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Spectroscopy and orbital periods of the old novae V533 Herculis, V446 Herculis and X Serpentis

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ABSTRACT
We report spectroscopic orbital periods of 0.147 d (= 3.53 h) for V533 Her, 0.207 d (= 4.97 h) for V446 Her and 1.478 d for X Ser. V533 Her (Nova Herculis 1963) shows absorption features in its He I and Balmer lines which appear only in a limited range of orbital phase, suggesting that it is a low-inclination SW Sextantis star. V446 Her is unusual in that it has started normal dwarf nova eruptions after a nova outburst, but we find nothing else unusual about it – in particular, a distance estimate based on its dwarf nova outbursts agrees nicely with another based on the rate of decline of its nova eruption, both giving $d \sim 1$ kpc. In X Ser, unlike in other old novae with long periods, no spectral features of the secondary star are visible. This and its outburst magnitude both suggest that it is quite distant and luminous, and at least 1 kpc from the Galactic plane.

Key words: binaries: close – stars: fundamental parameters – stars: individual: V446 Her – stars: individual: V533 Her – stars: individual: X Ser – novae, cataclysmic variables.

1 INTRODUCTION

Classical novae arise when hydrogen-rich material accreted on to the surface of a white dwarf ignites under degenerate conditions (Starrfield, Sparks & Truran 1976). The material that ignites generally comes from a close binary companion. When the companion is a main-sequence star, or at least a star that has not evolved very far from the main sequence, the system is called a cataclysmic variable, or CV (Warner 1995). The binary nature of novae is not obviously manifested in their outbursts; studies of old novae by (notably) Kraft (1964) have revealed that they are essentially all close binaries.

This paper presents observations of three old novae, which prove to have have arisen in three quite different underlying binaries. V446 Her is one of only two novae that have become dwarf novae (Honeycutt et al. 1998, hereafter HRTH98). It proves to have an orbital period $P_{\rm orb}$ quite typical of dwarf novae. V533 Her has become a luminous 'nova-like variable'. We derive a secure $P_{\rm orb}$ for the first time, and find that its spectrum intermittently shows symptoms of SW Sex-type behaviour. Finally, we find an unusually long $P_{\rm orb}$ for X Ser, implying an evolved secondary star.

Section 2 gives technical details of the observations and analysis. Sections 3, 4 and 5 examine V533 Her, V446 Her and X Ser in more detail. Section 6 gives a summary and discussion.

2 TECHNICALITIES

The observations reported here are spectra from MDM Observatory on Kitt Peak, Arizona. Nearly all are from the Hiltner 2.4-m telescope and modular spectrograph. For V446 Her and X Ser, the equipment and procedures were identical to those described by Thorstensen, Taylor & Kemp (1998). The observations of V533 Her are from several observing runs, detailed in Table 1; a smaller CCD was used for the first few runs, resulting in narrower wavelength coverage than for later data, and the 1999 June data were taken with a higher dispersion grating and a detector with smaller pixels. The 1997 September data were taken with the Mark III spectrograph mounted on the MDM 1.3-m McGraw-Hill telescope. We were always careful to maintain an accurate wavelength scale. The flux calibration is somewhat problematic, not just because of the usual problems with slit losses, but also because the modular spectrograph suffers from a poorly understood problem which distorts observed continua. Since the spectra shown here are averages of many, these problems should partially average out. As a rule, fluxes should be accurate to ~30 per cent. Table 2 lists features found in the mean spectra, and the apparent continuum flux at $\lambda = 5500$ Å.

We measured velocities of the Hα emission line using convolution algorithms (Schneider & Young 1980), and searched for periods using a 'residual-gram' method (Thorstensen et al. 1996). When necessary, we used the Monte Carlo test of Thorstensen & Freed (1985) to assess the reliability of choices of cycle count between observations. For various candidate periods we fitted the radial velocities using the function

$$v(t) = \gamma + K \sin\left[\frac{2\pi(t - T_0)}{P}\right].$$

The emission-line velocities probably do not faithfully trace the

Table 1. Observing log for V533 Her.

Run	Nights	Spectra	Range (Å)	Resolution (Å)
1996 July	4	59	4600–6700	3.5
1996 Sept	5	28	4600–6900	2.3
1997 Feb	4	14	4600–6700	5.0
1997 July	4	56	4000–7500	3.5
1997 Sept[a]	4	50	4000–7500	3.5
1998 Jan	2	10	4000–7500	3.5
1998 Mar	3	14	4000–7500	3.5
1999 June	1	25	6025–7250	1.2

[a] The 1997 September data are from the MDM 1.3-m McGraw-Hill telescope and Mark III spectrograph. All others are from the 2.4-m + modular spectrograph.

centre-of-mass motion of either star, so we caution the reader against using K and γ for dynamics. Experience does suggest that P should be a reliable measure of the binary orbital period $P_{\rm orb}$. Table 3 lists the velocity time series for all three stars.

3 V533 HERCULIS

V533 Her is the stellar remnant of Nova Herculis 1963. Patterson (1979) detected coherent photometric oscillations at 63.633 s, but these oscillations have not been detected for some years now. Coherent oscillations suggest the presence of a rotating, magnetized white dwarf (Patterson 1994), making this a DQ Her star (or intermediate polar). V533 Her evidently does not eclipse: Patterson (1979) does not mention finding any eclipses in his time-series photometry, and two of his runs were longer than the orbital period that we find below.

Hutchings (1987) obtained spectra in the blue ($3900 \leqslant \lambda \leqslant 5000$ Å) from 1981 to 1986, measured velocities, and searched for $P_{\rm orb}$. Because of 'non-orbital scatter' in his emission-line velocities, he could not determine $P_{\rm orb}$ uniquely, but found a most likely value of 0.209 7774 d. Although very tentative, this is tabulated (with a colon for caution) in the Ritter & Kolb (1998) catalogue. The lack of a definitive result is unfortunate, since DQ Her stars offer particularly rich possibilities for time-resolved studies, some of which depend on knowing $P_{\rm orb}$ (e.g. Robinson, Shafter & Balachandran 1991; Haswell et al. 1996). We therefore undertook a new search for the orbital period, using the observations listed in Tables 1 and 3.

