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A spectroscopic study of the long-period dwarf nova DX Andromedae

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Abstract. We present time-resolved spectra of the double-lined dwarf nova DX And in quiescence from two campaigns in 1989 and 1993. Using an unusual method, we have reconstructed the radial velocity amplitudes and phases of the absorption and emission line components from data suffering from serious wavelength calibration problems by measuring the relative motions of as well as the phase shift between the two line systems. We are thus able to refine the orbital period and to determine a long-term ephemeris. The relative contribution of the primary to the total light was measured as a function of wavelength, permitting to correct the absorption line spectrum for the veiling effect. The secondary star exhibits several spectral peculiarities: in addition to the enhanced Ca I absorption lines reported previously, we find several Cr I lines to be significantly stronger than in a comparison star of similar spectral type.

Key words: stars: binaries: close – stars: novae, cataclysmic variables – stars: individual: DX And

1. Introduction

Cataclysmic variables (CVs) are interacting binaries where a late type (roughly main sequence) secondary looses mass through Roche-lobe overflow via an accretion disk to a white dwarf primary. Although there are relatively few systems where the absorption lines of the secondary spectrum are not totally veiled by the normally much brighter accretion disk, these CV's are particularly important: the masses of the components and the evolutionary status of the systems can be studied in more detail.

The study of the absorption line spectrum of secondary stars is an important tool for understanding the role of CVs in the evolution of binary stars. Unfortunately, only a few of the rare CVs with a strong absorption line spectrum have been investigated in some detail with respect to the properties of the secondary. Examples are GK Per (Crampton et al. 1986), BV Cen (Gilliland 1982), RU Peg (Stover 1981), V426 Oph (Hessman 1988), and AE Aqr (Welsh et al. 1995).

DX And is one of the systems where the optical spectrum of the secondary star stands out particularly clearly (Bruch 1989). A first detailed investigation of the absorption line spectrum was performed by Drew et al. (1993; DJW hereafter). They found the secondary to be a K1 star in a 10.6 hour orbit. Such a star can only fill its Roche lobe if it is evolved, and DJW estimated its radius to be at least 40% larger than the corresponding main sequence radius. Moreover, the absorption spectrum directly shows features which do not match a normal main sequence star.

In this contribution, we present spectroscopy of DX And from two follow-up observations of Bruch's (1989) original study. We show how meaningful radial velocity (RV) information can be reconstructed from data containing serious wavelength calibration problems. The results of our RV study and analysis of the secondary spectrum confirm and extend the results of DJW.

2. Observations and reductions

The bulk of the spectra presented here was obtained on 4 nights between 1989, October 5 and 10 at the 3.5m-telescope of the DSAZ on Calar Alto. A grism spectrograph attached to a focal reducer in the prime focus of the telescope was used. Spectra were recorded on a 1024 × 512 pixel CCD with a pixel size of 15 μm. The useful spectral range was 3 900-5 560 Å at a dispersion of 1.7 Å/pixel. A total of 73 spectra of DX And – each exposed for 10 minutes – was obtained. Additionally, some late-type standard stars were also observed. Standard routines within IRAF were used to debias, flat-field and extract the spectra from the CCD frames (applying the optimized algorithm of Horne 1986), as well as for wavelength calibration. The subsequent

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⋆ Visiting Astronomer, German-Spanish Astronomical Centre, Calar Alto, operated by the Max-Planck-Institut für Astronomie Heidelberg jointly with the Spanish National Commission for Astronomy analysis of the data was done with the MIRA image processing system (Bruch 1993).

The observations were hampered by the unexpected absence of an internal wavelength calibration lamp. Though a well-exposed He-Ar spectrum was obtained at the end of each night, this permitted only a rough wavelength calibration: zero point shifts caused by telescope flexure etc. cannot be corrected for in this way. Unfortunately, the sky spectrum was too weak to serve as an additional calibration source, so – starting on the second night – an anonymous early F star close to DX And (hereafter called the "Neighbour") was intermittently observed with the idea that the position of its hydrogen lines could be used to monitor shifts of the wavelength scale zero point. For the purpose of RV measurements, we make the basic assumption that while the *zero point* of the dispersion curve may depend significantly on parameters such as telescope pointing, temperature, time etc., its *shape* is constant. Care was taken to expose the Neighbour on the same part of the detector as DX And itself in order not to introduce additional errors through a possible dependence of the dispersion curve on the spatial coordinate on the detector. It is then possible to measure the position of the lines in the spectra calibrated with the He-Ar lamp against a suitably chosen zero point. The results of our analysis indicate that this approximation is not a bad one.

