THE ASTROPHYSICAL JOURNAL, **193**:647–650, 1974 November 1

PARALLAX, ORBIT, AND MASS OF THE BINARY STAR 70 OPHIUCHI

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Received 1974 May 6

ABSTRACT

Plates taken with the Sproul refractor over the interval 1914–1971 give a relative parallax of +0".207 ± 0".007 (p.e.) and a fraction mass $f = 0.445 \pm 0.003$. With combined values for π and f, and a revised orbit ($P = 88.13$ yr; $a = 4''.545$; $K_1 = 3.3$ km s^{-1}), component masses $A = 0.81\ M_{\odot}$ and $B = 0.64\ M_{\odot}$ are obtained. The lack of evidence for a third body is sustained.

Subject headings: stars, individual — visual double or multiple stars

I. PARALLAX AND MASS RATIO

The well-known visual binary 70 Ophiuchi (BD + 2°3482 = ADS 11046) has components with visual magnitudes 4.2–6.0, and spectral types K0 V and K5 V. Since the last Sproul parallax determination (van de Kamp 1939) from measurements of the primary star on 48 plates, the material from the 24-inch (61-cm) refractor (scale 18".87 mm^{-1}) has increased to 136 plates on 60 nights, beginning in 1914. Although the series is of substandard quality and contains few morning plates, it was terminated in 1971 as the binary closed in; the images would now be blended for more than 20 years. Some measurable images of the companion on 20 nights (1914–1942 and one 1963 plate) are included in the present evaluation. The doubled weight of the parallax is somewhat offset by the increased probable error of unit weight (0".045 on the new Sproul weight scale), but the weight of the mass ratio has increased fourfold.

All plates were measured on the two-screw Grant measuring machine in both right ascension and declination in one direction. Linear plate constants were computed from the same reference stars as used before:

1. AC +2°18^{h}00^m no 121: $m_{pv} = 10.3$
2. BD +2°3479: $m_{pv} = 9.9$
3. BD +2°3483: $m_{pv} = 9.9$
4. BD +2°3487: $m_{pv} = 9.6$

In the new telescope tailpiece installed in 1967, narrow sectors for six and more magnitudes of light extinction cause diffraction. This has affected the present results (sector 6.2 mag) as it did in a recent study of β Persei (to be published by J. Hershey and P. Bachmann). Slight blending with the approaching companion may also have contributed to the effect.

Separate solutions for right ascension and declination, and for each component, were computed as well as combined ones (Heintz 1971). The two components agree to within the probable errors. Some other features of the combined solutions should be mentioned (all errors are p.e.):

1. From the complete material as it stands, the relative parallax $\pi = +0''.217 \pm 0''.008$ is obtained, the difference $\pi(\alpha) - \pi(\delta)$ being $-0''.040 \pm 0''.043$. The residuals are given in table 1. In this case, the mass ratio is $f = 0.451 \pm 0.003$.

2. The 1939 result ($\pi = 0''.172$) was influenced by the fact that virtually all of the few morning plates were poor. From remeasurements of the same material

TABLE 1
MEAN RESIDUALS FROM THE COMBINED MATERIAL
(unit 10^{-4} mm = 0".00189)

TIME	SOLUTION I (uncorrected) $\Delta\alpha \cos\delta$	SOLUTION I (uncorrected) $\Delta\delta$	SOLUTION IV (corrected) $\Delta\alpha \cos\delta$	SOLUTION IV (corrected) $\Delta\delta$	TOTAL WEIGHT
1914.9	+ 8	+14	+ 7	− 2	13
1921.4	−16	+ 3	−20	− 5	7
1934.8	−16	+ 9	−11	+12	17
1938.4	+12	− 8	+10	− 2	22
1942.8	+10	−13	+ 9	− 5	12
1955.3	−14	−23	+ 2	− 1	9
1958.8	−25	−27	− 9	− 4	11
1964.4	−29	−22	0	+ 2	6
1968.9	− 1	+ 4	−19	−24	10
1970.8	+34	+49	+17	+27	10

(1914–1938, primary star only), but omitting the very poor plates, π changes to $+0''.200 \pm 0''.010$.

