Optical observations of close binary systems with a compact component
Augusteijn, T.

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Time resolved spectroscopy of the dwarf nova VY Aquarii in superoutburst and quiescence

T. Augusteijn

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Abstract

Time resolved spectroscopy is presented of the SU UMa type dwarf nova VY Aqr in superoutburst and quiescence. From the radial velocity variations found in outburst I derive on the basis of the value for the superhump period an orbital period of 0.06348(12) days (or possibly 0.06787(13) days). The radial-velocity amplitude is 29(5) km/s. In the outburst spectra taken ~5 days after maximum light evidence is found for the presence of a blue shifted narrow emission component superposed on the broad absorption lines, which is not found in spectra taken 2 nights later. Also a change of ~150 km/s in the system velocity is found over these 2 nights.

Using various observational constraints I derive $q = M_{WD}/M_{RD} \approx 8-10$ and $i \approx 30-40^\circ$. The orbital period and mass ratio of VY Aqr are very similar to those of the well known SU UMa type dwarf nova OY Car. However, the amplitudes of the outburst in VY Aqr are ~3 magnitude larger than those of OY Car. I argue that this is due to a lower mass transfer rate during quiescence in VY Aqr compared to OY Car, which results in VY Aqr being relatively fainter in quiescence.

7.1 Introduction

The spectra of dwarf novae in quiescence are characterized by fairly strong H Balmer and He I emission lines. Occasionally, lines of He II, Ca II, Fe II, etc. can also be seen. The Balmer decrement generally is very flat. The emission lines appear in many objects to be double-peaked, with a separation between the two peaks of ~500–1000 km/s. The line wings generally extend to 1000–3000 km/s. All dwarf novae which show eclipses also show double-peaked emission lines, but many others do as well.

During outbursts the spectrum generally shows the same lines, but now in absorption. These absorption lines are very wide, extending over several thousand km/s, with a relatively narrow emission component in the line center. During the decline from an outburst the emission cores grow while the absorption gradually fades. At the bright stages of the outburst the emission lines are considerably narrower than during quiescence.
VY Aquarii was originally believed to be a classical nova (Payne-Gaposchkin 1957) after the detection of a single outburst on an archival photographic plate taken in 1907 (Ross 1925). The detection of a second eruption (in order of discovery) in 1962 (Strohmeier 1962) indicated that the source is a recurrent nova. However, the detection of many more outbursts in recent years and several outbursts on archival plates showed that VY Aqr is a dwarf nova (Della Valle and Augusteijn 1991; Patterson et al. 1993 and references therein). The detection of "superhumps" by Bond and Grauer (as referenced in Warner and Livio 1987) during the 1986 outburst firmly established that VY Aqr is a SU UMa type system (see, e.g., Warner 1985).

In this paper I present time resolved spectroscopy of VY Aqr during the 1990 superoutburst, and during quiescence (see also Augusteijn and Della Valle 1990, Della Valle and Augusteijn 1991 and Augusteijn 1993). The details of the observations are given in Sect. 7.2. The analysis of the outburst and quiescent spectra are presented in Sect. 7.3 and 7.4, respectively. System parameters are derived in Sect. 7.5 and the results are discussed in Sect. 7.6.

7.2 Observations

The 1990 superoutburst of VY Aqr was discovered by several amateur astronomers on June 30.75 UT (see IAU C 5046). VY Aqr was observed on July 4 and 6 1990 with the ESO 1.5m telescope equipped with the Boller and Chivens spectograph and an RCA CCD with 1024x640 pixels of 15 μm. A grating with 600 grooves per mm was used in second order giving a dispersion of 66 Å mm⁻¹. The spectra cover the range 4050–5040 Å. A slit width of 1.5" was used throughout the observations which resulted in a resolution of 2.5Å (as determined from the FWHM of the lines in the Helium-Argon calibration spectra). On July 4 a total of 33 spectra were obtained with an integration time of 2ᵐ between 8:49 and 10:25 UT. A further 21 spectra were obtained on July 6 with an integration time of 5ᵐ between 8:22 and 10:29 UT.

Also several spectra were obtained during quiescence. One spectrum was taken on November 7 1990 with the ESO/MPE 2.2m telescope equipped with the Boller and Chivens spectograph and an RCA CCD with 1024x640 pixels of 15 μm. A grating with 300 grooves per mm was used in first order giving a dispersion of 224 Å mm⁻¹. The exposure was started on 0:42 UT and lasted 90ᵐ. The spectrum covered the range 3810–7160 Å. A slit width of 1.5" was used which resulted in a resolution of 8.2 Å. A series of 13 spectra were obtained on July 10 1991 with the ESO 3.6m telescope and EFOSC and a similar RCA CCD. A grism was used which covers the range 3600–5590 Å with a dispersion of 120 Å mm⁻¹. The spectra were obtained between 8:10 and 10:40 UT with an integration time of 10ᵐ. A slit width of 1.5" was used which resulted in a resolution of 9.8 Å.

All the data were reduced using standard routines to subtract the bias, divide by the flat field and extract the spectra. Wavelength calibration was obtained by interpolating between Helium-Argon calibration spectra taken just before, in between and/or just after the star spectra were taken. Flux calibration was obtained by observing standard stars in the different spectral ranges. The spectra have also been corrected for atmospheric extinction by using the standard extinction curve for the La Silla observatory.

7.3 The outburst spectra

7.3.1 Brightness variations

In Fig. 7.1 I present the average flux calibrated spectra for the July 4 and 6 observations, respectively. The wide H Balmer and He I absorption lines seen in the spectra are very typical for dwarf novae in outburst (see, e.g., La Dous 1990). The two average spectra have been plotted on the same flux scale, and the difference between them indicates a decrease in brightness of ~0.4
mag in the two days between the observations. This is in fairly good agreement with the decline seen in the photometric observations (Della Valle and Augusteijn 1991). Absolute photometry extracted from spectroscopic observations is generally not very accurate, but relative brightness variations might still be detectable. As the weather was photometric and very stable throughout the observations I have looked if photometric variability could be detected. The total intensity in each individual spectrum was determined by summing the observed flux over the whole spectral range observed. These results were then normalized to the total intensity observed in the average spectrum of each night separately. The results are shown in Fig. 7.2.

