vary somewhat over long intervals, as shown by the mean UV spectrum of AM CVn obtained in 1995 with the GHRS in program 6085. The SED is flat ($f_v \propto$ constant) over the wavelength range 1260–1560 Å, with a mean continuum flux level of about 16.5 mJy, or about 15% higher than our nominal FUV/G140L mean flux level.

We have also compared the UV brightness of AM CVn found in our STIS observations with the flux level measured by IUE at several epochs between 1978 and 1988. (See Boggess et al. [1978] for a description of IUE instrumentation.) We considered only IUE observations made in the LOW dispersion mode using the LARGE aperture. We retrieved NEWSIPS (Final Archive) fluxes in ASCII form from the Browse facility at MAST4 and computed average flux densities for each observation, in 60 Å (100 Å) intervals centered at 1450 or 2700 Å, depending on the camera used. At 1450 Å, the IUE fluxes range between 2.1 and $2.4 \times 10^{-13}$ ergs cm$^{-2}$ s$^{-1}$ Å$^{-1}$, and the corresponding STIS measurement is 2.0 in the same units. At 2700 Å, the IUE fluxes lie between 5.5 and $6.0 \times 10^{-14}$ ergs cm$^{-2}$ s$^{-1}$ Å$^{-1}$, and the STIS measurement is $5.1 \times 10^{-14}$ in the same units. Thus, the STIS observations show AM

---

*4* Multimission Archive at Space Telescope, http://archive.stsci.edu/iue/.
CVn to be somewhat less bright in 2002 February than was recorded by *IUE*, although by only ~10%, comparable to the range of variation observed with *IUE*. Massa & Fitzpatrick (2000) point out some concerns about the NEWSIPS absolute calibration of *IUE* fluxes, at the 10% level, so our comparison of *IUE* and STIS fluxes is preliminary only.

Ramsay et al. (2005) present near-UV observations of AM CVn with the Optical Monitor aboard the *XMM-Newton* observatory, spanning an interval of about 12,000 s. The effective wavelength was 2910 Å (UVW1 filter, range 2400–3400 Å). Excepting a few outliers, count rates in 120 s bins do not show deviations from the mean rate that are larger than about 3%. This rate is not easily converted to absolute flux units for comparison with other instruments.

In physical terms, it is not difficult to imagine that variations in UV brightness at the ~10% level might occur, driven by variations in accretion rate through the disk and onto the central white dwarf. One might expect larger variations at UV wavelengths than in visible light, and indeed the higher amplitude at shorter wavelengths of the 27 s oscillations seen in the STIS data are an example (§ 2.3). Other cataclysmic variables (CVs) in a persistent high-luminosity state have also been observed to vary in the UV. Hartley et al. (2002) document ~30% variations in the continuum level of V3885 Sgr and less certain variations at the factor of 2 level in IX Vel, between observations with STIS spaced weeks or months apart.

To summarize, AM CVn’s brightness in the UV sometimes appears to be more strongly variable than in the visible on timescales of hours or longer, although the data are too sparse to allow full characterization of this variation, and some calibration uncertainties persist at the few percent level. Without further time-series observations in the UV, we cannot say whether or not this behavior (hours-long trends) happens frequently.

### 3.2. The Oscillations

Our power spectrum analysis of the UV light curve of AM CVn (§ 2.3) revealed a slightly broadened peak at 37 mHz, corresponding to an oscillation period of 27.0 s. Folding the light curve shows a waveform that is approximately sinusoidal, although alternating maxima have slightly different heights, suggesting the underlying period may be ~54 s. This is only a 2 σ effect, however, and we discuss the oscillation in terms of a 27 s period. The amplitude (half of the peak-to-peak variation) is ~1% in the shortest wavelengths, diminishing to about half this in the longest observed wavelengths (Fig. 10).

