

THE FIRST DIRECT SPECTROSCOPIC DETECTION OF A WHITE DWARF PRIMARY IN AN AM CVn SYSTEM

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ABSTRACT

We report the results of a synthetic spectral analysis of *HST* STIS spectra of the AM CVn-type cataclysmic variable CP Eri obtained when the system was in quiescence. The FUV spectrum is best fitted by a helium-dominated, hybrid composition (DBAZ) white dwarf with $T_{\text{eff}} \sim 17,000 \pm 1000$ K, $\log g \sim 8$, He/H abundance ratio by number ~ 1000 , metallicity $Z \sim 0.05 \times$ solar, and $V \sin i \sim 400 \pm 100$ km s⁻¹. This is the first directly detected primary white dwarf in any AM CVn system, and the surface abundance and rotation rate for the white dwarf primary are the first to be reported for AM CVn systems. The model-predicted distance is ~ 1000 pc. The spectral fits using pure He photospheres or He-rich accretion disks were significantly less successful. Based on the analysis of our FUV spectra, CP Eri appears to contain a hybrid composition DBAZ white dwarf with a metallicity that sets it apart from the other two AM CVn stars that have been observed in quiescence and are metal-poor. The implications of this analysis for evolutionary channels leading to AM CVn systems are discussed.

Subject headings: accretion, accretion disks — novae, cataclysmic variables — stars: individual (CP Eridani) — white dwarfs

1. INTRODUCTION

The AM CVn objects, like the essentially pure helium DB white dwarfs, are very H-poor and appear to be dominated by nearly pure helium accretion disks in the optical during outburst and (for those that have low states) in quiescence. In their bright states, they are spectroscopically similar to the spectra of AM CVn in its continual bright state in which the absorption lines of an optically thick helium disk and wind dominate their optical and far-UV (FUV) spectra (e.g., Groot et al. 2001 and references therein).

AM CVn objects are widely regarded as interacting binary white dwarfs in which the less massive degenerate companion (with $M_{\text{wd}} < 0.1 M_{\odot}$) fills its Roche lobe and transfers He-rich gas through an accretion disk to the more massive companion white dwarf primary. The basic model was first proposed by Paczyński (1967) and Faulkner et al. (1972), with their binary nature first confirmed by Nather et al. (1981). The properties of these systems are comprehensively reviewed by Warner (1995).

In addition to the interest in the evolutionary history that leads to their nearly pure helium composition and the accretion physics and physical conditions that prevail during helium accretion, these objects may contribute up to 25% of the Type Ia supernova production rate (Nelemans et al. 2001), although recent work suggests it is less than 1% (Solheim & Yungelson 2005).

The best distance estimates for AM CVn's are based on the Hubble distances given by P. Groot (2005, unpublished). For the two systems, CR Boo and V803 Cen, most similar to CP Eri, i.e., having outburst/quiescence states and similar orbital periods, $M_v = 6.5$ for CR Boo and 5.4 for V803 Cen (for their high states). If we assume for CP Eri an average $M_v = 6 \pm 0.5$ for the high state, we get a distance $1.2^{+0.8}_{-0.4}$ kpc.

The systems CR Boo, CP Eri, V803 Cen, 2QZ J142701.6–012310, KL Dra, and SN 2003aw are the only systems of the roughly dozen known AM CVn objects to have both high states and low states in analogy with their H-rich dwarf novae and nova-like counterparts. CP Eri, the topic of this Letter, has an orbital period of 28.73 minutes, an optical brightness range of 16.5 in outburst and 19.7 in quiescence with broad shallow optical He I absorption in outburst and, in quiescence, double-peaked He I and He II emission as well as Si II emission in the optical (Abbott et al. 1992). Abbott et al. (1992) did not detect H in either high- or low-state optical spectra.

A difficult obstacle to gaining information on the underlying stars has been that the quiescent spectra are rare and of poor signal-to-noise ratio due to the objects' faintness in both the optical and the FUV. In this Letter, we report the analysis of the first FUV spectrum of a quiescent AM CVn system that displays substantial continuum flux. All other AM CVn systems that display substantial continuum flux are in outburst like AM CVn itself.