Fig. 1 shows the averaged spectra from the observing runs with the most extensive data. No offsets are applied to the various spectra. The apparent variations in the continuum strength are probably approximately correct. The V magnitudes implied by the continuum range from ~15.4 in 1996 September to ~14.3 in 1996 July. The spectral features (Table 2) also change strength both in equivalent width and in flux. Curiously, the equivalent widths of the Balmer lines are *greatest* for the brightest state, in contrast to the usual trend of equivalent width with luminosity (Patterson 1984). He II λ4686 is very strong, nearly as strong as Hβ. The emission lines are generally single-peaked, but the Balmer lines show incipient doubling in the line core. In the 1996 July data, Hα has a FWHM of 900 km s^{-1} and a FWZI of nearly 4000 km s^{-1}. The Na D lines appear weakly in absorption, but their equivalent widths are difficult to measure because of blending with He I λ5876. A weak, broad emission feature appears consistently near 5805 Å. We suggest that this is a blend of C IV features at $\lambda\lambda$5801 and 5812 (Meinel, Aveni & Stockton 1975). He I λ5876 can be unmeasurably weak, possibly as a consequence of the phase-dependent absorption (see below).

3.1 Velocities and ephemeris

We measured radial velocities of the Hα emission in the 1996 July data using a convolution function optimized for a 26 Å FWHM Gaussian. This essentially gave the velocity of the whole line. The period search (Fig. 2) clearly indicates a frequency near 6.8 cycle d^{-1}, or 0.147 d, quite different from Hutchings' (1987) suggestion. The data from this run span 7.3 h of hour angle, and the Monte Carlo test confirms that the daily cycle count is unambiguously determined. The same periodicity appears in velocities from all subsequent observing runs for which sufficient data were collected.

With the rough period established, we re-analysed Hutchings' (1987) published velocities. His data had been recorded both photographically (1981–82) and with digital detectors (1984 onward). We separated his data into short segments, evidently from individual observing runs, and searched these for modulation at the binary period. His 1986 data (two observing runs) did show modulation at our period, but the previous runs did not. We have no ready explanation for this.

In an attempt to derive a precise ephemeris, we combined all of our better data and the data from Hutchings' 1986 runs into a single time series. The lower panel of Fig. 2 shows a search of this time series in the vicinity of the orbital period. There are two sets of allowed periods, one near 0.1469 d and the other near 0.1474 d; these differ by 1/44 cycle d^{-1}. Because of their time sampling, the present data unfortunately do not discriminate between frequencies spaced by this amount. There is also some ambiguity in the choice of cycle count between the present velocities and Hutchings' observations 10 years earlier. The allowed periods can be expressed succinctly as

$$P = \frac{4075.342 \pm 0.008}{27653 \pm 1}\ \mathrm{d}$$

or

$$P = \frac{4060.051 \pm 0.008}{27641 \pm 1}\ \mathrm{d},$$

with the central value in each family heavily favoured. Fig. 3 shows all the velocities (including those from Hutchings' 1986 runs) folded on the best-fitting period, and Table 4 gives parameters of the two best sinusoidal fits.

3.2 Behaviour of the emission lines with phase

The orbital period is determined well enough to phase together spectra from the same observing run. Accordingly, we rectified the spectra and synthesized a single-trailed representation using procedures described by Taylor, Thorstensen & Patterson (1999). Fig. 4 shows this version of the 1996 July spectra. Note the phase-dependent absorption, which is especially noticeable in He I λ5876. A similar feature is visible in the cores of the Balmer lines. This behaviour is strongly reminiscent of the SW Sex phenomenon (Thorstensen et al. 1991; Dhillon 1996; Hellier 1996; Taylor et al. 1999). The Balmer lines also show faint wings which move markedly with orbital phase. The wings are not obvious in the individual spectrograms, but from the trailed representation we estimate their full width at zero intensity (FWZI) to be ~2200 km s^{-1} and the apparent velocity amplitude K to be ~800 km s^{-1}. Similar features are seen in LS Peg (Taylor et al. 1999) and V795 Her (Haswell et al. 1994; Casares et al. 1996). The wings are clearest in 1996 July, when the source was

Table 2. Spectral features.

Feature	EW (Å)	Flux ($\mathrm{erg\,cm^{-2}\,s^{-1}}$)
V533 Her (1996 July)		
$f_{\lambda 5500}$		7.2×10^{-15} Å^{-1}
$\lambda4640$	4.4	$5.\times10^{-14}$
He II $\lambda4686$	8.1	9×10^{-14}
Hβ	12.7	1.2×10^{-13}
He I $\lambda4921$	1.9	1.9×10^{-14}
He I $\lambda5015$	1.8	1.6×10^{-14}
He II $\lambda5411$	0.4:	$3.4:\times10^{-15}$
$\lambda5806$	1.4	8.5×10^{-15}
He I $\lambda5876$	2.2:	$1.3:\times10^{-14}$
Na D	−0.7	…
Hα	24.	1.2×10^{-13}
V533 Her (1996 Sep)		
$f_{\lambda 5500}$		2.7×10^{-15} Å^{-1}
$\lambda4640$	4.2	1.5×10^{-14}
He II $\lambda4686$	3.5	1.3×10^{-14}
Hβ	8.0	2.7×10^{-14}
He I $\lambda4921$	1.5	5×10^{-15}
He I $\lambda5015$	1.1:	4×10^{-15}
He II $\lambda5411$	0.4:	$1:\times10^{-15}$
$\lambda5806$	1.5	3.7×10^{-15}
He I $\lambda5876$	0.8:	$1.9:\times10^{-15}$
Na D	−0.5:	…
Hα	18.	3.6×10^{-14}
He I $\lambda6678$	2.3	4.4×10^{-15}
V533 Her (1997 July)		
$f_{\lambda 5500}$		4.1×10^{-15} Å^{-1}
Hγ	3.1	2.2×10^{-14}
$\lambda4640$	2.8	1.7×10^{-14}
He II $\lambda4686$	4.4	2.6×10^{-14}
H β	4.4	2.6×10^{-14}
He I $\lambda4921$	0.9	4.5×10^{-15}
He I $\lambda5015$	0.6:	$3.1:\times10^{-15}$
He II $\lambda5411$	0.4	2×10^{-15}
$\lambda5806$	1.3	4.5×10^{-15}
He I $\lambda5876$	…	…
Na D	−0.7:	…
Hα	10.	2.7×10^{-14}
He I $\lambda6678$	1.5	$3.7:\times10^{-15}$
V533 Her (1997 Sept)		
$f_{\lambda 5500}$		4.0×10^{-15} Å^{-1}
$\lambda4640$	3.2	1.7×10^{-14}
He II $\lambda4686$	4.5	2.8×10^{-14}
Hβ	4.9	2.4×10^{-14}
He I $\lambda4921$	0.8	3.8×10^{-15}
He I $\lambda5015$	0.6:	$2.9:\times10^{-15}$
$\lambda5806$	1.3	4.6×10^{-15}
He I $\lambda5876$	…	…
Na D	−0.8:	…
Hα	12.7	3.2×10^{-14}
He I $\lambda6678$	1.5	$3.6:\times10^{-15}$
V533 Her (1998 March)		
$f_{\lambda 5500}$		5.8×10^{-15} Å^{-1}
Hγ	2.9	2.5×10^{-14}
$\lambda4640$	3.2	2.4×10^{-14}
He II $\lambda4686$	4.5	3.4×10^{-14}
Hβ	4.8	3.5×10^{-14}
He I $\lambda4921$	1.0	7.3×10^{-15}
He I $\lambda5015$	0.5:	$3.2:\times10^{-15}$
He II $\lambda5411$	0.4:	$2.3:\times10^{-15}$
$\lambda5806$	1.3	6.5×10^{-15}
He I $\lambda5876$	…	…
Na D	−0.5:	…
Hα	11.	4.5×10^{-14}
He I $\lambda6678$	1.5	$5.5:\times10^{-15}$
V446 Her		
$f_{\lambda 5500}$		3.7×10^{-16} Å^{-1}
Hγ	15:	$7:\times10^{-15}$
He I $\lambda4471$	5:	$2.5:\times10^{-15}$
He II $\lambda4686$	13:	$5:\times10^{-15}$
Hβ	20	8×10^{-15}
He I $\lambda4921$	4:	1.6×10^{-15}
He I $\lambda5015$	5:	1.9×10^{-15}
Fe I $\lambda5169$	1:	$4:\times10^{-16}$
He I $\lambda5876$	4	1.5×10^{-15}
Na D blend	−0.8:	…
Hα	30	9.2×10^{-15}
He I $\lambda6678$	4.5	1.4×10^{-15}
X Ser (1997 July)		
$f_{\lambda 5500}$		3.6×10^{-16} Å^{-1}
Hγ	7.5	3.1×10^{-15}
He II $\lambda4686$	4.3	1.7×10^{-15}
Hβ	11.9	4.5×10^{-15}
He I $\lambda4921$	2.3	8×10^{-16}
He I $\lambda5015$	2.1	8×10^{-16}
He I $\lambda5876$	4.5	1.5×10^{-15}
Na D	−0.8	…
Hα	26	8.6×10^{-15}
He I $\lambda6678$	4.3	1.4×10^{-15}
He I $\lambda7067$	3.5	1.1×10^{-15}
X Ser (1999 June)		
$f_{\lambda 5500}$		8.5×10^{-16} Å^{-1}
He II $\lambda4686$	3.8	3.7×10^{-15}
Hβ	5.8	5.4×10^{-15}
He I $\lambda4921$	0.8	7×10^{-16}
He I $\lambda5015$	0.8	7×10^{-16}
He I $\lambda5876$	2.2	1.7×10^{-15}
Na D	−0.7	…
Hα	19	1.3×10^{-14}
He I $\lambda6678$	3.2	2.1×10^{-15}
He I $\lambda7067$	1.7	$1.\times10^{-15}$

