THREE MASSIVE BINARIES AND THE 'STRUVE-SAHADE' EFFECT

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Introduction

The series of papers in this *Magazine* on the determination of spectroscopic-binary orbits using radial velocities derived from ultraviolet data began simply as a demonstration of the potential value of such data from the now huge archive of *IUE* spectra. In the first six papers, measurements were made, rather primitively, by cursor setting on individual lines displayed on a VDU; given the low signal-to-noise ratio of single *IUE* spectra the accuracy of those individual measurements was limited and the search for lines of companions was essentially unsuccessful. (Some features were recorded in the spectra of AO Cas[1] which might have been attributable to the secondary; the attempts to locate the O-type star in γ^2 Vel were generally unsatisfactory[2] although work on another WR+O binary, HD 193793, was somewhat more encouraging[3].)

With the development of the cross-correlation method[4] and its application to double-lined binaries[5], the doors were thrown open to a much more systematic attack on massive binary stars, with a view to a significant reappraisal of the masses of the earliest-type stars. That such a study is long overdue is evident from the paucity of data for O-type stars not only in the seminal review by Popper[6] but also by the more recent update by Hilditch & Bell[7]. Although some considerable progress has already been reported in these pages, the termination of *IUE* operations at the end of 1996 September prohibits the inclusion of some important systems, such as V3903 Sgr. This unfortunate situation has prompted a re-examination, with cross-correlation methods, of those stars treated at the beginning of the series, in the particular hope of recovering their secondary spectra, without which the mass problem is not tractable. Hilditch *et al.* have already executed[8] an admirable cross-correlation study of ι Ori (see also ref. 9), albeit with optical data, while preliminary inspection of some spectra taken at quadrature of δ Ori (see ref. 10) suggests that the velocity amplitude is too low and the rotational broadening too large to yield reliable measures of the secondary.

The purpose of the present paper was thus, at the outset, to reconsider the *IUE* dataset for AO Cas, which now includes a number of spectra secured by Drs. Sahade and Henrichs and which were not available for the earlier work[1]. As the analysis proceeded, it became apparent that the secondary-star's spectrum exhibited anomalies in the UV akin to those recorded by optical workers, notably Struve and Sahade, many years before. This inexorably led to re-examination of the UV spectra of Plaskett's Star, an object which so exercised Struve in his monograph[11] *Stellar Evolution*, and finally to a review of 29 CMa (see ref. 12), which in many respects presents the most serious problems for the determination of binary orbits of such massive stars.

AO Cassiopeiæ (HD 1337)

Paper 4 in the series on Spectroscopic Binary Orbits from Ultraviolet Radial Velocities[1] gives a brief summary of the optical work that had previously been

TABLE I

IUE radial-velocity observations of AO Cassiopeiæ

SWP Image	*HJD* −2 440 000	*Phase*	V_1 *km s*$^{-1}$	*(O−C) km s*$^{-1}$	V_2 *km s*$^{-1}$	*(O−C) km s*$^{-1}$
1692	3661·914	$\overline{169}$·773	−21·6	−23·4		
1712	3663·836	$\overline{168}$·319	−146·3	−15·6		
2363	3742·946	$\overline{146}$·771	−21·5	−19·8		
2384	3744·905	$\overline{145}$·327	−149·2	−7·6		
2489	3756·533	$\overline{142}$·627	−193·5	+2·9	+68·7	+4·6
3231	3818·599	$\overline{124}$·242	−15·3	+5·3		
3422	3835·837	$\overline{119}$·134	+128·3	+4·6	−130·4	−6·1
4455	3935·467	$\overline{91}$·410	−217·8	+13·1	+98·0	+13·6
4456	3935·493	$\overline{91}$·418	−222·1	+14·5	+103·8	+16·1
4745	3957·354	$\overline{85}$·622	−195·2	+6·5	+69·5	+2·3
5185	4003·369	$\overline{72}$·681	−137·3	−6·8		
5477	4035·091	$\overline{63}$·684	−131·8	−5·4		
5482	4035·451	$\overline{63}$·787	−19·9	−41·1		
7662	4254·526	$\overline{1}$·962	+186·6	−9·3	−161·4	+5·4
7666	4254·697	0·011	+199·9	−2·0	−167·3	+3·1
10146	4498·601	69·233	−10·3	−2·8		
32892	7200·954	836·187	+62·1	+3·7		
39329	8103·316	1092·286	−45·6	+39·3		
39331	8103·411	1092·313	−131·7	−8·9		
39333	8103·502	1092·339	−164·2	−7·6		
39337	8103·700	1092·395	−217·3	+0·6	+72·0	−4·7
39339	8103·786	1092·419	−240·0	−2·3	+84·6	−3·8
39341	8103·874	1092·444	−254·3	−1·2	+102·8	+5·4
39343	8103·972	1092·472	−258·2	+5·5	+111·8	+8·1
39345	8104·074	1092·501	−263·7	+3·6	+105·0	−0·8
39347	8104·171	1092·529	−264·1	−0·5	+101·9	−1·7
39349	8104·267	1092·556	−257·1	−4·0	+87·0	−10·4
39354	8104·500	1092·622	−200·1	+1·7	+58·2	−0·9
39356	8104·590	1092·647	−176·2	−2·6		
39358	8104·712	1092·682	−137·9	−8·2		
39360	8104·817	1092·712	−73·0	+15·2		
39362	8104·902	1092·736	−45·2	+7·9		
39364	8104·991	1092·761	−35·7	−19·8		
39366	8105·084	1092·788	−21·1	−43·7		
39368	8105·172	1092·813	+10·7	−46·9		
39369	8105·201	1092·821	+62·1	−6 6		

