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THE QUIESCENT SPECTRUM OF THE AM CANUM VENATICORUM STAR CP ERIDANI

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ABSTRACT

We used the 6.5 m Multiple Mirror Telescope to obtain a spectrum of the AM Canum Venaticorum star CP Eridani in quiescence. The spectrum is dominated by He I emission lines, which are clearly double-peaked with a peak-to-peak separation of ∼1900 km s^{-1}. The spectrum is similar to that of the longer period AM CVn systems GP Comae Berenices and CE 315, linking the short- and long-period AM CVn systems. In contrast to GP Com and CE 315, the spectrum of CP Eri does not show a central "spike" in the line profiles, but it does show lines of Si II in emission. The presence of these lines indicates that the material being transferred is of higher metallicity than in GP Com and CE 315, which, combined with the low proper motion of the system, probably excludes a halo origin of the progenitor of CP Eri. We constrain the primary mass to $M_1 > 0.27\ M_\odot$ and the orbital inclination to $33° < i \lesssim 80°$. The presence of the He I lines in emission opens up the possibility for phase-resolved spectroscopic studies, which will allow us to determine the system parameters and to study in detail helium accretion disks under highly varying circumstances.

Subject headings: accretion, accretion disks — line: profiles — stars: individual (CP Eridani)

1. INTRODUCTION

The AM Canum Venaticorum stars are a heterogeneous group of nine variable stars that are characterized by a complete lack of hydrogen and a strong dominance of helium in their spectra (see Table 1). Observationally, they can be roughly divided into three groups. First, the high-state systems, AM CVn and HP Librae, show broad, but shallow, helium absorption lines in their spectra, and they show low-level photometric variability with periods of less than 20 minutes. Second, the outburst systems (CR Bootis, V803 Centauri, CP Eridani) show large-amplitude (>1 mag) photometric variability on a timescale of days to weeks as well as lower level variability with periods of 20–30 minutes. In their bright state, these are spectroscopically similar to the high-state systems, and in their quiescent state, they show the He I lines in emission, but spectra of these systems in quiescence are rare and of low signal-to-noise ratio (S/N). The third category consists of the quiescent systems, GP Com and CE 315, that show He I emission lines and hardly any photometric variability.

It is commonly assumed that these systems are binary white dwarfs in which the mass is being transferred from a very low mass secondary (<0.1 $M_\odot$) via a helium accretion disk to a more massive primary. This scenario was first proposed by Paczyński (1967) and Faulkner, Flannery, & Warner (1972) to explain the photometric flickering found in AM CVn itself by Warner & Robinson (1972). Until recently, spectroscopic confirmation of this binary scenario was only possible for GP Com, in which a 46 minute spectroscopic variation was first detected by Nather, Robinson, & Stover (1981; see also Marsh, Horne, & Rosen 1991 and Marsh 1999). The high-state and outburst systems defied every attempt to unveil their binary nature spectroscopically, until the detection of an S-wave component in the He I lines of AM CVn (Nelemans, Steeghs, & Groot 2001b). By analogy, it follows that all AM CVn stars are binaries.

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The three categories can be understood as very similar binary systems in different phases of their evolution, which proceeds from short periods and high mass transfer rates for the high-state systems to longer periods and lower mass transfer rates for the quiescent systems (e.g., Warner 1995a; Tutukov & Yungelson 1996; Nelemans et al. 2001a). This evolution is driven by the loss of angular momentum due to gravitational wave emission.

When the mass accretion rate is high (high-state systems and outburst systems during outburst), the accretion disks are optically thick, leading to absorption-line spectra. When the mass accretion rate is low (outburst systems in quiescence and the quiescent systems), the accretion disk is optically thin, leading to emission-line spectra. A similar distinction is seen in the hydrogen-rich cataclysmic variables (CVs; see, e.g., Warner 1995b).

To support the evolutionary sequence, it would be of great benefit to show that the quiescent spectrum of the outburst systems is indeed similar to that of GP Com and CE 315. The few quiescent spectra of the outburst systems that are available (Abbott et al. 1992 for CP Eri, Wood et al. 1987 for CR Boo, and O'Donoghue, Menzies, & Hill 1987 for V803 Cen) show some emission lines of He I (especially He I λ5875), but none show a double-peaked profile. To close this gap in the spectroscopic sequence of AM CVn stars, we obtained a quiescent spectrum of the outburst system CP Eri with the refurbished 6.5 m Multiple Mirror Telescope (MMT) on Mount Hopkins, Arizona.