In Fig. 7.2 variations of ~0.15 mag full amplitude can be seen during both nights. The shape and amplitude of these light curves are remarkably similar to the photometric light curves observed during the 1986 superoutburst (see Patterson et al. 1993; their Fig. 7). The relatively
small spread of the individual points around the average light curve also indicates that the \(-0.15\) mag variation is intrinsic to the source. From Fig. 7.2 I derive times of maximum light at HJD 2448076.890(3) and 2448078.890(2) for the July 4 and 6 observations, respectively. The distance in time between these two maxima is consistent with the value of 0.06436 days for the superhump period during the 1986 superoutburst favoured by Patterson et al. (1993; the less likely alternative period of 0.06880 days is also consistent with this distance). From the resulting cycle count a superhump period of 0.06452(13) days (or possibly 0.06897(14) days) is derived for the 1990 superoutburst.

The overall shape of the photometric light curve, and the length of the 1990 outburst of VY Aqr (see, e.g., Della Valle and Augusteijn 1991) already suggested that this particular outburst was a superoutburst. The detection of brightness variations consistent with the superhump period supports this view.

I also looked for variations in the equivalent widths (EWs) of the different lines within each night. No variations were found for any of the lines. The average values for each night separately are listed in Table 7.1. The errors listed in this table are the errors in the mean of all the measurements in that night. The blends of H\(\gamma\) and He\(\text{I}\) 4388 Å, and H\(\beta\) and He\(\text{I}\) 4922 Å were measured together. From Table 7.1 it can be seen that the EWs of the Balmer lines and the He\(\text{I}\) lines show a slight increase going from the July 4 to the July 6 observations, whilst the EW of the He\(\text{II}\) 4686 Å line shows a decrease.

Table 7.1 The equivalent width of the absorption lines during outburst

<table>
<thead>
<tr>
<th>Line(s)</th>
<th>EW(Å)¹</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>July 4 Obs.</td>
</tr>
<tr>
<td>H(\gamma) + He(\text{I}) 4388</td>
<td>8.06 ± 0.14</td>
</tr>
<tr>
<td>He(\text{I}) 4471</td>
<td>1.39 ± 0.05</td>
</tr>
<tr>
<td>He(\text{II}) 4686</td>
<td>0.67 ± 0.06</td>
</tr>
<tr>
<td>H(\beta) + He(\text{I}) 4922</td>
<td>5.97 ± 0.10</td>
</tr>
</tbody>
</table>

¹ The errors are the errors in the mean.
7.3 The outburst spectra

7.3.2 Radial velocity variations from Gaussian fits

To look for radial-velocity variations several methods were used. The first step was to normalize the spectra. This was done by dividing each spectrum by a 4th-order polynomial fit to the continuum, i.e. excluding the absorption lines. In Fig. 7.3 I present the average normalized spectrum for the July 4 (top), and the July 6 observations (middle). The latter spectrum is shifted downward by 0.05 units. The spectra cover only the interval 4234–4970 Å as the broad absorption lines (of Hα and He I 5018 Å) at the extreme ends of the observed spectral range (see Fig. 7.1) prevent a proper determination of the continuum in these wavelength regions.

There are two main problems with determining reliable radial velocities from these spectra. In the first place most lines, in particular the strongest absorption lines, are blended. Secondly a clearly variable emission component is present in the core of the absorption lines (although the strength of this component is fairly small when compared to other dwarf novae in outburst; see, e.g., Szkody, Piché and Feinswig 1990). Furthermore, there is a change in the overall shape of the lines between the July 4 and July 6 observations (see the lower curve in Fig. 7.3; this will be discussed in more detail below).

As a result of these problems it is not easy to determine (variations in) the radial velocities in a simple way. The one thing that potentially has the strongest effect on both the amplitude and phasing of any variation in the spectra, is the presence of emission in the line cores. There is no a priori reason to believe that they are in phase with or have the same amplitude as radial velocity variations of the absorption component of the lines (see, e.g., Szkody, Piché and Feinswig 1990). I attempted to correct for this possible effect by simply excluding the emission cores. The extent of the emission core was determined by examining the individual spectra and determining by eye over which range variations in the emission component of the line profiles could be detected. In this way I excluded the emission cores of the Hγ line (4326–4353 Å), the He I 4471 Å line (4458–4481 Å), and the Hβ (4842–4875 Å) line. The line cores were only excluded for these lines as it was found that for the other (weaker) lines it was impossible to determine the extent of the emission core in the line profile in a reliable way.

Although, as discussed above, the line profiles are fairly complicated I first attempted to do Gaussian fits to the different lines. The best fits, in particular to the steep parts of the stronger hydrogen lines, were obtain by fitting the Hγ/He I 4388 Å and Hβ/He I 4922 Å blends with a single Gaussian. As expected the largest differences between the fits including or excluding the emission cores occurred for the July 4 observations, with significant changes in the measured velocities. For these observations significant variations were found in the velocities derived from the fits including the emission cores. However, when the emission cores were excluded the significance of the variations was strongly reduced. For the July 6 observations no significant variations were found, independent of whether the emission cores were included or not.

7.3.3 Radial velocity variations from cross correlations

Any radial-velocity variation is most easily seen in shifts of the steep parts of the line profiles. The main problem with fitting Gaussians to the line profiles seems to be that the lines are blended with weaker lines. This makes the line profiles asymmetric and might result in a relatively poor and uncertain fit to the steep part of the lines. I, therefore, also attempted to look for variations by cross correlating the individual spectra excluding the emission cores.

As the average spectra of the July 4 and July 6 observations are quite different I used the average for each night as template for the spectra taken during that night. The minimum value in each cross correlation curve was determined by fitting a 3rd-order polynomial to the five lowest points. Significant variations are found in both nights. In Fig. 7.4 I present a power spectrum of the resulting shifts from the two nights taken together. Also indicated in this figure is the frequency ($v_{SH}$) corresponding to the most likely value of the superhump period (Patterson et
al. 1993; the frequency of the least likely alternative for the superhump period can be obtained by subtracting 1 cy/day from $\nu_{\text{SH}}$).