done on AO Cas and then discusses the measurement of the 16 spectra that were available at the time. Those observations covered the 3·5-day orbit rather sparsely, if evenly. Since then, during a continuous run which included observations[13] of μ^1 Sco, a further 21 SWP, high-resolution spectra were obtained by Sahade & Henrichs, although, from the point of view of the present work, the phasing is unfortunate, with the primary's negative-velocity half of the cycle covered extremely well but with only two modestly-positive velocity points added. Nonetheless, the new data made a new investigation of this massive binary (O9·5 III+O8V according to tomograpic work on the original *IUE* dataset by Bagnuolo & Gies[14]) very worthwhile; a journal of all the observations is presented in Table I (excluding SWP 39335, the archive file for which was corrupted).

As with more recent work in the binary-star series, the new velocities have been put on a near-absolute scale through knowledge of the interstellar-line velocity of AO Cas, taken to be −11·1 km s^{-1} from the main component of

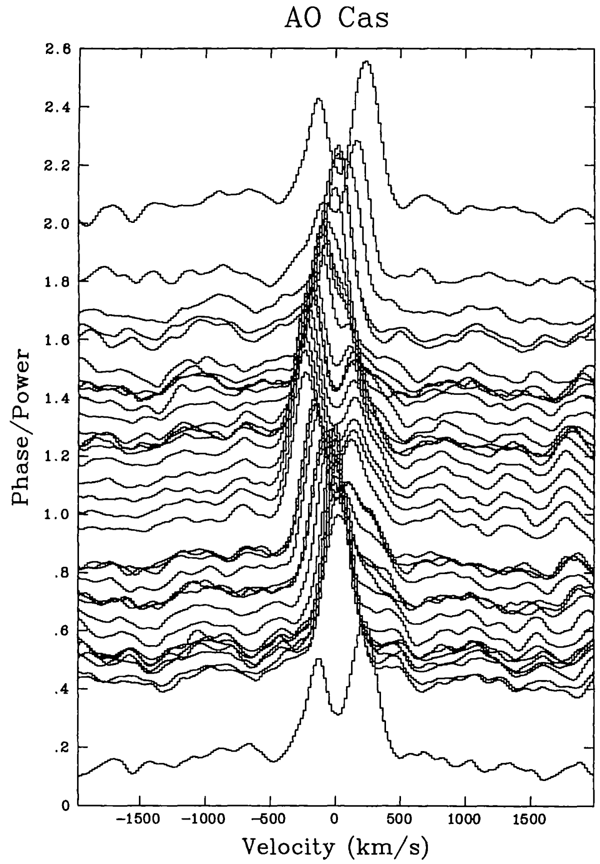

FIG. 1

A montage of cross-correlation functions for AO Cas. The vertical spacing has been adjusted so that the 'continuum' level for each observation represents the phase in the binary cycle, with phase zero at the top.

H & *K* measured by Adams[15] (although one might argue for a somewhat more negative velocity for the complex of lines present — Struve & Horak[16], for example, recorded $-24 \cdot 1$ km s^{-1}); this is combined with the interstellar and stellar velocities for τ Sco[35], with which 'primary standard' star the interstellar spectrum was cross correlated.

To measure the stellar velocities, tests were conducted employing several 'secondary standards' to discover which yielded the strongest and sharpest cross-correlation function (ccf); the mask finally chosen was provided by HD 150041 (B1/2 Ib). A montage of ccfs ordered by orbital phase is shown in Fig. 1, where the swing of the primary velocity is readily apparent and could be measured simply by fitting to the peak of the ccf; the velocities so obtained are included in Table I. The orbit thus derived is in excellent agreement with that found earlier from the manual measurements[1] and the elements are listed in Table II. The situation for the secondary component was less satisfactory and inspection of Fig. 1 suggests that the strength of the secondary ccf is highly variable, being much stronger when approaching the observer than when receding. This is highlighted in Fig. 2 where just two quadrature ccfs are shown: the secondary is quite strong and reasonably symmetrical when to the 'blue' of the primary, but weaker and asymmetrical when to the 'red'.

Exactly the same phenomenon was recorded by Adams & Stromberg[17] and

TABLE II

Orbital elements of AO Cassiopeiæ

	Primary	*Both*
P (days)	3·5234883±0·0000082	3·5234887±0·0000065
γ (km s^{-1})	−35·1±1·6	−32·4±1·7
K_1 (km s^{-1})	231·6±2·2	234·9±1·3
K_2 (km s^{-1})		138·2±2·2
e	0·0 (fixed)	0·0 (fixed)
ω (degrees)	undefined	undefined
T_0 (HJD −2 440000)	4254·661±0·006	4254·659±0·005
R.m.s. residual (km s^{-1})	6·7	7·3
$f(m)$ ($M_\odot$)	4·54±0·13	
q		0·588±0·010
$m_1 \sin^3 i$ ($M_\odot$)		7·04±0·20
$m_2 \sin^3 i$ ($M_\odot$)		11·96±0·21
$a_1 \sin i$ ($R_\odot$)		16·35±0·09
$a_2 \sin i$ ($R_\odot$)		9·62±0·15

