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The orbit of the supergiant component of Vela X-1 derived from *IUE* radial velocities

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ABSTRACT

47 short-wavelength, high-resolution *IUE* spectra have been used to derive the orbital elements of HD 77581, the supergiant companion to the neutron star in the X-ray source Vela X-1; the velocity amplitude is at the lower end of the range found by previous workers using primarily optical spectra, but other elements (e, ω) are in fair agreement with those derived from pulse timing studies of the X-ray source. The new results indicate that the mass of the neutron star is close to 1.4 $M_\odot$ and is not significantly larger than those measured for other members of this class of object.

Key words: binaries: general – stars: individual: HD 77581 – stars: individual: Vela X-1.

1 INTRODUCTION

In two recent papers (Stickland 1992; Stickland & Lloyd 1993), high-resolution *IUE* spectra of the massive X-ray binaries X Persei and HD 153919 were examined for radial-velocity variations. In view of the utility of such data for orbital determination amply demonstrated by the series of papers presently running in *The Observatory*, those two stars yielded rather disheartening results in the sense that no variation was forthcoming for X Per, while the velocity amplitude detected for HD 153919 was markedly less than that produced by the optical workers although with a convincingly small residual.

The present note describes an analysis of short-wavelength (SWP: i.e. 1150–2100 Å), high-resolution *IUE* spectra of the massive component of another X-ray binary, Vela X-1. In this case, however, most of the binary elements have been accurately determined from X-ray pulse timing observations of the X-ray component of the system (Deeter et al. 1987). For the B0.5Ib component, HD 77581, there have been numerous attempts to determine the elements through the use of optical spectra (see Batten, Fletcher & MacCarthy 1989) and the most recent, by van Kerkwijk et al. (1995), has also employed some *IUE* spectra. However, only about half of the 50 spectra listed in the *IUE* log and which were available at the time were measured; it was thus thought worthwhile to study the whole set by using the methods that have worked extremely well on other O- and early B-type binaries. The reason for our persistence lies in the fact that some previous determinations have indicated a mass for the neutron star which is significantly higher than the masses indicated for such compact stars in other systems [see the review in section 1 of van Kerkwijk et al. (1995)]. Since the mass determination of the compact object is critically dependent on the amplitude of the velocity curve of the luminous component, we believe a further examination to be valuable.

2 *IUE* OBSERVATIONS

The *IUE* archive contains 50 SWP high-resolution spectra of HD 77581, and we were able to extract 49 of these (the archive file containing SWP22287 was corrupted); two further spectra had to be rejected: SWP25850 was underexposed and SWP25851 had a very high background. The journal of the remaining 47 observations is presented in Table 1. For what is to follow, it is relevant to note that all but two of the spectra (SWP2390 and SWP3499) were taken through the large aperture of the spectrograph. Measurement progressed in two stages, with the first being to bring all of the spectra to the same reference frame through alignment, by cross-correlation, of the interstellar spectrum with that of our primary standard star, τ Sco. This also allows us ultimately to put the photospheric radial velocities on a near-absolute basis, provided that we know the stellar and interstellar velocities of the standard star [+2.0 and $-8.3\,\mathrm{km\,s^{-1}}$ respectively (Stickland & Lloyd 1995)] and the interstellar-line velocity of HD 77581; this has been taken to be $+24.0\,\mathrm{km\,s^{-1}}$ from the study by Wallerstein (1974), although Zuiderwijk, van den Heuvel & Hensberge (1975) report somewhat higher values: $+28.8\,\mathrm{km\,s^{-1}}$ for the Ca II lines and $+31.0\,\mathrm{km\,s^{-1}}$ for the Na I lines.

Measurement of the photospheric radial velocities has also been achieved through cross-correlation, but the spectrum against which HD 77581 was compared was only selected after a number of trials with our 'bank' of spectra of secondary standards consisting of relatively sharp-lined stars covering the range of spectral types from mid-O to mid-B. The most suitable standard for use in the present case turned out to be, quite appropriately, the B1/2Ib star HD 150041, with a $v\sin i$ of about $50\,\mathrm{km\,s^{-1}}$. The main difference between the present study and that of van Kerkwijk et al. (1995), insofar as the *IUE* data are concerned, is that they have performed the cross-correlation against one of the spectra of HD 77581 itself. Since the resulting

Table 1. The journal of *IUE* observations of HD 77581.