Patterson et al. (1979) reported a “transient coherent or quasi-coherent periodicity at 26.3 s” in visible-light time-series photometry of AM CVn. Patterson et al. (1992) showed the power spectrum of this oscillation. The amplitude was ~0.01 mag, uncertainly measured because of the poor coherence of the signal; they referred to the signal as a “quasi-periodic oscillation” and revised the mean period to 26.2 s. In a recharacterization, Skillman et al. (1999) stated that “the period and coherence of this signal are quite plausible for ‘dwarf nova oscillations’.” We adopt the point of view that the signal seen by Patterson et al. (1979) and by us at different times and in different wave bands arises from the same cause.

Are these variations “dwarf nova oscillations” (DNOs), or are they “quasi-periodic oscillations” (QPOs)? According to the review by Warner (2004), DNOs are moderately coherent (\(\Delta P/dt \equiv [\Delta P/\Delta t]^{-1} \gtrsim 10^4\), nearly sinusoidal signals with periods typically in the range 8–40 s. QPOs are less coherent, with periods typically ~10 times longer than the corresponding DNOs for a CV. DNOs and QPOs may appear simultaneously or not. DNOs are characteristically observed during the outbursts of dwarf novae, but are also seen in some luminous “novalike” CVs. In an outburst, the period of the DNO varies with time, inversely related to the luminosity of the dwarf nova. In addition to this luminosity-linked variation, the DNO period may show sudden small jumps, best studied by means of an amplitude and phase analysis, in which short segments of the light curve are fitted directly in a sliding window using a sinusoidal model for the variation. Given the similarity of the DNO period to the Keplerian period in the inner disk, DNOs are interpreted as having their origin at or near the surface of the accreting white dwarf or in the inner disk. Warner (1995) argues that QPOs, with their longest periods corresponding to the orbital timescale in the outer disk, may be linked to oscillations of the disk, with a mixture of periods corresponding to different radial zones.

If the 27 s (37 mHz) signal from AM CVn is a DNO, we might look for a QPO near 4–5 mHz. The power spectrum shows a “grassy” structure at these frequencies, which may indicate the presence of a QPO or may simply be part of poorly defined “1/f noise,” characteristic of low-level “flickering.” More data would be required to develop a well-averaged power spectrum that would show whether a broad QPO “bump” lies on top of a 1/f “continuum.”

We performed a simple analysis of amplitude and phase for the FUV light curve of AM CVn, using a moving window 270 s (10 cycles) long. We fitted a model consisting of a linear baseline and a pure sinusoid with fixed period. The form of the baseline is \(A + Bt\), and \(A\) and \(B\) vary as the window is shifted along, to take out some of the low-frequency wandering in the light curve. We note well-defined “DNO-like” phase drifts of duration several hundred seconds, indicating a period that is changing around the mean period, as in Warner (2004; his Fig. 2). We also note that the amplitude of the fitted sinusoid is typically higher in the first half of the time series than later (in our Fig. 6 there is high amplitude around relative time = 16 minutes, and low amplitude around 26 minutes, as extreme examples). The width (FWHM) of the spike in the power spectrum partly arises from this amplitude modulation (effectively, only half of the time series is useful in establishing the frequency of the signal), and partly arises from the small drifts of period during the half of the observation where the oscillation is strong.

Despite the difference in chemical composition of AM CVn’s disk compared with the usual hydrogen-rich CV, the temperature of the inner disk is likely similar to a dwarf nova in outburst. It would therefore not be surprising to observe DNOs from AM CVn in the same period range as normally observed. The amplitude of a DNO in the UV would be high relative to that in visible light, since the UV light from the inner disk is not diluted by light from the outer disk. We therefore adopt the interpretation of Skillman et al. (1999) in characterizing the 27 s oscillation as a DNO. We note, however, that the defining test of whether the period changes with system luminosity cannot be carried out, since AM CVn does not undergo “dwarf nova” outbursts. Labeling the oscillation as a DNO does not tell us the cause of the oscillation, which seems to be still very open to debate. Different points of view as to the physical mechanisms involved are represented by Warner & Woudt (2006), Mauche (2002), and Piro & Bildsten (2005).