During another observing campaign, 4 additional spectra of DX And were observed with the same telescope in 4 successive nights between 1993, June 29 and July 2, in order to use them together with the 1989 data and the data of DJW for the determination of the long-term ephemerides. This time the Cassegrain twin spectrograph was used which recorded simultaneously red and blue spectra (except for June 29 when the blue channel was out of order). Spectra in the range 3 900 – 6 750 Å were recorded on two 1030 × 1080 pixel CCDs with a pixel size of 24 μm at a dispersion of 1.8 Å/pixel. Additionally, the K0.5 V (Keenan & McNeil 1989) standard star HD 124752 was observed. This time the wavelength calibration could be performed in the standard manner.

The visual light curve of DX And obtained by members of the AAVSO, kindly provided by Janet Mattei (priv. comm.) shows that the system was in quiescence at the epoch of the first observations, at least 4 weeks after the previous outburst and about five weeks before the next one. We have no independent information about the photometric state of DX And during the observations in 1993. However, the spectra and the appearance at the telescope leave no doubt that they were also taken at quiescence.

3. Radial velocity measurements

The most direct way to measure the masses of CVs requires RV measurements of both components – the ubiquitous emission lines of the accretion disk and the well-defined absorption lines of the secondary. However, the lack of an accurate wavelength calibration makes the task of measuring the individual K-velocities nearly – *but not totally* – impossible. The crude relative calibration obtained from the Neighbour star introduces substantial "noise" in the individual RV measurements. The RV of the secondary's absorption lines relative to the primary's emission lines can be measured very accurately within a single spectrogram, however. In addition, we have DJW's measurement of the secondary's RV amplitude, $K_2 = 105.8 \pm 3.8$ km/s. Finally, even the "noisy" RV measurements permit one to measure the relative phase shift between the absorption and emission lines for a given measured orbital period: *while the additional "noise" significantly increases the error of the measured RV amplitude, the phase shift is affected much less.* Thus, given a measurement of this phase shift, the orbital period (either taken from DJW or measureable from the relative RV measurements), the relative RV amplitude of the line systems, K_0, and the value of K_2 from DJW, one can reconstruct the RV amplitude of the primary, K_1, and the absolute phase offset of the relative RV measurements, ϕ_0.

If the true RV's of the primary and secondary stars are given as $V_1 = \gamma_1 - K_1 \sin(\phi - \phi_1)$ and $V_2 = \gamma_2 + K_2 \sin\phi$ and their measured relative velocities $V_2 - V_1$ (assuming $\gamma_1 = \gamma_2$) are measured as $K_0 \sin(\phi - \phi_0)$, then measurements of K_2, ϕ_1, and K_0 can be used to find K_1 and ϕ_0 via

$$\phi_0 = \arcsin\left(-\frac{K_2 \sin\phi_1}{K_0}\right) + \phi_1$$

$$K_1 = \sqrt{K_0^2 - K_2^2 \sin^2\phi_1} - K_2 \cos\phi_1 \quad (1)$$

3.1. The relative radial velocities

The relative velocities of the components in DX And were measured in a manner similar to that used by Stover (1981) using SAO 024073 as a cross-correlation template (spectral type K0 V; close to K1 V, the type determined by DJW for the secondary of DX And). First, we measured the velocities of the absorption line spectra relative to those of the Hβ emission line (the strongest line available), the latter initially determined via Gaussian fits. In order to test for possible residual distortions of the shape of the dispersion curve over large wavelength ranges, the cross correlation was performed independently in the wavelength range between Hβ and Hγ (avoiding the noisy range bluewards of Hγ) and redwards of Hβ: no significant differences were found in the results. In a second stage, the emission lines were re-measured after the spectrum of the standard star was shifted, scaled, and subtracted from the DX And spectra in order to largely remove the distortion of the emission lines by the underlying absorption lines. The use of more sophisticated methods than Gaussian fits to measure the RV of the emission lines (e.g. the double Gaussian convolution method of Schneider & Young (1980) in connection with Shafter's (1983) diagnostic diagrams) is inhibited by the extremely strong absorption line spectrum which did not permit us to measure the high velocity parts of the emission line profiles.