3. The combined solution 1914–1965, omitting the diffracted plates, makes $\pi = +0''.206 \pm 0''.008$.

4. Finally, the 1967 discontinuity was determined by a least-squares solution and taken out. This result was adopted because of its slightly lower probable errors, although the difference $\pi(\alpha) - \pi(\delta)$ now rises to $-0''.059 \pm 0''.038$. The results are

$$\mu_\alpha = +0''.2599 \pm 0''.0002\,,$$

$$\mu_\delta = -1''.0839 \pm 0''.0004\,,$$

$$\pi = +0''.2069 \pm 0''.0072\,,$$

$$\alpha = +2''.021 \quad \pm 0''.0012\,,$$

and the residuals are listed in table 1. The semiaxis major α of the primary orbit yields a fractional mass $f = \alpha/a = B/(A + B) = 0.445 \pm 0.003$. No motion of the reference frame is shown by the present result, as recent transit observations indicate that the proper motion μ_δ of 70 Oph is close to $-1''.08$, and that the GC value of $-1''.097$ is too large. It is seen from table 1 that no systematic residuals indicative of a third body remain.

TABLE 2

THE ORBITAL ELEMENTS

$P = 88.13$ yr	$\omega = 13.2$
$\mu = 4.0849$	$\Omega = 301.7$ asc
$T = 1984.05$	prec. $= -0°.0056(t - 2000)$
$e = 0.500$	$K_1 = 3.26$ km s^{-1}
$f = 0.442$	$A = +1''.8684$
$\gamma = -7.15$ km s^{-1}	$B = -4''.0469$
$a = 4''.545$	$F = -2''.4928$
$i = 121°.15$	$G = -0''.3197$

II. THE ORBIT

Visual observers have vastly overdone this bright pair in the past, and many hundreds of poor observations by inexperienced observers have to be rejected. Moreover, in this particular case several well-known and reliable observers show conspicuous systematic errors in the separations. For this reason, the third-body hypothesis has repeatedly been preferred to the assumption of rather unbelievably large errors, until photographic measurements enabled Strand to present strong evidence to the contrary. An agreement on the elements of the hypothetical body had not been reached anyway, except for a period of 17 or 18 years

TABLE 3

PHOTOGRAPHIC OBSERVATIONS AND RESIDUALS (equator 2000)

t	θ	ρ	n		$O - C$	
1915.198.....	140°.51	4''.556	7	P π	−0°.2	−0''.01
1916.960.....	137.59	4.941	3	P π	−0.1	+0.02
1919.328.....	134.26	5.373	3	P π	−0.1	+0.02
1922.989.....	130.01	5.931	6	K P	0.0	+0.03
1926.921.....	125.59	6.363	7	K MC Mos	−0.4	+0.04
1928.965.....	124.09	6.477	3	K D	0.0	−0.01
1931.965.....	121.33	6.654	11	J MC Mos π	−0.2	0.00
1934.653.....	119.26	6.761	3	MC π	0.0	+0.03
1935.572.....	118.30	6.762	12	P MC π	−0.2	+0.02
1936.588.....	117.64	6.755	5	MC π	0.0	+0.01
1937.608.....	116.69	6.747	10	L MC π	−0.1	+0.01
1938.558.....	115.96	6.742	4	MC π	0.0	+0.02
1939.565.....	115.04	6.713	7	S MC π	−0.1	+0.01
1940.594.....	114.09	6.666	6	S	−0.2	0.00
1941.581.....	113.38	6.620	8	S MC π	0.0	−0.01
1942.583.....	112.49	6.568	5	S MC π	−0.1	−0.01
1947.912.....	107.45	6.167	6	D L	−0.2	−0.01
1949.622.....	105.59	5.981	9	D L	−0.3	−0.01
1950.570.....	104.72	5.884	9	D Lm L	−0.1	0.00
1951.463.....	103.69	5.786	12	D Lm	−0.2	+0.01
1952.584.....	102.49	5.626	9	D	−0.1	−0.01
1953.536.....	101.47	5.496	13	D P	+0.1	0.00
1954.510.....	100.16	5.370	13	D P Lm L	0.0	+0.01
1955.512.....	98.84	5.205	12	D P Lm	0.0	0.00
1956.530.....	97.28	5.039	10	W	−0.1	0.00
1957.552.....	95.79	4.880	13	W M Vl LM P	0.0	+0.01
1958.571.....	93.95	4.648	3	W Vl	−0.1	−0.04
1959.374.....	92.53	4.533	8	W	−0.1	−0.01
1960.421.....	90.54	4.347	13	W	−0.1	0.00
1961.421.....	88.45	4.165	7	W	−0.1	+0.01
1962.430.....	86.27	3.951	11	W P	0.0	−0.01
1963.470.....	83.71	3.741	7	W	+0.1	0.00
1964.541.....	80.60	3.516	20	W	+0.1	−0.01
1965.588.....	77.25	3.295	11	W	+0.1	−0.01
1966.549.....	73.90	3.099	6	W	+0.3	−0.01
1967.443.....	70.09	2.906	4	W	+0.2	−0.02