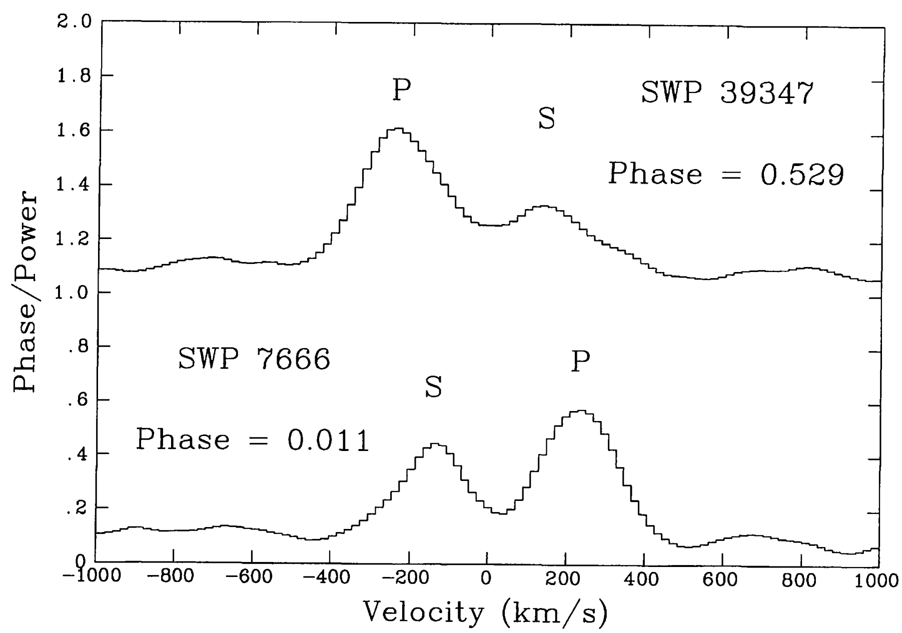

FIG. 2

Cross-correlation functions of AO Cas at the two quadratures, showing the predicted positions of both components. Note the apparent strength of the 'secondary' peak when shifted to negative velocities in comparison with the case when it is shifted positive; note also the asymmetry of the secondary peak when shifted positive.

later by Struve & Horak[16] who also, from optical observations, produced a velocity curve[16] for the secondary resembling that derived from the manual measurements of *IUE* data. Struve & Horak utilized the largest collection of optical data and we accordingly give considerable weight to their findings, although it is only fair to point out that Pearce[18] obtained a result at some variance with that from McDonald Observatory, particularly in respect of the amplitude of the secondary velocity; nor did Abhyankar[19] mention any variation in the strength of the secondary spectrum from his optical study. And perhaps of more concern for the present study, Bagnuolo & Gies[14] made no mention of variations with phase in their *IUE*-based work on the system, although it is right to

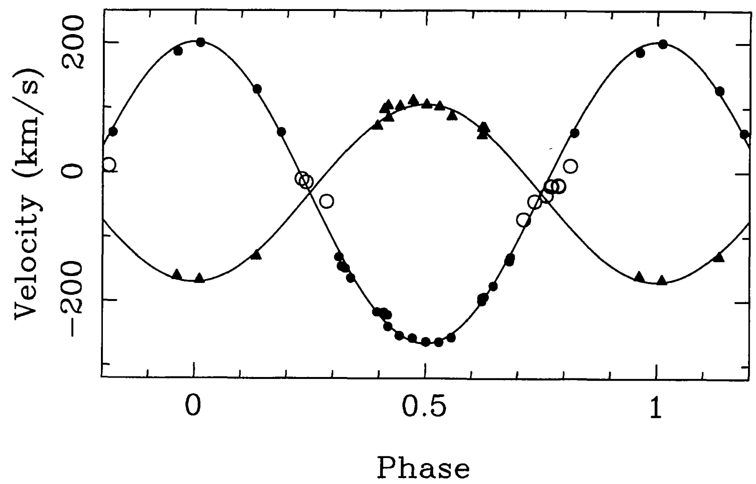

FIG. 3

The radial-velocity data and orbital solution for AO Cas; the primary is represented by the circles (zero weighted — open circles — near the conjunctions) while the triangles represent the velocities of the peak of the 'secondary' ccf.

point out that any significant variation which is widespread among all the photospheric features (as is implied in the 'broad-brush' cross-correlation method) would vitiate the tomograpic approach; the effect may be evident in the related cross-correlation study of *IUE* spectra by Gies & Wiggs[20] (see their Fig. 3).

Various approaches were tried to measure the velocity of the secondary, but those employing the usual gaussian fitting gave results akin to those of Struve & Horak (see their Fig. 1 and also Fig. 4 of ref. 1). This seemed to be due mainly to the asymmetry of the ccfs. When, however, just the *peaks* of the secondary ccfs were recorded (by parabola fitting) in those spectra where the two ccf peaks were clearly separated, a much more satisfactory outcome was obtained: the measures not only fitted a realistic curve (based on the mirror image of the primary curve) but the systemic velocity came out very close to that of the primary; *i.e.*, the results made sense dynamically. The velocities obtained in this way have been added to Table I and the elements of a double-lined orbital solution using them have been entered into Table II, where it will be apparent that the residuals are close to those of the primary-only solution; the double-lined solution and the data are depicted in Fig. 3.

The conclusion from this study of AO Cas would appear to be that the secondary spectrum is clearly visible when that component is approaching the observer but is weakened and/or distorted during recession; there is, further, some evidence that the ccf of the secondary during recession may be composed of a broad contribution which does not have Keplerian motion, and an underlying remnant of the true secondary which is sharp enough to give a peak in the combined ccf which does exhibit true orbital motion. If we have properly recorded the motion of the secondary, then clearly it is more massive than the luminous primary: $q = (M_1/M_2) = 0{\cdot}59$ and implies a history of evolution with extensive mass loss and/or exchange. The luminosity class of the primary (III) does argue for evolution, but to discover a general principle we need to examine other cases. Curiously, two examples of perhaps more extreme evolution were also studied in the pre-cross-correlation epoch of the binary-star series and were thus due for reconsideration anyway; the findings for AO Cas make their contemplation even more apposite.