brightest. The appearance of such wings may therefore correlate with luminosity.

The resemblance to SW Sex stars raises the question: Does the phase of this absorption match that observed in SW Sex stars? The answer is somewhat complicated by the lack of an eclipse. In 'classic' SW Sex stars, the binary phase $\phi_{\rm bin}$ can be determined accurately from eclipses, and the phase-dependent absorption occurs around $\phi_{\rm bin}=0.5$, where $\phi_{\rm bin}=0$ is eclipse centre. The velocities of the Balmer lines in these stars lag the eclipse in phase, that is, the red-to-blue crossing of the Balmer lines (at which an eclipse would be expected if the Balmer lines traced the white dwarf motion) occurs around $\phi_{\rm bin}=0.2$. The phase in Fig. 4 is $\phi_{\rm spec}$ derived from the sinusoidal fit, for which $\phi_{\rm spec}=0$ occurs at the *blue-to-red* crossing of the velocities. Assuming for the moment that the velocity phases lag by 0.2, we find

$$\phi_{\rm bin}=\phi_{\rm spec}+0.7.$$

The absorption in Fig. 4 is maximum around $\phi_{\rm spec}=0.75$, which with our assumption corresponds to $\phi_{\rm bin}=1.45=0.45$. This is consistent with the $\phi_{\rm bin}\approx0.5$ expected. Furthermore, the detailed appearance of the absorption in the trailed spectrogram – starting redward, moving blueward and strengthening, then moving redward and weakening – strikingly resembles the appearance in PX And and LS Peg (Taylor et al. 1999). We conclude that *V533 Her is an SW Sextantis star*, albeit one for which the inclination is low enough to avoid eclipses.

Table 3. Hα radial velocities. Times are given as heliocentric Julian date of mid-integration minus 2450000. Velocities are heliocentric.