2. HUBBLE STIS OBSERVATION

We obtained two *Hubble Space Telescope* (*HST*) Space Telescope Imaging Spectrograph (STIS) spectra of CP Eri on 2000 September 11 with the STIS FUV/MAMA configuration and the G140L grating through the 52×0.2 aperture with exposure times of 1919 and 2580 s for spectra O5B606010 and O5B606020, respectively. The STIS CCD acquisition image obtained immediately before the G140L spectrum was used to measure the optical brightness of CP Eri during the *HST* observations. The image was obtained with the F28 $\times$ 50LP filter, which has a pivot wavelength at 7229 Å and a bandwidth of 5400–10,000 Å, roughly comparable to an R-band filter (see Araujo-Betancor et al. 2005 for details of the procedure).

Unlike the optical spectrum of CP Eri seen in quiescence, the FUV spectrum contains many observed absorption features, including a strong feature at Ly α , strong C III (λ 1175), C II (λ 1335), Si II (λ 1260, 1265), C I (λ 1270), O I + Si III (λ 1300), C II (λ 1335), C I (λ 1356, 1490, 1657), Si II (λ 1526, 1533), and moderately strong emission features at Si IV (λ 1393,

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TABLE 1
HELIUM ACCRETION DISK MODEL FIT

Model	χ^2	Scale Factor ($\times 10^{-4}$)	Distance (kpc)
cperim4i30	3.15	2.91	1.34
cperim4i45	2.42	4.82	1.04
cperim9i45	3.12	3.56	1.21
cperim10i30	4.52	3.26	1.27
cperim10i45	4.54	3.99	1.15

1400), possible N v ($\lambda\lambda 1238, 1242$) emission, and possible He II ($\lambda 1640$) emission.

3. SYNTHETIC SPECTRAL FITTING WITH HELIUM DISKS AND PHOTOSPHERES

The grid of helium accretion disk models described by Nasser et al. (2001) were compared with the *HST* STIS spectrum of CP Eri over the effective wavelength range of the STIS spectrum, 1150–1716 Å. The helium accretion disks are steady state non-LTE models, which are more appropriate for the high state of AM CVn systems. However, as a first approximation to the accretion disk during a low state, we applied the optically thick models to CP Eri’s spectrum.

The composition and designation of the disk models (see Table 1 below) is as follows. The disk models labeled cperim4i* have He/H = 1000 by number, $Z = 0.001$ solar, and an outer radius (of the outermost annulus) of 15 white dwarf radii. The “i” is the inclination angle in degrees. The disk model cperim9i45 has He/H = 10^5 , CNO abundances = 3, 900, $1.5 \times$ solar, respectively, and outermost disk radius = 15 white dwarf radii. The disk model cperim10i* has He/H = 10^5 , metallicity $Z =$ solar, and outer disk radius $r_{\text{max}} = 8$ white dwarf radii. Curiously, the disk fits are improved considerably below 1350 Å if Fe is overabundant because of the large number of low-excitation Fe lines whose collective absorption eats away at the continuum and broadens line profiles. This is especially noticeable at 1260 Å. On the other hand, when the same disk models are applied to AM CVn itself, the elevation of Fe does not result in a better fit. It is possible that this difference between CP Eri and AM CVn points to a different progenitor evolution.

In preparation for the model fitting, emission lines in the data were masked out. We used a χ^2 minimization fitting routine *wddiskfit*, which yields the χ^2 -value, the scale factor, and the distance computed from the scale factor. We have tabulated the results in Table 1, where the first column lists the model designation (see above), the second column the χ^2 -value, the third column the scale factor, and the last column the distance in units of kiloparsecs. To obtain the distances from the model normalization for each fit, we scaled down by a factor corresponding to the magnitude difference between the high state (16.5) and the low state (19.7). This corresponds to a factor of 0.0524 or a distance ratio 0.229. This yields distances of 1.34, 1.04, 1.21, 1.27, 1.15 kpc, which are all quite reasonable. The best-fitting accretion disk model is cperi4i45, which has He/H = 1000, $Z = 0.001$ (including Fe), a disk inclination angle of 45° , and $\chi^2 = 2.4162$. The “best-fit” helium accretion disk fit is displayed in Figure 1.