SWP Image	HJD −2440000	Phase	V km s^{-1}	O−C km s^{-1}
1442	3628.708	0.279	+7.4	+7.3
1488	3634.119	0.882	+4.0	+2.2
2087	3712.991	0.681	−22.2	−5.2
2390	3745.199	0.274	+2.8	+2.2
3499	3843.593	0.250	+8.5	+5.5
3510	3845.206	0.430	−19.1	−5.7
3519	3846.189	0.539	−14.4	+4.1
3550	3850.014	0.966	+0.4	−10.3
3649	3862.532	0.363	−17.8	−9.8
4718	3954.271	0.596	−23.2	−4.1
18823	5323.021	0.284	+8.2	+8.7
18958	5341.591	0.356	−5.8	+1.6
18970	5343.512	0.570	−8.3	+10.7
18983	5345.598	0.803	−14.3	−6.9
19012	5351.276	0.436	−22.6	−8.8
19040	5354.586	0.806	−8.1	−1.0
19041	5354.635	0.811	−9.8	−3.3
19061	5357.305	0.109	+18.2	+4.1
19062	5357.414	0.121	+20.7	+7.1
22278	5746.817	0.560	−20.1	−1.2
22301	5749.821	0.895	+7.4	+4.1
22309	5751.810	0.117	+22.9	+9.1
22324	5752.859	0.234	+5.7	+1.1
25761	6177.276	0.579	−8.0	+11.1
25762	6177.363	0.589	−24.6	−5.5
25763	6177.426	0.596	−23.2	−4.1
25764	6177.494	0.603	−16.3	+2.8
25847	6189.173	0.906	+6.9	+2.3
25848	6189.247	0.914	+4.5	−1.0
25849	6189.313	0.922	+8.9	+2.6
25880	6192.858	0.317	+4.5	+8.3
25881	6192.974	0.330	+6.6	+11.6
25882	6193.083	0.342	−5.9	+0.3
32961	7214.053	0.235	−5.5	−10.0
32967	7215.046	0.345	−16.5	−10.0
33085	7233.039	0.353	−18.3	−11.2
46144	8933.054	0.994	+9.0	−3.8
46151	8934.070	0.107	+3.1	−11.1
46167	8935.214	0.235	+3.3	−1.2
49086	9295.056	0.377	−7.4	+1.9
49093	9296.045	0.487	−17.6	−0.9
49111	9297.210	0.617	−19.7	−0.8
49128	9298.224	0.730	−12.5	+1.5
49141	9299.040	0.821	+7.1	+12.5
49173	9301.049	0.045	+15.3	+0.4
49186	9302.048	0.157	+0.7	−10.7
49202	9303.207	0.286	+2.8	+3.5

cross-correlation function (ccf) is essentially a convolution of the line profiles of the two spectra, we believe it preferable to use as narrow-lined a spectrum as practicable for the comparison in order to keep the ccf peak as sharp as possible. Zuiderwijk (1995) has shown that the $v\sin i$ of HD 77581 is 116 ± 6 km s^{-1}, which we have confirmed through our calibration with τ Sco; this we feel provides a somewhat less than ideal comparison. We show the different ccfs in Fig. 1, where SWP32967 has been cross-correlated against SWP3550 which was employed by van Kerkwijk et al. (1995) and against our standard spectrum (HD 150041; SWP13776).

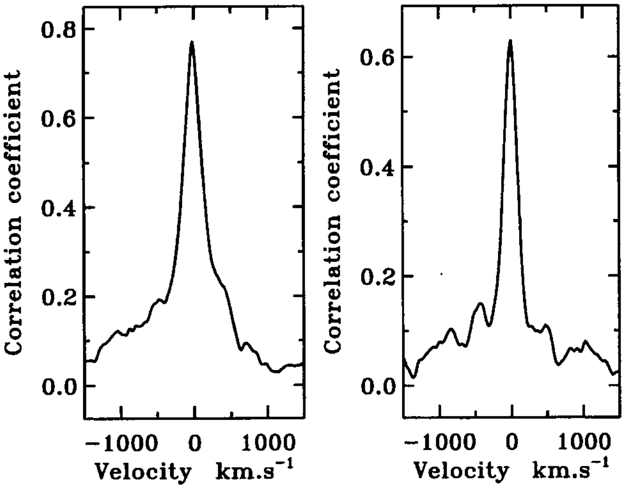

Figure 1. The cross-correlation functions derived by using two spectra of HD 77581 (left) and HD 77581 against the standard, HD 150041 (right).