It is clear from Fig. 7.4 that one cannot decide which is the correct period on the basis of the power spectrum alone. However, it is also clear that radial-velocity variations occur with a period different from the superhump period. This is commonly found in radial-velocity variations of SU UMa stars in quiescence (see, e.g., La Dou 1990, and references therein). The periods determined from these radial velocity variations are always a few percent shorter than the superhump period, and are identified with the orbital period of these systems (actually this is a defining characteristic of SU UMa type dwarf novae). The difference between the orbital and superhump period in other SU UMa stars with periods in the range 80–120 min is 1–4% (see, e.g., Lemm et al. 1993). Only a period for the radial velocity variations corresponding to the peak just to the right of the line indicating the superhump frequency gives a period difference consistent with the observed range. I, therefore, identify this peak with radial-velocity variations at the orbital period of VY Aqr. Sine fits, with the period fixed to the value derived from the power spectrum, to the data from each night separately gave consistent values of the amplitude of the radial velocity curves.

To check this result the cross correlation was also done in several other ways. To see what the effect was of excluding the line cores I also applied the cross correlation technique to the spectra including the line cores. The resulting shifts gave practically the same power spectrum as that seen in Fig. 7.4. Also the amplitude and phasing of sine fits to the shifts are nearly the same as those obtained when the line cores were excluded, and are consistent within their errors. This indicates that the contribution of the emission cores to the radial velocity determined from cross correlating the spectra is only minor. A further check was made by dividing the spectra in two parts (4234–4602 Å and 4602–4970 Å) and cross correlating these separately. Again the results are consistent within the errors.

A final problem in the determination of the amplitude of the radial-velocity curves might be that the average spectrum in each night was used as template. This means that the noise in each spectrum is correlated, to some extent, with the noise in the template spectrum (see Van Kerkwijk et al. 1993). Although each template spectrum is the average of a fairly large number of spectra this effect still might be important as the amplitude of the variations is quite small. To check this I performed the cross correlation of the spectra with the emission cores excluded and used the average spectrum from one night as template for the spectra from the other night. Again the phasing and amplitude of the radial velocity variations in the two nights were consistent with the previous values.

The period was determined by taking the times of superior conjunction in each night (determined from a sine fit with a fixed period determined from the power spectrum) and taking an
7.3 The outburst spectra

The outburst spectra

![Figure 7.5. The radial velocity curve of the outburst spectra as determined from the cross correlation of the spectra in one night with respect to the average spectrum in the other night folded with a period of 0.06348 days. The line cores of the Hβ, Hγ and He I lines were excluded (see text). Phase zero corresponds to superior conjunction which occurs at HJD 2448076.8766(17). Crosses correspond to the July 4 observations, and circles to the July 6 observations. A sine fit to the data is also shown. The data are shown twice for clarity.](image)

integral number of cycles between them. The amplitude was determined by subtracting from each night the gamma velocity determined from the sine fit, and fitting a sine curve to the combined data. In this way I derive a period of 0.06348(12) days, and a radial velocity amplitude of 29(5) km/s. Superior conjunction occurs at HJD 2448076.8766(17). The radial velocity curve is shown in Fig. 7.5. In this figure the crosses correspond to the July 4 observations, and the circles to the July 6 observations. The sine fit to the data is also shown in the figure.

If I assume that the superhump period is the less likely alternative of 0.06880 days, i.e. the 1 cy/day alias of the 0.06436 days period favoured by Patterson et al. (1993), the corresponding orbital period would then be the 1 cy/day alias of the orbital period derived above. In the same way as described above I then derive an orbital period of 0.06787(13) days, a radial velocity amplitude of 30(4) km/s, and superior conjunction occurs at HJD 2448076.8751(17).

7.3.4 Variations of the system velocity

From the cross correlation of the spectra from one night with the average spectrum of the other night I noticed a difference of ~150 km/s in the shifts with respect to the shifts obtained from the cross correlations of the spectra with the average spectrum in the same night. The average value of this shift was determined by cross correlating the average spectrum from the July 4 observations with the average spectrum from the July 6 observations. To exclude variations with the orbital period the spectra in each night were averaged over one orbital period. The emission cores of the absorption lines were excluded. A blue shift of 153 km/s was found for the July 6 observations with respect to the July 4 observations. To check this result I determined the difference in system velocity derived from single Gaussian fits to the Hγ/He I 4388 Å, and Hβ/He I 4922 Å blends, and the He I 4471 Å line in the spectrum averaged over one orbital period in each night with the line cores excluded. The derived shifts were 192(16), 138(10), and 207(52) km/s, respectively. These values are consistent with the shift determined from cross correlating the spectra. The error-weighted average of the shifts determined from the Gaussian fits is 155(8) km/s.

Variations of the system velocity have also been found for TU Men (Stolz and Schoembs 1984), Z Cha (Honey et al 1988) and TY PsA (Warner, O'Donoghue and Wargau 1989) during superoutburst, and have been explained with the “precessing eccentric disk” model of Whitehurst (1988) for superhumps. The system velocity is expected to vary with the precession period of the
disk, which is equal to the beat period between the superhump period and the orbital period. For VY Aqr the expected precession period of the disk is ~4 days. The velocity difference derived above is, therefore, a good lower limit to the full amplitude of the variation in the system velocity of VY Aqr. For TU Men Stolz and Schoembs (1984) derived a full amplitude of ~560 km/s, for Z Cha Honey et al. (1988) derived ~160 km/s, and for TY PsA Warner, O'Donoghue and Wargau (1989) derived ~600 km/s.

7.3.5 The emission component in the broad absorption lines

As I already mentioned before there is a clear difference in the line profiles in the two nights. Looking at the two average spectra presented in Fig. 7.3 it seems that during the July 4 observations there is an extra blue shifted emission component present which is superimposed on top of a more or less symmetric absorption line profile as seen in the July 6 observations. This is best seen by looking at the relative strong asymmetry of the bottom part of the absorption line profiles seen in the average spectrum of the July 4 observations compared to the average spectrum of the July 6 observations.