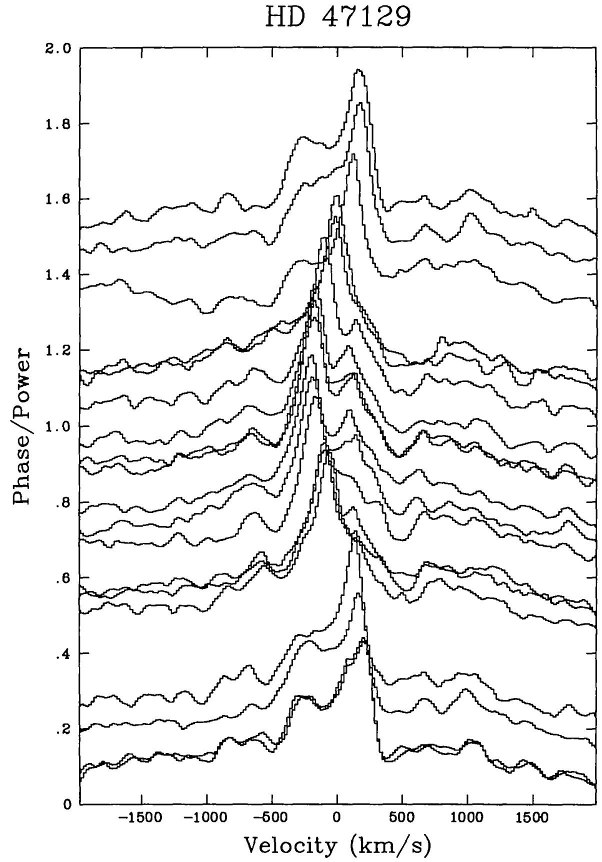

FIG. 4

A montage of ccfs for Plaskett's Star; description as for Fig. 1.

Plaskett's Star (HD 47129)

For many years, Plaskett's Star held its place in the record books as the most massive known binary, although this was based on the large mass function ($f(m) = 12 \cdot 6\ M_{\odot}$) and caveats attend its use. Sightings of the secondary components were surrounded with a large degree of uncertainty: Plaskett referred[21] to its "faint and diffuse lines" while Struve asserted[22] that the secondary lines "show very large and erratic fluctuations in velocity and intensity"; Abhyankar[19] confirmed these findings. More recently, other contenders for the 'heavyweight championship' have emerged: the primary of HD 93205[23] and HD 92740[24] (WR 22).

Since the earlier investigation of the archival *IUE* observations of Plaskett's Star[25], no further spectra have been obtained; the journal is reproduced in Table III. The velocities have been converted to near-absolute values after adopting the interstellar-line radial velocity given by Plaskett and confirmed by Struve ($+16$ km s^{-1}), which is in good agreement with average of the components listed by Adams[15]. Yet again a search was made for the optimal mask for comparison, and the star selected was HD 99546 (O8, the same spectral class as Plaskett's Star, O8e). A montage showing the resulting ccfs is displayed in Fig. 4, where the movement of the primary is clear, yielding the velocities listed in Table III. The orbit derived from these data, illustrated in Fig. 5 with the

TABLE III

IUE radial-velocity observations of Plaskett's Star

SWP Image	*HJD* −2 440 000	*Phase*	V_1 *km s*$^{-1}$	*(O−C)* *km s*$^{-1}$	V_2 *km s*$^{-1}$
2360	3742·707	$\overline{16}$·141	+134·8	−14·1	−234·3
2516	3759·061	$\overline{15}$·277	+4·0	+14·1	
2626	3762·990	$\overline{15}$·550	−159·9	+5·5	+161·8
3236	3818·986	$\overline{11}$·440	−154·9	+6·0	+154·6
3347	3827·144	$\overline{10}$·006	+217·6	−4·2	−236·7
4774	3960·393	$\overline{1}$·262	+13·6	+4·7	
4797	3962·345	$\overline{1}$·397	−145·4	−10·2	+107·3
4819	3964·095	$\overline{1}$·519	−185·5	−11·8	+114·8
6295	4113·018	9·863	+153·1	+0·1	
6369	4119·797	10·334	−78·0	−1·4	+163·7
6438	4125·022	10·697	−40·2	+1·3	
7077	4181·038	14·588	−143·3	+2·3	
8867	4359·406	26·977	+226·2	+6·2	−246·2
8868	4359·433	26·979	+225·7	+5·4	−268·4
9950	4481·131	35·433	−158·0	−0·5	+135·4
10048	4490·325	36·071	+203·3	+0·8	−224·6
10152	4498·969	36·672	−68·8	+1·7	+143·2
10689	4570·921	41·669	−73·7	−0·9	
13924	4732·768	52·911	+187·3	−4·7	−190·3

TABLE IV

Orbital elements of Plaskett's Star

	Primary
P (days)	14·3966±0·0015
γ (km s^{-1})	+23·5±1·8
K_1 (km s^{-1})	198·5±2·0
e	0·0 (fixed)
ω (degrees)	undefined
T_0 (HJD −2 440000)	3971·022±0·033
R.m.s. residual (km s^{-1})	6·7
$f(m)$ ($M_\odot$)	11·69±0·35
$a_1 \sin i$ ($R_\odot$)	56·4±0·6

elements given in Table IV, is essentially identical to that found in Paper 2 of the binary series with manual measurements, but with smaller residuals.