2. CP ERI

CP Eri was found as a faint, variable, blue star at high Galactic latitude by Luyten & Haro (1959), who observed it at 17th magnitude, ∼2.5 mag brighter than its quiescent magnitude of $B \sim 19.7$. A photometric periodicity of 29 minutes was found by Howell et al. (1991). CP Eri belongs to the outburst systems and, among them, is the one with the longest orbital period; therefore, among the outbursting systems, it should be the one that resembles GP Com and CE 315 the most. The system was spectroscopically studied by Abbott et al. (1992), who show the outburst spectrum to be similar to that of the high-state systems. Their quiescent spectrum shows

TABLE 1
SPECTROSCOPIC CHARATERISTICS OF THE AM CVn STARS[a]

Name	P_{orb} (s)	m_V	State	Spectral Characteristics	References
AM CVn	1028.7	13.7–14.2	High	Broad, shallow He I absorption; He II sometimes in emission	1–3
HP Lib	1119	13.6–13.7	High	Broad, shallow He I absorption	4
CR Boo	1471.3	13.0–18.0	Outburst	Broad, shallow He I absorption	5
			Quiescence	He I emission	5
V803 Cen	1611	13.2–17.4	Outburst	Broad, shallow He I absorption	6
			Quiescence	He I emission	7
CP Eri	1724	16.5–19.7	Outburst	Broad, shallow He I absorption	8
			Quiescence	Double-peaked emission He I, He II; Si II emission, no "spike"	
GP Com	2790	15.7–16.0	Quiescence	Double-peaked He I, He II emission; N I emission, central spike in He I	9–12
CE 315	3906	17.5	Quiescence	Double-peaked He I, He II emission; N I emission, central spike in He I	13
KL Dra	?	16–20	Outburst	Broad, shallow He I absorption	14
			Quiescence	?	
RX J1914+24	569	$m_I = 18.5$	Magnetic	?	

REFERENCES.—(1) Patterson et al. 1992; (2) Patterson, Halpern, & Shambrook 1993; (3) Nelemans et al. 2001b; (4) O'Donoghue et al. 1994; (5) Wood et al. 1987; (6) O'Donoghue & Kilkenny 1989; (7) O'Donoghue et al. 1987; (8) Abbott et al. 1992; (9) Burbidge & Strittmatter 1971; (10) Nather et al. 1981; (11) Marsh et al. 1991; (12) Marsh 1999; (13) Ruiz et al. 2001; (14) Jha et al. 1998.

[a] For periods and magnitudes, see Warner 1995a and references therein; for RX J1914+24, see Cropper et al. 1998 and Ramsay et al. 2000.

a blue continuum with the lines of He I λ5015 and λ5875 in emission. Although a double-peaked profile is hinted at, the S/N of the spectrum was too low to establish this firmly. A very low S/N spectrum is also shown in Zwitter & Munari (1995), but no lines are visible at all in this spectrum.

3. OBSERVATIONS

We observed the source on the night of 2000 December 1 with the Blue Channel Spectrograph on the 6.5 m MMT located on Mount Hopkins, Arizona. The 500 grooves mm^{-1} grating, centered on 5200 Å, was used with a 1\".0 slit width and a 3072 × 1024 pixel Loral CCD. Weather conditions were nonphotometric, with scattered high clouds. Therefore, no attempt to obtain flux standards was made. The setup resulted in an effective spectral resolution of 3 Å (180 km s^{-1} at 5000 Å) over a wavelength range of 3400–7000 Å. Observations were made as a sequence of three 20 minute exposures between 07:43 and 08:48 UT. HeNeAr wavelength comparison spectra were taken at the beginning and end of each observation.

All data have been reduced using standard IRAF tasks. The spectra were extracted using the optimal extraction routine of Horne (1986), wavelength-calibrated by using the HeNeAr comparison spectra (with typical residuals of ∼0.3 Å) and normalized by using a cubic spline fit to selected wavelength regions.

4. THE QUIESCENT SPECTRUM OF CP ERI

The median-averaged, 3 pixel boxcar-smoothed, quiescent spectrum of CP Eri is shown in Figure 1. We see that it is dominated by He I emission lines, similar to GP Com and CE 315. We list the identified lines and the equivalent widths in Table 2.

