The following full text is a preprint version which may differ from the publisher's version.

For additional information about this publication click this link.
http://hdl.handle.net/2066/156200

Please be advised that this information was generated on 2019-05-05 and may be subject to change.
The quiescent spectrum of the AM CVn star CP Eri

P.J. Groot\textsuperscript{1}, G. Nelemans\textsuperscript{2}, D. Steeghs\textsuperscript{3}, T.R. Marsh\textsuperscript{3}

\textbf{ABSTRACT}

We used the 6.5m MMT to obtain a spectrum of the AM CVn star CP Eri in quiescence. The spectrum is dominated by He\textsc{i} emission lines, which are clearly double peaked with a peak-to-peak separation of $\sim$1900 km s$^{-1}$. The spectrum is similar to that of the longer period AM CVn systems GP Com and CE 315, linking the short and the long period AM CVn systems. In contrast with 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\textsc{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 $33^\circ < i < 80^\circ$. The presence of the He\textsc{i} lines in emission opens up the possibility for phase resolved spectroscopic studies which allows a determination of the system parameters and a detailed study of helium accretion disks under highly varying circumstances.

\textit{Subject headings:} accretion disks—line:profiles—binaries:individual (CP Eri)

1. Introduction

The AM CVn 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 Tab. 1). Observationally they can be roughly divided in three groups. First, the high state systems, AM CVn and HP Lib, that show broad, but shallow, helium absorption lines in
their spectra and show low-level photometric variability with periods less than 20 minutes. Second, the outburst systems (CR Boo, V803 Cen, CP Eri), that 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\textsc{i} lines in emission, but spectra of these systems in quiescence are rare and of low S/N. The third category are the quiescent systems, GP Com and CE 315, that show He\textsc{i} emission lines and hardly any photometric variability.

It is commonly assumed that these systems are binary white dwarfs where mass is being transferred from a very low-mass secondary (<0.1M\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, where a 46 min 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\textsc{i} lines of AM CVn (Nelemans, Steeghs & Groot, 2001a). By analogy it follows that all AM CVn stars are binaries.

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., 2001b). 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 et al., 1987 for V803 Cen) show some emission lines of He\textsc{i} (especially He \textsc{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 6.5m MMT on Mt. Hopkins, AZ.

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 magnitudes brighter than its quiescent magnitude of B∼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, and therefore should be, among the outbursting systems, 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 a blue continuum with the lines of He\textsc{i} λ5015 and λ5875 in emission. Although a double-peaked profile is hinted at, the S/N ratio of the spectrum was too low to firmly establish this. 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 Dec. 1, 2000 with the Blue Channel Spectrograph on the 6.5m MMT, located on Mt. Hopkins, AZ. The 500 grooves/mm grating, centered on 5200 Å was used with a 1"0 slit width and a 3072×1024 pixel Loral CCD. Weather conditions were non-photometric, with scattered high clouds. Therefore no attempt to obtain flux standards was made. The set-up resulted in an effective spectral resolution of 3Å (180 km s\(^{-1}\) at 5000 Å) over a wavelength range of 3400-7000 Å. Observations were made as a sequence of three 20m exposures between 07:43-08:48 UT. HeNeAr wavelength comparison spectra were taken at the beginning and end of each observation.

All data has 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 (typical residuals of ∼0.3Å) and normalized by using a cubic spline fit to selected wavelength regions.
4. The quiescent spectrum of CP Eri

The median-averaged, 3-pixel box-car smoothed, quiescent spectrum of CP Eri is shown in Fig. 1. We see that it is dominated by He\textsc{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 novalike 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 S/N we have added (in velocity space) the profiles of the most prominent He\textsc{i} lines in our spectrum: He\textsc{i} \(\lambda 6678\), \(\lambda 5875\), \(\lambda 5015\), \(\lambda 4921\), \(\lambda 4471\) and \(\lambda 3888\). We did not use the He\textsc{i} \(\lambda 4713\) line because of its blend with He\textsc{ii} \(\lambda 4686\). In Fig. 2 (upper 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 is shown in the bottom panel of Fig. 2. For the Gaussian fit we have used a symmetric profile where the width and height of the two components were kept equal. The best fitted values are given in Tab. 3. A fit with all parameters 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, \(\gamma = 23 \pm 5\) km s\(^{-1}\), i.e. not significantly different from zero. From half of the peak-to-peak separation of the the profile we deduce a rotational velocity of the material in the outer disk of CP Eri of 946\(\pm\)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):