I attempted to extract this emission component by subtracting a Gaussian fit to the absorption lines excluding the emission core. However, the resulting line profiles are very complicated due to the presence of other, more centrally placed, emission components, which can also be seen in the average spectrum of the July 6 observations. I, therefore, decided to use the spectrum of the July 6 observations as an approximation of the spectrum underlying the extra emission component in an attempt to also correct for these central emission components. To do this the spectra in each night were averaged over one orbital period, and a red shift of 153 km/s was applied to the average spectrum for the July 6 observations (see above). This spectrum was then subtracted from the average spectrum of the July 4 observations. The result is presented as the lower curve in Fig. 7.3, and shows two clear blue shifted emission lines for Hγ and Hβ. From Gaussian fits to these lines I derive velocities of -583(34) km/s and -401(19) km/s, with respect to the rest wavelength of these lines, and FWHM of 16(1) and 14(1) Å, for Hγ and Hβ, respectively. This method is admittedly very crude, which might possibly explain why the velocities appear discrepant.

I also looked for radial velocity variations in these emission components by subtracting the average curve for the July 6 observations from the individual spectra of the July 4 observations. I find in most cases values of the velocity and the FWHM of the emission components which are consistent with the values given above. There is no evidence for radial velocity variations with the orbital period.

7.4 The quiescence spectra

7.4.1 Absorption components

In Fig. 7.6 I present the November 7, 1990 spectrum of VY Aqr in quiescence. The double-peaked emission lines are very common in dwarf novae in quiescence (see, e.g., La Dous 1990). However, the H Balmer lines, in particular Hβ, Hγ and Hδ, also show a very wide absorption component underlying the emission lines. These absorption features have been seen in only a small number of dwarf novae, and are thought to arise in the white dwarf primary.

The H Balmer, Hei, CaII and FeII emission lines seen in the spectrum shown in Fig. 7.6 are typical for dwarf novae below the period gap (see, e.g., Shafter and Szkody 1984, Thorstensen, Wade and Oke 1986, Shafter, Szkody and Thorstensen 1986, Szkody 1987, Marsh, Horne and Shipman 1987 and Shafter and Hessman 1988), and the spectrum looks remarkably similar to the quiescent spectrum of OY Car (Hessman et al. 1989; their Fig. 1), which is also a SU UMa type dwarf nova and has an orbital period of 0.063121 days, nearly equal to the most likely
7.4 The quiescence spectra

Figure 7.6. The November 7, 1990 spectrum of VY Aqr in quiescence. The spectrum covers the range 3810–7160 Å at a resolution of 8.2 Å. The exposure time was 90 min.

value for the orbital period of VY Aqr. The main difference between the two spectra is the depth of the minimum between the two peaks of the emission lines. In OY Car this is very deep, extending below the continuum level for Hγ and higher Balmer series members, whilst in VY Aqr it is only just visible. Part, but not all, of this difference can be explained by the higher resolution of the OY Car spectrum presented by Hessman et al. (1989).

OY Car is known to show total eclipses, and the inclination angle of this system is very well constrained to be 83.3(2)° (Wood et al. 1989). If the emission lines are optically thick, as is thought to be the case for dwarf novae in quiescence, the central minima in the emission lines are expected to decrease in strength with decreasing inclination (see, e.g., Horne and Marsh 1986). The difference between the two spectra can then be understood as the result of a lower inclination angle of VY Aqr compared to that of OY Car. I will discuss this in some more detail in Sect. 7.5.

The best way to determine the radial velocity curve of the white dwarf is to measure directly the velocity variations of the wide absorption lines from the white dwarf. To determine these radial velocities I fitted a “V-shaped” profile to those parts of the absorption lines of the Hγ and Hβ lines not contaminated by (other) emission lines (the same technique was also used by Hessmann et al. 1989 for OY Car). However, as can be seen in Fig. 7.7 presented below the noise level in those parts of the line profile is quite high, and I was only able to obtain a 3-σ upper limit of 420 km/s to radial velocity variations at the expected period.

7.4.2 Emission lines

The 13 spectra covering the range 3600–5590 Å obtained on July 10 1991 look very similar to the same part of the spectrum presented in Fig. 7.6. Before analyzing the spectra, they were normalized by dividing them by a 2nd-order polynomial fit to the continuum in the wavelength regions 4180–4205, 4600–4660 and 5060–5130 Å. To look for periodic variations in the data I performed single Gaussian fits to the emission lines. Power spectra were made of the derived velocities for each line separately to search for the presence of any periodicity. Significant variations were found for Hδ, Hγ, Hβ, and HeI 4471 Å. The period found for each line was
Time resolved spectroscopy of the dwarf nova VY Aquarii in superoutburst and quiescence

Consistent with the value of the orbital period derived in the previous section. The error-weighted average of these periods is 0.0636(46) days. For the remainder of this section I will adopt the period of 0.06348 days derived for the outburst spectra.

In Fig. 7.7 the region around Hγ and He I 4471 Å is shown for all 13 normalized spectra. The first spectrum is shown at the top shifted upward by 12.0 units, each subsequent spectrum is shifted upward by 1.0 units less. The spectra span, from top to bottom, 1.65 orbital period. Clear variations in the strength and shape can be seen in both lines. This complex structure of the emission lines, with varying strength of the two peaks and the varying depth of the central minimum in each line, has been seen in many dwarf nova. Generally this is thought to be the result of a narrow emission component moving through the line profile, which originates in the hot spot at the outer disk and reflects its radial velocity variations. Such a narrow component seems to be very prominent in the He I 4471 Å line. It is clear that the radial velocity amplitudes derived from fitting the entire line will be distorted and not reflect the motion of the white dwarf.

A method commonly used to derive the radial velocity curve of the white dwarf is to measure only the line wings of the emission lines, which are predominantly formed in the inner region of the accretion disk, and are believed to be less distorted. To measure the (emission) line wings

Figure 7.7. The region around Hγ and He I 4471 Å normalized to the continuum for the 13 spectra of VY Aqr in quiescence obtained on July 10, 1991. The spectra have a resolution of 9.8 Å. The first spectrum is shown at the top shifted upward by 12.0 units, each subsequent spectrum is shifted upward by 1.0 units less. The time between subsequent spectra is ~12.5m. The spectra span 1.65 times the orbital period
I used the double Gaussian convolution technique introduced by Schneider and Young (1980, see also Shafter, Szkody and Thorstensen 1986). In this technique two Gaussians with fixed width and separation are convolved with the 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 spectral resolution.