All clearly identified lines are double-peaked. This double-peaked profile is commonly seen, not only in GP Com and CE 315 but also in dwarf novae and nova-like CVs, and is taken as an indication of the formation of these lines in a rotating accretion disk (see, e.g., Horne & Marsh 1986). The peak velocity of these profiles is a measure of the rotational velocity of the outer parts of the accretion disk and can therefore be used to constrain the system parameters. In order to improve on the S/N, we have added (in velocity space) the profiles of the most prominent He I lines in our spectrum: He I λ6678, λ5875, λ5015, λ4921, λ4471, and λ3888. We did not use the line He I λ4713 because of its blend with He II λ4686. In Figure 2 (*top six panels*), we show the line profiles of these lines. The sum-averaged profile in 100 km s^{-1} bins (*binned line*) and a double-Gaussian profile fit to this sum-averaged profile are shown in the bottom panel of Figure 2. For the Gaussian fit, we have used a symmetric profile in which the width and height of the two components were kept equal. The best-fit values are given in Table 3. A fit with all of the parameters being free gave a slightly wider red peak and similar peak velocities but did not provide a significantly better fit. From the asymmetry in the central velocity of the peaks, we deduce a systemic velocity, $\gamma = 23 \pm 53$ km s^{-1}, i.e., not significantly different from zero. From half of the peak-to-peak separation of the profile, we deduce a rotational velocity of the material in the outer disk of CP Eri of 946 ± 52 km s^{-1}.

5. LIMITS ON THE PRIMARY MASS AND INCLINATION

We can use the outer disk velocity of 946 km s^{-1} to set limits on the mass of the primary star and the inclination of the system. The size of the primary Roche lobe can be approximated by (Paczyński 1967)

$$R_{L_1} = 0.462a\left(\frac{M_1}{M_1 + M_2}\right)^{1/3}, \tag{1}$$

where M_1 and M_2 are the mass of the primary and secondary, respectively, and a is the orbital separation of the components in the binary. Using Kepler's third law to write a in terms of the component masses and the orbital period and collecting all numerical constants, we can rewrite equation (1) as

$$R_{L_1} = 5.48 \times 10^{-5} P_{orb}^{2/3} M_1^{1/3}\ \mathrm{m}, \tag{2}$$

with the orbital period P_{orb} in seconds and the primary mass in kilograms.