Since the “outer disk” in AM CVn is less extensive than in longer period CVs, one is observing the inner disk with relatively low dilution by lower temperature gas, even in visible light. It might therefore be regarded as slightly puzzling that the ~26 s oscillation has not been reported more frequently. But the source is relatively faint, and attention historically has been focused on the “orbital/superhump” modulation at 1029/1051 s, both factors...
tending to the use of integration times that are long compared with 26 s. In the UV, the same is true. The analysis by Solheim et al. (1997) of time-resolved UV spectra, obtained with the GHRS, made use of data binned in ~50 s intervals (with gaps). It thus is not sensitive to the frequency range that includes the signal we report here. Ramsay et al. (2005) report a power spectrum of the integrated UV light from AM CVn, from their observations using the XMM-Newton Optical Monitor. It shows significant power near periods of 996, 529, and 332 s. Their analysis does not extend to periods as short as 27 or 54 s, however.

3.3. The Wind Lines

The blueshifted broad absorption features in the UV spectrum of AM CVn (Table 1 and Figs. 4 and 5), with redshifted emission apparent only in N v and perhaps He ii, are typical of the wind-formed lines seen in the spectra of all luminous CVs seen at low or moderate inclination. In AM CVn, the deepest lines are N v and C iv. The terminal velocity of the absorption trough is near −3000 km s⁻¹, most cleanly seen in N v.

Time-resolved UV spectra of AM CVn, obtained in 1995 with the GHRS, have apparently not been published in detail, although a mean spectrum and some time-series analysis are reported in Solheim et al. (1997). A superficial comparison of the mean GHRS and STIS spectra in the region of overlap shows that they are very similar, apart from the difference in overall brightness level mentioned earlier.

Proga (2005) reviews the modeling of CV winds, while Froning (2005) reviews the observations and highlights some of the difficulties that models have in reproducing the diversity of behavior that is seen in the lines. Kinematic models of CV wind lines (e.g., Knigge & Drew 1996) explain them as being formed mainly by scattering in a nonspherically symmetric, or “biconical,” outflow. The winds lines are stronger in higher luminosity CVs, suggesting that they are driven by radiation pressure. Two-dimensional, time-dependent hydrodynamic models of radiation-driven winds indeed produce a slow, dense, “equatorial” wind bounded on the poleward side by a faster, more tenuous flow (Proga et al. 1998, 1999). The winds are predicted to be stronger for a higher luminosity system. The terminal velocities are a few times the escape velocity from the white dwarf. If the disk luminosity is higher than that of the central white dwarf, the outflow tends to become unstable and clumpy. Some qualitative success has been achieved at matching predicted line profiles with observations, although problems remain, and a unique matching of a model to a data set is elusive (e.g., Proga et al. 2002; Proga 2003; Long & Knigge 2002; Froning 2005).

We have made a qualitative comparison of the mean profiles from Figure 4 with illustrative computed profiles presented in Proga et al. (2002), Long & Knigge (2002), and Proga (2003). We concentrate mainly on the C iv profile. AM CVn is not an eclipsing binary system, so an intermediate inclination angle is inferred. Consistent with this, the overall observed shape in C iv (terminal velocity, concavity, and location of maximum depth close to zero velocity) matches reasonably well to model profiles calculated for intermediate inclinations ($i = 30°$ or $55°$). The fixed parameters of these models (white dwarf mass and radius, disk radius, etc.) are not tuned to AM CVn, and the sampling of the variable parameters (inclination, wind mass loss rate) is too coarse to allow more quantitative conclusions to be drawn, but the explanation of the observed line profiles in terms of a biconical wind seems to be secure.

It is reassuring that CV wind theory seems to be applicable in the case of hydrogen-deficient, “ultracompact” binaries such as AM CVn. Nor is this a surprising result, if the wind originates in the inner disk and is viewed against continuum light from the inner disk. The outer disk is “missing,” but seems to have little effect on the shaping of the absorption part of the line profile, and the UV opacities in the UV-forming inner disk are affected at only the factor of 2 level by the absence of hydrogen. The shape of the ionizing continuum from a hydrogen-deficient disk is expected to be different, however, so the interpretation of the strength of a wind line profile in terms of a wind mass loss rate may be expected to differ from the hydrogen-dominated case. (The strength of the line depends on the population of the ion, hence on the ionization state of the gas as well as the overall density of the wind.)