t (HJD)	*v* (km s^{-1})	*t* (HJD)	*v* (km s^{-1})	*t* (HJD)	*v* (km s^{-1})	*t* (HJD)	*v* (km s^{-1})	*t* (HJD)	*v* (km s^{-1})
				V533 Herculis:					
266.752	10	270.846	34	624.872	−125	632.920	−17	845.029	−70
266.804	−6	270.852	−55	625.913	−132	709.613	−196	845.036	−59
266.810	−18	270.940	81	625.919	−123	709.622	−96	845.044	−155
266.816	−21	270.945	131	625.925	−89	709.629	−5	845.051	−109
266.821	17	270.957	119	625.931	−43	709.637	−96	847.025	−57
266.827	9	272.841	72	625.938	−55	709.648	21	847.032	−34
269.655	113	272.846	−41	625.945	55	709.656	−13	847.040	20
269.661	100	353.740	−87	625.952	−50	709.664	−60	847.048	6
269.667	104	353.746	−26	625.958	−62	711.613	76	847.055	4
269.672	55	353.752	−44	625.964	−61	711.622	31	893.984	−75
269.678	13	355.598	46	626.831	26	711.631	68	893.990	−95
269.726	83	355.604	12	626.837	10	711.639	−13	893.996	−71
269.732	−15	355.610	13	626.843	10	711.647	−20	894.002	−55
269.737	−64	358.591	−38	626.850	−2	711.658	76	894.009	−61
269.743	60	358.597	−35	626.856	24	711.666	−57	894.015	−59
269.749	11	359.590	−54	626.862	32	711.674	−114	894.024	−14
269.804	118	359.596	−61	626.870	29	711.683	−169	894.030	−15
269.810	108	359.691	22	626.877	8	711.691	−156	895.984	−10
269.816	76	359.697	9	626.883	−4	711.701	−159	895.991	45
269.822	36	359.720	−65	626.889	15	711.710	−51	896.965	−74
269.827	−9	359.726	−34	626.895	−72	711.718	−42	896.971	−41
269.835	−114	359.732	−113	626.901	−103	711.726	29	896.977	35
269.840	−188	359.738	−119	626.909	−126	712.640	22	896.984	23
269.846	−169	359.744	−81	626.915	−110	712.648	54	1330.689	19
269.852	−188	359.750	−145	626.921	−100	712.657	17	1330.697	34
269.858	−221	360.664	77	626.928	−201	712.665	43	1330.704	27
269.916	87	360.670	38	626.934	−133	712.673	1	1330.712	54
269.924	197	360.676	33	626.940	−113	712.684	−69	1330.719	71
269.930	235	360.682	52	626.948	−218	712.692	−166	1330.728	63
269.935	177	360.689	108	626.954	−148	712.702	−159	1330.735	82
269.940	169	360.697	86	626.960	−114	712.712	−79	1330.743	55
270.664	148	360.703	123	626.966	−66	712.722	−156	1330.750	61
270.685	88	360.709	134	626.972	−12	712.731	−119	1330.758	82
270.694	148	360.715	152	632.838	−125	712.740	−102	1330.767	63
270.701	126	360.721	151	632.842	−116	712.751	−41	1330.775	24
270.706	109	495.050	38	632.847	−114	713.641	87	1330.782	−2
270.712	−7	498.038	9	632.851	−118	713.649	56	1330.790	−8
270.718	−42	498.046	−4	632.855	−75	713.657	57	1330.797	−30
270.727	−104	499.989	18	632.859	−99	713.665	32	1330.806	−30
270.735	−145	499.996	−5	632.863	−44	713.674	23	1330.813	0
270.742	−148	500.003	−102	632.867	61	713.684	−7	1330.821	−14
270.749	−108	500.011	−173	632.873	77	713.693	94	1330.828	−3
270.775	−49	500.018	−188	632.877	10	713.701	−69	1330.836	18
270.784	29	500.025	−185	632.881	−24	713.709	−138	1330.844	35
270.791	78	500.035	−151	632.885	27	713.729	−47	1330.852	49
270.796	111	500.042	−129	632.889	−24	713.737	−53	1330.859	71
270.806	171	500.049	−156	632.893	−12	713.745	−36	1330.867	69
270.813	191	501.044	45	632.897	−35	713.754	3	1330.874	97
270.820	129	501.051	−38	632.901	14	713.762	−6		
270.829	111	624.853	−113	632.908	−9	713.772	−29		
270.835	46	624.859	−120	632.912	17	713.781	64		
270.840	10	624.866	−146	632.916	7	845.021	−70		
				V446 Herculis:					
626.721	−5	628.692	−80	628.919	−133	629.801	−35	630.898	40
626.727	105	628.699	−119	628.925	−130	629.809	−34	630.913	3
626.733	99	628.705	−137	628.932	−124	629.816	33	632.799	−7
626.739	46	628.711	−107	628.938	−120	629.824	60	632.807	29
628.660	87	628.717	−63	628.944	−126	629.867	91	632.815	−60
628.666	−80	628.725	−141	628.952	−29	629.874	59	632.822	−85
628.672	12	628.731	−165	628.958	−81	629.882	72		
628.678	−51	628.738	−148	628.964	−14	629.952	−152		
628.685	−165	628.744	−60	628.970	−81	629.960	−157		
				X Serpentis:					
624.825	−11	625.859	−16	626.822	−80	630.674	−43	1338.894	−50
624.831	−10	625.865	−33	627.659	−13	630.681	−12	1339.656	−39

Table 3 – *continued*

t (HJD)	*v* (km s^{-1})	*t* (HJD)	*v* (km s^{-1})	*t* (HJD)	*v* (km s^{-1})	*t* (HJD)	*v* (km s^{-1})	*t* (HJD)	*v* (km s^{-1})
624.838	−16	625.873	−29	627.671	−24	630.689	−16	1339.660	−43
624.844	−33	625.880	−14	627.877	−26	630.697	−16	1339.890	−88
625.660	−84	625.886	−27	627.884	−50	631.748	−11	1339.894	−75
625.666	−84	625.892	−13	627.890	−21	631.756	−32	1340.730	2
625.672	−86	625.898	−5	628.755	−86	631.763	2	1340.837	−9
625.678	−77	625.904	1	628.761	−57	631.848	−26	1341.649	−94
625.726	−77	626.680	−78	628.767	−73	631.856	5	1341.901	−48
625.732	−53	626.686	−50	628.866	−24	631.863	−41	1341.907	−51
625.738	−38	626.692	−55	628.872	−49	632.661	−94	1342.869	−94
625.744	−36	626.750	−90	628.878	1	632.668	−65	1342.876	−82
625.750	−35	626.756	−94	629.695	−105	632.676	−68		
625.832	−34	626.762	−82	629.708	−124	632.683	−91		
625.846	−27	626.810	−80	629.714	−107	1338.656	−98		
625.853	−26	626.816	−73	629.721	−118	1338.662	−78		

4 V446 HERCULIS

As noted earlier, classical novae evidently arise from nuclear ignition of material accreted on to the surface of a white dwarf in a close binary system, while the outbursts of dwarf novae, which are generally smaller in amplitude and more frequent than classical nova outbursts, are explained by a disc instability model (e.g. Cannizzo 1993 and references therein). Hardly any systems have shown both types of outburst; GK Per, an unusual magnetic system in a 2-d binary orbit, has been the only generally accepted example (HRTH98).[1] However, Honeycutt, Robertson & Turner (1995, hereafter HRT95) found outburst-like behaviour in V446 Her (= Nova Herculis 1960). The amplitude of these outbursts seemed too small for a normal dwarf nova, so HRT95 sought other explanations. Then HRTH98 used improved images to show that V446 Her is in an optical triple, in which the other two stars contribute most of the light when V446 Her is faint. The true outburst amplitude is therefore larger than HRT95 had thought, and V446 Her takes its rightful place as a classical nova that has developed into a dwarf nova. Because classical/dwarf nova systems are so rare, and the other case (GK Per) is so unusual, we took spectra of V446 Her to find its binary period and search for any anomaly that might explain its behaviour.

Fig. 5 gives the mean flux-calibrated spectrum. The flux level implies that $V \sim 17.6$. In HRTH98's corrected light curve, the minimum is $V \sim 18.0$ to 18.2, so the star may have been a bit brighter than minimum light. The emission lines (Table 2) are a little weaker than in some dwarf novae, again suggesting that the star was a little brighter than minimum light, but otherwise the spectrum is not unusual. He II λ4686 is not anomalously strong, so the excitation is not unusually high; He I lines are easily detected, so it is not unusually low. The simultaneous presence of hydrogen and helium, and the detection of a weak iron feature near λ5167 (Taylor & Thorstensen 1996), suggests that the chemical composition is fairly normal.