The final RVs were subjected to an analysis-of-variance test (Schwarzenberg-Czerny 1989) and a sine curve fit, yielding an an orbital period of 0.44107 days, identical within the error limits to the value measured by DJW. The epoch

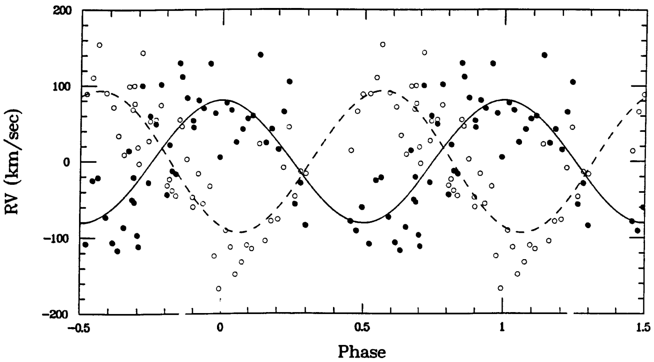

Fig. 1. Individual radial velocity curves derived from the 1989 data of DX And (after subtraction of the γ-velocities): the absorption lines (filled circles and solid line); and the Hβ emission lines (open circles and broken line).

of maximum RV of the absorption lines relative to the Hβ emission is HJD 2447800.4063. The fitted amplitude K_0 is 172.4 ± 5.3 km/sec. The mean error of the individual RVs can be estimated as 17.0 km/sec from the standard deviation between the measured values and the best fit sine curve, assuming a circular orbit of DX And.

3.2. The absolute radial velocities

The observations of the Neighbour star close to DX And, assumed to have a constant RV, enabled us to follow approximately the zero point shift of the dispersion curve by monitoring the position of its absorption lines and thus to independently measure of the motion of emission and absorption lines in DX And. The position of Hβ in the Neighbour star spectrum (the only line of sufficient strength to be reliably measured) was determined by fitting it with a high-order polynomial, yielding the zero point shift as a function of time. This function was linearly interpolated at the observing times of the DX And spectra to correct the wavelength scale of the DX And spectra to a still arbitrary but fixed wavelength zero point. Since the Neighbour star was not observed on the first night, only the data of the remaining nights can be treated in this way.

The absolute RV measurements were then performed in a similar manner to that described before. The RVs were folded on the orbital period, and then fit to a sine curve in order to derive the phases and amplitudes. The absorption line data (omitting three successive points with large deviations), the emission line data (after discarting four deviating points, three of them corresponding to the deviating absorption line RVs), and the fitted sine curves are shown in Fig. 1 as filled dots, open circles, and solid curves, respectively, after subtraction of the arbitrary γ-velocities. The measured amplitude K_1 = 93.4 ± 6.1 km/sec and K_2 = 80.6 ± 7.4 km/sec.

The standard deviation between the measured RVs and the best fit sine curves leads to error estimated for the individual data points of 49.2 km/sec and 43.1 km/sec for the absorption and emission line RVs, respectively. These errors are much larger than those of the relative motion, indicating that the main source of error is the Neighbour. In fact, the spectra of the Neighbour are only of mediocre quality, and the position of its Hβ line can therefore only be measured with limited accuracy. Tests showed that different methods to determine the centre of the Hβ absorption of the Neighbour (Gauss-fit, polynomial fits of different degrees) lead to an uncertainty of the order of 0.4 Å which must be regarded as a lower limit for the position error. This uncertainty alone translates into an RV error of 25 km/sec.

Another source of error may be due to residual absorption in the emission line profiles. Tests – subtracting the absorption lines assuming values between 0 and 0.3 for the veiling factor (the true value at Hβ is 0.19; see Sect. 5.1) – show that the corresponding error is smaller than ±10 km/sec for individual spectra.

The measured phase difference between the RVs of the absorption lines and Hβ is $\Delta\Phi$ = (0.434 ± 0.017) × $P_{\rm orb}$ or an excess phase shift ϕ_1 of 23°.8 ± 6°.1. A similar, but less well defined shift was also observed in the case of Hγ. Considering the measured phase shift, the relative RV curve should have an amplitude of 170.3 ± 15.2 km/sec: in view of the uncertainties of the wavelength calibration, this is pleasantly close to the measured value of 172.4 ± 5.3 km/sec.