The resulting velocities determined for a given separation a of the two Gaussians were fitted with a nonlinear least-squares fit of the form

\[ V(t, a) = \gamma(a) + K(a) \cdot \sin\left[2\pi(t - t_0(a))/P\right] \]

where P is the orbital period.

The orbital elements are derived using the “diagnostic diagram” introduced by Shafter (1983). In such a diagram K, its associated relative error \( \sigma_K/K \), \( \gamma \), and the phase is plotted as function of the separation a of the two Gaussians. Here, phase is the time of superior conjunction for a line with respect to the time of superior conjunction of the H\( \beta \) line, i.e. for H\( \beta \) this phase is 0.0. In this way one can see the degree of asymmetry in the emission line profile as a function of velocity from line center (i.e., as a function of a). If there is any extra emission component (e.g., from a hot spot) which is confined to low (Keplerian) velocities, one would expect the disk emission to become axi-symmetric in the high-velocity line wings. The orbital elements should then converge to their true values for sufficiently large separation of the two Gaussians. At very large separations the velocity measurements become less reliable because the Gaussians are sampling an increasingly smaller part of the line wings. The optimal orbital elements are chosen as those values for which \( \sigma_K/K \) reaches a minimum.

In Fig. 7.8 I show the diagnostic diagram for the H\( \gamma \) line. For this line the minimum in \( \sigma_K/K \) is reached for a separation \( a = 2200 \text{ km/s} \) of the two Gaussians. The \( \gamma \) velocity does...
not change significantly as function of the velocity from line center, whilst the phase of superior conjunction seems to converge nicely for \( a \gtrsim 2000 \text{ km/s} \). The radial velocity amplitude \( K \) hardly changes for separations between 2000 and 3000 km/s. Very similar curves for the variation of the orbital elements as function of \( a \) were found in the diagnostic diagrams of \( \text{H} \delta \), \( \text{H} \gamma \) and \( \text{He} \) 4471 Å. The results for these lines together with that of \( \text{H} \gamma \) are listed in Table 7.2.

As can be seen in Table 7.2 the orbital elements derived from the different lines do not present a consistent picture, with both \( K \) and \( \gamma \) varying widely. Especially the radial velocity amplitude, \( K \), of the \( \text{He} \) 4471 Å line is much higher than those of the Balmer lines. As I already mentioned above this line shows a prominent narrow emission component which is much less obvious in the Balmer lines (see Fig. 7.7). A simple explanation for the difference in amplitude would then be that the narrow emission component is not confined to the line center, but also distorts the line wings, with the \( \text{He} \) being most affected. The difference between the amplitudes of different Balmer lines can be understood as the result of the Gaussian convolution method being able to sample further out into the line wings as the lines become stronger (going from \( \text{H} \delta \) to \( \text{H} \beta \)) and the distortion is less.

To explore this somewhat further I tried to determine the radial velocity curve of the narrow component. As this component is most prominent in the \( \text{He} \) 4471 Å line, I concentrated on that line and determined the velocity of the narrow component in each spectrum by eye. The result is shown in Fig. 7.9. A clear variation can be seen with a period of approximately 0.063 days. From a least-squares sine fit with a fixed period I derive: \( \gamma = -128(43) \text{ km/s, } K = 598(63) \text{ km/s, and superior conjunction occurring at } JD_{\odot} = 2448447.92009(96) \) (which corresponds to phase 0.119 \( \pm 0.015 \) as defined in Table 7.2). These values are consistent with the idea that the narrow emission component affects the radial velocity curves of the line wings, and that the effect increases toward the higher members of the Balmer series. This results in progressively more distorted values of the radial velocity amplitude, the \( \gamma \)-velocity and the phase of conjunction (see Table 7.2).

One puzzling result is the large difference between the \( \gamma \)-velocity determined from the line wings of the \( \text{He} \) 4471 Å line using the double Gaussian method (see Table 7.2) and that determined for the narrow emission component. One possible explanation is that the line is blended with the \( \text{Mg} \) II 4481 line. This line has been observed in the SU UMa type dwarf nova SU UMa in quiescence (Thorstensen, Wade and Oke 1986). An argument for the presence of this line might be the presence of other lines from single ionized metals (see Fig. 7.6). If the \( \text{He} \) 4471 and \( \text{Mg} \) II lines have similar relative strength in VY Aqr as in SU UMa one would expect the narrow
emission component to be at most only slightly affect, whilst the red wing of the He I 4471 line would be strongly distorted, shifting the $\gamma$-velocity determined from the line wings to the red. This possible blend might also explain why the line wings of the He I 4471 line can be traced just as far from the line center as H\footnote{see Table 7.2}, although H\footnote{see Table 7.3}. It is interesting to note that the line profile of the He I 4471 line in the spectrum of OY Car presented by Hessmann et al. (1989; their Fig. 1) shows a clear distortion towards longer wavelength. The Mg\footnote{see text} line in absorption has also been detected in the UX UMa type cataclysmic variable IX Vel (Beuermann and Thomas 1990).

From the above it follows that the orbital elements derived from the line wings of H\footnote{see Table 7.2} are expected to be least distorted. The question remains whether there is residual distortion in H\footnote{see Table 7.3} that would affect the results significantly, or whether the orbital elements reflect the true radial velocity variations of the white dwarf. This is of importance since the quiescence H\footnote{see Table 7.3} results disagree with the outburst results (see Sect. 7.3.3).