We also explored the possibility that the STIS spectrum of CP Eri in its low brightness state, like the FUV spectra of the shortest period dwarf novae, is produced by a white dwarf with essentially no contribution from an accretion disk. Therefore, we

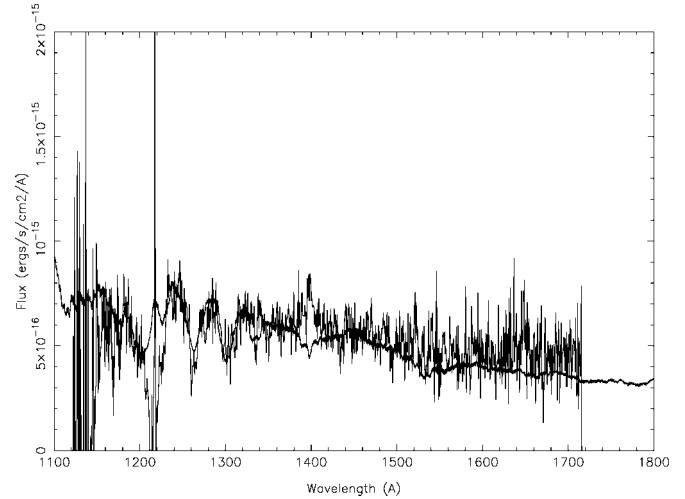


FIG. 1.—Flux distribution, flux vs. wavelength, for the best-fitting helium accretion disk model with $Z = 0.001$ and inclination $i = 45^\circ$ compared with the *HST* STIS spectrum of CP Eri.

constructed an initial grid of helium-rich photospheres with He/H = 10^5 and $Z = 10^{-4}$. The grid covers the following parameter ranges: temperatures of 15,000–30,000 K in steps of 3000 K; surface gravities $\log g = 7.5, 8.0$, and 8.5 ; and rotational velocities $V \sin i = 200, 400$, and 600 km s^{-1} . The best-fitting helium-rich photosphere model has $T_{\text{eff}} = 15,000 \text{ K}$ and $\log g = 8.0$. The rotational velocity is meaningless since the low-metallicity model had no strong metal absorption lines to match with the STIS spectrum. This model yielded a $\chi^2 = 2.5702$, a scale factor $= 3.29 \times 10^{-4}$, and a distance of 804 pc for a white dwarf radius $R_{\text{wd}}/R_\odot = 1.46 \times 10^{-2}$. The best-fitting He photosphere (no H) is displayed in Figure 2. However, this model does not fit the absorption lines well.

The rather deep absorption line near 1216 Å could not be due to He II at the T_{eff} of the white dwarf indicated by the continuum and by low-ionization metal line profile fits. Hence, unless the absorption has a hydrogen interstellar origin, which is unlikely given its breadth, there is a possibility it is photospheric H I Ly α . Therefore, we explored hybrid composition “DBA” atmospheres in which the dominant element is helium, with hydrogen

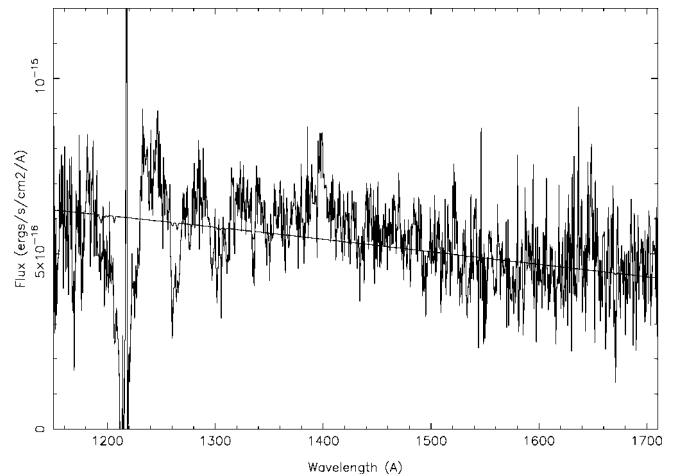


FIG. 2.—Flux distribution, flux vs. wavelength, for the best-fitting pure helium photosphere model with $\log g = 8$, $T_{\text{eff}} = 15,000 \text{ K}$, $Z = 0.05$, and $V \sin i = 200 \text{ km s}^{-1}$, compared with the *HST* STIS spectrum of CP Eri.

