Optical observations of close binary systems with a compact component
Augusteijn, T.
V485 Centauri: a dwarf nova with a $59\,\text{m}$ orbital period

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**Abstract**

We present time resolved photometry and spectroscopy of the dwarf nova V485 Cen. The average photometric light curve at the previously detected 59 min period (Augusteijn et al. 1993, Chapter 8) shows a single “hump” extending over approximately half the period. Significant radial velocity variations are detected in Hα only for a period equal to the photometric period. The line shows two components which vary with this period; one component dominates the line wings and has a low radial velocity amplitude, and the second component dominates the line center and has a high radial velocity amplitude. The phasing of the two components with respect to the light curve is consistent with the component dominating the line center originating in the hot spot (the so-called S-wave) and the component dominating the line wings originating from a region centered on the white dwarf, and we conclude that the $59\,\text{m}$ is the orbital period of the system. Using various observational constraints we derive a mass ratio of $q = M_{\text{WD}}/M_{\text{sec}} \sim 2.6$ and a inclination of $i \sim 20-30^\circ$. Strong evidence is found for a significant contribution from the secondary to the spectrum at wavelengths longer than $\sim 5900$ Å. We discuss the discovery of a $59\,\text{m}$ orbital period in the framework of evolutionary ideas about cataclysmic variables. The most likely explanation is that the secondary has a low, but finite, hydrogen content.

**9.1 Introduction**

The only physical property known accurately for a large number of cataclysmic variables (CV's) is the orbital period (Ritter and Kolb 1994). The period distribution of CV's shows two striking features: (i) there is a ‘period gap’ between $\sim 2^h$ and $\sim 3^h$; (ii) the distribution has a cut-off at a minimum period of $\sim 80\,\text{m}$. The period distribution can be understood as a result of the orbital evolution of CVs. The evolution from a detached binary (the pre-CV) to the semi-detached CV, and the subsequent mass transfer and long-term evolution to shorter orbital periods is driven by the loss of orbital angular momentum caused by gravitational radiation (e.g., Patterson 1984) and magnetic braking (see, e.g., Verbunt and Zwaan 1981).
The period gap can then be understood as the result of the termination (or substantial weakening), at a period of ~3\(^h\), of the magnetic braking (Spruit and Ritter 1983, Rappaport, Verbunt, Joss 1983): the secondary, which is out of thermal equilibrium because of the mass loss, and therefore somewhat oversized, contracts, and as a result mass transfer ceases. The orbit continues to shrink (but more slowly than before) due to gravitational radiation alone until the secondary again fills its Roche lobe at an orbital period of ~2\(^h\) and mass transfer resumes.

The mass of the late-type companion in a CV decreases as it transfers mass to the white-dwarf primary. As long as the mass of the secondary star is large enough to support hydrogen burning in its core, it is near the main-sequence mass-radius relation, and its radius decreases as its mass decreases. However, once the late-type star has lost so much mass that it can no longer burn hydrogen in its core, it becomes degenerate and its radius will increase as its mass decreases. As the orbital period of a CV depends to first order only on the radius of the secondary star, this implies that there is a minimum orbital period when the secondary star becomes degenerate. The value of this minimum orbital period depends on the total mass of the system and its chemical composition (Paczynski and Sienkiewicz 1981, Rappaport, Joss, and Webbink 1982, Sienkiewicz 1984). For a system with solar abundances this minimum period is ~80\(^m\).

There is presently only one group of CV's known with orbital periods less than 80\(^m\): the AM CVn stars. They are characterized by the total absence of hydrogen lines in their spectra, and they show photometric and/or spectroscopic periods of 17.5–46.5\(^m\) (Ritter and Kolb 1994). These systems are probably CV's containing a (helium degenerate) white-dwarf secondary.

The variable star V485 Cen is classified in the General Catalogue of Variable Stars (Kholopov et al. 1985) as a U Gem type dwarf nova. In an earlier article (Augusteijn et al. 1993, Chapter 8) we reported the discovery of a 59\(^m\) photometric period in this dwarf nova. We also found that the optical spectrum of V485 Cen shows both H and HeI emission lines. In this article we present time resolved spectroscopy and photometry of V485 Cen to investigate the nature of this period. We will show that this period represents the orbital period of this system, and discuss the implication of this period in the framework of evolutionary ideas about CV's.

## 9.2 Photometry

We observed V485 Cen in quiescence during 9 nights with a CCD attached to the 91cm Dutch telescope at the European Southern Observatory in Chile. The source was monitored using a standard V filter. In Table 9.1 we give a summary of our observations. In all cases the integration time was 4 min. Differential magnitudes of the source with respect to several "comparison" stars within the field of view were determined using aperture photometry. The errors in the differential magnitudes taking into account only Poisson noise were typically 1–2\%. The comparison stars were checked for variability in each night separately, and over the entire data set. For stars of similar brightness to V485 Cen we find within single nights standard deviations in their brightness of 2–4\%. For the average brightness per night of these stars taken over the entire data set we find standard deviations of ~2\%. The largest difference in the average brightness per night for all comparison stars was ~6\%, practically independent of the brightness of the comparison stars. This latter result indicates that systematic effects dominate the calibration of the data. We believe this to be the result of using different (types of) CCDs during different observing nights combined with the spread in colours of the comparison stars. We obtained a photometric calibration of the differential magnitudes using the standard magnitudes of two of the comparison stars (see Augusteijn et al. 1993, Chapter 8).