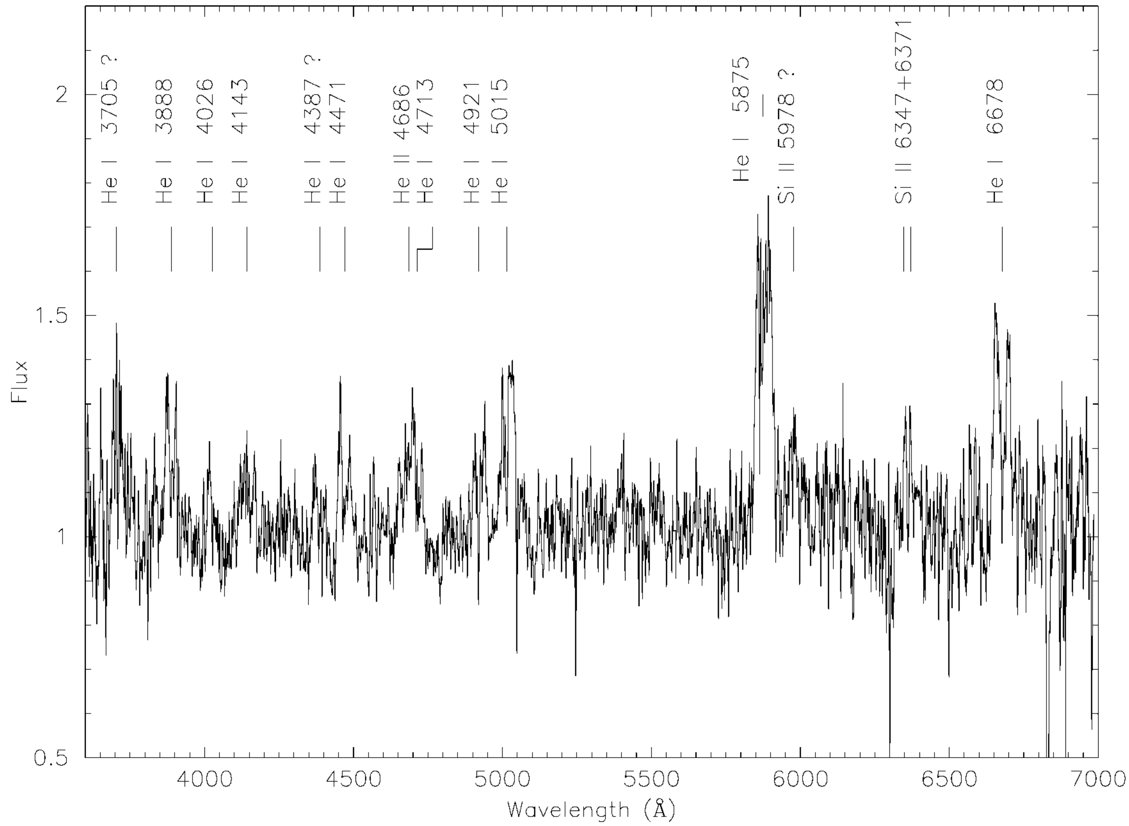

FIG. 1.—Normalized spectrum of CP Eri in quiescence. Line identifications are shown.

If we assume that the gas in the outer disk is in Keplerian motion around the primary and that the disk extends to 70% of the primary Roche lobe radius, before being truncated by tidal forces, we can equate the radius at which a Keplerian motion of 946 km s^{-1} is reached with 70% of the Roche lobe radius and obtain

$$\frac{GM_1}{(v/\sin i)^2} = 3.83 \times 10^{-5} P^{2/3} M_1^{1/3}, \qquad (3)$$

with G, M_1, v, and P all in SI units. This can be rewritten as

$$M_1 = 4.35 \times 10^8 v^3 P \sin^{-3} i = 0.32 \sin^{-3} i \ M_{\odot}. \qquad (4)$$

From the fact that the light curve does not show any (grazing) eclipses (Howell et al. 1991), we can set an upper limit to the inclination of $i \lesssim 80°$, which gives a lower limit to the primary mass of 0.34 $M_{\odot}$. Since the primary mass must be lower than the Chandrasekhar mass of 1.4 $M_{\odot}$, this sets a lower limit on the inclination of $i > 38°$. If the accretion disk only reaches 50% of the Roche lobe radius, as is often seen in CV dwarf novae (Harrop-Allin & Warner 1996), the lower limit to the mass becomes 0.27 $M_{\odot}$, and the lower limit to the inclination is 33°.

TABLE 2

EQUIVALENT WIDTH OF THE EMISSION LINES IN CP ERI

Line	Wavelength Region (Å)	EW (Å)
He I λ3705	3661–3780	−9.5 ± 1.8
He I λ3888	3837–3930	−9.3 ± 1.4
He I λ4026	3977–4050	−1.7 ± 1.2
He I λ4143	4086–4190	−5.4 ± 1.4
He I λ4387	4334–4417	−1.5 ± 1.2
He I λ4471	4433–4531	−5.3 ± 1.4
He λλ4686, 4713	4634–4764	−10.4 ±1 .6
He I λ4921	4878–4976	−6.0 ± 1.3
He I λ5015	4966–5095	−14.1 ± 1.5
He I λ5875	5789–5934	−32.4 ± 1.8
Si II λ5978	5944–6011	−7.5 ± 1.2
Si II λλ6347, 6371	6327–6400	−6.7 ± 1.2
He I λ6678	6617–6720	−18.2 ± 1.6

6. COMPARISON WITH GP COM AND CE 315

The resemblance of our quiescent spectrum with that of GP Com is remarkable, firmly establishing the connection between the long- and short-period AM CVn systems. Apart from the similarities to GP Com, there are also a few marked differences. In both GP Com (Marsh 1999) and CE 315 (Ruiz et al. 2001), a clear "central spike" with a very low radial velocity amplitude (<10 km s^{-1}) is seen in the He I line profiles, which Marsh (1999) attributes to emission from the primary white dwarf. No such central spike is seen in the average line profile of CP Eri (Fig. 2).

A further difference between CP Eri and GP Com/CE 315 is the presence in our spectrum of Si II λ6347, 6371 and possibly Si II λ5987. These are not present in the spectra of GP Com and CE 315. Marsh et al. (1991) show that this indicates that the material in the accretion disk of GP Com has a severely subsolar metal abundance, further indicating that the object is probably a halo star. Marsh et al. (1991) show that for a progenitor with solar metallicity, the strongest metal lines that should be visible from the accretion disk are the Si II lines that we see in our spectrum of CP Eri. A preliminary comparison of the quiescent spectrum of CP Eri with the models as used

TABLE 3
Parameter Values for a Double-Gaussian Fit to the Averaged Summed He i Line Profile[a]

Parameter	Value
Blue central velocity (km s^{-1})	−923 ± 36
Red central velocity (km s^{-1})	970 ± 39
Gaussian width (km s^{-1})	794 ± 52
Peak flux	1.39 ± 0.02