The shifting positions of the resonance line absorption features shown in Figure 5 is a small but real effect, likely showing that conditions in the outflow are not steady. In AM CVn, the profiles as a whole seem to shift back and forth, maintaining their shapes. Certain other luminous CVs show much more “wild” behavior in the wind lines, e.g., V603 Aql (Pirinza et al. 2000a) and BZ Cam (Pirinza et al. 2000b), in which the shapes of the lines and their equivalent widths change drastically, and individual “blobs” or clumps may be traced as their velocities change with time. The theory of radiation-driven winds suggests that the outflow becomes unstable and clumpy if the disk luminosity (vertically directed) dominates over the radially directed luminosity from the central star (Proga et al. 1998). There is thus some hope that this aspect of disk wind theory can be confronted by the AM CVn observations, where the instability seems to be marginal, if the disk and white dwarf luminosities can be determined. In the case of RW Sex, on the other hand, the time variations in the profiles of far-UV wind lines seem to be related to orbital modulation, and any fluctuations of density or speed in the wind may occur on scales small enough that they do not appear with adequate contrast in the observed line profiles (Pirinza et al. 2003). We noted in § 2.3 a rough timescale for the observed line variations of ~900 s, comparable to the orbital period of AM CVn (1029 s), but only further observations could establish whether there is a strict correspondence. (Interest is added, owing to the fact that the secondary star in AM CVn, although small, is much closer to the source of the wind and thus might present a means of modulating the outflow on the orbital period.) At present, our only firm conclusion is that there are variations present in the wind line profiles, with the cause yet to be determined.

3.4. The Observed Spectral Energy Distribution

We show in Figure 11 the observed SED of AM CVn, assembled from several different sources. Data at the shortest wavelengths come from FUSE observations (epoch 2004 December 26), as read by eye from “preview” spectra provided at the MAST Web site; the points represent estimated continuum fluxes at 1000, 1050, 1100, and 1150 Å. Next are the STIS data reported earlier in this paper (“G140L,” and “G230L”). Optical and near-infrared data (“MCSP”) are from the Multichannel Spectrophotometer formerly in use at the Hale 5 m telescope. These data are described in Oke & Wade (1982), and can be made available in machine-readable form on request; we suggest that these quasimonochromatic flux measurements be used in place of broadband $UBVRI$ magnitudes when modeling the SED. Finally, the infrared broadband fluxes from 2MASS (Skrutskie et al. 2006) are given, using the absolute calibration and zero-point offsets from Cohen et al. (2003). We summarize these data here: isophotal wavelengths of the 2MASS $J$, $H$, and $K_s$ bands are 1.235, 1.662,
The spectrum of AM CVn can be modeled to infer $dM/dt$ and perhaps other quantities such as $M_1$, $M_2$ (the mass of the donor star), the distance $d$, and the inclination $i$ of the disk orbital plane to the line of sight. An accurate knowledge of $dM/dt$ is needed to (1) confirm that the disk in AM CVn satisfies the thermal stability criterion for disks in a permanent “high” state (Smak 1983; Tsugawa & Osaki 1997); (2) assess the thermal and evolutionary properties of the donor star (e.g., Deloye et al. 2005); and (3) properly partition the observed flux between the disk and the other contributors to the radiation. Item 3 is necessary for deriving abundances from modeling of the absorption line spectrum in the UV, where some of the light may come from the central white dwarf and some from the disk.