In the top panel of Fig. 9.1 we present the result of a Fourier spectrum analysis of all the photometric observations in quiescence combined. The observations have been corrected for the average brightness in each night separately (see below). Strong peaks are found centered at a
To look more closely at the $\sim 1^h$ period and its first harmonic we present enlargements of the regions around a frequency of $2.8\times10^{-4}$ Hz (bottom left in Fig. 9.1) and around a frequency of $5.6\times10^{-4}$ Hz (bottom right in Fig. 9.1), respectively. The highest peak in the region around $2.8\times10^{-4}$ Hz corresponds to a frequency of $2.82329\times10^{-4}$ Hz ($P = 0.040995$ days), but frequencies corresponding to the two peaks on either side of the highest peak ($2.82032\times10^{-4}$ and $2.82626\times10^{-4}$ Hz, respectively) cannot be excluded. The highest peak in the region of the first harmonic shown in the bottom panel of Fig. 9.1 is at a frequency of $5.64660\times10^{-4}$ Hz, which is very close to the frequency expected if the fundamental frequency is $2.82329\times10^{-4}$ Hz.
Table 9.1 Arrival time of maximum light

<table>
<thead>
<tr>
<th>$T_{\text{start}}$ (HJD)</th>
<th>Duration (days)</th>
<th>No. of obs.</th>
<th>$T_{\text{max}}$ (HJD)</th>
<th>Cycle number</th>
<th>Average $V$ (mag)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-2440000</td>
<td></td>
<td></td>
<td>-2440000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8715.55762</td>
<td>0.23438</td>
<td>67</td>
<td>8715.67453(54)</td>
<td>0</td>
<td>18.0784(80)</td>
</tr>
<tr>
<td>8716.56055</td>
<td>0.12305</td>
<td>37</td>
<td>8716.61868(57)</td>
<td>23</td>
<td>18.0608(88)</td>
</tr>
<tr>
<td>8749.59082</td>
<td>0.14258</td>
<td>42</td>
<td>8749.6601(20)</td>
<td>829</td>
<td>18.286(13)</td>
</tr>
<tr>
<td>8754.48633</td>
<td>0.31543</td>
<td>58</td>
<td>8754.7007(14)</td>
<td>952</td>
<td>18.285(20)</td>
</tr>
<tr>
<td>9106.65723</td>
<td>0.18555</td>
<td>53</td>
<td>9106.76762(60)</td>
<td>9540</td>
<td>17.9859(85)</td>
</tr>
<tr>
<td>9107.55762</td>
<td>0.12402</td>
<td>37</td>
<td>9107.6263(13)</td>
<td>9561</td>
<td>17.895(10)</td>
</tr>
<tr>
<td>9179.48047</td>
<td>0.09375</td>
<td>26</td>
<td>9179.5334(10)</td>
<td>11315</td>
<td>18.285(12)</td>
</tr>
<tr>
<td>9187.47363</td>
<td>0.08105</td>
<td>20</td>
<td>9187.5285(11)</td>
<td>11510</td>
<td>18.075(12)</td>
</tr>
<tr>
<td>9375.69531</td>
<td>0.18457</td>
<td>46</td>
<td>9375.77636(11)</td>
<td>16102</td>
<td>18.2047(78)</td>
</tr>
</tbody>
</table>

The peaks corresponding to the harmonics of the other two possible fundamental frequencies are substantially smaller. We, therefore, believe that the peak at a frequency of $2.82329 \times 10^{-4}$ Hz corresponds to the true fundamental frequency. However, more closely spaced, and longer photometric observations are needed to determine the exact value of the period conclusively.

We performed sinusoidal fits with a fixed period of 0.040995 days to the observations in each night separately. The resulting arrival times of maximum light and the mean magnitude are listed in Table 9.1 together with the respective cycle numbers. The errors listed in this table are the formal errors derived from the sinusoidal fit for $\chi^2_{\text{red}} = 1.0$. The errors in the average magnitude do not include the uncertainty in the absolute calibration of the magnitudes which might be as large as 0.06 mag (see above). From a least-squares fit to the arrival times we derive the following ephemeris:

$$T_{\text{max}}(\text{HJD}) = 244.8988.20980(27) + 0.040995001(44) \times N$$

(9.1)

$$\text{Cov}(T_o, P_o) = 1.7 \times 10^{-11} \text{ days}^2$$

with $\chi^2_{\text{red}} = 1.04$ for 7 degrees of freedom. A 2nd-order polynomial fit to the arrival times does not show a significant period derivative, and we derive a 3-σ lower limit of $|P|/|\dot{P}| \geq 6.4 \times 10^4$ yrs.