Close inspection of what was initially assumed to be the secondary component of the ccf in Fig. 4 shows rather little movement around each quadrature, and measurement confirms this impression; not only that, but the 'systemic' velocity given by these features is manifestly different, by almost −60 km s^{-1}, from that of the primary (Fig. 5). This situation is strikingly similar to that found by Struve[22] and shown in his Fig. 2 and argues strongly that the present approach is at least compatible with more traditional methods. Struve also complained of strong variability of the 'secondary' features and some indication of this phenomenon is provided by the *IUE*-based ccfs, although it is perhaps more apparent in structural changes of the profiles than in obvious changes of strength; this may be clearer in the plot of just one ccf from each quadrature shown in Fig. 6.

Bagnuolo *et al.*[26] have studied the same set of *IUE* spectra and subjected them to tomography in the hope of separating the two components. Their prepara-

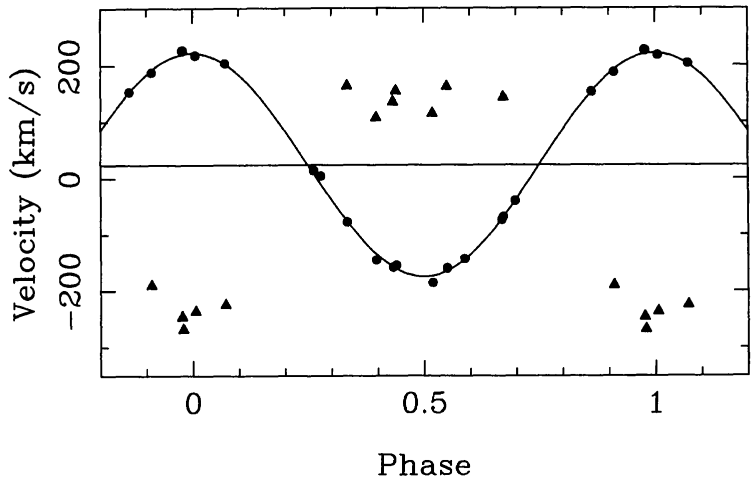

FIG. 5

The radial-velocity data and orbital solution for the primary component of Plaskett's Star (filled circles); the 'secondary' data (triangles) make little dynamical sense.

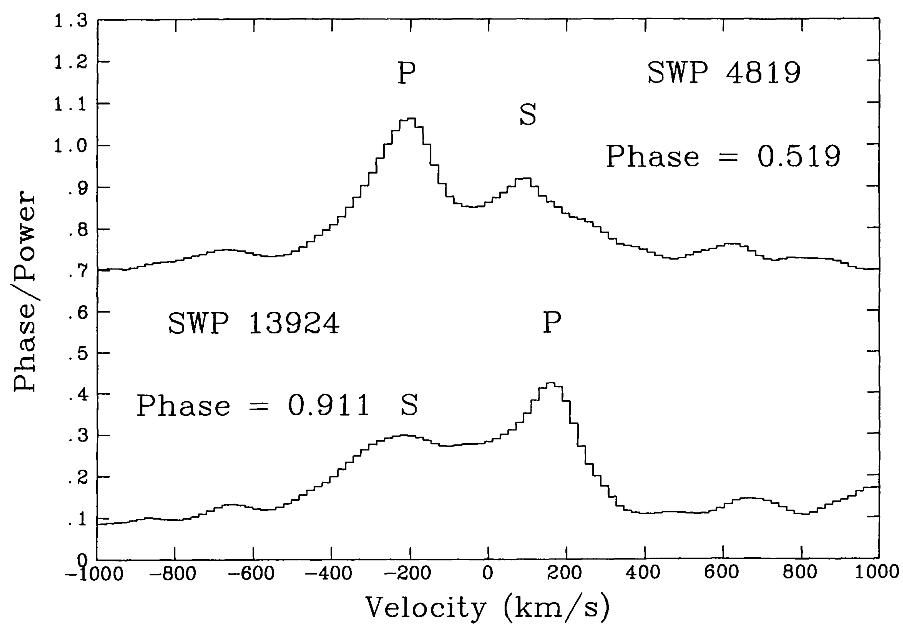

FIG. 6

Cross-correlation functions of Plaskett's Star at quadratures; note the breadth and the variable structure of the 'secondary' peak.

tory work includes construction of ccfs derived by using a single-lined spectrum of Plaskett's Star to provide the mask, an approach which delivers rather wide profiles; it is on the basis of these profiles that they find similar systemic velocities for the two components and a plausible radial-velocity curve for the secondary. Reasons for the disagreement between their work and ours is not clear; the main difference in practice is that our ccf template includes all of the spectrum in the region 1250–1900 Å with only the strong wind features and interstellar lines removed, while they restricted their attention to three short stretches of spectrum.

Our conclusion is that Plaskett's Star, another massive binary with an evolved and luminous primary, is giving apparent secondary features whose velocities make no sense dynamically. This is not to say that the secondary's spectrum is not contributing to this feature, but rather that it is sufficiently distorted and/or blended to render void both peak- and gaussian-fitting measurements; the breadth of the secondary lines[26] (310 km s^{-1}) may exacerbate the problem. The system has a high mass-loss rate and shell features, and one is very tempted to endorse Struve's feeling[11] that gaseous streams or envelopes must be responsible.