A mean emission line spectrum was constructed by shifting the individual spectra to the Hβ rest frame after subtracting the standard star spectrum corrected for the wavelength dependent veiling effect (see Sect. 5.1), renormalizing and summing up all spectra. The mean spectrum exhibits the usual dwarf nova features: the dominant Balmer lines and He I lines at $\lambda\lambda$ 4026, 4471, 4922, 5016, 5876 and 6678 Å. The shape of Hβ has no obvious phase dependence, and its equivalent width does not vary significantly around the orbit.

3.3. The reconstructed radial velocity amplitudes and phases

Using Eq. (1), one obtains the reconstructed K_1 velocity of 70.2 ± 6.6 km/s. DJW – using a version of the double-Gaussian method – derived an emission line RV amplitude in the range 80-105 km/sec – marginally compatible with our results from Gaussian fits. Formally, the K-values lead to a mass ratio $q \equiv M_2/M_1$ = 0.66 ± 0.08, somewhat less than the value of q = 0.96 ± 0.12 derived by DJW. Similarly, the reconstructed phase-correction for the relative velocities is ϕ_0 of 9°.4 ± 2°.7. This value will be used in the next section to try to refine the orbital ephemeris.

An excess phase shift between the motion of the secondary star in CVs – determined either by the absorption line RVs or by eclipses – and the primary, if the emission lines are assumed to be centred on the white dwarf, has often been observed. A compilation was published by Hessman (1987), and since then many more examples have been found. The reasons for this behaviour are not finally understood. However, an asymmetric emission distribution or non-Keplerian velocity distribution may play a role (see e.g. the discussion in Warner 1995). In the present case the phase excess is such that it can qualitatively be explained by an enhancement of the Hβ emission in the direction of the hot spot. Thus, the RVs derived from Hβ will not represent the mo-

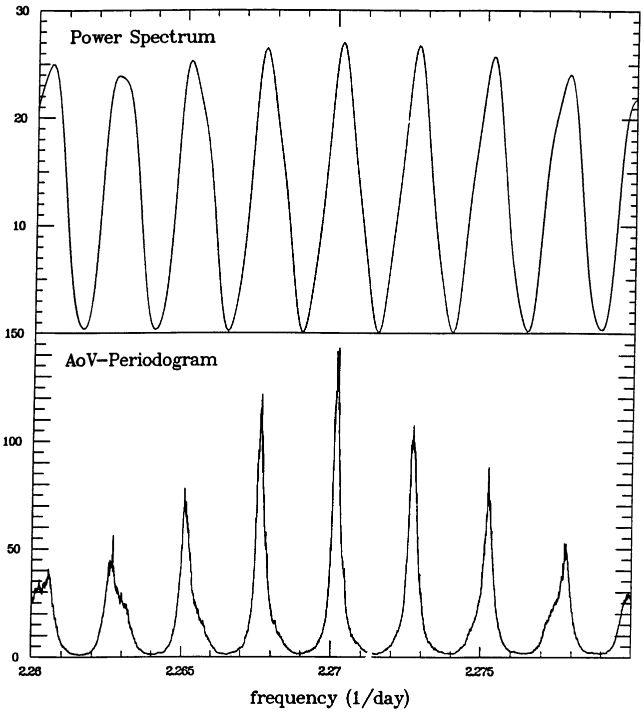

Fig. 2. Power spectrum (top) and AoV periodogram (bottom) of the combined radial velocity curves of the DX And absorption lines of 1989, 1990 and 1993.

tion of the white dwarf and any dynamical property (apart from the period) based on these values will be unreliable. Therefore, we will not discuss the dynamics of DX And any further here.