For many dwarf novae the radial velocity amplitudes measured from the broad absorption lines during outburst agree with those obtained from the emission lines during quiescence (see, e.g., Hessman et al. 1984, Feinswog et al. 1988, Szkody et al. 1990; see, however, O'Donoghue and Soltynski 1992 and Warner, O'Donoghue and Wargau 1989). From the large amplitude of the narrow component in VY Aqr and the relatively poor resolution of the quiescent spectra (\footnote{see text}) one would still expect to see some effect of this component even as far from the line center as sampled by the double Gaussians for H\footnote{see Table 7.2} (this apart form the intrinsic width of the narrow component which might very well exceed the resolution). Although the contribution of the narrow component is hard to quantify exactly it is clear from the line profile variations seen in Fig. 7.7 that this component is quite strong. If the narrow component reflects the radial velocity of the hot spot then, given the fact that the mass ratio $q(=M_{WD}/M_{RD})$ in SU UMa type dwarf nova is generally high (see also Sect. 7.5), one would expect the phase difference between this component and the motion of the white dwarf to be of the order of 0.25–0.35. Since the phase difference between the radial velocity curve of the narrow component in the He I 4471 Å line and that of the line wings of H\footnote{see Table 7.2} is only 0.12, the line wings of H\footnote{see Table 7.2} are probably still affected by the narrow component. Finally, like what is shown for H\footnote{see Table 7.2} in Fig. 7.8, the H\footnote{see Table 7.2} line also shows a trend of a decreasing radial velocity amplitude with increasing separation of the two Gaussian, which indicates that the true radial velocity amplitude of the line wings is in fact smaller.

I therefore conclude that the result obtained for the H\footnote{see Table 7.2} line in quiescence is probably still affected by the narrow emission component, and that the radial velocity amplitude derived from the outburst spectra gives a better representation of the motion of the white dwarf.

I also looked for variations in the EWs of the different emission lines. More than half of the lines showed some indication of a variation with a period consistent with half the orbital period.
Table 7.3 The equivalent width of the emission lines during quiescence

<table>
<thead>
<tr>
<th>Line(s)</th>
<th>EW(Å) (^1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hδ</td>
<td>20.2 ± 1.2</td>
</tr>
<tr>
<td>Ca K</td>
<td>13.94 ± 0.80</td>
</tr>
<tr>
<td>Hγ + Ca H</td>
<td>29.83 ± 0.88</td>
</tr>
<tr>
<td>He I 4026</td>
<td>2.84 ± 0.35</td>
</tr>
<tr>
<td>Hγ</td>
<td>36.2 ± 1.2</td>
</tr>
<tr>
<td>Hγ + Mg II 4481 (^2)</td>
<td>46.2 ± 1.5</td>
</tr>
<tr>
<td>He I 4471 + Mg II 4481</td>
<td>7.76 ± 0.50</td>
</tr>
<tr>
<td>Hβ</td>
<td>83.1 ± 2.4</td>
</tr>
<tr>
<td>He I 4922 + Fe II 4923</td>
<td>5.09 ± 0.41</td>
</tr>
<tr>
<td>He I 5015 + Fe II 5018</td>
<td>5.63 ± 0.24</td>
</tr>
<tr>
<td>Fe II 5169</td>
<td>7.56 ± 0.41</td>
</tr>
</tbody>
</table>

\(^1\) The errors are the errors in the mean
\(^2\) See text

However, in all cases the significance of the periodicities that were found was not very high. In Table 7.3 the average values over the 13 spectra are listed of the EWs of those lines for which we could determine the continuum level with some accuracy. The spectra were not correct for the contribution from the wide H Balmer absorption lines coming from the white dwarf, so the values for these lines should be considered as lower limits. The errors listed in Table 7.3 are the errors in the mean.

7.5 The mass ratio and inclination

One of the predictions of Whitehurst’s (1988; see also Molnar and Kobulnicky 1992) superhump model for SU UMa systems is that in these systems the mass ratio \(q = \frac{M_{WD}}{M_{RD}} \gtrsim 4.5\). On the basis of the results obtained in Sect. 7.3 and 7.4 one can see if the mass ratio of VY Aqr is consistent with this limit.

In this section I will assume the most likely values for the orbital and superhump periods of 0.06348(12) and 0.06452(13) days, respectively. However, none of the results derived below change significantly if the less likely alternatives for these periods are used.

Patterson (1984) derived a semi-empirical mass-radius relation for the secondary in a cataclysmic variable (CV) of the form

\[
\frac{R_{RD}}{R_\odot} = \alpha \left( \frac{M_{RD}}{M_\odot} \right)^{0.88} \tag{7.1}
\]

where \(\alpha\) reflects departures from main-sequence structure (\(\alpha = 1\) for a main-sequence star).

Paczynski (1971) showed that the radius of a spherical star having the same volume as that of the Roche-lobe can be written as

\[
\frac{R_{RD}}{a} = 0.462 \left( \frac{1}{1 + q} \right)^{1/3} \quad \text{for} \quad q > 2 \tag{7.2}
\]

where \(a\) is the orbital separation. Kepler’s third law can be re-written to obtain

\[
a = \left( \frac{G M_{RD} (1 + q) P^2}{4 \pi^2} \right)^{1/3} \tag{7.3}
\]
7.5 The mass ratio and inclination

where \( P \) is the orbital period.

Equating Eqs. (7.1) and (7.2), and substituting Eq. (7.3) one can easily derive

\[
\frac{M_{RD}}{M_\odot} = 3.38 \alpha^{-1.83} P^{1.220}
\]

(7.4)

where \( P \) is in days.

From the study of the eclipse light curves of dwarf novae both the mass and the radius of the secondary can be derived, which allows a direct check on Eq. (7.1). The three SU UMa type dwarf novae which have been studied in detail using their eclipse light curves (Z Cha, Wood et al. 1986; OY Car, Wood et al. 1989; HT Cas, Horne, Wood and Stiening 1991) all have secondaries which are undermassive compared to Eq. (7.1) with \( \alpha=1.0 \). The error-weighted average for these three systems is \( \alpha = 1.34(3) \). Inserting this value in Eq. (7.4) I derive

\[
\frac{M_{RD}}{M_\odot} = 2.0 P^{1.220}
\]

(7.5)

Of course, this relation is uncertain as it is based on only a few sources with a small range in orbital period. As the masses and radii were determine using one method there is also the possibility of systematic errors. Smak (1993) recently redetermined the system parameters for WZ Sge and derived a secondary mass of \( M_{RD} \approx 0.06 M_\odot \) which is consistent with Eq. (7.5).