We measured 42 Hα radial velocities using a double-Gaussian convolution function with a separation of 32 Å. The mean profile of Hα has a FWHM of 26 Å, so this emphasized the steep wings of the line profile. Fig. 6 shows a period search of these velocities, which indicates a strong candidate periodicity just below 5 cycle d^{-1}, flanked by daily cycle-count aliases. The Monte Carlo test confirms that the alias choice is unambiguous, and the sinusoidal fit (Fig. 7 and Table 4) gives a period of 0.2070 d = 4.97 h.

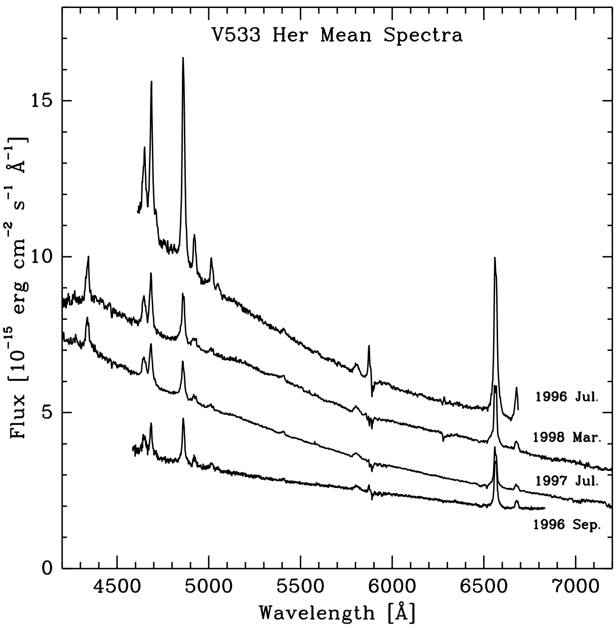

Figure 1. Spectra of V533 Her from four different observing runs. No offsets or scalings have been applied. The mean spectrum from 1997 September is omitted, as it closely resembles that from 1997 July.

The absolute magnitudes of classical novae can be estimated from the maximum magnitude versus rate of decline relation (hereafter MMRD: Warner 1995, ch. 5). Also, Warner (1987) derived a tight relationship between the inclination-adjusted absolute magnitudes of dwarf novae in outburst and their orbital periods. Because V446 Her spans both classes, and has a newly measured orbital period, it is interesting to compare these two estimates; a disagreement might shed light on its odd behaviour. Duerbeck (1987) tabulates V446 Her as a well-observed fast nova, with $m_{pg} = 3$ and a value of t_3 (the time required to fade 3 mag from its maximum light) of 16 d. The work of de Vaucouleurs (1978) gives a calibration of MMRD for photographic magnitudes,

[1] Another possible example, V1017 Sgr (Sekiguchi 1992), is also an unusual system with a long orbital period. However, its dwarf nova outbursts are very long, symmetric and infrequent, its classical nova outburst was not confirmed spectroscopically, and its 5.7-d orbital period is not determined unambiguously.

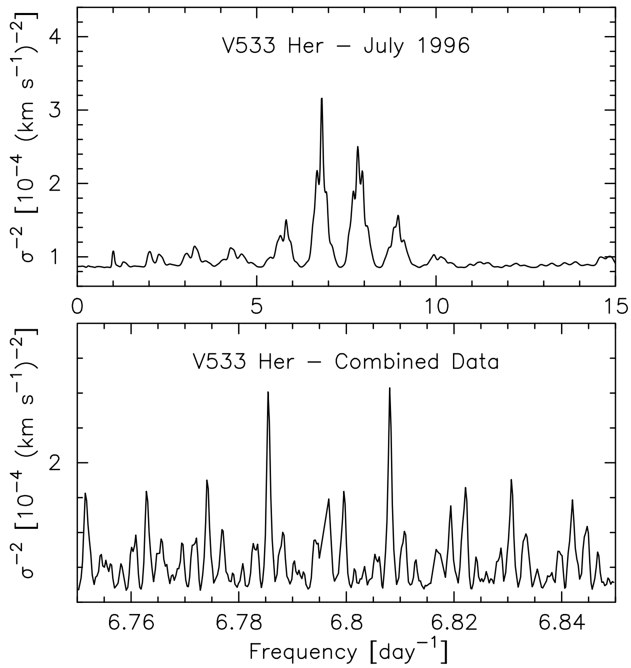

Figure 2. Upper panel: period search of the 1996 July Hα velocities of V533 Her. Lower panel: period search of the combined data set in the vicinity of the orbital period. The full periodogram has fine-scale ringing caused by the 10-yr gap between our velocities and those of Hutchings (1987). The function plotted here is formed by finding the local maxima of the full function and connecting them with straight lines.

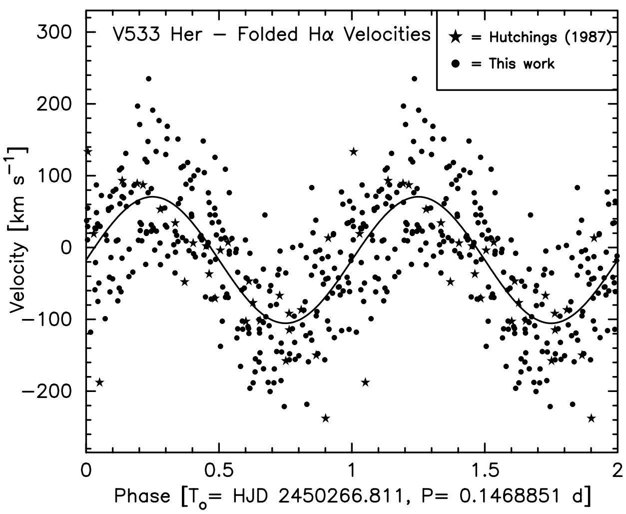

Figure 3. All the velocities of V533 Her folded on the single best-fitting period; the choice of cycle counts between observing runs is not certain (see text). The star symbols are from Hutchings (1987).

which yields $M_{\rm pg} = -8.4$ for V446 Her, giving an uncorrected modulus $m - M = 11.4$. Allowing for 1 mag of extinction in the photographic band (Warner 1995 tabulates $A_V = 0.8$), we find $(m - M)_0 = 10.4$. Warner's (1987) relation for dwarf novae predicts $M_V = 4.5$ at this orbital period, subject to a possibly sizeable inclination correction (the correction is zero for $i = 56°$). The inclination is unknown, but eclipses are unlikely given that HRTH98 do not detect them in extensive observations, and the radial velocity variations suggest that the inclination is not unusually low. In any case, setting the correction to zero and using the observed $V = 15.5$ at maximum dwarf nova outburst (HRTH98) gives $m - M = 11.0$, or $(m - M)_0 = 10.2$. The agreement with $(m - M)_0 = 10.4$ derived from MMRD is excellent; the distance is evidently ~1 kpc, and the object does not appear to violate trends found in other members of its two classes.