\[
R_{L1} = 0.462 \ a \ \left( \frac{M_1}{M_1 + M_2} \right)^{1/3},
\]

with \(M_1\) and \(M_2\) the mass of the primary and secondary, and \(a\) 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 Eq. 1 as:

\[
R_{L1} = 5.48 \times 10^{-5} \ P_{\text{orb}}^{2/3} \ M_1^{1/3} \ \text{m},
\]
with the orbital period, $P_{\text{orb}}$, in seconds and the primary mass in kg.

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:

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

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

$$M_1 = 4.35 \times 10^8 \frac{v^3}{P \sin^{-3} i} = 0.32 \sin^{-3} i \ M_\odot$$

From the fact that the light curve does not show any (grazing) eclipses (Howell, 1992), we can set an upper limit to the inclination of $i \lesssim 80^\circ$, 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 $i > 38^\circ$.

If the accretion disk only reaches to 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 33°.

### 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 the short period AM CVn systems.

Apart from the similarities with GP Com, there are also a few marked differences. Both in GP Com (Marsh 1999) as well as in 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 the Si II $\lambda 6347$, 6371 lines and possibly the Si II $\lambda 5987$ line. These are not present in the spectra of GP Com and CE 315. Marsh, Horne & Rosen (1991) showed that this indicates that the material in the accretion disk of GP Com has a severely sub-solar metal abundance, indicating that the object is probably a halo star. Marsh et al. show that for a progenitor with solar metallicity, the strongest metal lines that should be visible from the
accretion disk are the Si\textsc{ii} lines we see in our spectrum of CP Eri. A preliminary comparison of the quiescent spectrum of CP Eri with the models as used 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 is however of too low S/N to perform a quantitative modelling and also to verify whether the Si\textsc{ii} lines are double-peaked and therefore originating in the disk. However, if they do not originate in the disk they must come from either the secondary, the primary or from 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 ‘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 many fields in astronomy where large gaps in our knowledge still exist. According to evolutionary models (e.g. Nelemans et al., 2001), to be 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 SN Ia rate (see Nelemans et al., 2001b).

The detection of Si\textsc{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 the possibility to constrain 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: \(\mu_{\text{RA}}=6.3\pm0.6\ \text{mas/yr}\) and \(\mu_{\text{Dec}}=-15.0\pm0.6\ \text{mas/yr}\) (Van Kerkwijk, private communication). Together with 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.

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 the possibility of studying the dynamics of the outbursting AM CVn stars in greater detail.
It will also allow for the study of helium accretion disks that experience periodic changes from high to low mass-transfer rates. Following the behaviour of the spectral lines during these transitions is an important tool to track 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. cataclysmic variables.

Acknowledgments We would like to thank Nelson Caldwell for obtaining the observations, and the referee, Dr. Alon Retter for very useful comments. PJG is supported by a Harvard-Smithsonian CfA fellowship. GN is supported by NWO Spinoza Grant 08-0 to E.P.J. van den Heuvel. DS is supported by a PPARC fellowship.

REFERENCES

Howell S. B., 1991, IBVS, 3653
Jha S., Garnavich P., Challis P., Kirshner R., Berlind P., 1998, IAUC, 6983
Luyten W. J. & Haro G., 1959, PASP, 71, 469