29 (UW) Canis Majoris (HD 57060)

29 CMa is the prototype Of star, having been classified by Pearce as O7fsk; this implies a measure of evolution from the main sequence and extensive mass loss. What should thus be anticipated, from the observations described above, is that it comes as no surprise to find that this 4.4-day binary exhibits all the symptoms of the effects which were considered at some length by Struve in Part III of his monograph[11], *Stellar Evolution*, and which we propose to call 'the Struve-Sahade effect', in recognition also of Sahade's efforts to highlight the problem.

TABLE V

IUE radial-velocity observations of 29 CMa

SWP Image	*HJD* −2 440 000	*Phase*	V_1 *km* s^{-1}	*(O−C)* *km* s^{-1}	V_2 *km* s^{-1}
1369	3614·842	0·166	−127·8	+7·9	
1417	3624·431	2·348	−215·6	+2·7	
1418	3624·510	2·366	−216·2	−3·5	
1697	3662·324	10·973	+151·2	−11·2	−253·7
1716	3664·259	11·413	−202·8	−14·1	
2071	3711·306	22·122	−81·6	−6·7	
2145	3719·199	23·918	+201·5	−13·2	−241·2
2515	3758·988	32·974	+168·5	+8·1	−204·2
2715	3772·949	36·152	−114·8	+3·8	
2741	3775·148	36·653	+56·4	−2·5	
2778	3778·536	37·424	−189·3	−7·5	
2972	3795·979	41·394	−207·1	−7·1	
3390	3831·854	49·559	−48·1	+5·0	
3485	3841·748	51·811	+201·0	−14·8	−203·3
4771	3960·283	78·791	+214·0	+10·9	−229·9
4772	3960·314	78·798	+216·2	+8·3	−229·4
4818	3964·059	79·651	+53·2	−3·2	
6368	4119·762	115·090	+5·9	+30·0	
6400	4122·150	115·634	+47·1	+11·5	
6437	4124·991	116·280	−200·3	+19·2	
6740	4150·821	122·159	−145·8	−17·8	
6741	4150·843	122·164	−149·8	−15·5	
6742	4150·864	122·169	−150·1	−10·0	
6743	4150·886	122·174	−162·6	−16·7	
6744	4150·907	122·179	−162·5	−11·1	
9620	4449·124	190·056	+45·9	+11·9	
9654	4452·238	190·765	+171·2	−10·8	−96·8
9671	4454·002	191·166	−129·6	+6·9	
46919	9030·608	1232·845	+240·3	+11·5	−146·8
49902	9379·580	1312·274	−184·8	+33·0	
53188	9712·783	1388·114	−68·1	−5·0	

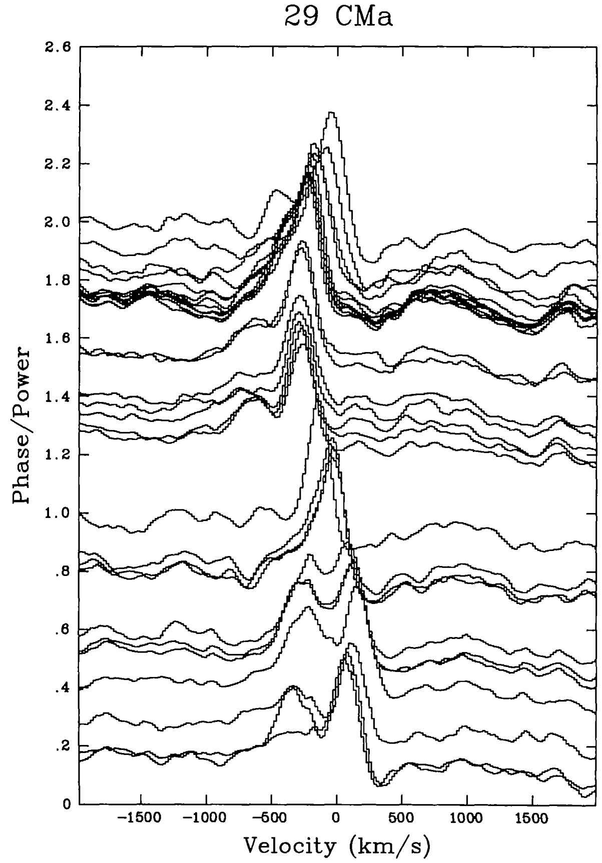

FIG. 7

A montage of ccfs for 29 CMa; description as for Fig. 1.

The archive of *IUE* short-wavelength, high-resolution observations contains just three images in addition to the 28 discussed in the earlier paper[12]; the complete journal is given in Table V. In that previous paper, an attempt was made, by trying to identify a number of photospheric features, to put the velocities on an absolute basis and a systemic velocity of +20 km s^{-1} was found. In the present work, we have adopted an interstellar-line velocity of +31 km s^{-1} from the average value for the *H* & *K* lines in 29 CMa, taken from the work of several optical observers[12], to deduce a γ-velocity closer to −10 km s^{-1}, although it is somewhat dependent on the standard spectrum used in the photospheric cross correlation; the reason for the discrepancy is not clear but for consistency with other papers in this series, the newer value is preferred.