being far less abundant. Assuming that the profile is entirely H I, we kept the gravity fixed at $\log g = 8$ and experimented with various He/H ratios from 10^2 to 10^5 ; metal abundances $Z = 0.5, 0.1, 0.05$, and 0.005 ; and $T_{\text{eff}} = 14,000, 15,000, \dots, 20,000$ K. We found that the optimal He/H ratio needed to replicate the profile is He/H = 1000. This ratio is smaller than the stringent He/H ratio characterizing the DB white dwarfs where He/H $> 10^5$ in order for Balmer lines not to be detected in their optical spectra (which they are not). The best-fitting hybrid composition DBA model had the following parameters: $\chi^2 = 1.45$, scale factor $S = 2.224 \times 10^{-4}$, $\log g = 8$ (fixed), $T_{\text{eff}} = 17,000$ K, $V \sin i = 400 \text{ km s}^{-1}$, He/H = 10^3 , $Z = 0.05$, and a model-predicted distance of 978 pc. This best-fit model, compared with the STIS data, is shown in Figure 3. The hybrid atmosphere fit (H+He) provides a reasonably good fit to both the continuum and the absorption-line profiles. The Ly α absorption profile, if we assume no part of it is interstellar, is fit very well with the chosen mix of H and He. However, at the metal abundance of 0.005 solar, while the Si II features at 1260 and 1265 Å are quite well fit along with C II ($\lambda 1335$) and Si II ($\lambda \lambda 1526, 1533$), the C III ($\lambda 1175$), S III+O I ($\lambda 1300$), and C I ($\lambda \lambda 1356, 1657$) absorption features are not well fit by the model with the synthetic profiles, being considerably weaker than the observed ones. Still, we are encouraged that at least for the Ly α profile, and the lower ionization lines of C and Si, the fit appears to be somewhat consistent. This model, compared with the best-fit disk model, has a lower χ^2 and fits the metal lines and the Ly α region successfully, whereas the best-fit disk model fails to do this.

An additional test of the consistency of our DBAZ composition white dwarf fit is offered by the constraint that the magnitude corresponding to the optical or IR flux of the model is not brighter than the corresponding observed magnitude of CP Eri in the same wavelength range, since it is expected that other sources of systemic light (e.g., a hot spot, accretion disk, secondary) are contributing to the system brightness as well. The STIS F28 $\times$ 50LP magnitude at the time of the *HST* observation was 19.9. Our best-fit white dwarf model folded with the acquisition filter transmission predicts a magnitude of 20.8, fainter than the observed value.

4. DISCUSSION AND CONCLUSIONS

Our analysis suggests that CP Eri may not be a typical AM CVn system in that we find a significant abundance of H and a higher metallicity compared with other AM CVn systems such as the well-studied object GP Com, which is metal-poor, has shown little evidence of any H, and is always seen in a low state. It is obviously important to explore whether the abundance of H from our UV analysis would lead to detected H features in the optical spectrum. While a reexamination of the optical quiescent spectrum of Groot et al. (2001) suggests a possible hint of very weak H I emission features in the optical low-state spectrum (see Fig. 1 in Groot et al. 2001), much higher signal-to-noise ratio optical spectra are clearly needed. In any case, the metallicity we derive is consistent with the Groot et al. conclusion that CP Eri has higher metallicity than GP Com and CE 315, implying that it is not a Population II object.