TABLE 4

Visual Observations and Residuals (equator 2000)

t	θ	ρ	$O - C$		t	θ	ρ	$O - C$	
1825.57......	147°2	3″98	+3°6	−0″25	1902.64......	211°3	1″70	−0°6	+0″12
1828.15......	140.9	4.65	+2.1	−0.14	1903.56......	197.3	1.73	−1.6	+0.03
1829.59......	137.1	5.09	+0.5	+0.02	1904.55......	187.1	1.92	0.0	+0.01
1831.44......	134.1	5.38	+0.1	−0.01	1905.54......	178.2	2.18	+0.4	+0.03
1834.51......	130.8	5.88	+0.4	+0.03	1906.63......	170.3	2.39	+0.7	−0.06
1837.01......	128.1	6.14	+0.4	−0.01	1907.58......	164.6	2.73	+0.6	+0.08
1840.37......	125.2	6.49	+0.7	+0.04	1908.56......	159.9	2.99	+0.7	+0.07
1842.15......	123.3	6.54	+0.3	−0.03	1909.55......	155.2	3.23	0.0	+0.04
1844.82......	121.0	6.59	+0.3	−0.10	1910.56......	151.7	3.48	0.0	+0.03
1847.05......	119.0	6.69	+0.2	−0.04	1911.60......	148.9	3.70	+0.2	−0.02
1849.48......	116.6	6.79	−0.2	+0.05	1912.59......	146.5	3.90	+0.4	−0.07
1852.09......	114.0	6.63	−0.6	−0.05	1913.51......	143.7	4.13	−0.3	−0.05
1854.21......	112.7	6.43	−0.1	−0.16	1914.53......	141.2	4.39	−0.7	−0.03
1856.19......	111.3	6.38	+0.3	−0.09	1915.49......	139.9	4.57	−0.3	−0.05
1857.90......	109.1	6.23	−0.3	−0.11	1916.54......	138.2	4.84	−0.2	0.00
1860.78......	106.3	6.13	−0.3	+0.06	1917.55......	136.7	4.96	−0.1	−0.08
1863.26......	104.0	5.68	0.0	−0.11	1918.59......	135.5	5.20	+0.2	−0.03
1865.94......	101.0	5.32	+0.3	−0.10	1919.57......	134.1	5.38	+0.1	−0.01
1868.47......	97.7	4.94	+0.5	−0.09	1920.57......	132.9	5.55	+0.1	0.00
1871.23......	92.7	4.45	0.0	−0.10	1921.57......	131.2	5.78	−0.4	+0.08
1872.86......	89.9	4.14	+0.4	−0.10	1922.61......	130.3	5.85	−0.1	0.00
1875.28......	84.6	3.63	+0.9	−0.13	1923.55......	129.3	5.98	−0.1	+0.01
1876.56......	80.2	3.42	+0.1	−0.07	1924.54......	128.0	6.05	−0.3	−0.04
1877.63......	77.2	3.21	+0.7	−0.06	1925.54......	127.4	6.12	+0.1	−0.07
1878.57......	74.1	3.06	+1.1	−0.02	1926.77......	125.6	6.25	−0.5	−0.06
1879.59......	69.2	2.91	+0.6	+0.04	1929.09......	123.4	6.52	−0.6	+0.02
1880.58......	64.1	2.68	+0.4	+0.01	1931.07......	121.8	6.63	−0.5	+0.02
1881.64......	58.2	2.49	+0.6	+0.02	1932.92......	121.0	6.66	+0.3	−0.03
1882.60......	51.4	2.29	+0.2	−0.01	1935.70......	118.5	6.71	+0.2	−0.03
1883.62......	43.6	2.24	+0.2	+0.09	1938.08......	116.1	6.73	−0.3	0.00
1884.61......	34.7	2.19	0.0	+0.17	1940.33......	114.6	6.67	+0.1	0.00