[a] All errors are 1 σ.

in Marsh et al. (1991) suggests that the progenitor of the secondary currently seen in CP Eri had lower than solar metallicity but was certainly not as metal-poor as in GP Com and CE 315. The current spectrum's S/N, however, is too low to perform a quantitative modeling or to verify whether the Si ii lines are double-peaked and therefore whether they originate in the disk. However, if they do not originate in the disk, they must come from either the secondary, the primary, or circumbinary material after being expelled from the system. In all these cases, the ultimate origin of this material is the secondary star, and our conclusions on the metallicity of the secondary's progenitor remain valid. Any silicon that is "native" to the primary will have diffused to the white dwarf center and will not be visible on the surface.

7. DISCUSSION

Understanding the evolution of AM CVn stars is of great astrophysical importance because it touches on many fields in astronomy where large gaps in our knowledge still exist. According to the evolutionary models (e.g., Nelemans et al. 2001a) seen today, AM CVn systems must have survived three mass transfer phases of which at least one was a common-envelope phase; they could be contributors to the low-frequency gravitational radiation background, and "failed" AM CVn stars of the He family (white dwarf plus low-mass helium star) could explode as Type Ia supernovae in an edge-lit detonation and thereby contribute up to 25% of the galactic Type Ia supernova rate (see Nelemans et al. 2001a).

The detection of Si ii lines in the quiescent spectrum of CP Eri shows that its progenitor must have had an appreciably higher metal abundance than the progenitors of GP Com and CE 315. Detecting the metal lines also opens up the possibility of constraining the evolutionary history of these systems from the chemical composition of the transferred material.

The proper motion of CP Eri can be derived from comparing the POSS-I (on which the source is in outburst) and POSS-II plates: $\mu_{\rm R.A.} = 6.3 \pm 0.6$ mas yr^{-1} and $\mu_{\rm decl.} = -15.0 \pm 0.6$ mas yr^{-1} (M. van Kerkwijk 2001, private communication). Together with the detection of the metal lines, which point to a higher metallicity than in GP Com and CE 315, it seems likely that CP Eri is not a Population II object.

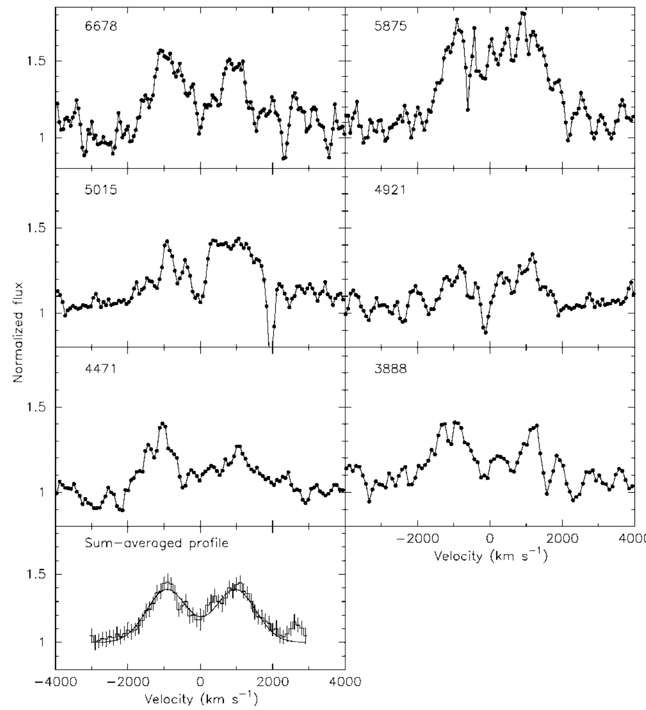

Fig. 2.—Line profiles of the clearly identified He i lines (*top six panels*) and the sum-averaged He i line profile in 100 km s^{-1} velocity bins (*binned line, bottom panel*) and a double-Gaussian profile fit to this average profile (*smooth curve, bottom panel*).

The detection of double-peaked emission lines in the quiescent spectrum of CP Eri shows the physical homogeneity of the AM CVn stars as mass transferring white dwarf binaries and opens up the possibility of studying the dynamics of the outbursting AM CVn stars in greater detail. It will also allow us to study helium accretion disks that experience periodic changes from high to low mass transfer rates. Following the behavior of the spectral lines during these transitions is an important tool for tracking the changing physical conditions in these unique disks, especially when these results are compared with the hydrogen-rich disks found in many other systems (e.g., CVs).

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