Van Kerkwijk et al. (1995) went to great lengths to eliminate the effects of what they believed to be 'fixed-pattern noise' (FPN) from the ccfs of their *IUE* spectra. This noise is due to inadequate registration of the image with the composite 'images' of the intensity transfer function (ITF) used for photometric calibration. Evans (1988) has shown that, when spectra from the same camera *and the same aperture* are cross-correlated, a small sharp spike can often be observed in the ccf. Van Kerkwijk et al. have attempted to remove this by subtraction of a Gaussian peak of fixed width within the peak of the ccf. In unpublished experiments involving high-resolution spectra of white dwarf stars, we have confirmed the existence of small and very sharp FPN spikes in the ccf, but they are very weak *and at variable positions* up to ± 40 km s^{-1}, as was also found by Evans. It must also be noted that such spikes will be in a fixed position in the spectrograph frame of reference, whereas the spectra of any celestial objects will be Doppler shifted by variable amounts due to satellite- and Earth-orbital motion, in the present case ranging over almost ± 20 km s^{-1}, and by variations in the accuracy of centring in the large aperture (which is 10×20 arcsec; the size of the stellar image is roughly 3-arcsec diameter depending on focus). In our cross-correlation measurements on HD 77581, the symmetry of our sharper ccfs suggested strongly that any very narrow FPN spike was not significantly affecting measurements of the peaks. However, as confirmation, we repeated all the measurements with a spectrum of HD 150041 (SWP7745) taken in the small aperture, i.e. so that there could be *no correlation of the FPN* with the large-aperture spectra of HD 77581. The results were the same within the errors (see values of K_1 in Table 2), as indeed they were when Gaussian fitting to the ccfs was performed instead of parabola fitting to the peak; the mean fitting error is 2.2 km s^{-1}(which represents the internal error).

A further difference between the present analysis of *IUE* data and that of van Kerkwijk et al. (1995) pertains to the spectral template over which the cross-correlation is performed. They have used six segments averaging 38 Å between 1560 and 1842 Å, carefully selected to avoid strong wind and interstellar lines. We have used a much larger region, from 1265 to 1900 Å, but have also excluded interstellar lines (1277, 1304, 1370, 1477, 1608, 1657, 1670, 1710, 1803, 1808, 1827, 1851–1856, 1862 and 1879 Å) and wind lines (1325–1345, 1381–1453 and 1523–1563 Å). The rationale for this is based on our experience that the use of short stretches of what are

Table 2. The orbital elements of HD 77581.

Element	Unconstrained	elements	X-ray source	elements	Small-aperture	standard
P (days)	8.96302	± 0.00045	8.964353	(fixed)	8.964353	(fixed)
γ (km s^{-1})	−3.2	± 0.9	−3.4	± 1.0	+0.5	± 1.2
K_1 (km s^{-1})	17.8	± 1.6	17.1	± 1.5	18.7	± 1.9
e	0.107	± 0.079	0.090	(fixed)	0.090	(fixed)
ω (degrees)	335	± 42	332.8	(fixed)	332.8	(fixed)
T (HJD - 2440000)	4003.1	± 1.0	3957.89	(fixed)	3957.89	(fixed)
$f(m)$ (M$_\odot$)	0.0052	± 0.0014	0.0047	± 0.0012	0.0061	± 0.0024
rms residual (km s^{-1})	6.2		6.6		8.3	
K_2 (km s^{-1})	274.3	(adopted)	274.3	(adopted)	274.3	(adopted)
$M_1 \sin^3 i$ (M$_\odot$)	21.41	± 0.60	21.42	± 0.22	21.42	± 0.22
$M_2 \sin^3 i$ (M$_\odot$)	1.39	± 0.14	1.33	± 0.13	1.45	± 0.14
$a_1 \sin i$ (R$_\odot$)	3.13	± 0.28	3.02	± 0.26	3.30	± 0.33
$a_2 \sin i$ (R$_\odot$)	48.30	± 0.41	48.38	± 0.00	48.38	± 0.00

intrinsically rather low signal-to-noise ratio spectra produces correspondingly noisy ccfs. The radial velocities measured with the above precepts have been added to Table 1.