As usual, several standards were tested for strength of cross correlation against the spectra of 29 CMa, and several were found to be satisfactory. Hereinafter, we consider the results based upon the use of HD 91824 (O7V). The montage of ccfs is shown in Fig. 7 where the motion of the primary (brighter) component is obvious; measurement of it leads to the radial velocities added to Table V and to the elements detailed in Table VI. Somewhat disconcertingly, the residuals are rather larger than those achieved during the manual examination of the *IUE* spectra[12], although they are still quite reasonable in comparison with the residuals produced by the optical workers. The orbital elements are very similar to those recorded previously and, more significantly, so is the distribu-

TABLE VI

Orbital elements of 29 CMa

	Primary
P (days)	4·393492 ± 0·000029
γ (km s^{-1})	−8·2 ± 2·6
K_1 (km s^{-1})	227·2 ± 3·5
e	0·101 ± 0·014
ω (degrees)	57·8 ± 10·0
T (HJD − 2 440000)	3614·115 ± 0·119
R.m.s. residual (km s^{-1})	13·0
$f(m)$ ($M_\odot$)	5·27 ± 0·24
$a_1 \sin i$ ($R_\odot$)	19·62 ± 0·30
K_1 (km s^{-1})	210·0 ± 3·0(:)
q	0·92 ± 0·01(:)

tion of residuals around the cycle shown in Fig. 8, in particular, around the quadrature when the primary is approaching: at first they are negative, then strikingly positive, before running off negative again. Thus there is some evidence that even the primary's velocities are nudged off course by non-Keplerian effects of some kind.

If the primary behaves somewhat strangely, then the 'secondary' in this system is quite bizarre! A peak naively attributable to the secondary is quite prominent around the quadrature when the secondary should be approaching the observer, but during the other quadrature there is effectively nothing to be seen at all! If this phenomenon were not also prominent in optical spectra — as demonstrated by some excellent photographic reproductions[27] by Sahade — one would be inclined to have serious doubts about the present application of the cross-correlation method. The effect does seem to us to be present in the pre-tomography cross-correlation study[28] of *IUE* spectra of 29 CMa by Bagnuolo *et al.* (their Fig. 1) although not perhaps so dramatically. They dismissed the effect and went on to assign spectral types of O7·5–8Iab and O9·7Ib to the primary and secondary, respectively; the tomograpic method does, however, depend on the constancy of the spectrum in the data set employed, and if this is *not* the case, then it is not clear as to just what is being recorded. On the other hand, it is justified to ask which individual features are partaking of the Struve-Sahade effect, something that the ccf does not tell us. However, high-S/N spectra around the cycle will be required before that question can be properly addressed, and for the ultraviolet region, only the *HST* can presently provide the answer.

Ignoring, for a moment, the implication of the peculiar behaviour of the 'secondary' spectrum, it is possible, albeit with little confidence, to measure on most spectra around phase 0·8–1·0 the velocities of the violet-shifted components of the ccf. These are added to Table V and the data are shown as filled triangles in Fig. 8; they make little dynamical sense and the mass ratio blindly derived from them, $q = (M_1/M_2) = 0{\cdot}92$, probably has no significance. Perhaps some extra insight into the problem comes from noting in Fig. 7 that, around phase 0·2–0·4, when the primary is itself violet shifted, there is an additional peak in the ccf even further out to the violet, at about the same velocity separation from the primary as the secondary would be expected to be at the other quadrature; this is illustrated in Fig. 9. The origin of this peak remains to be debated but one cannot help but wonder whether it is a significant contributor to the 'secondary' feature around phases 0·8–1·0.

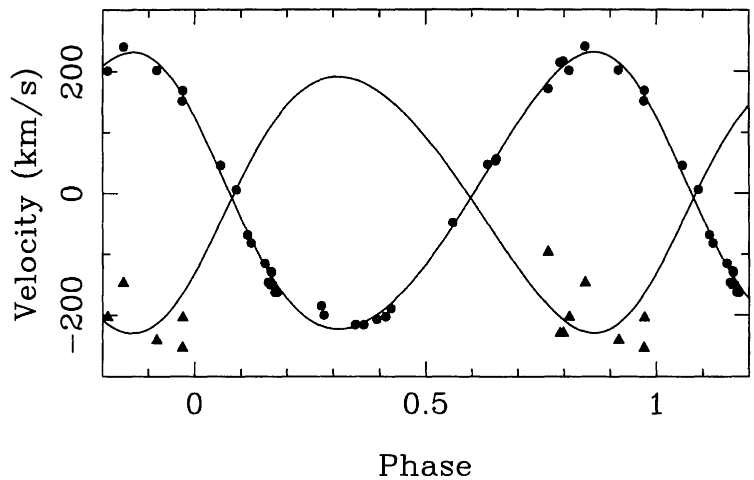

FIG. 8

The radial-velocity data and orbital solution for 29 CMa. All the elements are derived from measures of the primary, except for the semi-amplitude of the 'secondary'. The 'secondary' ccf is essentially only observed when shifted to negative velocities and even then, its provenance is not at all certain.