Is it reasonable for the white dwarf in an AM CVn star like CP Eri to be accreting both He and H? If so, what are the implications for the ancestry of CP Eri and other AM CVn objects? There are currently three formation channels favored

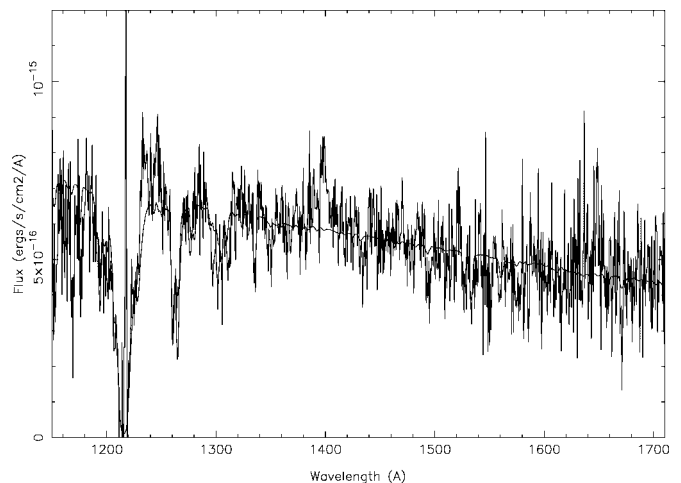


FIG. 3.—Flux distribution, flux vs. wavelength, for the best-fitting hybrid composition, DBAZ, photosphere model with $\log g = 8$, $T_{\text{eff}} = 17,000$ K, He/H = 10^3 , $Z = 0.05$, and $V \sin i = 400 \text{ km s}^{-1}$, compared with the *HST* STIS spectrum of CP Eri.

for AM CVn stars: (1) the double degenerate scenario (Tutukov & Yungelson 1979); (2) the semidegenerate helium star scenario (Iben & Tutukov 1991); and (3) the subset of H-rich cataclysmic variables with evolved secondaries (Podsiadlowski et al. 2003). In the latter scenario, a normal H-rich star of mass $\sim 1 M_{\odot}$ fills its Roche lobe near the end of, or just after, core hydrogen burning while the initially nondegenerate and H-rich companion becomes increasingly helium-rich and degenerate during its evolution. In their early evolution, these systems would appear as “normal” H-rich cataclysmic variables with evolved secondaries. A number of theoretical investigations of all three formation channels have been carried out with stellar evolution codes and binary population synthesis simulations (e.g., Nelemans et al. 2001; Podsiadlowski et al. 2003). Binary stellar evolution model sequences using a Henyey-type code and including angular momentum losses due to magnetic braking and gravitational wave emission are available for different evolutionary phases of the evolved donor at the onset of mass transfer (Podsiadlowski et al. 2003). Only two of their four evolutionary sequences reach orbital period minima shorter than 55 minutes (75 minutes is the P_{orb} minimum for an H-rich cataclysmic variable). The two sequences correspond to donors with H-exhausted cores of 0.037 and 0.063 $M_{\odot}$, which both transform themselves into nearly pure He degenerates but with traces of H remaining. Both of these sequences pass through the range of AM CVn periods twice, once with the period decreasing toward the minimum, once after the period minimum.

Which case might be applicable to CP Eri? Since the degenerate donors in systems before the period minimum have larger amounts of H left in their envelopes, it seems more likely this case applies to CP Eri. For its observed P_{orb} (28.73 minutes), the binary population synthesis calculations of Podsiadlowski et al. (2003) yield predicted values of secondary mass $M_2 = 0.100^{+0.003}_{-0.021} M_{\odot}$, mass transfer rate $\dot{M} = 10^{-9.4} M_{\odot} \text{ yr}^{-1}$, and surface hydrogen abundance on the secondary $X = 0.22$ for CP Eri if its P_{orb} is decreasing (i.e., it is evolving before the period minimum). If, however, CP Eri is evolving after the period minimum (i.e., P_{orb} is increasing), then the simulations predict $M_2 = 0.040^{+0.005}_{-0.004} M_{\odot}$, $\dot{M} = 10^{-9.8} M_{\odot} \text{ yr}^{-1}$, and $X = 0.03^{+0.01}_{-0.03} M_{\odot}$.

Since CP Eri's accretor is the only white dwarf in an AM CVn so far with a directly determined photospheric H abundance, we cannot compare with any other AM CVn cases. Therefore, analyses of other exposed white dwarfs in these objects are clearly needed.

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