The library of local disk spectra that is used to construct a model SED of the entire disk is of paramount importance. Blackbody spectra, for example, differ greatly from the SEDs of helium atmospheres. We illustrate in Figure 11 the difference between a blackbody disk (BBD) and a helium-atmosphere disk (HeD), computed with the same model parameters. Our model disk is the usual steady-state, geometrically thin, optically thick, nonirradiated accretion disk. We choose $M_1 = 0.69 M_\odot$, $R_1 = R_{\text{wd}} = 7.8 \times 10^6$ cm, $R_d = 7.6 \times 10^9$ cm, $dM/dt = 6.7 \times 10^{-9} M_\odot \text{ yr}^{-1}$, $d = 600$ pc, and $v = 43^\circ$, similar to the model for AM CVn proposed by Roelofs et al. (2006). Here $R_1 = R_{\text{wd}}$ is the inner radius of the disk, taken to be the radius of the white dwarf; and $R_d$ is the outer radius of the disk. For this illustration we have used angle-averaged fluxes from Wesemael (1981) and D. Koester (2006, private communication). No sources of light other than the disk are included. The UV-optical-infrared model fluxes from the HeD are a factor of $\sim 1.6$ lower than those from the BBD, owing to different bolometric corrections in the two cases (the “missing” flux is emitted in the extreme UV). With the chosen parameters, the overall fit of the HeD model is worse than that of the BBD. By increasing $dM/dt$, the HeD model can be made to better match the normalization of the observed SED.

Independent constraints on $d$, $M_1$, $R_1$, $M_2$, and $i$, if they are trustworthy, are very important for reducing the number of correlated parameters or the degree of correlation in a model of the accretion disk. In the AM CVn system, two constraints are especially significant for inferring $dM/dt$ from the SED. The first is the system’s mass ratio $q$, for which estimates range from $q = 0.087$ (Nelemans et al. 2001) to $q = 0.22$ (Pearson 2003). Roelofs et al. (2006) have put forward a spectrophotometrically determined $q = 0.18 \pm 0.01$. Once $q$ is determined, $M_1$ and $M_2$ cannot be varied independently. Varying $M_1$ affects both temperatures and orbital speeds (line smearing) in the disk, as well as affecting the fundamental solid angle ($R_1/\Delta$), hence $dM/dt$ as inferred from observation is also affected. Meanwhile, $dM/dt$ is tied to $M_2$ through the theory of mass transfer driven by angular momentum loss.

The second constraint is the distance. The often-used value $d = 235$ pc is based on an unpublished parallax, $\pi_{\text{abs}} = 4.25 \pm 0.43$ mas, from the USNO parallax team (C. Dahn 2003, 2006, private communication; 62 observations over 8.1 yr; seven stars in the astrometric reference frame). Recently, a new parallax determination using the Fine Guidance Sensor aboard the HST, $\pi = 1.65 \pm 0.30$ mas ($d \approx 606$ pc), has been published (Roelofs et al. 2007). This study has a duration of 1.6 yr and relies on three astrometric reference stars, all to the south of AM CVn. In Figure 11, reducing $d$ from 600 pc to a smaller value would raise the predicted fluxes of the model for a given $dM/dt$. A substantially smaller distance such as $d = 235$ pc would therefore mandate a reduction in the model $dM/dt$ in order to match the observed flux level, leading also to a cooler and “redder” model disk; in the case of the HeD model, the model would better match the observed relative SED. The formal difference between the two parallax measurements is statistically very significant, and $d^2$ differs by a factor of $\approx 7$. Choosing to apply one of the advertised distance estimates over the other, as a modeling constraint, has a huge impact on whether any particular model for AM CVn can successfully account for both the SED and spectroscopic observations of that system. We are not in a position to resolve this discrepancy.

The strong linkages among $q$, $d$, $dM/dt$, and other system parameters are illustrated in the analysis of several AM CVn-type systems by Roelofs et al. (2007).