4. The orbital period

The individual absorption line velocities of Nov. 1990 measured by DJW were kindly put at our disposal by J. Drew. RV measurement of DX And from three different seasons are thus available, warranting an attempt to improve the orbital period and to obtain long-term ephemeris. Using our reconstruction, relatively accurate RVs for the secondary can be obtained from the relative RVs from the 1989 data. A least squares sine fit to the 1993 data, fixing period, amplitude and γ-velocity to the preliminary values of DJW, leaving only the phase as a free parameter, showed the measurements to lie systematically below the best sine curve. Permitting the γ-velocity also to vary gave an excellent fit and yielded practically the same solution for the phase as the first attempt. While due to the few measurements in 1993 the number of degrees of freedom of the fit is quite small, the constancy of phase in the two fits gives us some confidence that the results of the second attempt are to be preferred. Therefore, we subtracted the independently derived γ-velocity from the 1993 data.

The combined data, homogenized in the manner described, were subjected to an analysis-of-variance (AoV) test (Schwarzenberg-Czerny 1989) and to a discrete power spectrum analysis (Deeming 1975). The interesting frequency range of the power spectrum and the AoV periodogram are shown

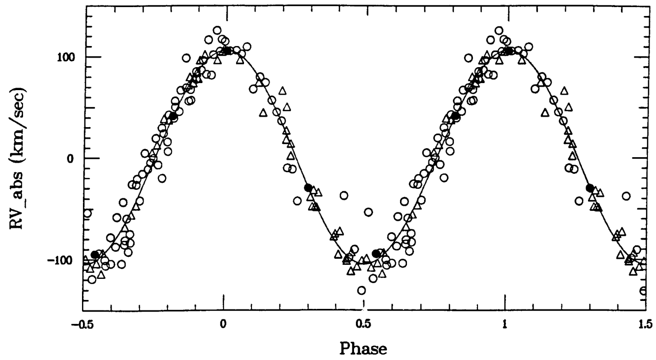

Fig. 3. Radial velocities of the secondary of DX And (after subtraction of the γ-velocity) folded on an orbital period of 0.4405019 days. Open and filled circles refer to the reconstructed data of 1989 and 1993, respectively (see text for details). Triangles indicate RVs taken from DJW.

in the top and bottom frames, respectively, of Fig. 2. As expected, a number of aliases peaks appear. Although in particular in the AoV periodogram they form a clear pattern, suggesting the central, highest peak to correspond to the true orbital period of DX And, this choice is not unambiguous. Therefore, we will regard the three highest peaks in the AoV periodogram here. In order to refine the period and to get the zero point phase for the RV curves, non-linear sine fits were performed, using the Simplex-algorithm (Caceci & Cacheris 1984), resulting in the following ephemeris E_-, E, and E_+ of the absorption line radial velocities (time of assumed inferior conjunction of the secondary):

$$E_-: \quad \mathrm{HJD} = \underset{\pm 14}{2447800.2825} + \underset{\pm 21}{0.4409918} \times \mathrm{E}$$

$$E: \quad \mathrm{HJD} = \underset{\pm 13}{2447800.2935} + \underset{\pm 19}{0.4405019} \times \mathrm{E}$$

$$E_+: \quad \mathrm{HJD} = \underset{\pm 15}{2447800.3050} + \underset{\pm 21}{0.4400113} \times \mathrm{E}$$

Here, the errors are formal errors provided by the fit routine. The χ^2-value for the ephemeris E_- and E_+ are 22% and 30% larger than for E, respectively. The period of E_+ differs by almost 3σ from DJW's period. While the period of E_- is quite close to that found from the 1989 data alone (0.44107 days) and only 1σ away from the best period of DJW, it is statistically inferior to E. However, this is only true as long as the four 1993 data points are considered. If they are disregarded the periods of the three ephemeris remain the same within the formal errors, but the alias pattern in Fig. 2 changes in such a way that the peak corresponding to E_- is the highest one.

In Fig. 3 the radial velocity curve of the secondary, folded on E, is shown. Measurements from different epochs are distinguished by different symbols. The two outliers close to phase 0.5 correspond to spectra with a relatively low S/N-ratio.

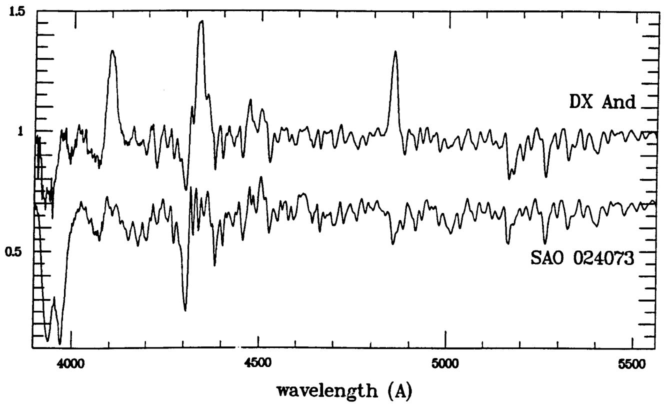

Fig. 4. Mean absorption line spectrum of DX And in 1989 compared to the spectrum of the K0 V standard star SAO 024073.

