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A Discussion on New *VBLUW* Observations of the X-ray Binary Sk. 160 = SMC X-1

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Summary. *VBLUW* photometry (Walraven system) of Sk. 160 = SMC X-1 made in 1973, 1975, and 1977 are discussed. They are compared with those of van Paradijs (1977) made in 1976. Using all available photometric and X-ray mid-eclipse data, a new period is determined by a weighted least-squares solution: $P=3^d.89235\pm0^d.00002$ m.e.

Key words: X-ray binaries – photometry – variable stars

1. Introduction

VBLUW photometry (Walraven system) of the X-ray binary Sk. 160 = SMC X-1 has been made by the first author in 1973 and 1975 (van Genderen, 1974: a preliminary report, and 1977: hereafter called Paper I) and by van Paradijs (1977) in 1976. In Paper I only the observations in the *B* band have been given. Van Paradijs (1977) having made a much larger number of observations in 1976, gives them in all five passbands. Based on this larger sample van Paradijs and Zuiderwijk (1977) discussed it theoretically and found evidence for the existence of an accretion disk around the neutron star.

Between the large photometric routine programs, there was some time left to perform new observations during 1977 in *VBUW* and in a kind of white light called *l* (Sect. 2). These observations and those made in 1973 and 1975 are tabulated in Table 1.

2. The Observations and Reductions

The observations have been made with the *VBLUW* (Walraven system) simultaneous photometer, attached to the 90-cm light-collector of the Leiden Southern Station (at the SAAO annex) in South Afrika. Details and references on the photometric system and on the transformation into the *V* and *B–V* of the *UBV* system (with subscript *J*) can be found in the references mentioned in Sect. 1.

The new observations have been made from August to December 1977, but now the *L* filter (3840 A) which defines the *L* band, was removed. The resulting readings were higher by a factor three as compared to the readings of the *B* band, which has normally the highest response. The reason was to suppress the scatter. The so obtained intensity, called *l*, is the sum of the intensities of the wavelength areas between the other passbands *V*, *B*, *U*, and *W* (Walraven and Walraven, 1960). In this manner *l* is a kind of white light.

Another difference with the years 1973 and 1975, is the fact that HD 7187, a galactic foreground star, has been used as a comparison star instead of Sk. 159, a B0 Ia member of the SMC. HD 7187 has been also used by van Paradijs.

The averages of two to four measurements each of an integration time of 2 min are corrected for differential extinction and tabulated in Table 1.

3. The Period

The latest period so far was determined by Bonnet-Bidaud and van der Klis (1981).

$P=3^d.89239\pm0^d.00007$ m.e.

They used five X-ray eclipse centres and only one optical eclipse centre.

Table 2 lists all these eclipse centres together with three photometric eclipse centres, amongst others a new one of this paper.

Since there is some difference between the accurateness with which these eclipse data are determined (see for example the Ariel 5 Satellite epoch), it was decided to perform a weighted least squares solution. The weights assigned to the eclipse centres and listed in column two are based on the size of the estimated errors. The solution resulted in the following new formula for the centre of mid-eclipse:

$$\text{time of mid-eclipse} = \text{Hel. J.D. } 2443000.163 + 3^d.89235\,E$$
$$\pm 0.002 \quad 0.00002 \text{ m.e.}$$

Column six lists the O–C values.

As a matter of interest this formula is tried on the photographic observations discussed by Butler and Byrne (1973) made between 12 and 23 yr ago, to check the constancy of the orbital revolution. Although the scatter is large, there is no reason to believe that the period is subject to large variations. (Yet the scatter is not much of an improvement when compared with that based on a period of $3^d.89284$, determined by Butler and Byrne.)

