SPECTROSCOPIC BINARY ORBITS FROM ULTRAVIOLET RADIAL VELOCITIES

PAPER 23: π SCORPII (HD 143018)

By D. J. Stickland, C. Lloyd*, R. H. Koch† & I. Pachoulakis†*
**Rutherford Appleton Laboratory*
†University of Pennsylvania

Introduction

The binary nature of π Sco (HD 143018, HR 5944, 6 Sco) has been known for almost a century, having been announced by Pickering in 1899[1], and although the period of the system, 1·571 days, was determined by Bailey in 1902, it remained for Struve & Elvey[2] to produce the first determination of the orbit, on the basis of 48 prism spectrograms with a dispersion of about 40 Å mm^{-1} taken at Yerkes and Dearborn observatories. They found that the "lines are very broad and hazy and are difficult to measure", so it is not too surprising that their orbit for this pair of early B-type stars (B1V+B2 according to Hiltner *et al.*[3]) shows a fair amount of scatter, especially for the secondary. A more precise value of the period was uncovered as a result of further spectroscopic studies by Inglis[4] and by Hetzler & Summers[5], although little impression was made on the remaining orbital elements by this later work. The most recent attempt to improve matters was by Levato *et al.*[6] who provided the elements which now grace the *Eighth Catalogue*[7]; aside from the period, they are not in especially good agreement with the earlier studies, particularly with regard to the velocity amplitudes.

While the brightness of π Sco ($V=2^{m}\cdot 9$) renders it strange that more effort was not put into spectroscopic studies of this short-period system, the difficulties attending photometric work on very bright stars perhaps explain why no results of any comprehensive monitoring have been published; and yet Struve does refer[8] to the absence of any ellipticity effects.

It appears that rather more interest has been taken in the interstellar spectrum of π Sco, although the reddening of this member of the Upper Scorpius Complex is not extreme[9] ($B-V=-0\cdot 18$, $U-B=-0\cdot 91$, $E(B-V)=0\cdot 08$). Indeed, its interstellar lines have been sought both in the optical region of the spectrum (see, *e.g.*, ref. 10), and in the ultraviolet from the very beginnings of UV astronomy[11,12]. Almost certainly for this latter reason, the *IUE* archive was found to contain a number of high-resolution spectra which prompted us to see whether they might be used to improve the orbit.

IUE observations

Prior to a campaign in 1995 April, which ran through two orbital cycles and netted 16 short-wavelength (SWP) images, there were 11 suitable spectra for study; the journal of all of these observations is presented in Table I. Reduction of the spectra from the photometrically-corrected images proceeded, as usual, through the IUEDR routines[13] on the *Starlink* computers at RAL, whilst the DIPSO package[14] was employed in the analysis.

To put the *IUE* spectra on the same velocity reference frame, they were all cross-correlated against the interstellar spectrum of τ Sco; with the stellar and

TABLE I

IUE radial-velocity observations of π Scorpii

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*$^{-1}$
2035	3707·142	$\overline{3893}$·951	+115·3	+4·5	−187·6	+6·5
17328	5159·080	$\overline{2968}$·697	−46·1	+1·6	+47·2	−9·2
17383	5159·181	$\overline{2968}$·762	−2·7	−4·4	+4·4	+26·1
29142	6679·027	$\overline{2000}$·759	−5·3	−5·2	−29·8	−10·9
29143	6679·075	$\overline{2000}$·790	+14·8	−8·6	−71·4	−15·3
29144	6679·107	$\overline{2000}$·810	+42·2	+3·6	−91·2	−11·3
49984	9393·634	$\overline{271}$·706	−38·6	+2·3	+43·4	−2·2
49997	9396·423	$\overline{269}$·483	−132·2	−1·4	+186·6	−1·0
50051	9402·445	$\overline{265}$·318	−66·3	−7·3	+72·0	−2·2
50058	9402·698	$\overline{265}$·479	−130·5	0·0	+194·3	+7·2
54302	9813·287	$\overline{4}$·986	+122·3	+6·0	−190·0	+12·7
54358	9818·022	0·001	+119·8	+3·0	−193·2	+10·3
54362	9818·204	0·117	+88·3	+3·7	−143·0	+9·6
54365	9818·319	0·191	+41·8	+3·9	−86·8	−7·8
56366	9818·340	0·204	+25·2	−2·9	−72·8	−9·4
54367	9818·362	0·218	+11·1	−6·4	−46·9	−0·3
54368	9818·384	0·232	−4·7	−11·4	−25·7	+3·9
54372	9818·581	0·357	−85·5	−0·6	+115·4	+0·2
54380	9819·009	0·630	−93·1	−0·8	+132·2	+5·3
54384	9819·183	0·741	−15·5	−1·0	+10·1	+6·2
54388	9819·386	0·870	+76·5	−1·2	−137·0	+4·7
54393	9819·617	1·017	+116·3	+0·3	−204·5	−2·1
54398	9819·868	1·177	+50·7	+3·2	−102·3	−8·2
54409	9820·714	1·716	−36·7	−3·0	+37·0	+2·7
54413	9820·894	1·831	+52·6	−0·2	−108·1	−5·6
54417	9821·086	1·953	+113·6	+2·2	−188·4	+6·6
54422	9821·318	2·101	+94·1	+1·3	−151·9	+13·7