5. The secondary spectrum of DX And

Mean absorption line spectra of the secondary of DX And were constructed by shifting the individual spectra to a common rest frame (Figs. 4 and 5, together with the spectra of the K0 V spectral type standards SAO 024073 and HD 124752, both shifted downwards for clarity). It is obvious – in particular from the higher resolution data of 1993 – that the spectral type of the secondary of DX And is very similar to that of the standard stars. DJW classify it as K1, having, however, no comparison spectra of earlier type.

5.1. Determination of the veiling

DJW determined veiling factors, defined as the fractional contribution of the primary to the total light, by calculating χ^2-values for the difference between DX And and a suitably scaled comparison spectrum. They could only conclude that the veiling factor must be between 0 and 0.3. We adopted the same method to determine the veiling factor (with very slight differences). Four spectral regions were selected, centred on the wavelengths 4690 Å, 5210 Å, 5690 Å and 6220 Å. The veiling factor, shown as a function of wavelength in Fig. 6, drops smoothly from short to long wavelengths as expected. In the short wavelength range, where measurements from 1989 and 1993 are available, results from both epochs are the same to within 10%. Due to the intricate way to determine the veiling factor it is difficult to assign formal errors. However, the smooth wavelength dependence suggests that they are not significantly larger than the residua between the measured points and the formal linear least squares fit which is shown as a solid line in Fig. 6. Within the covered wavelength range the spectrum of a K0 V star is essentially flat (see e.g. Straižys & Sviderskienė 1972). Thus, the wavelength dependence of the veiling factor reflects directly the spectrum of the primary.

For illustrative purposes only, we have calculated the veiling factor which a steady state accretion disk would cause. Following Tylenda (1981) and Hessman (1985), we model the accretion disk as a uniform LTE slab. The fixed system and disk parameters used are: 45° inclination; a white dwarf mass of 0.8 $M_\odot$ with a corresponding inner disk radius; an outer disk radius of 10^{11} cm; and a value of the viscosity parameter α of 0.1. The mass-accretion rate was then varied until a reasonable agreement between the model and the observed values was obtained for a value of $4 \cdot 10^{-11}$ $M_\odot$/year. The result is shown as a dashed line in Fig. 6.

A further increase of the veiling factor towards short wavelengths where a quantitative determination is inhibited by a low S/N-ratio is indicated by the reduced strength of the Ca II

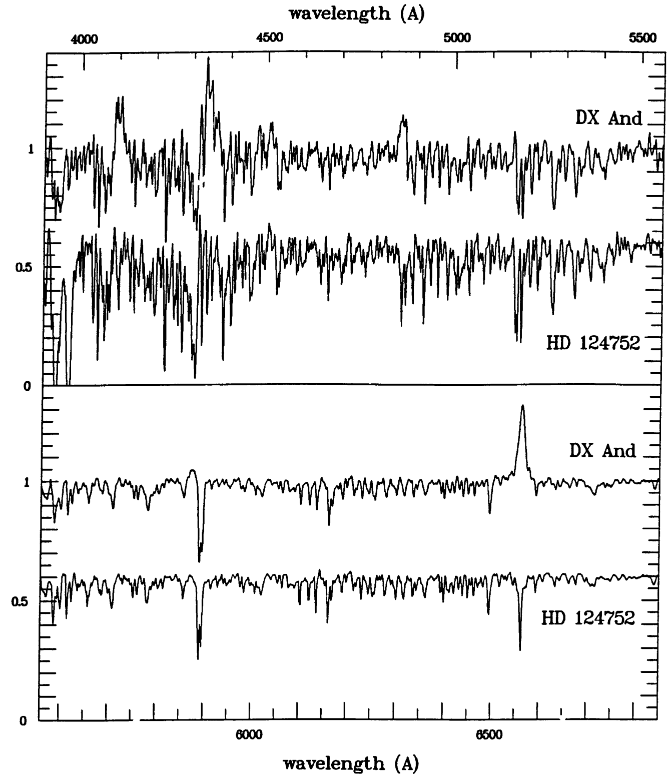

Fig. 5. Mean absorption line spectrum of DX And in 1993 compared to the K0 V standard star HD 124752 in the blue-green (top) and yellow-red (bottom) range.