4. The Light Curves

Figure 1 depicts the *l* light curve relative to the comparison star HD 7187 (in log intensity scale). Observations made in the same night, but with a time interval of several hours are connected by

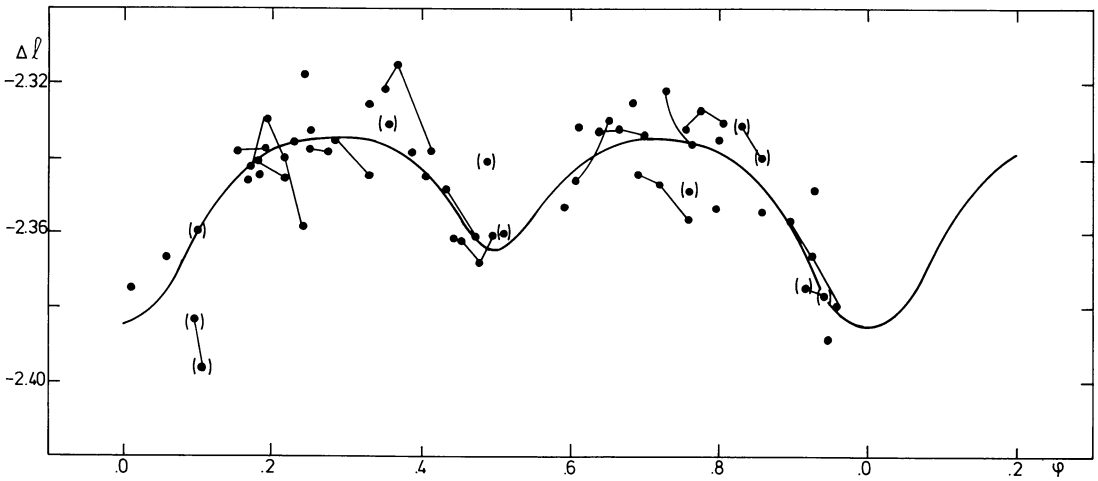

Fig. 1. The light curve in l of Sk. 160 relative to HD 7187 (in log intensity scale). Phases are according to the new ephemeris of Sect. 3. Observations made in the same night are connected by a line. Unreliable observations are bracketed

Table 1. *VBLUW* and *l* observations of Sk. 160 = SMC X-1 relative to HD 7187 (in log intensity scale)

J.D. – 244 0000	ΔV	Δ(V–B)	Δ(B–U)	Δ(U–W)	Δ(B–L)	Δl
1867.597	-2.480	-.076	-.491	-.075	-.195	
1870.576	-2.432	-.072	-.530	-.051	-.210	
1889.514	-2.437	-.081	-.514	-.089	-.192	
1891.556	-2.424	-.067	-.518	-.023	-.227	
1894.545	-2.474	-.088	-.512	-.098	-.203	
1896.556	-2.459	-.060	-.517	-.038	-.190	
1897.576	-2.430	-.071	-.516	-.117	-.191	
1903.576	-2.426	-.081	-.515	-.137	-.228	
1905.545	-2.427	-.082	-.504	-.088	-.200	
1915.413	-2.429	-.074	-.497	-.071	-.187	
1917.389	-2.439	-.058	-.507	-.122	-.213	
1917.500	-2.462	-.078	-.515	+.044	-.208	
1918.417	-2.454	-.068	-.508	-.093	-.210	
1922.410	-2.448	-.068	-.526	-.090	-.203	
1923.474	-2.448	-.080	-.484	-.129	-.199	
1923.539	-2.456	-.105	-.509	-.098	-.193	
1925.500	-2.462	-.088	-.487	-.159	-.202	
1931.517	-2.476	-.086	-.493	-.186	-.188	
1941.448	-2.464	-.080	-.505	-.032	-.195	
1944.358	-2.401	-.072	-.520	-.109	-.219	
1944.385	-2.445	-.122	-.512	-.227	-.196	
1944.580	-2.409	-.074	-.487	-.195	-.169	
1945.375	-2.466	-.070	-.520	-.095	-.208	
1948.382	-2.450	-.095	-.510	-.072	-.201	
1951.375	-2.442	-.066	-.537	-.099	-.205	
1956.380	-2.443	-.070	-.533	-.093	-.210	
1959.444	-2.443	-.064	-.506	-.062	-.196	
1985.316	-2.411	-.077	-.511	-.152	-.201	
2004.292	-2.423	-.065	-.506	-.122	-.227	
2006 320	-2.428	-.073	-.506	-.073	-.223	
2014.320	-2.466	-.106	-.525	-.006	-.216	
2712.360	-2.463	-.067	-.520	-.147	-.199	
2714.341	-2.468	-.077	-.508	-.139	-.177	
2716.267	-2.479	-.060	-.506	-	-.197	
3364.524	-2.438	-.098	-.515	-.130		-2.331
3371.434	-2.401	-.062	-.492	-.122		-2.338
3374.465	-2.407	-.069	-.493	-.241		-2.345
3375.556	-2.436	-.057	-.538	-.090		-2.361
3376.475	-2.394	-.075	-.503	+.062		-2.325
3377.424	-2.423	-.076	-.474	-.025		-2.348
3378.424	-2.425	-.082	-.499	-.145		-2.344
3383.493	-2.471:	-.124:	-.502:	-.090:		-2.341:
3387.476	-2.446:	-.082:	-.506:	+.009:		-2.360:
3388.448	-2.420	-.068	-.503	-.092		-2.349
3392.483	-2.443	-.079	-.499	-.185		-2.353
3394.382	-2.411	-.072	-.483	-.087		-2.335
3394.559	-2.416	-.069	-.488	-.133		-2.344
3398.447	-2.395	-.056	-.508	-.435		-2.325
3401.435	-2.446:	-.074:	-.491:	-.123:		-2.383:

Table1 (continued)

J.D. – 244 0000	ΔV	Δ(V–B)	Δ(B–U)	Δ(U–W)	Δ(B–L)	Δl
3401.489	-2.470	-.088:	-.507:			-2.396:
3403.375	-2.421	-.060	-.563	-.032		-2.353
3406.323	-2.384	-.061	-.529	-.263		-2.321
3406.385	-2.386	-.076	-.486	-.236		-2.314
3406.565	-2.426	-.094	-.477	-.129		-2.338
3416.309	-2.471:	-.104:	-.540:			-2.375:
3416.403	-2.475:	-.069:	-.506:	-.307:		-2.377:
3417.308	-2.412	-.079	-.530	-.175		-2.342
3417.385	-2.400	-.050	-.502	-.116		-2.329
3417.474	-2.408	-.070	-.512	-.022		-2.339
3417.571	-2.436	-.096	-.468	-.016		-2.358
3421.471	-2.397	-.075	-.518	-.117		-2.317
3422.282	-2.457	-.085	-.490	-.063		-2.362
3422.392	-2.449	-.073	-.488			-2.368
3422.453	-2.446	-.075	-.489	-.044		-2.360
3423.359	-2.413	-.086	-.502	+.167:		-2.322
3423.500	-2.419	-.085	-.492	-.160		-2.336
3427.349	-2.425	-.081	-.526	-.421		-2.332
3427.425	-2.416	-.081	-.517	-.262		-2.327
3427.554	-2.400	-.071	-.517	-.215		-2.331
3428.346	-2.479	-.105	-.488	-.186		-2.374
3429.290	-2.413	-.074	-.490	-.101		-2.337
3429.378	-2.418	-.079	-.513	-.137		-2.338
3431.420	-2.419	-.084	-.502	-.060		-2.335
3436.322	-2.440	-.084	-.475	-.143		-2.366
3439.315	-2.431:	-.099:	-.494:	-.155:		-2.332:
3439.428	-2.413:	-.072:	-.497:	-.067:		-2.340:
3440.365	-2.456:	-.089:	-.503:	-.118:		-2.359:
3441.371	-2.409:	-.075:	-.492:	-.006:		-2.331:
3449.346	-2.432	-.081	-.489	-.028		-2.344
3450.262	-2.414	-.075	-.472	-.164		-2.333
3450.362	-2.409	-.072	-.486	-.109		-2.332
3450.494	-2.405	-.070	-.479	-.109		-2.334
3451.254	-2.445	-.080	-.497	-.238		-2.357
3451.369	-2.440	-.074	-.492	-.191		-2.366
3451.490	-2.457	-.092	-.487	-.210		-2.380
3452.371	-2.414	-.069	-.477	-.194		-2.340
3452.505	-2.424	-.080	-.520	-.161		-2.345
3453.338	-2.422	-.050	-.530	-.164		-2.348
3453.508	-2.433	-.079	-.502	+.031		-2.361
3458.250	-2.428	-.081	-.492	-.173		-2.344
3458.357	-2.431	-.084	-.493	-.224		-2.347
3458.491	-2.433	-.094	-.476	-.131		-2.356
3460.340	-2.434	-.100	-.491	-.232		-2.335
3464.327	-2.401	-.073	-.485	-.485		-2.332
3481.268	-2.416	-.070	-.482	-.174		-2.346
3481.440	-2.412	-.078	-.475	-.213		-2.330
3487.286	-2.427	-.084	-.475	-.191		-2.338
3487.431	-2.411	-.078	-.491	+.015		-2.337
3494.268	-2.490	-.087	-.517			-2.389
3496.263	-2.447:	-.061:	-.520:	-.042:		-2.400:

a line. Unreliable observations are bracketed. Since the maxima are practically symmetric, the smooth curve is determined by combining the observations between $\phi = 0.0$ and 0.5 with those of $\phi = 0.5$ and 1.0. There is however no confirmation of a dip between $\phi = 0.5$ and 0.7 as in the case of the curve of van Paradijs. More observations are likely needed to confirm the reality of that phenomenon. This dip arose according to van Paradijs and Zuiderwijk by the presence of an accretion disk around the neutron star.

Figure 2 depicts the light curves in the Walraven V and B bands relative to HD 7187 (in log intensity scale) and folded at $\phi = 0.5$. The scatter is as expected larger than for l. Small and

Table 2. List of observed Hel. J. D. of mid-eclipses of Sk. 160 = SMC X-1

Hel. J. D. mid eclipse		Technique and Reference	Weight	E	O–C (d)
2440964.49	±0.02	X-ray (Uhuru) Schreier et al., 1972	2	−523	+0.026
1867.44	0.04	Photom. (*VBLUW*) van Genderen, 1976	1	−291	−0.049
2276.15	0.04	X-ray (Copernicus) Tuohy and Rapley, 1975	1	−186	−0.036
2836.69	0.01	X-ray (SAS-3) Primini et al., 1976	4	− 42	+0.006
3000.1562	0.0016	X-ray (Ariel-5) Davison, 1976	20	0	−0.007
3019.59	0.04	Photom. (*VBLUW*) van Paradijs, 1977	1	5	−0.035
3116.9443	0.0022	X-ray (Cos-B) Bonnet-Bidaud and van der Klis, 1981	15	30	+0.010
3428.35	0.04	Photom. (*VBLUW*) this paper	1	110	+0.028

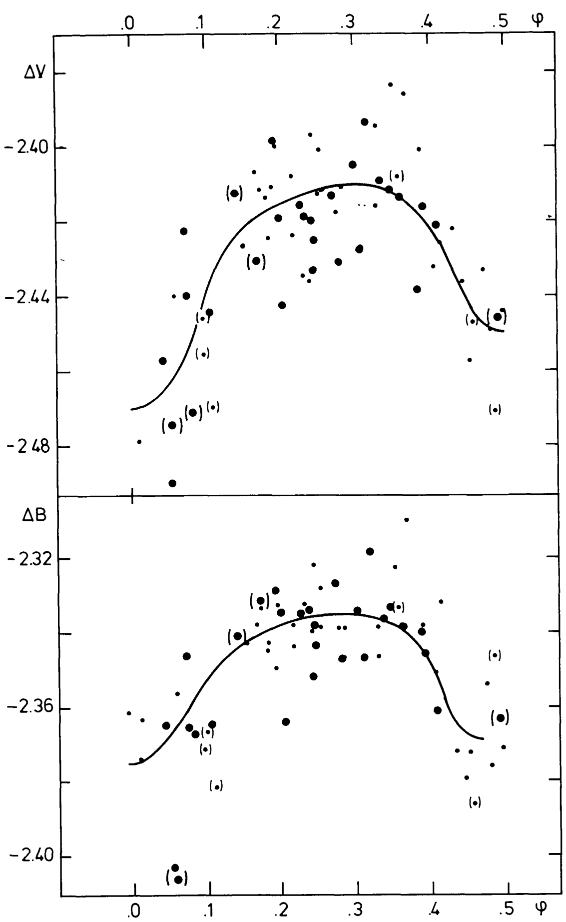

Fig. 2. The light curves in V and B relative to HD 7187 (in log intensity scale) and folded at $\phi = 0.5$. Phases are according to the new ephemeris of Sect. 3. Unreliable observations are bracketed. Small dots: $\phi = 0.0$ to 0.5, large dots: $\phi = 0.5$ to 1.0