1885.60......	25.7	2.02	+0.5	+0.08	1943.15......	112.2	6.54	+0.1	0.00
1886.64......	13.5	1.98	−0.9	+0.09	1945.97......	109.2	6.25	−0.3	−0.10
1887.65......	2.9	1.97	−0.7	+0.08	1948.57......	106.9	6.01	−0.1	−0.10
1888.59......	352.8	2.05	−1.1	+0.12	1951.47......	103.4	5.78	−0.5	0.00
1889.57......	344.6	2.03	+0.4	+0.04	1954.30......	100.2	5.34	−0.2	−0.05
1890.62......	335.2	2.16	+0.6	+0.07	1955.91......	97.8	5.04	−0.4	−0.10
1891.58......	326.6	2.24	0.0	+0.07	1957.53......	95.9	4.92	+0.1	+0.05
1892.56......	320.0	2.27	+0.9	+0.02	1959.11......	93.7	4.61	+0.6	+0.02
1893.63......	311.3	2.30	0.0	0.00	1961.35......	88.9	4.14	+0.2	−0.03
1894.65......	304.0	2.30	−0.1	0.00	1962.88......	85.9	3.79	+0.8	−0.08
1895.60......	297.7	2.26	+0.5	0.00	1965.07......	78.7	3.36	−0.2	−0.05
1896.60......	288.7	2.20	−0.7	+0.05	1966.87......	73.0	2.90	+0.7	−0.14
1897.60......	281.0	2.02	+0.3	+0.01	1969.05......	61.8	2.60	−0.1	0.00
1898.54......	271.5	1.90	+0.3	+0.04	1970.57......	53.0	2.43	+0.6	+0.10
1899.56......	259.5	1.80	+0.6	+0.11	1971.55......	46.0	2.12	+1.0	−0.05
1900.55......	244.8	1.64	−0.1	+0.06	1972.52......	36.9	1.98	+0.1	−0.07
1901.63......	226.9	1.60	−0.9	+0.07	1973.43......	28.6	1.85	+0.4	−0.11

on which Berman (1932) and Reuyl and Holmberg (1943) agreed.

Forty orbits have been published for this pair, the latest elements being contained in Strand's studies (1937, 1952). Since then, the observed motion has fallen increasingly behind prediction, at present by 3°. Small though this difference is, it may impair the mass-ratio and third-body analysis. It is removed by the revised elements of table 2. The representation of the photographic data (table 3) shows no significant short-period effect, and the residuals from recent visual data (table 4) also are no longer uncommonly large. The changes in the elements due to proper motion are still negligible.

In the photographic places of table 3, some multiple-exposure plates of lower accuracy (Königsberg, McCormick, Moscow, München) are given half plate weight. Some astrometric plates are included with weights 0.1 or 0.05, and are indicated by the letter π without being counted with the plate numbers n. The visual means in table 4 have been formed from the following observations:

1825–1837: Σ only.