4. SUMMARY

We have presented new, time-resolved STIS observations of AM CVn, which show a UV spectrum that is approximately flat in $f_\nu$. The absorption profiles of N v $\lambda 1240$, Si iv $\lambda 1398$, C iv $\lambda 1549$, He ii $\lambda 1640$, and N iv $\lambda 1718$ are asymmetric and blue-shifted, evidencing a wind that is partly occulted by the accretion disk. There is also weak emission at N v and He ii. These features are consistent with profiles predicted for scattering in a biconical wind from an accretion disk, viewed at intermediate inclination. The profiles of these wind lines vary mildly with time, showing shifts in the observed wavelengths of both red and blue absorption edges. Sharp (interstellar) absorption lines are also seen. The H i Ly$\alpha$ feature is presumably interstellar, but may be blended with the He ii (2–4) transition arising in AM CVn itself. Numerous weaker spectral features of various widths are found, probably arising in the accretion disk and kinematically blended.
The UV light curve of AM CVn from the STIS observations shows an apparent, relatively steady decline by ~20% over the span of the observations. Only a portion of the nominal decline can be attributed to possible calibration uncertainties. We summarize data that suggest AM CVn’s brightness varies by a larger amount in the UV than in the optical. There are also short-term “white light” variations, including a 27 s DNO that is stronger at shorter wavelengths. The true period of the DNO may be 54 s.

We have assembled the UV-visible-infrared SED of AM CVn by combining the STIS observations with data from FUSE, the Palomar MSCP instrument, and 2MASS. Successful models of the accretion process in AM CVn, accounting for the shape and normalization of the entire observed SED, may give a robust estimate of the mass accretion rate $dM/dt$ and other parameters of the system. The mass accretion rate is of great interest to understanding the origin and subsequent evolution of HeCVs. Inferences about $dM/dt$ depend strongly on the local radiative properties of the gas that makes up the accretion disk. We have illustrated this by explicit computation of the SED from a blackbody disk and a helium-atmosphere disk, using the same example specification of $M_1$, $R_1$, $R_d$, $dM/dt$, and $j$ in both cases. The results are quite different. Other key factors in inferring $dM/dt$ include what is assumed about the mass of the accreting star (strongly influenced by the adopted mass ratio $q$) and the distance to the system.

We are grateful to R. K. Honeycutt for communicating to us the results of RoboScope synoptic observations of AM CVn, to M. Rogers for assistance in the review of literature, and to C. Dahn for some correspondence about the USNO parallax result. D. Koester kindly provided some model spectra for pure helium atmospheres. We benefitted from helpful comments by an anonymous referee. M. E. acknowledges the hospitality of the Astrophysics Department at the American Museum of Natural History.

This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France. This publication makes use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation. Some of the data presented in this paper were obtained from the Multimission Archive at the Space Telescope Science Institute (MAST). STScI is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555. Support for MAST for non-HST data is provided by the NASA Office of Space Science via grant NAG5-7584 and by other grants and contracts. Support for HST GO program 8159 was provided by NASA through a grant from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555.