interstellar-line velocities known for that star[15] and the interstellar-line velocity available[10] for π Sco (−15 km s^{-1}), the whole set could be put on a near-absolute basis.

Measurement of the photospheric velocities of π Sco was carried out by cross correlation against the spectrum of γ Peg (B2 IV), which proved an ideal match for both components of the binary. Tests carried out with other standard stars delivered cross-correlation functions that were weaker and generally less well resolved, although the comparisons did confirm that the primary and more massive component is of slightly earlier spectral type than the secondary, perhaps by one subclass. Although three forms of the cross-correlation procedure were tried, wherein different approaches to the removal of the underlying 'continuum' are used, the results were essentially identical and give greater confidence in the final results. The measurements have been added to Table I. Although Struve & Elvey complained that the lines were "very broad and hazy", compared with other short-period systems covered in this series, *e.g.*, TU Mus[16], the lines were modest in width and the $v_e \sin i$ values have been estimated at 120 and 70 km s^{-1}, with errors of about 10 and 20%, for the primary and secondary, respectively.

Although Levato *et al.*[6] quote a small eccentricity, one is not evident in our results, and the elements listed in Table II are for circular solutions; Monet also concluded[17], from his reanalysis of the optical measurements, that the eccentricity was insignificant. Once again in this series, separate solutions were made

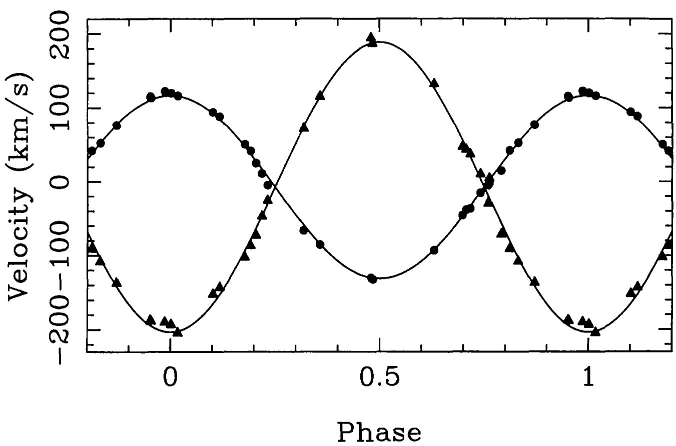

FIG. 1

The circular, double-lined orbital solution for π Sco based on *IUE* radial velocities. The measurements for the primary star are represented by ● while the secondary velocities are denoted by ▲.

TABLE II

Orbital elements of π Scorpii

	Both components	*Primary*	*Secondary*
P (days)	1·5700925±0·000019	fixed	fixed
γ_1 (km s^{-1})	−7·4±1·3	−8·3±0·9	−6·1±2·0
K_1 (km s^{-1})	124·1±1·5	126·8±1·3	
K_2 (km s^{-1})	196·1±1·8		193·6±2·9
e	0·0	0·0	0·0
ω (degree)	undefined	undefined	undefined
Tmax (−2 440 000)	9818·020±0·002	9818·017±0·002	9818·806±0·003
R.m.s. residual (km s^{-1})	7·2	3·9	9·0
q (M_1/M_2)	1·58±0·02		
$M_1 \sin^3 i$ ($M_\odot$)	3·28±0·07		
$M_2 \sin^3 i$ ($M_\odot$)	2·07±0·05		
$a_1 \sin i$ ($R_\odot$)	3·85±0·04		
$a_2 \sin i$ ($R_\odot$)	6·08±0·06		

for the two components but the difference found between their systemic velocities is small enough that the equal-weight, double-lined solution, depicted in Fig. 1, may be adopted for further discussion. Perhaps the major improvement over previous work is the precision given to the velocity amplitudes: we find 124·1 and 196·1 km s^{-1} for the primary and secondary, respectively, with errors less than 2 km s^{-1}, while Struve & Elvey quote 138 and 180 km s^{-1} (without errors) and Levato *et al.* give 121±5 and 156±6 km s^{-1}.