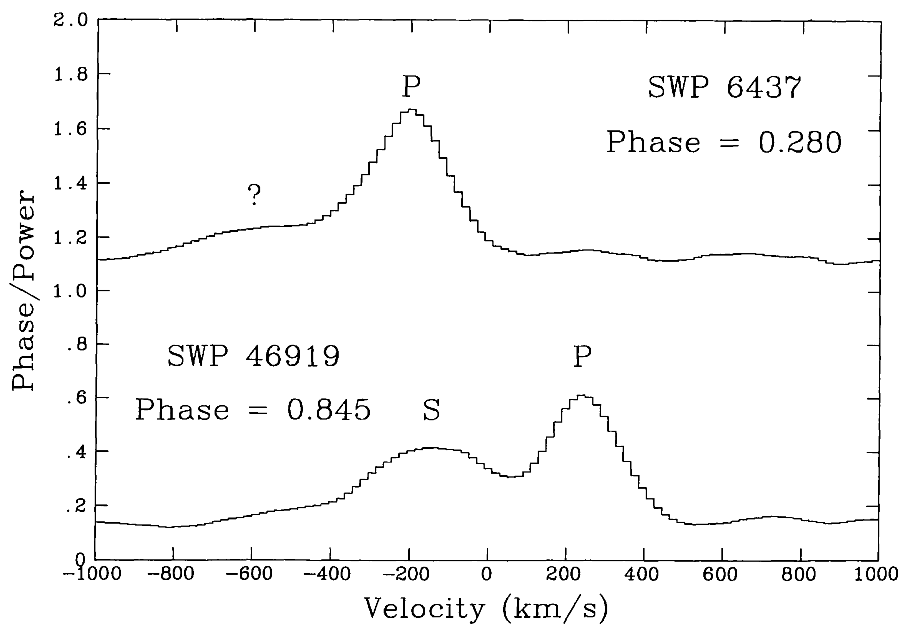

FIG. 9

Cross-correlation functions of 29 CMa at quadratures. Note the disappearance of the 'secondary' peak when it should be shifted to positive velocities, and also the additional weak peak which appears to the negative-velocity side of the primary peak when it is itself at negative velocities.

Discussion

The *IUE* radial-velocity analyses described above have brought once again into the limelight a phenomenon that has been observed in the optical in both massive binaries and W-UMa systems for many years, in which the spectrum of (at least) one component of a close binary is found to exhibit variable strength and/or radial velocities that are distinctly non-Keplerian. It is to be noted that, in each of the three cases examined here, the more luminous and less affected star is evolved from the main sequence and is undergoing serious mass loss and perhaps mass exchange to its companion.

Given that mass loss is widespread amongst massive stars, might the phenomenon be much more common than has been acknowledged thus far? During the measurement of radial velocities of several O-type binary stars treated in the series currently running in these pages, the relative ccf strengths of the two components have on several occasions been suspected of being (or even recorded as being) inconstant, but without having a very obvious effect on the velocities. A very convenient summary of these findings has been recently compiled[29] by Howarth *et al.* in a study of 'Cross-correlation characteristics of OB stars from IUE spectroscopy'; in addition to the three stars which form the subject of this paper, four others appear to demonstrate the effect, at least in respect of variable spectrum strength: HD 100213 (TU Mus)[30], HD 149404 (V918 Sco)[31], HD 152248[32], and HD 159176[33]. Of particular interest is TU Mus, where the strength of the secondary spectrum is evidently stronger during recession (see Fig. 9 of ref. 29). Although no *very obvious* effects on the velocities were recorded for those stars, a more detailed analysis of the residuals may well reveal insidious problems that will need to be resolved in the future; as part of the UK–USA collaboration on these systems, Prof. R. H. Koch is presently examining this matter. It is also pertinent to indicate that, as for the three stars studied here in detail, both HD 149404 (O9 Ia) and HD 152248 (O7 Ib:(n)(f)p) appear to be evolved. On the other hand, the classifications (see ref. 29) of TU Mus (O8·5 Vn) and HD 159176 (O7 V) imply no evolution, although we have had grounds to question that assumption for TU Mus[30].

The purpose of this contribution is principally to draw attention to the long-standing problem we have chosen to call the Struve-Sahade effect in the hope of stimulating a quantitative search for a solution, but it would be inappropriate to conclude without some speculation as to its cause. Clearly Struve was of the opinion that gaseous streams in these interacting systems were primarily responsible, although his ideas, expressed in *Stellar Evolution*, were essentially qualitative. That this seems to us as the most promising avenue of approach stems from the dynamical demand that any gas flow from the more luminous component tends to be directed first around the trailing side of the companion. Depending upon the density, geometry, and velocity of this gas, one might anticipate some impact on the spectrum of the component situated behind it, through both attenuation of the underlying spectrum and redirection of light from regions that might otherwise make a lesser contribution to the observed spectrum. This could yield a spectrum in which the photospheric features during recession of the less-luminous star would be weakened and/or distorted, as is observed. Unless the gas stream is drawn back around the less-luminous star, the leading side should present a more normal appearance, which is more or less the case for AO Cas although less certainly so for Plaskett's Star and 29 CMa. A difficulty for the gas-stream scenario is that the effect might be expected to be severely curtailed for systems where the inclination is not close to 90°, which is the case with AO Cas (about 50°); for 29 CMa (about 70°) the orientation is perhaps acceptable and for Plaskett's Star it is unknown but cannot be very close to 90° since eclipses are not observed.

A rather different direction has been taken by Gies *et al.*, who have proposed[34] that the cause of the problem lies on the leading face of the secondary which has been heated by proximity to the bow-shock region between the winds of the two stars, since the region of the bow shock closest to the surface of the secondary will be shifted towards the leading face by Coriolis deflection due to orbital motion. This heating will generate a higher surface luminosity at that point and will thus produce a stronger spectrum. We have some reservations that this scheme might not produce some of the more extreme effects that we observe: could the dramatic changes of strength between the quadratures witnessed for 29 CMa be achieved? Why would the (relatively) unheated trailing face of Plaskett's Star (and indeed the other two) give such poor velocities from a dynamical standpoint? And wouldn't the extra heating, while making the continuum brighter, weaken those ionic species which give the ccf its strength?

There is clearly much work to be done to elucidate the cause or causes of the Struve-Sahade effect, but without that work a cloud of doubt will always hang over the validity of fundamental data, and especially masses, derived for the most massive stars, if not for a plethora of smaller interacting systems. The observations presented here exhibit perhaps the most extreme cases but if we can resolve the situation for them, we would have confidence in the results for most other systems.

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