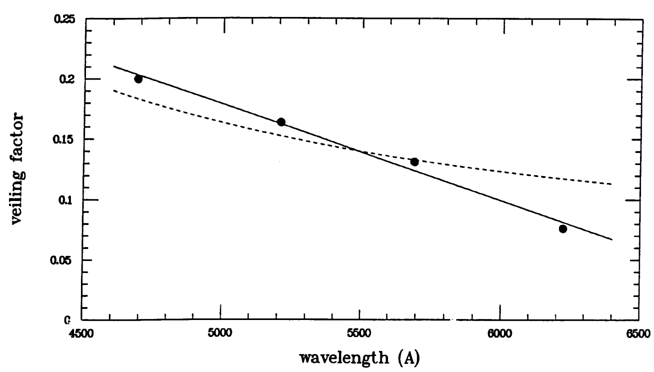

Fig. 6. The veiling factor as a function of wavelength (dots) together with a linear least squares fit (solid line) and veiling factor expected to be caused by a standard steady state accretion disk (broken line; included for illustrative purposes only!).

3934 Å absorption compared to the standard stars (see Figs. 4 and 5). Ca II 3968 Å is apparently filled in by Hϵ emission.

5.2. The absorption line spectrum

On close inspection, DJW found some lines in DX And which appear to be enhanced in comparison to those in their K1 spectral type standards. Our 1993 spectra have a considerably higher resolution than the 1989 data, making it easier to detect subtle spectral differences, and encompass a much wider spectral range. Three regions largely free from emission lines were selected: 5050-5550 Å (masking the Mg I b lines which are also contaminated by Fe II 5170 Å emission), 5580-5850 Å and 5955-6535 Å. In Fig. 7, the ratio between DX And and the HD 124752, suitably scaled assuming a wavelength dependent veiling factor as derived above is shown. Gradual variations due to residual normalization uncertainties were removed through division of the ratio by a suitable spline fit. The broken lines indicate the $\pm 3\sigma$ level per resolution element of two pixels. Because of the intricacies of the previous data reduction they should be regarded as guidelines rather than rigorous error limits. The dotted lines may be regarded as a firm lower limit of the errors: They were derived from the ratio of two individual spectra of the bright standard star HD 124752, treated in the same way as the DX And / HD 124752 ratio. Vertical bars indicate the enhanced absorptions found by DJW (dashed, if not significant in our spectra) and other lines discussed below. They are listed along with their tentative identification in Table 1.

DJW attribute enhanced absorption at 6471.4 Å and 6498.5 Å to Ca I (MP 18; Moore 1945). In our spectra these lines can at most be regarded as marginally enhanced. However, features seen at 6122.2 Å and 6162.2 Å, as well as a broad complex close to 6166-6170 Å could be due to Ca I (multiplets 3 and 20, respectively). MP 21 of Ca I at 5588.8 Å may also be enhanced. Thus, the present data support the evidence for enhanced Ca I absorption.

The strongest enhancement is seen at 5543.7 Å. This is also a strong feature in DJW's spectra. They attribute it fo Fe I. On the other hand, the enhancement of Ti I at 5248.6 Å is only marginally significant in our spectra. DJW identify a line at 5298.3 Å as Cr I (MP 18). The large width of this line in our spectra suggests it to be blended with further, unidentified lines. Other lines may also be due to Cr I: 5204.5 – 5208.4 Å (MP 7), 5702.3 Å (MP 203), 5777.8 Å (MP 257) and 5982 – 5983 Å (MP 185). There is thus evidence that apart from Ca I also Cr I is enhanced in DX And. However, we stress than in view of the remaining uncertainties and the differences between our results and those of DJW neither the enhancements nor the identification can be considered as certain.