The orbital period determined here is similar to those of many other dwarf novae, and also similar to those of other old novae that have not become dwarf novae (Warner 1995; Ritter & Kolb 1998). It is also not particularly surprising, since HRTH98 conclude from their study of the outburst characteristics that the behaviour of V446 Her is consistent with that of an SS Cyg-type system with an orbital period longer than the 2–3 h period 'gap'. The spectrum also appears typical of dwarf novae, not showing any clue to the unusual behaviour of the star. Determination of the orbital period does substantially increase our store of knowledge on this object, but this study only deepens the mystery of the unusual behaviour – aside from behaving strangely, it does not look strange at all.

5 X SERPENTIS

X Serpentis was Nova Serpentis 1903 (Duerbeck 1987). The nova reached $m_{\rm pg} = 8.9$. Duerbeck characterizes it as a 'very slow nova without spectroscopic confirmation during outburst.' Modern spectra have been published by Williams (1983) and Ringwald, Naylor & Mukai (1996).

We obtained 62 usable spectra in 1997 July and 14 in 1999 June. Fig. 8 shows the mean spectra. In the 1997 spectrum, the emission lines are relatively narrow, with a Gaussian fit giving a 9-Å full width at half-maximum (FWHM) for Hα. The continuum flux corresponds to $V \sim 17.6$, and the continuum is fairly nearly flat in F_λ, following roughly $F_\lambda \propto \lambda^{-0.5}$ between Hα and Hβ. The 1999 June spectrum has a brighter ($V \approx 16.7$) and bluer ($F_\lambda \propto \lambda^{-1.1}$) continuum, but a similar line spectrum, save for He II λ4686 which increases somewhat in relative strength. The spectrum obtained by Ringwald et al. (1996) showed the object still brighter ($V = 16.2$) and considerably bluer ($F_\lambda \propto \lambda^{-1.57}$), and with emission equivalent widths roughly half of those seen here (Table 2).

Velocities were measured using the derivative of a Gaussian as the convolution function, optimized for a 10 Å FWHM line. The strongest periodicity in the 1997 July data (Fig. 9) was at 1.468 ± 0.016 d, with a daily cycle-count alias near 0.6 d. We found no convincing features at shorter periods, despite a sampling strategy designed to turn up the short periods more typical of cataclysmic variables. The Monte Carlo test indicates that the 1.47-d period is preferred over the 0.6-d period at the 98 per cent confidence level in the 1997 data.

We obtained the 1999 June spectra to confirm the unexpectedly long period. The new velocities showed periodicity at 1.489 ± 0.017 d, consistent with the fit to the 1997 velocities, and the sinusoidal fit at 1.49 d was dramatically better than at 0.6 d. The 1999 velocities were significantly 'quieter' than the 1997 velocities, and gave well-determined fit parameters. This second detection independently confirmed the existence of a long periodicity, and the good fit removes any significant doubt concerning the choice of the longer period. The weighted average of the periods from the two runs is 1.478 ± 0.012 d. The interval between the two observing runs is too long for us to specify a unique cycle count, but the periods implied by various choices of

Table 4. Sinusoidal fits to velocities.[a]

Star	T_0 (HJD)	P (d)	K (km s^{-1})	γ (km s^{-1})	N	σ (km s^{-1})
V533 Her – Alias 1	245 0266.810(3)	0.146 8851(3)	88(9)	−17(6)	282	64
V533 Her – Alias 2	245 0266.795(3)	0.147 3743(3)	88(9)	−16(6)	282	65
V446 Her – 1997 July	245 0628.976(3)	0.2070(4)	106(10)	−23(7)	42	40
X Ser – 1997 July	245 0627.23(3)	1.468(16)	42(5)	−49(3)	62	19
X Ser – 1999 June	245 1340.42(2)	1.489(17)	46(4)	−47(3)	14	8

[a] Parentheses denote formal 1 standard deviation uncertainties in the last quoted digit. The penultimate column gives the number of fitted points, and the last column gives the uncertainty of a single velocity estimated from the scatter about the best fit.

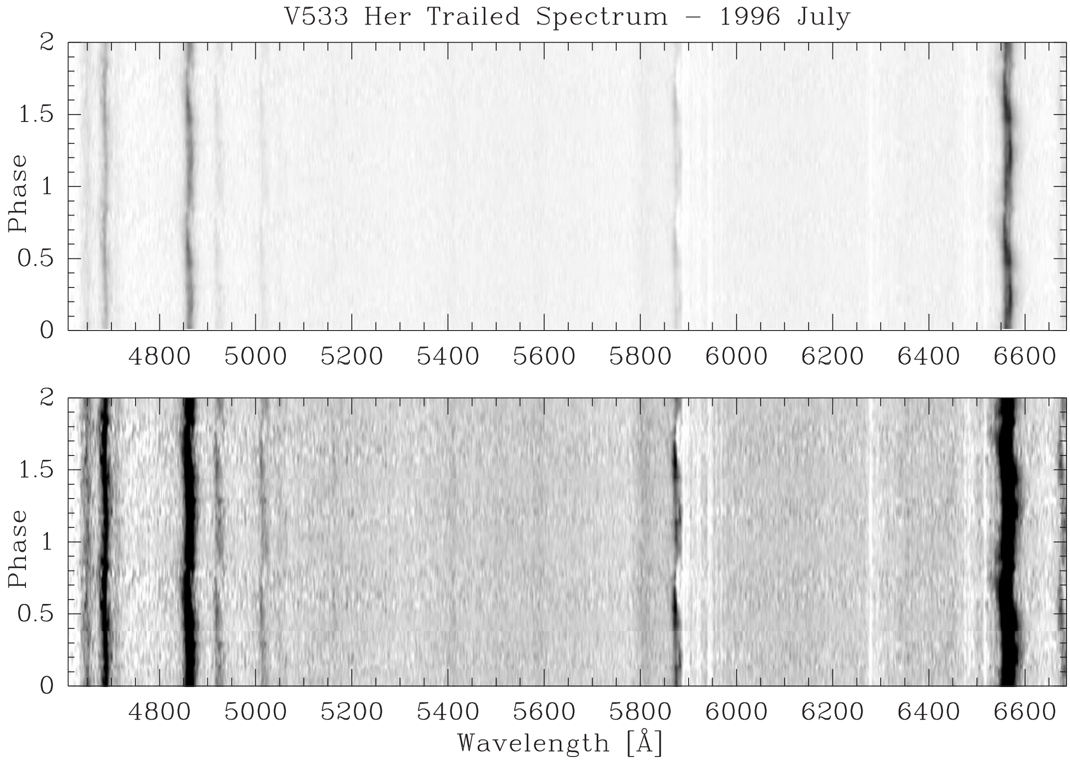

Figure 4. Spectra of V533 Her from 1996 July, rectified and arranged in phase on the binary period and displayed as a single-trailed spectrum. The data are repeated for clarity, and the two panels show different choices of grey-scale to optimize the display of lines of different strength. The grey-scale is inverted (the emission appears dark).