Pacyński, B., 1967, ActA, 17, 287


Table 1: Spectroscopic characteristics of the AM CVn stars

<table>
<thead>
<tr>
<th>Name</th>
<th>$P_{\text{orb}}$ (s)</th>
<th>$m_V$</th>
<th>Spectral characteristics</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>AM CVn</td>
<td>1028.7</td>
<td>13.7-14.2</td>
<td>High state: Broad, shallow He\textsc{i} absorption, He\textsc{ii} sometimes in emission</td>
<td>1-3</td>
</tr>
<tr>
<td>HP Lib</td>
<td>1119</td>
<td>13.6-13.7</td>
<td>High state: Broad, shallow He\textsc{i} absorption</td>
<td>4</td>
</tr>
<tr>
<td>CR Boo</td>
<td>1471.3</td>
<td>13.0-18.0</td>
<td>Outburst: Broad, shallow He\textsc{i} absorption</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Quiescence: He\textsc{i} emission</td>
<td>5</td>
</tr>
<tr>
<td>V803 Cen</td>
<td>1611</td>
<td>13.2-17.4</td>
<td>Outburst: Broad, shallow He\textsc{i} absorption</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Quiescence: He\textsc{i} emission</td>
<td>7</td>
</tr>
<tr>
<td>CP Eri</td>
<td>1724</td>
<td>16.5-19.7</td>
<td>Outburst: Broad, shallow He\textsc{i} absorption</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Quiescence: Double peaked emission He\textsc{i}, He\textsc{ii} emission, no 'spike'</td>
<td></td>
</tr>
<tr>
<td>GP Com</td>
<td>2790</td>
<td>15.7-16.0</td>
<td>Quiescence: Double peaked He\textsc{i}, He\textsc{ii} emission, Ni emission, central spike in He\textsc{i}</td>
<td>9-12</td>
</tr>
<tr>
<td>CE 315</td>
<td>3906</td>
<td>17.5</td>
<td>Quiescence: Double peaked He\textsc{i}, He\textsc{ii} emission, Ni emission, central spike in He\textsc{i}</td>
<td>13</td>
</tr>
<tr>
<td>KL Dra</td>
<td>?</td>
<td>16-20</td>
<td>Outburst: Broad, shallow He\textsc{i} absorption</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Quiescence: ?</td>
<td></td>
</tr>
<tr>
<td>RX J1914+24</td>
<td>569</td>
<td>$m_{\text{I}}=18.5$</td>
<td>Magnetic</td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Equivalent width of the emission lines in CP Eri

<table>
<thead>
<tr>
<th>Line</th>
<th>Wavelength region</th>
<th>EW (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>He i λ3705</td>
<td>3661-3780</td>
<td>-9.5±1.8</td>
</tr>
<tr>
<td>He i λ3888</td>
<td>3837-3930</td>
<td>-9.3±1.4</td>
</tr>
<tr>
<td>He i λ4026</td>
<td>3977-4050</td>
<td>-1.7±1.2</td>
</tr>
<tr>
<td>He i λ4143</td>
<td>4086-4190</td>
<td>-5.4±1.4</td>
</tr>
<tr>
<td>He i λ4387</td>
<td>4334-4417</td>
<td>-1.5±1.2</td>
</tr>
<tr>
<td>He i λ4471</td>
<td>4433-4531</td>
<td>-5.3±1.4</td>
</tr>
<tr>
<td>He λ4686/4713</td>
<td>4634-4764</td>
<td>-10.4±1.6</td>
</tr>
<tr>
<td>He i λ4921</td>
<td>4878-4976</td>
<td>-6.0±1.3</td>
</tr>
<tr>
<td>He i λ5015</td>
<td>4966-5095</td>
<td>-14.1±1.5</td>
</tr>
<tr>
<td>He i λ5875</td>
<td>5789-5934</td>
<td>-32.4±1.8</td>
</tr>
<tr>
<td>Si ii λ5978</td>
<td>5944-6011</td>
<td>-7.5±1.2</td>
</tr>
<tr>
<td>Si ii λ6347/71</td>
<td>6327-6400</td>
<td>-6.7±1.2</td>
</tr>
<tr>
<td>He i λ6678</td>
<td>6617-6720</td>
<td>-18.2±1.6</td>
</tr>
</tbody>
</table>

Table 3: Parameter values for a double Gaussian fit to the averaged summed He i line profile (all errors are 1-σ)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blue central velocity</td>
<td>-923±36 km s⁻¹</td>
</tr>
<tr>
<td>Red central velocity</td>
<td>970±39 km s⁻¹</td>
</tr>
<tr>
<td>Gaussian width</td>
<td>794±52 km s⁻¹</td>
</tr>
<tr>
<td>Peak flux</td>
<td>1.39±0.02</td>
</tr>
</tbody>
</table>
Fig. 1.— The normalized spectrum of CP Eri in quiescence. Line identifications are shown.
Fig. 2.— The line profiles of the clearly identified He I lines (top 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).