In Fig. 9.2 we show the differential magnitude of the source with respect to the comparison stars as a function of phase at a period of 0.040995 days. We show the error-weighted averaged magnitude of V485 Cen as a function of the 0.040995 days period. The error-weighted average is shown of the data in 20 phase bins. The corresponding error in this average of each bin is indicated. Phase zero corresponds to maximum light. The light curve is shown twice for clarity.
9.3 Spectroscopy

9.3.1 Observations and data reduction

To clarify the nature of the $\sim 1^h$ photometric period, we obtained spectra of the source on March 23rd 1993, with the 3.6m telescope at the European Southern Observatory in Chile, using EFOSC1 and a grism (Orange 150), which covers the wavelength range 5200–6950 Å. The detector was a TEK CCD with 512$^2$ pixels. The pixel size of this CCD is 27µm, which corresponds to 0'6 on the sky. The slit was orientated such that a nearby star ($V=15.04(2)$, $(B-V)=0.64(4)$; Augusteijn et al. 1993, Chapter 8) located ~50' W and ~10' S with respect to V485 Cen was observed simultaneously. The source was monitored during the night for two periods of $\sim 2$ and $\sim 3$ hours, respectively, with an interruption of $\sim 100$ min. A total of 31 spectra were obtained with an integration time of 9 min each. Helium-Argon calibration exposures were obtained approximately every hour. A slit width of 1" was used which resulted in a resolution of 5 Å (as derived from the FWHM of the Helium-Argon calibration spectrum). Additional spectra were obtained of both the source and the second star on the slit, and of a flux standard (Kopff 27; Stone 1977), using a 10" slit. All the spectra were extracted using the optimal extraction method as described by Horne (1986), and wavelength calibrated using the Helium-Argon exposure closest in time. The wide-slit spectra were corrected for atmospheric absorption using the standard extinction curve for the La Silla observatory.

We used the wide-slit exposure to determine the flux calibrated spectrum of the second star on the slit. From a comparison of this spectrum with the spectra of standard stars provided by Silva & Cornell (1992) and its photometric colour we derive an approximate spectral type of G2 v for this star. We then determined the ratio of the spectrum of this comparison star in each narrow slit exposure with the flux calibrated spectrum. Next, this "ratio" spectrum was fitted as a function of wavelength using a 3rd-order polynomial excluding the regions 5825–5925Å, 6125–6350 Å, 6475–6600 Å and $\geq 6850$ Å, to avoid strong stellar and atmospheric features. By dividing the spectrum of V485 Cen taken in the same narrow slit exposure by this polynomial fit we obtained a flux calibrated spectrum of the source. Unfortunately, the slit was not placed exactly over the centers of both V485 Cen and the comparison star, and the relative position of the slit with respect to the two stars was also slightly different in the two sets of exposures before and after the ~100 min interruption. This resulted in an off-set between the flux zero points in the two sets of spectra and a slight colour difference. In the second set of spectra we also find a small airmass dependent change in the flux zero point and colours, which probably is the result of the comparison star being positioned close to the edge of the slit. This particularly affected the last few spectra.

In Fig. 9.3 we present the total flux integrated over the whole wavelength range on a magnitude scale for the individual calibrated spectra of V485 Cen as a function of Heliocentric Julian Date; a clear variation can be seen with a period of $\sim 1$ hour. In the top panel of Fig. 9.4 we present a Fourier spectrum analysis using the Lomb-Scargle method and the CLEAN algorithm.
of the integrate flux. We performed sine fits to the two sets of spectra separately, where we excluded the last five spectra which are most affected by the positioning of the comparison star close to the edge of the slit. Assuming an integral number of cycles between the average times of maximum light in the two sets of spectra as determined from the sine fits we derive a period of 0.04060(30) days, which is consistent with the period we derived from our extensive photometric data-set presented above. Maximum light occurs at HJD 2449069.74803(65), which corresponds to phase 0.98(2) with respect to the ephemeris presented in Eq. (9.1). In Fig. 9.5 we present the folded light curve where we have removed the offset between the two sets of spectra. Also the “colour” curve, as determined by the ratio of the integrated flux in the wavelength range 5200–6100 Å over the integrated flux in the range 6100–6950 Å, shows a clear variation with this period. The folded “colour”-curve shown in Fig. 9.5 seems to be shifted slightly to later phase, and from a sine fit we derive a formal difference in phase of 0.094(27). In other dwarf novae that show an orbital hump these two variations are generally in phase (e.g., La Dous 1993).

In Fig. 9.6 we present the average flux calibrated spectrum of V485 Cen, where we have excluded the five last spectra (see above). The spectrum is very typical for a dwarf nova in quiescence, showing double-peaked emission lines of Hα, and He I 6678 and 5876 Å, and a fairly flat continuum. Absorption by Na i at 5890/5896 Å distorts the profile of the latter line. The broad absorption feature near 6280 Å is due to the diffuse interstellar line at 6283.9 Å. The continuum shows a change in slope around 5900 Å. We carefully checked if this feature might be the result of the particular way in which we reduce our spectra. However, this feature can also be seen in the average of the raw spectra and we believe it to be real.

9.3.2 Radial-velocity variations

To look for radial-velocity variations in the individual spectra we used the double Gaussian convolution technique introduced by Schneider & Young (1980; see also Shafter, Szkody & Thorstensen 1986). In this technique two Gaussians with fixed width and separation are convolved with an emission line. The position where the intensities through the two Gaussians is equal is a measurement of the central wavelength of the line. By varying the separation between the two Gaussians different parts of the lines can be sampled. The width of the Gaussians is set equal to the resolution. Before applying this method we normalized the individual spectra by dividing them by a 6th-order polynomial fit to the continuum, where we exclude the wavelength ranges around the emission lines from the source, and the atmospheric and interstellar absorption features (see Fig. 9.6).