It is not easy to assess the significance of the observed line enhancements. One reason might be simply a difference in the spectral types of the DX And secondary and the comparison star. With published spectra of stars of similar type we found it difficult to verify or reject this hypothesis. To do so would require spectra of similar resolution and quality. However, the significant enhancement of the 5208 Å line in the spectrum of Gl 886 as compared to Gl 166A (see the lower frame of Fig. 8 of DJW), both of type K1 V, indicates that such differences of line strengths can occur in stars of the same temperature and luminosity class. Further reasons for the spectral anomalies have been discussed by DJW: their arguments will not be repeated here.

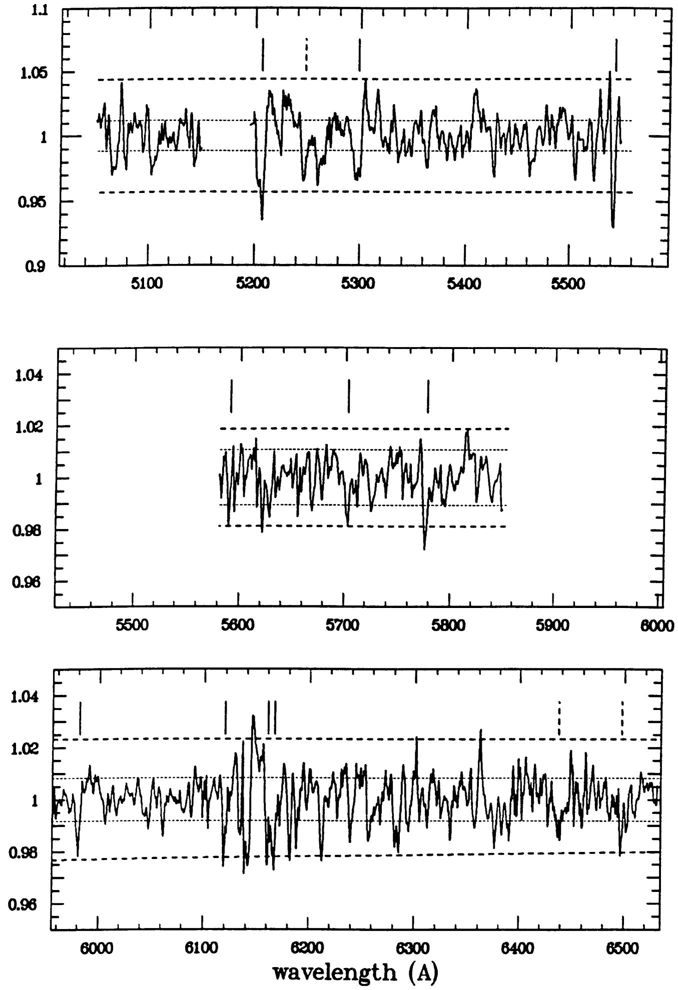

Fig. 7. Ratio of the spectra of DX And and the K0 V standard HD 124752. Spectral lines considered to be significantly enhanced in DX And and discussed in the text are marked by vertical bars.

Table 1. Spectral lines enhanced in DX And

Line	Multiplet	Line	Multiplet
Ca I 5588.8	21	Cr I 5205-08	7
Ca I 6122.2	3	Cr I 5298.3	18
Ca I 6162.2	3	Cr I 5702.3	204
Ca I 6166-70	20	Cr I 5777.8	257
Fe I 5573.7		Cr I 5982-83	185

6. Summary

We have presented time resolved spectroscopy of the blue-green region of the long-period dwarf nova DX And obtained in October 1989, supplemented by a few spectra covering a larger spectral range obtained in June-July 1993. Although the 1989 observations were plagued with serious wavelength calibration problems, is was possible to reconstruct the radial velocity amplitudes and phase shifts well enough to confirm the orbital period and mass-ratio found by Drew et al. (1993). Using their data together with ours, the total time base of almost four years permit a significant refinement of the period and the determination of a plausible long-term ephemeris.

The veiling factor, i.e. the fractional contribution of the primary to the total light could be determined as a function of wavelength. It drops from $\approx$ 19% at Hβ to $\approx$ 5% at Hα. In addition to enhanced Ca I absorption features found by Drew et al. (1993), the larger spectral range and resolution of our 1993 observations resulted in the detection of further spectral lines which appear to be enhanced compared to standard stars of similar spectral type, e.g. several lines of Cr I.

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