From the value of the orbital period of VY Aqr and using Eq. (7.5) it follows that \( M_{RD} = 0.07 M_\odot \). Considering the uncertainty in Eq. (7.5) I adopt a mass range of \( M_{RD} = 0.07-0.12 M_\odot \) (i.e., \( \alpha \) is in the range 1.0–1.34).

From the radial velocity amplitude determined in Sect. 7.3.3 and Kepler’s third law a relation can be derived between the masses of the components and the inclination angle \( i \). A lower limit to the mass of the white dwarf primary can be derived from the HWZI of the emission lines. 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, i.e.,

\[
\sqrt{\frac{G M_{WD}}{R_{WD}}} \sin i \geq V_{HWZI}
\]

(7.6)

I approximate the mass-radius relation for white dwarfs (Hamada and Salpeter 1961) by

\[
R_9 = 0.5 \left( \frac{M_{WD}}{M_\odot} \right)^{-0.8}
\]

(7.7)

where \( R_9 \) is the white dwarf radius in units of \( 10^9 \) cm.

By combining Eqs. (7.6) and (7.7) I derive

\[
\frac{M_{WD}}{M_\odot} \sin i \geq 0.162 \left( \frac{V_{HWZI}}{10^3 \text{ km/s}} \right)^{2/1.8}
\]

(7.8)

The problem with measuring the HWZI of the emission lines for VY Aqr is that they are affected by the underlying absorption line profile from the white dwarf which reduces their width. From Fig. 7.6 it appears that the higher the quantum number, the stronger the H Balmer line is affected. This is reflected in the decrease of HWZI with increasing quantum number. I make a conservative estimate and take the average for the H\( \alpha \), H\( \beta \), H\( \gamma \) and H\( \delta \) lines and derive \( V_{HWZI} = 1800 \) km/s. This places a lower limit to the mass of the white dwarf of \( M_{WD} = 0.31 M_\odot \).

A further constraint is set by the fact that photometric data do not show any eclipses (Patterson et al. 1993). This together with the expression of Paczynski (1971) for the size of
the Roche-lobe filling secondary gives a lower limit to the inclination as function of the mass ratio.

All the constraints are combined and shown together in Fig. 7.10 for a secondary mass of $M_{RD} = 0.07 \, M_{\odot}$, and in Fig. 7.11 for a secondary mass of $M_{RD} = 0.12 \, M_{\odot}$. It appears from these figures that the mass ratio for VY Aqr must be very high. The secondary is expected to be out of thermal equilibrium as a result of the continuing mass transfer, i.e. $\alpha > 1$. Therefore, $0.12 \, M_{\odot}$ can be considered as a reasonable upper limit to the mass of the secondary and I derive a lower limit to the mass ratio of $q \gtrsim 6$, consistent with the precessing-disk model of Whitehurst (1988). For $M_{RD} = 0.07 \, M_{\odot}$ the inclination is constrained to the range $i \sim 30-80^\circ$, and for $M_{RD} = 0.12 \, M_{\odot}$ to the range $i \sim 20-45^\circ$.

There are more ways to constraining $q$ and $i$. A model dependent estimate of the mass ratio can be obtained from the values of the orbital period ($P_{\text{orb}}$) and superhump period ($P_{\text{SH}}$) I determined in Sect. 7.3. Osaki (1985) derived for the relative difference ($\Delta P = (P_{\text{SH}} - P_{\text{orb}})/P_{\text{orb}}$) between $P_{\text{orb}}$ and $P_{\text{SH}}$:

$$\Delta P = \frac{3}{4} \frac{1}{\sqrt{q^2 + q}} \frac{1}{a} (r_d)_{\text{crit}}^{3/2} \approx \frac{1}{4 \sqrt{q^2 + q}} \eta^{3/2} .$$

(7.9)

Here $\eta \equiv (r_d/r_{d,\text{crit}})$ and $r_{d,\text{crit}} (\simeq 0.48 \, a)$ is the critical disk radius for which the disk instability occurs which gives rise to the superhump phenomena (see, e.g., Hirose and Osaki 1990). Mineshige, Hirose and Osaki (1992) found that, independent of the specific outburst mechanism, Eq. (7.9) gives a good representation for the observed $\Delta P-q$ relation for SU UMa type dwarf novae with $\eta$ in the range 0.6–1.0.

Solving Eq. (7.9) I derive

$$q = -\frac{1}{2} + \frac{1}{2} \sqrt{1 + \frac{\eta^3}{4 \Delta P^2}} .$$

(7.10)
From the results in Sect. 7.3 it follows that $\Delta P = 0.0164$, and with $\eta$ in the range 0.6–1.0 I derive from Eq. (7.10) $q = 7-15$ (for an average value of $\eta = 0.8$ I derive $q = 10$).

Warner (1976) derived a relation between the projected velocity of the outer disk rim and the radial velocity amplitude of the white dwarf

$$\frac{K_{WD}}{V_{\text{disk} \sin i}} = \frac{f^2}{q}$$

(7.11)

where

$$f = (0.500 + 0.227 \log q)$$

(7.12)

is the distance from the center of the primary to the inner Lagrangian point.

I estimate $V_{\text{disk} \sin i}$ from the half separation of the double peaked emission lines in quiescence (see, e.g., Horne and Marsh 1986), and derive for H$\beta$ and H$\gamma$ an average value of 470 km/s. Together with the radial velocity amplitude of 29(6) km/s derived in Sect. 7.3.3 I obtain a value of 0.062 for the left hand side in Eq. (7.11), which corresponds to a mass ratio $q \approx 8$.

The inclination is not easy to constrain in a quantitative way. However, the fact that the lines are double peak tells us that the inclination can not be very low. Comparing the line profiles of the H Balmer lines to the theoretical profiles calculated by Horne and Marsh (1986) for optically thick lines I estimate the inclination to be in the range $i \sim 30-60^\circ$.