We looked for periodic variations in the radial velocity measurements for Hα and He I 6678 Å using a range in separations between the two Gaussians of 200–3000 km/s. Significant vari-
Figure 9.4. In the top two panels we show a Fourier spectrum analysis using the Lomb-Scargle method (on the left) and the CLEAN algorithm (on the right) of the integrated flux over the wavelength range 5200–6950 Å. In the middle and bottom panel we present a Fourier spectrum analysis using the Lomb-Scargle method and the CLEAN algorithm of the radial velocities of Hα for separations between the two Gaussians of 600 and 1800 km/s, respectively.

Variations were only found in the Hα line for separations of 400–1000 km/s and 1400–2600 km/s, respectively. In all cases the period was consistent with the period derived from the photometric brightness variations. In the middle and bottom panel of Fig. 9.4 we present a Fourier spectrum analysis using the Lomb-Scargle method and the CLEAN algorithm of the radial velocities of Hα for separations between the two Gaussians of 600 and 1800 km/s, respectively. It is clear from Fig. 9.4 that the brightness and the radial velocities vary with the same period within the accuracy of our data. We do not detect any significant radial velocity variations with a period other than the \(\sim 1^\text{hr}\) period.

The observations are spaced in time in such a way that the spectra are grouped together in phase as a function of the \(\sim 1^\text{hr}\) period. They fall into six phase intervals containing between 4 and 6 spectra. In these groups the spread in phase of the different spectra is in one case 0.09 in phase, and in the other five cases 0.03 in phase. We, therefore, decided to average the spectra in these six phase bins, thereby increasing the signal-to-noise ratio in the resulting spectra. We then determined radial velocities for these average spectra using the double Gaussian technique.

To investigate the radial-velocity variations in more detail we fitted the derived velocities with a non-linear least-squares fit of the form

\[
V(\phi, a) = \gamma(a) + K(a) \cdot \sin \phi
\]
where \( \phi \) is the average phase in each phase bin which was calculated using the period derived from the brightness variations in the integrated flux of the calibrated spectra (see above), and constructed a so-called “diagnostic diagram” (Shafter 1983) where we show the system parameters as a function of the separation (\( a \)) of the two Gaussians.

In Fig. 9.7 we show the “diagnostic diagram” for H\( \alpha \) in which we plot \( K \), its associated error \( \sigma_K/K \), \( \gamma \), and the phase as a function of \( a \). Here, phase corresponds to the time of superior conjunction, where phase zero corresponds to photometric maximum. This figure shows that there are two components present in the line which vary with the 0.04060 days period. One component dominates in the line center and has a high velocity amplitude, and the second component dominates in the line wings and has a low velocity amplitude. The component which dominates the line center trail the line wings by \( \sim 0.4 \) in phase. The large value of \( \sigma_K/K \)
and the lack of significant radial velocity variation at a separation of 1200 km/s (see Fig. 9.7) can be understood as the result of the two components being comparable in strength at this separation between the two Gaussians, and practically half a cycle out of phase.

For separations of the two Gaussian smaller than the separation between the two peaks in the emission line profile, the double Gaussian method is not very well suited to determine velocities. In some cases it finds velocities which correspond to one of the two peaks instead of the peak which corresponds to the emission component which dominates the variations in the line center. We, therefore, determined the velocity of this component in the six average phase binned spectra by eye. The resulting orbital elements are listed in Table 9.2. These results are within the errors equal to those determined with the double Gaussian method for a separation of $a = 800$ km/s, where $\sigma_K/K$ reaches a local minimum.

To derive the orbital elements of the line wings we took the values that correspond to the largest separation just before $\sigma_K/K$ shows a sharp increase, i.e. for $a = 2400$ km/s. The resulting orbital elements are listed in Table 9.2. The reason for choosing this particular separation is that

<table>
<thead>
<tr>
<th>Table 9.2 Orbital elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>$\gamma$ (km/s)</td>
</tr>
<tr>
<td>$K$ (km/s)</td>
</tr>
<tr>
<td>Phase</td>
</tr>
</tbody>
</table>
any distortion due to variations at low (Keplerian) velocities (e.g., from a hot spot) is expect to be minimal in the line wings, whilst at very large separations the velocity measurements become less reliable because the two Gaussians are sampling an increasingly smaller part of the line wings. Fig. 9.7 seems to indicate that any distortion due to the component at low velocities in the disk is confined to low velocities and well separated from the line wings at $a \geq 1600$ km/s. However, both $K$ and $\gamma$ show a trend towards smaller $K$ and more positive $\gamma$ going from $a = 1800$ to 2400 km/s, whilst $\sigma_K/K$ reaches a local maximum at $a = 2000$ km/s. This might reflect a distortion of the line at relative high velocities which diminishes as one moves out to higher velocities, and one must consider the possibility that high-velocity non-Keplerian motion in the disk might still distort the line wings. We also performed single-Gaussian fits to the Hα line profile excluding part of the line centered around the rest wavelength. For excluded wavelength intervals larger than 40 Å the fits to the derived velocities were very poor. However, for widths between 20 and 40 Å the resulting orbital elements remain practically constant. The best fit was obtained excluding the central 30 Å of the line with resulting values of: $\gamma = -22(8)$ km/s, $K = 89(10)$ km/s, and phase = 0.135(57). These values compare well to the orbital elements listed in Table 9.2, and give us some confidence that the orbital elements derived for the line wings are not strongly distorted and describe the orbital motion of the white dwarf.