Discussion

The absence of any optical photometry indicating variability strongly suggests that the plane of the orbit of π Sco is not close to the line of sight: obvious variations would surely have encouraged a monitoring campaign of some description. However, the shortness of the period almost demands that variation at some level be sought and to that end we have examined the *IUE* spectra; all of them, except the first, were secured through the large aperture which admits all the light from point sources. A correction was made to the earlier spectra to

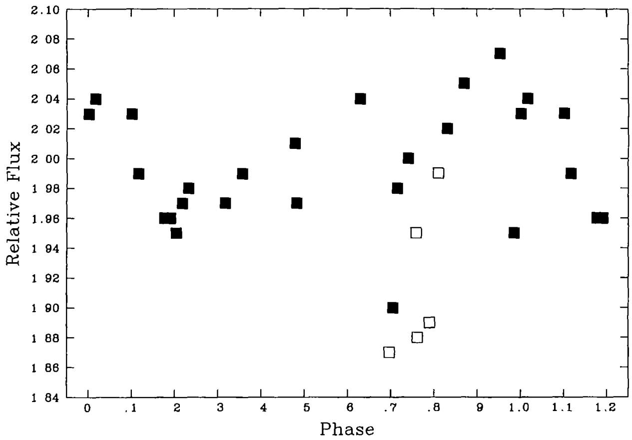

FIG. 2

Relative fluxes in the region 1300–1900 Å measured from *IUE* spectra, plotted as a function of phase in the circular orbit. Open symbols denote observations made before 1994/5.

account for the slight degradation of the cameras over the 17 years spanned by the observations; this was taken from the sensitivity-monitoring programme carried out at the *IUE* observatories and reported in the various *Proceedings* of the *IUE* Three-Agency Co-ordination Meetings. The accuracy is expected to be at the level of one or two per cent for the flux integrated over the bandpass 1300–1900 Å. The results are somewhat inconclusive (Fig. 2) but dips are apparent at the expected times of conjunction. Suffice it to say that these data are inadequate for a realistic attempt to model the light-curve, but they may act as an incentive for a more systematic campaign from the ground. (As an aside, it should be mentioned that the brightness of the star, as well as the recent problem of scattered sunlight, have made it impractical to use measurements from *IUE*'s Fine Error Sensor.)

The mass of a B1V star is estimated[18] to be about 11 $M_{\odot}$, which suggests that the inclination is about 42°. If the radius of such a star, representing the primary, is about 5 $R_{\odot}$, and that of the secondary is taken to be about 4 $R_{\odot}$, the system should be well detached, with the separation being 15 $R_{\odot}$. Some support is given to the suggested inclination by the estimates of the projected equatorial rotation velocities coupled with the assumption that the stars rotate synchronously with the orbit: the adopted radii and inclination yield values of $v_e \sin i$ of 108 and 87 km s^{-1} respectively, not significantly outside the errors on the measured values.

The ratio of strengths of the cross-correlation functions is a little over five and although no calibration exists relating such measures with spectral type, if we assume that this is a measure of the UV brightness ratio, we can get a very rough estimate of the luminosity ratio of the two components by applying a temperature correction based on the assumed spectral types and the model fluxes calculated by Kurucz *et al.*[19], and the bolometric corrections given by Allen[20]. This luminosity ratio is very approximately 3·7, so that the power of the *M–L* relationship given by these two stars is about 2·8. This reinforces the result discussed in the last paper in this series[21] and goes some way (although probably not all the way) to resolving the problem posed by Popper[22] concerning overluminous secondaries, *i.e.*, the *M–L* relationship for mid-B-type and cooler stars cannot be applied to objects at the uppermost end of the main sequence.

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REVEALING THE GALAXY ASSOCIATIONS IN ABELL 119

By V. G. Gurzadyan and A. Mazure†*
**Yerevan Physics Institute, Armenia*
†Laboratoire d'Astronomie Spatiale, Marseille

We report the results of an analysis of the hierarchical properties of the cluster of galaxies Abell 119. Observational data from the ESO Nearby Abell Cluster Survey (ENACS) are used, complemented by data from previous studies, while the analysis is performed with the *S*-tree method. The main physical system and three subgroups with truncated Gaussian velocity distributions are identified; we call these subgroups 'galaxy associations'. The mass centre of the core of the main system is shown to coincide with the X-ray centre of the cluster. An alignment of the mass centres of the three galaxy associations is also shown.