cycle count can be summarized as

$$P = \frac{713.18 \pm 0.04\,\mathrm{d}}{483 \pm 11}.$$

The error on the cycle count gives periods within $\pm 3\sigma$ of the weighted average. Fig. 10 shows all the velocities folded on the period derived from the single best choice of cycle count.

Of the classical novae listed in Ritter & Kolb's (1998) catalogue, only V1017 Sgr and GK Per have longer periods (5.714 and 1.997 d, respectively). It may be interesting that both V1017 Sgr and X Ser declined very slowly from outburst (Duerbeck 1987).

Given the long period, it is puzzling that our spectra do not show any obvious contribution from the photosphere of the secondary. To quantify this, we subtracted scaled spectra of late-type stars from our 1997 July spectrum, and found that at most ~20 per cent of the light at 5500 Å could come from a G- or K-type secondary. There is a hint that the contribution of the secondary may lurk just below this limit. We cross-correlated the $5100 < \lambda < 5800$ Å region with a K-type velocity standard, and found a weak correlation. When we prepared a summed X Ser spectrum which was compensated for orbital motion of 120 km s^{-1} antiphased with the emission lines, the correlation grew a little stronger. Even so, no features attributable to the secondary, save Na D which may be interstellar, could be seen in the spectrum. Because the correlation was barely significant (and no doubt affected by weak telluric features), and because the spectral resolution corresponds to ~ 200 km s^{-1} FWHM, we did not search exhaustively for the best correlation; we mention it because it gave the only evidence for a secondary contribution.

The upper limits on the contribution of the secondary lead to lower limits on the luminosity of the system. At this orbital period a Roche lobe filling secondary should have $R \sim 5\,\mathrm{R}_\odot$, with only weak dependence on the mass ratio and the mass of the primary. Suppose as an illustration that the secondary is of type K5, and that its atmosphere approximates a K5 III. Then its effective

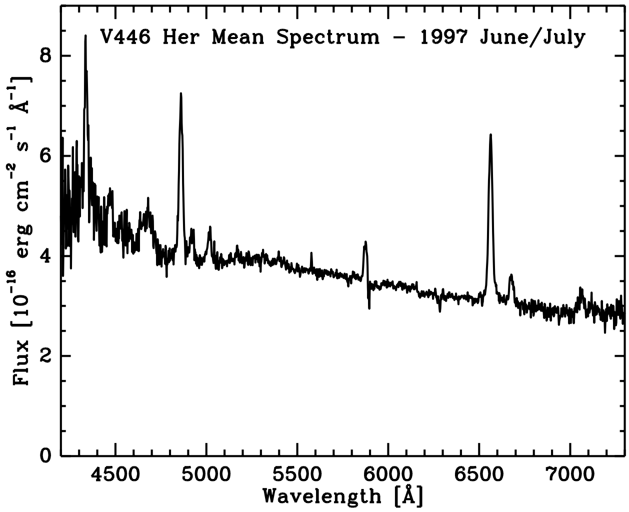

Figure 5. Mean spectrum of V446 Her from 1997 July.

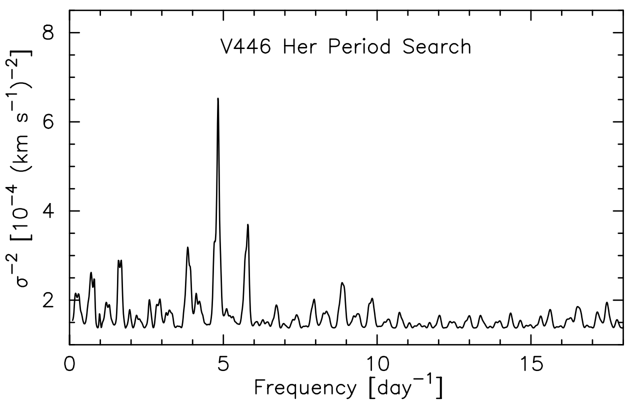

Figure 6. Period search of the V446 Her velocities.

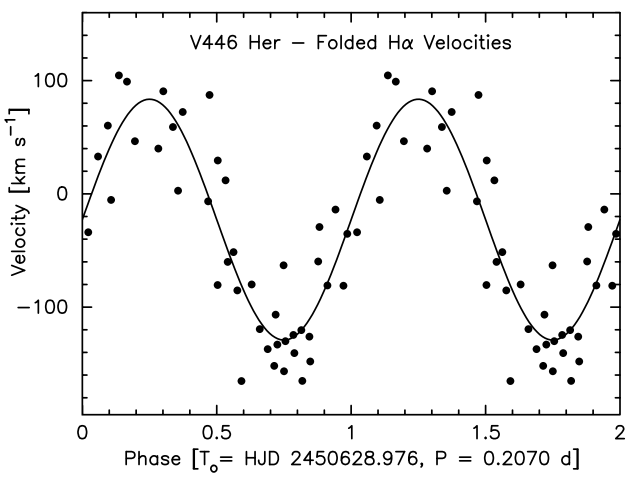

Figure 7. The V446 Her velocities folded on the best period, with the sinusoidal fit superposed.

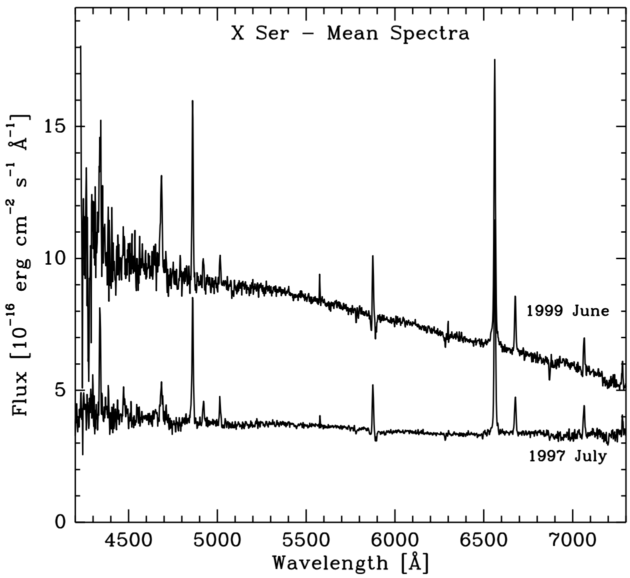

Figure 8. Mean spectra of X Ser obtained in 1999 June (upper trace) and 1997 July (lower trace). No scaling or offsets have been applied.