In the lower panels of Fig. 9.5 we show the radial-velocity variation of the components that dominate the line center and the line wing as a function of the 0.04060 days period. For the former component we show the radial velocities as derived by eye from the average spectra divided in 6 orbital phase bins (see above). Phase zero correspond to photometric maximum. Also shown in Fig. 9.5 are the sine fits representing the radial-velocity variations corresponding to the orbital elements presented in Table 9.2.

To demonstrate the presence of the two components more clearly we show in Fig. 9.8 a grey-scale plot of the Hα emission line as a function of phase at the photometric period. In this figure the data have been smoothed in the phase direction for representation purposes only. Looking
at this figure the interpretation of the two components is straightforward. The component which dominates in the line center is the so-called “S-wave”, which results from emission from the hot spot at the outer edge of the disk and reflects its radial-velocity variation. The component which dominates in the line wings is predominantly formed in the inner disk and is thought to reflect the radial-velocity variations of the white dwarf.

If, like in other dwarf novae, maximum light corresponds to viewing the hot spot face-on (see Sect. 9.2.1) superior conjunction of the white dwarf is expected to occur \(\sim 0.10-0.15\) in phase after maximum light, whilst for the S-wave superior conjunction should occur around phase 0.5. The phasing of the radial velocity variations from the line wings and from the line center listed in Table 9.3 are consistent with this interpretation. We, therefore, concluded that the 0.041 day period is the orbital period. The orbital photometric and spectroscopic variations of V485 Cen are very similar to those of other (“normal”) dwarf novae.

In Fig. 9.9 the average profiles of H\(\alpha\) and the He\(i\) lines are presented on a velocity scale, where the individual spectra first have been corrected to the rest frame of the hot spot and of the white dwarf, respectively, using the elements listed in Table 9.2. The profiles corrected to the rest frame of the white dwarf are practically the same as the average uncorrected profiles. The intensity of the different lines have been scaled arbitrarily. The average line profile of H\(\alpha\) corrected for the S-wave shows a clear emission component in the line center. A similar feature
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Figure 9.9. The average profiles of Hα and the He I lines are presented on a velocity scale.

The individual spectra first have been corrected to the rest frame of the hot spot (left) and the white dwarf (right), respectively, using the elements listed in Table 9.2.

may be present in He I 5876 Å, but this line is heavily affected by the Na I absorption lines. The He I 6678 Å line does not show a clear emission component. The line profiles in the rest frame of the white dwarf are the typical double peaked emission lines one would expect from an accretion disk centered around the white dwarf. The separation between the two peaks is significantly wider for the He I lines (2000 ± 100 km/s) compared to Hα (1150 ± 50 km/s). A simple explanation for this might be that the outer disk is too cool to excite helium sufficiently, which result in an effectively smaller disk from which the line emission originates. If the separation of the two peaks reflect the Keplerian velocity of the outer edge of the respective (disk shaped) emission regions this would imply a radial extent of the Hα emitting region which is ~3 times larger than the He I emitting region. The line wings in the average line profiles corrected for the motion of the white dwarf are quite similar, although the line wings of Hα can be traced further outward as this line is relatively stronger. For Hα we derive a HWZI of 2250 km/s. The central depression seen in the line profile of He I 5876 Å is much deeper than those of Hα and the He I 6678 Å line.

9.3.3 The spectral distribution

As our spectra are flux calibrated we looked at the intrinsic variation in the shape of the spectrum as a function of orbital phase. To avoid any colour effects as a result of the comparison star moving out of the slit we excluded the last few spectra (see above). For those observations that were included the “colour” (see Sect. 9.3.1) of the atmospheric extinction corrected spectra of the comparison star were within 2% equal to the “colour” of the flux calibrated spectrum of the star derived from the spectrum obtained with the 10" slit. Average flux calibrated spectra were determined in the six phase intervals as defined above. The spectra averaged in each phase bin were chosen such that in each bin 2 spectra from the first, and 2 spectra from the second set of exposures were included. This was done to reduce the effect of the offset in brightness.
Figure 9.10. The average flux calibrated spectrum of V485 Cen at photometric maximum (upper curve) and at photometric minimum (middle curve). The lower curve is the difference between the upper two curves, and represent the spectrum of the varying component (see text). This later curve has been shifted upward by 0.1 mJy

between the two sets of spectra (see Fig. 9.3).

In Fig. 9.10 we show the average flux calibrated spectrum of V485 Cen near photometric maximum (top curve; average phase 0.99) and near photometric minimum (middle curve; average phase 0.48). It is clear from this figure that the change in slope near \( \sim 5900 \, \text{Å} \) is more pronounced in the spectrum near photometric minimum. If we now subtracted the spectrum near photometric minimum from the spectrum near photometric maximum we obtain the spectral shape of the varying component. This "difference" spectrum is shown in Fig. 9.10 as the lower curve. It can be seen that the varying component has a smooth flat spectrum with a slope different from that of the average spectrum. The fact that there is no change in slope near \( \sim 5900 \, \text{Å} \) in the spectrum of the varying component indicates that this is a persistent feature in the spectrum.