Table 3. Amplitudes of the light curves of Sk. 160 (in mag), (between brackets amplitudes according to van Paradijs, 1977)

Channel	Ampl. (1)	Ampl. (2)
V	0.15 (0.123)	0.10 (0.075)
B	0.10 (0.085)	0.088 (0.055)
l	0.125	0.075

large dots represent observations made between $\phi = 0.0$ und 0.5 and between $\phi = 0.5$ and 1.0 respectively.

Similar to the van Paradijs curves, the amplitude in B is smaller than in V, therefore the $V-B$ index is bluest in the minima (see van Paradijs). This is in contrast with the X-ray binaries HD 153919 and HD 77581 (= Vela X-1), where we see the opposite result (e.a. Zuiderwijk et al., 1977; Hammerschlag-Hensberge and Zuiderwijk, 1977; van Genderen and Windhorst, 1981; van Genderen, 1981). Zuiderwijk et al. (1977) showed that the orbital variations of the colours in HD 77581 are indicative of temperature and gravity variations over the ellipsoidal stellar surface. It is therefore odd that Sk. 160 does not show this physical effect and that even the opposite is observed. Perhaps Sk. 160 has intenser circumstellar complicating gas streams.

It is remarkable that the minima of this paper are narrower and consequently the maxima broader than those made in 1976 by van Paradijs. It is possible that statistical effects and scatter in both light curves are the cause of this difference.

Table 3 tabulates the light amplitudes for V, B, and l in mag. Ampl. (1) corresponds to the difference between the minimum at $\phi = 0.0$ and maximum, ampl. (2) corresponds to that between $\phi = 0.5$ and maximum. Those of van Paradijs are added between brackets. Within the range of the uncertainties, there is not much evidence of a change between 1976 and 1977.

5. The Colour Indices and the Reddening

No colour curves are shown, since the number of observations is too small to see colour changes during the orbital revolution (see therefore van Paradijs).

As mentioned before the comparison star used in 1973/1975 was different from the one used in 1976 (by van Paradijs) and 1977. In order to check whether the *VBLUW* data of the two comparison stars are consistent and to check the constancy of the average photometric parameters of Sk. 160, the 1973/1975 observations are transformed into values relative to HD 7187. Table 4 tabulates the median values in chronological order. In V the systematic differences are larger than one would conclude on account of the scatter in the light curve. The systematic differences in the colour indices $B-L$ and $B-U$ (underlined values) are also too large. In case of real physical changes say in one of the stars, one expects consistent changes in $B-L$ and $B-U$ in one and the same season. Since this is not the case, it is likely that systematic errors in the *VBLUW* data are the cause. The last line in Table 4 shows the averages for Sk. 160 on the standard *VBLUW* and *UBV* systems. These figures have been obtained by adding the

Table 4. Median photometric parameters of Sk. 160 relative to HD 7187 and averages on the standard *VBLUW* and *UBV* systems

Year and Ref.	Comparison star used	V	$V-B$ (log intensity)	$B-L$	$B-U$	$U-W$	V_J (mag)	$(B-V)_J$
1973/1975, van Genderen (1977)	Sk. 159	−2.445	−0.075	−0.202	−0.510	−0.10		
1976, van Paradijs (1977)	HD 7187	−2.43	−0.071	−0.214	−0.511	−0.12		
1977, this paper	HD 7187	−2.44	−0.075		−0.500	−0.10		
Averages on the standard systems		−2.54	−0.045	−0.035	−0.073	+0.006	13.23	−0.14

differential values of Table 4 to the *VBLUW* and *UBV* data of HD 7187 as listed by van Paradijs.

The interstellar reddening is derived by plotting these averages in the three two-colour diagrams of the *VBLUW* system. A reddening of $E_{V-B}=0.04\pm0.005$ seems to be the best value, consistent with that used by van Paradijs and Zuiderwijk. Thus $E_{(B-V)_J}=0.11\pm0.014$ mag.

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