REFERENCES

Boggess, A., et al. 1978, Nature, 275, 372
Cohen, M., Wheaton, W. A., & Meggath, S. T. 2003, AJ, 126, 1090
Deloye, C. J., Bildsten, L., & Nelemans, G. 2005, ApJ, 624, 934
El-Khoury, W., & Wickramasinghe, D. 2000, A&A, 358, 154
Elsworth, Y., Grimshaw, L., & James, J. F. 1982, MNRAS, 201, 45P
Froning, C. S. 2005, in ASP Conf. Ser. 330, The Astrophysics of Cataclysmic Variables and Related Objects, ed. J.-M. Hameury & J.-P. Lasota (San Francisco: ASP), 81
Hartley, L. E., Drew, J. E. Long, K. S., Knigge, C., & Proga, D. 2002, MNRAS, 332, 127
Honeycutt, R. K., Robertson, J. W., Turner, G. W., & Vesper, D. N. 1994, in ASP Conf. Ser. 56, Interacting Binary Stars, ed. A. W. Shafter (San Francisco: ASP), 277
Knigge, C., & Drew, J. E. 1996, MNRAS, 281, 1352
Long, K. S., & Knigge, C. 2002, ApJ, 579, 725
Mauche, C. W. 2002, ApJ, 580, 423
Morton, D. C. 2003, ApJS, 149, 205
Nager, T. Dreizler, S., Rauch, T., & Werner, K. 2004, A&A, 428, 109
Nasar, M. R., Solheim, J.-E., & Semionoff, D. A. 2001, A&A, 373, 222
Nelemans, G. 2005, in ASP Conf. Ser. 330, Astrophysics of Cataclysmic Variables and Related Objects, ed. J.-M. Hameury & J.-P. Lasota (San Francisco: ASP), 27
Nelemans, G., Steeghs, D., & Groot, P. J. 2001, MNRAS, 326, 621
Oke, J. B., & Wade, R. A. 1982, AJ, 87, 670
Pearson, K. J. 2003, MNRAS, 346, 121
Piro, A. L., & Bildsten, L. 2005, in ASP Conf. Ser. 330, Astrophysics of Cataclysmic Variables and Related Objects, ed. J.-M. Hameury & J.-P. Lasota (San Francisco: ASP), 197
Prinja, R. K., Knigge, C., Ringwald, F. A., & Wade, R. A. 2000a, MNRAS, 318, 368
Prinja, R. K., Long, K. S., Froning, C. S., Witherick, D. K., Clark, J. S., & Ringwald, F. A. 2003, MNRAS, 340, 551
Prinja, R. K., Ringwald, F. A., Wade, R. A., & Knigge, C. 2000b, MNRAS, 312, 316
Proga, D. 2003, ApJ, 592, L9
———. 2005, in ASP Conf. Ser. 330, The Astrophysics of Catalcylic Variables and Related Objects, ed. J.-M. Hameury & J.-P. Lasota (San Francisco: ASP), 103
Proga, D., Kallman, T. R., Drew, J. E., & Hartley, L. E. 2002, ApJ, 572, 382
Proga, D., Stone, J. M., & Drew, J. E. 1998, MNRAS, 295, 595
———. 1999, MNRAS, 310, 476
Ramsay, G., Kakala, P., Marsh, T., Nelemans, G., Steeghs, D., & Cropper, M. 2005, A&A, 440, 675
Roeufs, G. H. A., Groot, P. J., Benedict, G. F., McArthur, B. E., Steeghs, D., Morales-Rueda, L., Marsh, T. R., & Nelemans, G. 2007, ApJ, 666, 1174
Roeufs, G. H. A., Groot, P. J., Nelemans, G., Marsh, T. R., & Steeghs, D. 2006, MNRAS, 371, 1231
Rountree, J., & Sonneborn, G. 1993, Spectral Classification with the International Ultraviolet Explorer: An Atlas of B-Type Spectra (Greenbelt: NASA)
Skillman, D. R., Patterson, J., Harvey, D. A., Fried, R. E., Retter, A., Lipkin, V., & Vannumster, T. 1999, PASP, 111, 1281
Smak, J. 1983, Acta Astron., 33, 333
Solheim, J.-E., Provenal, J. L., & Sion, E. M. 1997, in White Dwarfs, ed. I. Isern, M. Hernanz, & E. Garcia-Berro (Dordrecht: Kluwer), 337
Tsuruta, H., & Osaki, Y. 1997, PASJ, 49, 75
Walborn, N. R., Parker, J. W., & Nichols, J. S. 1995, International Ultraviolet Explorer Atlas of B-Type Spectra from 1200 to 1900 Å (Greenbelt: NASA)
Warner, B. 1995, Cataclysmic Variable Stars (Cambridge: Cambridge Univ. Press), chap. 8.6
———. 2004, PASP, 116, 115
Warner, B., & Woudt, P. A. 2006, MNRAS, 367, 1562
Wesemael, F. 1981, ApJS, 45, 177
Wu, C.-C., Crenshaw, D. M., Blackwell, J. H., Jr., Wilson-Diaz, D., Schiffer, F. H., Ill, Burstein, D., Fanelli, M. N., & O’Connell, R. W. 1991, The IUE Ultraviolet Spectral Atlas (Greenbelt: NASA)