As the slope of the spectrum of the varying component is different from the slope of the average spectrum on either side of \( \sim 5900 \, \text{Å} \) there seem to be at least three components contributing to the overall spectrum. As the hump in the orbital light curve is the result of the varying aspect of the hot spot the "difference" spectrum should represent the spectrum of the hot spot. There is a second component which dominates the blue part of the spectrum and which has a different slope than the spectrum of the hot spot, and which most likely can be identified with emission from the disk. The third component becomes visible in the red part of the spectrum and might be identified with a contribution from the secondary (see also Sect. 9.5).
9.4 System parameters

From the results we derived in the previous section we can limit the system parameters of V485 Cen. Warner (1976) derived a relation between the ratio of the radial velocity amplitude ($K$) and the projected velocity of the outer disk rim ($V_{\text{disk}}$), and the mass ratio. $V_{\text{disk}}$ can be derived from the half separation of the double peaked emission lines (see Horne and Marsh 1986). As mentioned above the separation of the double peaked emission line is different for the HeI lines and Hα. As the temperature in the outer disk in CV's is expected to be sufficiently high to produce Hα emission (see, e.g., La Dous 1993) the half separation of the double peaked Hα line should reflect the velocity at the disk rim, and we adopt a value of $V_{\text{disk}} = 575(25)$ km/s (see above). Using this value and the relation presented by Warner (1976) we derive a mass ratio $q = M_{\text{WD}}/M_{\text{sec}} \sim 2.6$; if the velocity at the disk rim is lower than derived from Hα, i.e. the Hα line emitting region does not extend to the disk rim, the derived mass ratio is an upper limit.

Using the observed radial-velocity amplitude of the white dwarf (see Table 9.2) and the above estimate of the mass ratio we derive a relation between the mass of the white dwarf and the inclination (the drawn line in Fig. 9.11). We also derived the same relation taking values for the mass ratio corresponding to a 2-$\sigma$ variation in the ratio $K/V_{\text{disk}}$ to reflect possible systematic errors in the relation between this ratio and $q$. In Fig. 9.11 the lower dashed line corresponds to $q = 1.8$, the upper dashed line corresponds to $q = 4.0$.

A lower limit to the mass of the white dwarf can be derived from the HWZI of the Hα emission line: if the line wings reflect the Keplerian motion in the disk then the velocity of the extreme line wings does not exceed the Keplerian velocity at the surface of the white dwarf. By using a mass-radius relation for white dwarfs (Hamada and Salpeter 1961) we obtain from the HWZI a lower limit to the mass of the white dwarf as a function of the inclination (see, e.g., Eq. (7.8); Augusteijn 1994, Chapter 7). For V485 Cen we derive $M_{\text{WD}} \geq 0.40 M_\odot \sin i$. This lower limit is shown in Fig. 9.11 as the dotted line. The vertical line on the right in Fig. 9.11
shows the upper limit to the inclination (for $q = 2.6$) derived from the lack of eclipses in the photometric light curve. The precise value of this inclination depends only weakly on $q$. All the lines in Fig. 9.11 extend upward to $M_{\text{WD}} = 1.44 \, M_\odot$.

Taking the different constraints shown in Fig. 9.11 we find that the system has a fairly low inclination of $i \sim 20$–$30^\circ$ and a white dwarf with a fairly high mass $M_{\text{WD}} > 0.7 \, M_\odot$, i.e. it is most likely a CO white dwarf. Taking the relation between the mass of the white dwarf and the inclination for a value of $q = 4.0$ (i.e., the upper dashed curve in Fig. 9.11) as an upper limit to the allowed system parameter we derive an upper limit to the inclination of $i \leq 46^\circ$, and a lower limit to the mass of the secondary of $M_{\text{sec}} = 0.14 \, M_\odot$.

The inclination is not easy to constrain in an independent way. We compared the line profile of Hα to the theoretical profiles calculated by Horne and Marsh (1986) for optically thick lines, and find that the relative depth of the central part of the line best agrees with that of the theoretical profile for an inclination of $i = 30^\circ$. We also compared the amplitude of the orbital hump (see Sect. 9.2.1) to that of some other dwarf novae in quiescence which have orbital periods below the period gap. Unfortunately, only very few dwarf novae show a well developed stable orbital hump in quiescence. We find that the amplitude of the orbital hump in V485 Cen is similar to that of SW UMa (Robinson et al. 1987), and slightly smaller than that of VW Hyi (see, e.g., Van Amerongen et al. 1987). The former system has an inclination of $45 \pm 18$ degrees, and the latter $60 \pm 10$ degrees (Ritter and Kolb 1994). The corresponding crude estimate of $i$ for V485 Cen are in reasonable agreement with the constraints shown in Fig. 9.11.