The inclination may also be estimated from the separation of the double peaked emission lines which gives an estimate for the projected velocity at the outer disk rim. Warner (1976) derived for the size $r_d$ of the disk

$$\frac{r_d}{a} = f^4 \left( \frac{1 + q}{q} \right)$$

(7.13)

where $f$ is given in Eq. (7.12). Using Eqs. (7.3) and (7.4) one can derive for the velocity at the outer disk rim

$$V_d = \sqrt{\frac{G M_{\text{WD}}}{r_d}} = 139 \left( \frac{P^{0.220} q^3}{\alpha^{1.83} (1 + q)^2 f^6} \right)^{1/3} \text{km/s}$$

(7.14)

where $P$ is in seconds and all other parameters have the same meaning as before. Note that Eq. (7.14) is practically independent of the orbital period. For $\alpha$ in the range 1.0–1.34, and $q$ in the range 7–15 (see Eq. (7.10)) I derive velocities in the range 800–1050 km/s. The velocity estimate given above then implies an inclination of the system of $i \sim 27-36^\circ$. Of course this is a very rough estimate, and the result depends on the validity of the assumptions that were made. However,
the lack of any clear photometric variations at the orbital period in quiescence (Patterson et al. 1993) also points to a fairly low inclination.

The independent estimates of \( q \) and \( i \) are consistent with the constraints shown in Figs. 7.10 and 7.11 for both a secondary mass of \( M_{RD} = 0.07 \, M_\odot \) and \( 0.12 \, M_\odot \). Taken all this together they indicate for VY Aqr values of \( i \approx 30-40^\circ \) and \( q \approx 8-10 \). The latter corresponds to \( M_{WD} \approx 0.6-1.2 \, M_\odot \).

If the radial velocity amplitude of 81 km/s, as found for H\( \beta \) in quiescence (see Table 7.2), was used to construct \((q, i)\) diagrams similar to Figs. 7.10 and 7.11 no allowed pair of values \((q, i)\) would have been found for \( M_{RD} = 0.07 \, M_\odot \); for \( M_{RD} = 0.12 \, M_\odot \) only an area in the \((q, i)\) diagram with \( q \leq 5 \) and \( i \geq 60^\circ \) would be allowed. These latter values are not consistent with the other independent estimates for \( q \) and \( i \) derived above. This supports my suspicion that the quiescence H\( \beta \) radial-velocity amplitude is affected by systematic errors.

### 7.6 Discussion

As derived in the previous sections VY Aqr has very similar systems parameters to OY Car, which is also a SU UMa type dwarf nova. However, the amplitudes of the outbursts seen in VY Aqr are typically 3 magnitudes larger than those in OY Car. The large amplitude outbursts make VY Aqr member of a class which has been recently named "tremendous amplitude outburst dwarf novae" (TOADs; Howell 1993). Several of these TOADs are found to have absolute magnitudes in quiescence which are 2-4 magnitudes fainter than "normal" dwarf novae (Howell and Szkody 1992). Van Paradijs (1983) and Warner (1987) argue that the larger the amplitude of dwarf nova outbursts is, the lower is the mass transfer rate (\( \dot{M} \)) in quiescence. The difference in outburst amplitude between VY Aqr and OY Car might, therefore, indicate a difference in \( \dot{M} \).

Patterson (1984) derived a relation between the EW of H\( \beta \) and the intrinsic brightness of the disk, which depends on \( \dot{M} \). The EW of H\( \beta \) for VY Aqr (83 \( \AA \)) is substantially larger than the EW of H\( \beta \) (47 \( \AA \); Patterson 1984) derived for OY Car. Comparing these values to Fig. 6 of Patterson (1984) I derive \( \dot{M}_{OV} \sim 5 \dot{M}_{VY} \). Osaki (1989) found from model calculations that the recurrence time (\( t_S \)) of superoutbursts in SU UMa systems is proportional to \( \dot{M}^{-1} \). For OY Car \( t_S \sim 300 \) days (see, e.g., Warner 1987). VY Aqr has been followed regularly during the past decade; as the superoutburst last for about two weeks the chances of missing one or more superoutbursts are fairly small. From the observations of the the Variable Star Section of the RASNZ over the past ten years (up to May 1993) I find an average of \( t_S \sim 860 \) days. This implies \( \dot{M}_{OV} \sim 3 \dot{M}_{VY} \).

Thus, a variety of evidence indicates that the quiescent mass transfer rate of VY Aqr is substantially lower than that of OY Car.

VY Aqr and OY Car have orbital periods below the period gap found in the period distribution of cataclysmic variables (see, e.g., Patterson 1984, La Dous 1990). Below the period gap the evolution of cataclysmic variables, and as a result \( \dot{M} \), is thought to be governed by the loss of orbital angular momentum through gravitational radiation (e.g., Rappaport, Joss and Webbink 1982). With this mechanism \( \dot{M} \) is expected to be similar for systems with similar system parameters, and it is hard to understand how it can account for the difference by a factor \( \sim 3-5 \) (possibly more for other TOADs) found in \( \dot{M} \) between VY Aqr and OY Car. One possibility that comes to mind is that VY Aqr has already evolved through the minimum period for cataclysmic variables (Rappaport, Joss and Webbink 1982), and its secondary is a degenerate dwarf. However, in that case the difference in \( \dot{M} \) between OY Car and VY Aqr is expected to be much larger than a factor \( \sim 3-5 \). Another possibility is that VY Aqr and OY Car are at somewhat different phases in the cycle between recurring nova explosions as envisioned in the hibernation theory (Shara et al. 1986). Also other mechanisms which give rise to a varying \( \dot{M} \) with time
(e.g., solar-type cycles; see Warner 1988) might explain the difference between VY Aqr and OY Car.

Finally, I note that for TOADs with known quiescent absolute magnitude (Howell and Szkody 1992) and outburst amplitude (e.g., Ritter 1990), the absolute magnitude in outburst are consistent with Warner's (1987) relation between absolute magnitude in outburst and orbital period. This is of interest as determining the distance to these systems can have important implications for the space density of dwarf novae, and cataclysmic variables in general. From the apparent magnitude of VY Aqr in outburst I derive a distance of d~110 pc.

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