3 THE ORBIT

The radial velocities presented in Table 1 have been entered into the RVORBIT program of Hill (1988), with starting elements taken from Deeter et al. (1987). The orbital elements derived by allowing all elements to float are listed in Table 2. The rms residual of 6.2 km s^{-1} is in good accord with similar values found in work on other binaries conducted with *IUE* data; further, although the force of the argument is constrained by the limited number of velocities measured, the residuals show no obvious dependence on phase. Van Kerkwijk et al. also discussed non-Keplerian velocity changes which appeared to be present in runs of velocities secured on single nights, and suggested that they might be linked to some kind of pulsational activity. The *IUE* data are too few to confirm this but any short term variation would contribute to the errors and uncertainty in the solution.

The application of a standard statistical test (Lucy 1989) indicates that the eccentricity determined in the unconstrained orbital solution is not significant (the rms residual is 6.3 km s^{-1} for a circular solution), a finding which might anyway have been questioned in what is clearly an evolved system were it not for the similar value derived with higher precision from the X-ray timings of the neutron star (Deeter et al. 1987). This has prompted a second run of RVORBIT in which the period, eccentricity, longitude of periastron, and time of periastron passage have been set at the values obtained from the X-ray source. [The time of periastron was derived from the 'orbital epoch' given by Deeter et al. (1987) by using equation (9) of Boynton et al. (1986).] The resulting amplitude and the rms residual are very similar to those found in the unconstrained run; the results are added to Table 2 and it is this solution which is depicted in Fig. 2 and yields the phases given in Table 1. Also shown in this table are the results of using velocities measured when the small-aperture spectrum of the standard was employed.

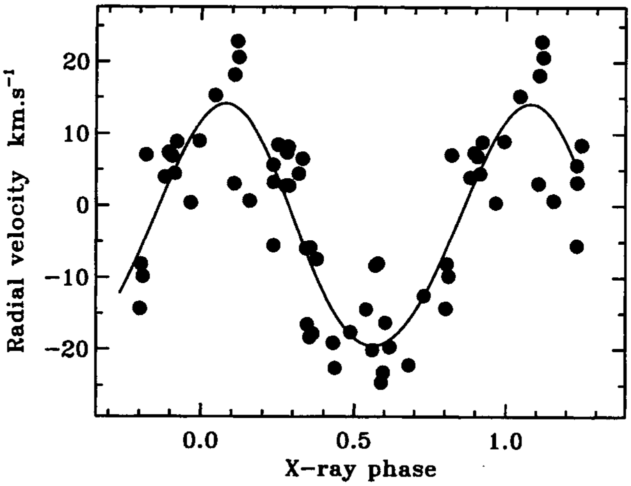

Figure 2. The spectroscopic orbit of HD 77581 derived from archival *IUE* data. The solution shown by the line assumes P, T, e and ω from the X-ray timing analysis (Deeter et al. 1987).

4 DISCUSSION

Adding the velocity amplitude of the neutron star [derived from the mass function and other elements quoted by Deeter et al. (1987)] to the elements listed in Table 2 allows the computation of the quantities $M_{1,2} \sin^3 i$. For the X-ray source, these turn out to be at the lower boundary for neutron star masses of around 1.4 M$_\odot$, with the departure from that value totally dependent on the inclination of the orbit, i. A lower boundary to i can be set from knowing that the X-ray source undergoes eclipses. A general discussion of this problem is given by Stickland & Lloyd (1993), but for the Vela X-1 system we can turn to the analysis by van Kerkwijk et al. (1995), who have reviewed the various values of eclipse duration angle, θ_{ecl}, recorded by numerous X-ray satellite monitoring programmes, and combined it with the radius of the supergiant inferred from the $v\sin i$ reported by Zuiderwijk (1995) (with which we agree). They conclude that i is probably close to 90° but may range as low as about 73°. With the X-ray source-constrained elements quoted in Table 2, this leads to neutron star masses between 1.34 ± 0.13 M$_\odot$ for $i = 90°$ and 1.53 M$_\odot$ at $i = 73°$, which lie on the lower boundary of the values found by van Kerkwijk et al. (1995).

5 CONCLUSION

Radial velocities of HD 77581 derived from measurement of high-resolution *IUE* spectra, by employing well-tried procedures which have provided excellent results on a large number of O- and early B-type stars, have been combined with information provided by X-ray observations of the source Vela X-1 to deduce that the mass of the neutron star is in good agreement with masses derived for other compact objects of this type.

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