### 9.5 Discussion

#### 9.5.1 Evolutionary considerations

It is generally accepted that (pre-) CVs are produced through a common-envelope phase in which a low-mass star spirals into the envelope of a giant star. During this spiral in phase the envelope of the giant is expelled, and a large amount of orbital angular momentum lost; what remains is a compact detached binary consisting of the low-mass star and a white dwarf (the core of the red giant that lost its envelope). The evolution of the AM CVn type CVs is very different since its intermediate predecessor is thought to have been a pair of detached white dwarfs in close orbit around each other. This pair of white dwarfs is presumably formed through a second common-envelope phase in which the white dwarf spirals into the envelope of the secondary which has evolved into a giant. What remains is the degenerate core of the giant in close orbit around the original white dwarf (see, e.g., Iben and Tutukov 1984a). If the secondary in V485 Cen would be a degenerate dwarf the lower limit to its mass derived in the previous section gives an upper limit to its size which is an order of magnitude smaller than its Roche-lobe. This, together with the fact that hydrogen lines are observed in the optical spectrum of V485 Cen, shows that this system is different from AM CVn type CVs; its mass donor is not fully degenerate.

In principle the secondary in a CV with an orbital period of 1 hr might be a normal main-sequence like star, but this is only possible if such a system becomes semi-detached (i.e., it starts transferring mass and becomes observable as a CV) practically at this period, and the secondary is not far out of thermal equilibrium as a result of the continuous mass transfer during its evolution towards a shorter period. However, observing a system in this particular stage seems very unlikely. The mass of the secondary in such a system is expected to be $\sim 0.1 \, M_\odot$ (see, e.g., King 1988), which is somewhat below the lower limit we derived in the previous section.

A much more likely possibility is that the secondary is not fully degenerate, and has a low, but finite, hydrogen content. Theoretical calculations have been made to determine the minimum period as a function of hydrogen content of the secondary (see, e.g., Sienkiewicz 1984, Nelson,
Rappaport and Joss (1986), which show a smooth decrease in the minimum period as a function of the hydrogen content. For a 1 hour period this gives an upper limit of 30%. However, these calculations assume a homogeneous distribution of the hydrogen in the secondary, and do not take the previous evolution of the system into account. In this case the previous evolution of V485 Cen must have been different from that of the “normal” CVs. A possible evolutionary scenario for systems like V485 Cen has been discussed by Iben & Tutukov (1984b), Tutukov et al. (1985), and Pylyser and Savonije (1989). A system like V485 Cen might be produced if the low-mass star has a mass of \( \sim 1.5M_\odot \), and starts transferring mass (upon first contact with its Roche lobe) near the end of its main-sequence lifetime. Since the donor is then more massive than the white dwarf, the initial phase of mass transfer will be unstable and proceed on a short time-scale (\( \dot{M} \sim 10^{-7}M_\odot \text{yr}^{-1} \)), approximately the thermal time-scale of the secondary, until the mass of the secondary has decreased to less than \( \sim 70% \) of that of the white dwarf. During this phase the source might resemble the ultra-soft X-ray sources as proposed by Van den Heuvel et al. (1992). After this phase of rapid mass transfer the secondary has a high helium content, which will remain high because of the transfer of the (relatively) hydrogen rich envelope material. According to the evolutionary calculations such a system can sustain a mass transfer rate of \( \dot{M} \sim 1 - 5 \times 10^{-10}M_\odot/\text{yr} \) at periods below the 80 minute period cut-off of hydrogen rich systems.

Preliminary results of recent detailed model calculation have been published by Singer et al. (1993) and Ritter (1994). These authors calculated the evolution of a CV using a full stellar code and including computation of the mass transfer. Models were calculated starting with secondaries with the central hydrogen burnt up to a varying fraction. These calculations show that the minimum period of CVs as function of the central hydrogen abundance (\( X_c \)) slowly decreases and only sharply drops for very low values of \( X_c \). (U. Kolb 1994, private communication).

In all these different models the authors find that the minimum period can get \( \sim 20 \) min lower than the minimum period for a ZAMS secondary, but only for very low values of \( X_c \) (i.e., \( X_c \sim 0.0 \)). This would indicate that the secondary in V485 Cen has a low value of \( X_c \) and is close to its minimum period. However, there is still considerable uncertainty in determining the minimum period, largely as a result of the poorly known opacities at low temperatures. We are somewhat concerned that in all these models at the minimum period the mass of the secondary is 0.05–0.10 \( M_\odot \), which does not agree with the constraints we derived in Sect. 9.4.

We have also considered the possibility that V485 Cen is a Population II object. Population II stars are smaller (\( R^{\text{II}}/R^{\text{I}} \sim 0.8–0.9 \)) in comparison to Population I stars resulting in a smaller value of the minimum period for a CV. However, recent model calculations (Stehle 1993) show that the minimum period of population II CVs with respect to Population I CVs is reduced by \( \sim 11 \) min, which is not enough to explain the observed period of V485 Cen.

### 9.5.2 The mass transfer rate

For “normal” CVs Patterson (1984) found a close inverse relation between the equivalent width (EW) of H\( \beta \) and the mass accretion rate, in which the EW of H\( \beta \) increases with decreasing mass accretion rate. Using this relation and the EW of H\( \beta \) for V485 Cen (see Augusteijn et al. 1993, Chapter 8) would imply a mass accretion rate \( \dot{M} \sim 1 \times 10^{-9}M_\odot/\text{yr} \). However, as the accreted material is hydrogen poor, H\( \beta \) will be relatively weak compared to “normal” CVs with the same accretion rate, and Patterson’s relation does not apply to V485 Cen; it is expected that the accretion rate is lower than the value derived above from the EW of H\( \beta \).