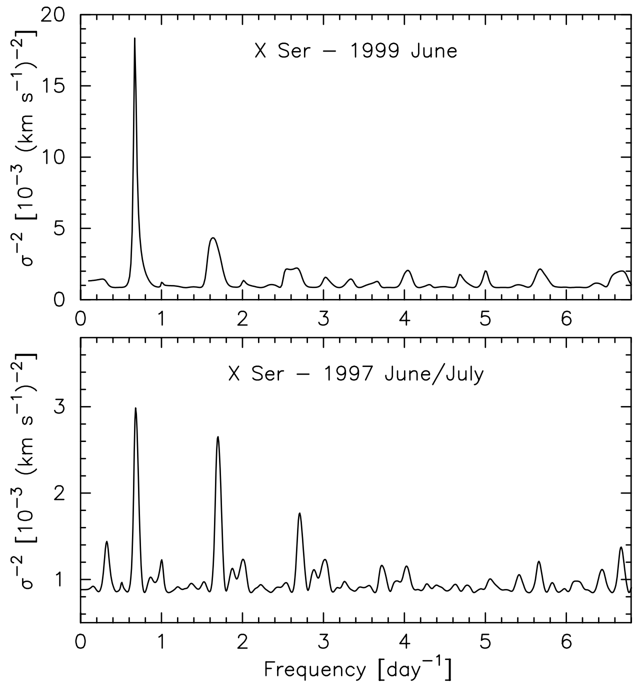

Figure 9. Lower panel: period search of the 1997 July X Ser velocities. Upper panel: period search of the 1999 June X Ser velocities.

temperature would be $\sim$3800 K and its bolometric correction -0.9 (Allen 1973), yielding $M_V = +3.8$. The 20 per cent limit then implies $M_V < +2.1$ for the entire system. Our $V = 17.6$ gives $(m - M) \geqslant 15.5$ for these parameters. The blueness of the observed spectrum and the high Galactic latitude of X Ser (31°.8) argue that the extinction is unlikely to be large; however, the Na D blend strength, if entirely interstellar, suggests that $E(B - V) \sim 0.25$ (Munari & Zwitter 1997) or $A_V \sim 0.8$; we adopt this value to be conservative, and find $(m - M)_0 \geqslant 14.7$. If the secondary were of a cooler type, the limit on absolute magnitude could be somewhat fainter and the system somewhat closer. For comparison, a rough average spectral type for the secondary in GK Per ($P_{\rm orb} = 1.997$ d) is K2 IV (Kraft 1964).

We can also estimate the absolute magnitude from MMRD (de Vaucouleurs 1978). Duerbeck (1987) does not list a value for t_3, but Ringwald et al. (1996) quote 555 d. This is outside the range

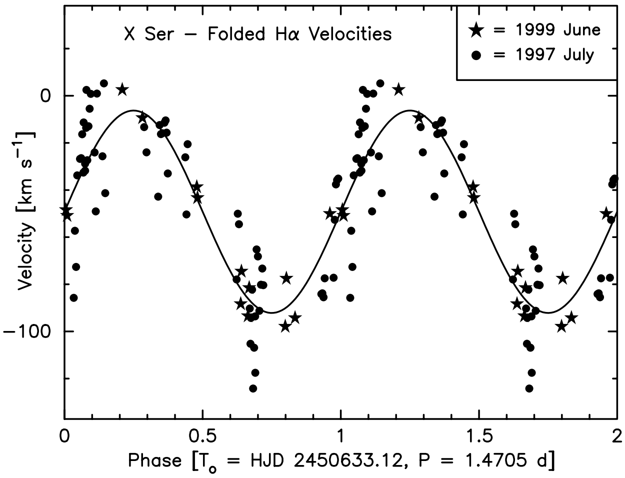

Figure 10. Velocities of X Ser folded on the best-fitting period, with the best-fitting sinusoid superposed. The choice of cycle count between 1997 and 1999 is indeterminate, so the period is not known as accurately as the horizontal axis label would imply.

over which de Vaucouleurs' relation is calibrated, but a blind application gives $M_0(\mathrm{pg}) = -4.7$, which for $m_{\mathrm{pg}} = +8.9$ at maximum (Duerbeck 1987) gives $(m - M) = 13.6$, implying a distance of 3–5 kpc assuming $1 > A_V > 0$.

Both these distance estimates are fairly crude, but they broadly indicate that the distance is ~3 kpc or greater. At 5 kpc, the 1999 June spectrum would imply $M_V \sim +3$. The disc in X Ser therefore appears to have remained luminous, probably substantially brighter than the disc in GK Per, for which Anumpama & Prabhu (1993) estimated $M_V = +4.9$. Furthermore, at this high latitude, the distances estimated here put X Ser over 1 kpc from the Galactic plane.

6 DISCUSSION

At $P_{\mathrm{orb}} = 3.53$ and 4.97 h respectively, V533 Her and V446 Her resemble other systems with similar orbital periods. As Shafter (1992) and others have noted, systems in the 3–4 h range tend to be nova-like variables, while dwarf novae above the 2–3 h 'gap' tend to have $P_{\mathrm{orb}} > 4$ h. The period of V533 Her is nearly equal to those of a number of other SW Sextantis stars – the phenomena were first noticed in nova-likes near 3.5 h. V533 Her is of interest as yet another non-eclipsing (hence not too close to edge-on) system that shows strongly phase-dependent absorption events. Why V446 Her should have returned to dwarf nova status when other old novae of comparable period and greater time since outburst have not remains a mystery.

The long period of X Ser comes as a surprise. The non-detection of a secondary star contribution to the spectrum and the faint apparent magnitude at maximum light both indicate that the distance is likely to be at least several kpc. The quiescent disc remains fairly luminous and the distance from the Galactic plane is apparently at least 1 kpc. Our knowledge of the system would be greatly enhanced by a positive detection of the secondary star, which would require somewhat greater signal-to-noise ratio than available here.

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We acknowledge partial support from the United States NSF (through grant AST-9314787), Joe Patterson for a continuing fruitful collaboration, and the MDM staff for their usual excellent support. This research made use of the Simbad data base operated at CDS, Strasbourg, France.

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