Another way to determine the accretion rate of a dwarf nova is by using the absolute magnitude during the peak of the outbursts, which is fairly well established at \( M_V \sim 4.7 \) (Vogt 1981, Warner 1987). Theoretical calculations (see, e.g., Pojmanski 1986) indicate that with decreasing hydrogen abundances for a given accretion rate the disk will be brighter. On the other hand
Warner (1987) has shown that the absolute magnitude of a dwarf nova in outburst is a function of orbital period, with decreasing brightness for shorter orbital periods. As, furthermore, the inclination of V485 Cen derived in the previous section is not extremely high or low we will adopt a value of $M_V=4.7$ for the absolute magnitude of V485 Cen in outburst.

The hump seen in the light curve during quiescence is the result of the varying aspect of the hot spot. This hump has an amplitude of ~0.25 mag in the V band light curve (see Fig. 9.2). Following Paczynski and Schwarzenberg-Czerny (1980) we consider the hot spot as a flat disk perpendicular to the orbital plane which radiates only outward, and assume a limb-darkening coefficient of $u = 0.6$. For an inclination angle of $i \sim 30^\circ$ (see Sect. 9.4), the absolute magnitude in outburst, and the observed outburst amplitude ($\Delta V \sim 4$ mag; Ritter & Kolb 1994) we derive for the visual brightness of the hot spot averaged over the orbital period $M_{V, HS}=11.2$ mag.

To derive the bolometric luminosity we need to apply the bolometric correction. The spectral distribution of the radiation from the hot spot is shown in Fig. 9.10 (lower curve). If we assume Black-body radiation, we find that a reasonable fit to the slope of this spectrum can only be obtained for temperatures $\geq 20000$ K. Taking a B.C. $\sim -1.5$ ($T = 20000$ K) we derive $M_{\text{Bol, } HS}=9.7$ mag, or $L_{\text{Bol, } HS}=0.01 L_\odot$. If we now assume that all the kinetic energy of the infalling matter onto the hot spot is converted in radiation we can derive the mass accretion rate from the secondary from the equation

$$L_{HS} = \frac{GM_{WD}\dot{M}}{R_{\text{disk}}}. $$

For a mass of the white dwarf of 1.0 $M_\odot$, a mass ratio of $q = 2.6$ (see Sect. 9.4) and a disk which has a radius of 0.8 of the Roche-lobe radius we derive a mass accretion rate of $\sim 1 \times 10^{-10} M_\odot/\text{yr}$. We believe that this, admittingly very rough estimate, reflects the right order of magnitude and we note that it is in consistent with the theoretical models mentioned above.

### 9.5.3 The secondary

As we mentioned in Sect. 9.3.3 there is a strong indication that the secondary contributes significantly to the flux distribution at wavelengths longer than $\sim 5900$ Å. The main problem in quantifying this contribution is the lack of knowledge of the spectral type of the secondary, the limited spectral range of our data, and the strongly varying depth of the molecular absorption bands as a function of spectral type in late type stars.

Looking at Fig. 9.5 one might argue that the secondary does not contribute to the spectrum at wavelengths shorter than $\sim 5900$ Å, and that this part of the spectrum reflects only contributions from the disk and the hot spot. By drawing a line through the continuum of the spectrum at wavelengths shorter than $\sim 5900$ Å and extrapolating it to longer wavelength we estimate the contribution of the secondary to the continuum at Hα to be $\sim 10\%$.

In the article by Ritter (1994) on model calculations of CV evolution the author presents the mean density versus effective temperature of the secondary for different values of $X_c$. From the value of the orbital period of V485 Cen we can directly derive the mean density of the secondary (e.g., Warner 1976), and we find $\rho_{\text{mean}}=114$ g cm$^{-3}$. From Ritter (1994; his Fig. 2) we then derive an upper limit to the effective temperature of the secondary of $\sim 3500$ K, which corresponds to a spectral type of M1–2 v (Johnson 1966). For such a spectral type one expects a fairly strong (with a depth of $\sim 30\%$) absorption band of TiO at $\sim 6800$ Å. In the spectrum covering the range 5700–10000 Å we presented in Augusteijn et al. (1993, Chapter 8; their Fig. 4) there is indeed some indication for this absorption band with a depth of at most 5%, which would indicate a contribution of the secondary at this wavelength of less than 15%.

If we assume that the V485 Cen has $M_V=4.7$ in outburst, i.e. in quiescence $M_V=8.7$ (see above), we can derive an upper limit to the contribution from the secondary using the upper
limit to the effective temperature given above. Given the orbital period, a mass of the white
dwarf of 1.0 $M_\odot$, and a mass ratio of 2.6 (see Sect. 9.4) we can derive the size of the secondary.
For an effective temperature of 3500 K we then derive for the secondary $M_V = 12.2$, i.e. the
secondary contributes at most $\sim 4\%$ to the total brightness in V. For the brightness in the R
band (i.e., in the region of Hα) we find $M_R = 10.7$. Using the observed spectral distribution,
and assuming no interstellar redening, we derive for the total system $M_R = 8.2$, i.e. the secondary
contributes at most $\sim 10\%$ of the light in R. Considering the uncertainties involved the different
estimates are fairly consistent, but more detailed observations, especially in the infrared, will be
needed to constrain the parameters of the secondary sufficiently.

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