1839–1884: OΣ, Da, Ma, Kai, Gsh, Jac, Dem, Se, Mrt, Auwers, Romberg, Hl, En, Dun, Searle, Main, Knott, WS, Sp, Jed, Dob, Plm, Winn, Schur, Stone, Goldney, Howe, Egbert, Franz, Perr, Prit, HΣ, Tarr, Cel, Com, Maw, Lv, and some Washington observers. Compare the lists by Schur (1894) and by Strand (1937), p. 59.

1885–1926: Chiefly the means of ADS and Strand, with a few measurements rejected, added, or weighted differently.

1926–1973: GΣ, Bz, Phil, Kom, Dob, Ol, B, ϕ, V, VB, Beals, Sim, Pokr, Brt, Rabe, Duruy, Kpr, Mlr, Strand, Korbut, Semirot, Ahnert, Armellini, Fl-G, Cester, Clouet, Sagot, Postma, Soulie, C, Kni, Wak, New, Wor, hz, and the Beograd, Babelsberg, Vatican, and Greenwich observers. The last five places contain few observations.

In the solution, equal total weight was given to each photographic coordinate and to the visual position angles (the latter extending over an angular motion seven times the photographic coverage), and one fifth thereof to the visual separations.

The published radial velocities from Lick, Cape, Mount Wilson, and Victoria end in 1931. Hence, the derived amplitude $K_1 = 2.97 \text{ km s}^{-1}$, corresponding to $f = 0.403$, is weakly determined. The final ratio 0.442 gives the elements K_1 and γ in table 2, and the residuals in table 5. The early Mount Wilson measurements of the secondary have been excluded. The ephemeris provided by table 6 covers the periastron section of the orbit.

III. DISCUSSION

Other determinations of the relative parallax of 70 Oph are (cf. Strand 1952):

Allegheny:	+0.″192 ±	0.″004;
McCormick:	0.191	0.004;
Yale:	+0.″211 ±	0.″008;
Yerkes:	0.210	0.006.

TABLE 5

The Radial Velocities

t	RV	n		$O - C$
Primary:				
1898.07	−10.3	3	L	+ 0.9
1901.85	− 9.6	2	L	− 0.5
1905.49	− 8.4	1	L	− 0.7
1909.14	− 6.7	6	L 5 C 1	+ 0.1
1910.93	− 6.2	4	L	+ 0.3
1913.49	− 7.0	5	L C 2 W 1	− 0.8
1918.02	− 5.1	7	L 4 W 2 V 1	+ 0.7
1924.10	− 6.8	7	W 4 L 2 V 1	− 1.2
1929.88	− 5.0	3	L	+ 0.5
1931.66	− 5.2	5	L	+ 0.3
Secondary:				
1912.91	−18.4	6	W	−10.1
1923.07	− 8.6	5	W 3 V 2	+ 0.5

TABLE 6

Ephemeris (equator of date)

t	θ	ρ	RV(A)
1974.0	22.°6	1.″92	− 9.0
1975.0	12.1	1.89	− 9.4
1976.0	1.5	1.90	− 9.7
1977.0	351.2	1.94	−10.1
1978.0	341.5	2.02	−10.5
1979.0	332.6	2.11	−10.9
1980.0	324.5	2.20	−11.3
1981.0	316.9	2.27	−11.7
1982.0	309.7	2.31	−11.9
1983.0	302.6	2.30	−12.0
1984.0	295.3	2.23	−12.0
1985.0	287.3	2.12	−11.7
1986.0	278.3	1.97	−11.3
1987.0	267.5	1.80	−10.7
1988.0	254.8	1.65	−10.2
1989.0	240.0	1.55	− 9.6
1990.0	224.0	1.54	− 9.1
1991.0	208.5	1.61	− 8.7
1992.0	195.0	1.75	− 8.2
1993.0	183.9	1.96	− 7.9
1994.0	175.1	2.20	− 7.6
1995.0	168.1	2.46	− 7.3
1996.0	162.5	2.73	− 7.1
1997.0	157.9	3.00	− 6.9
1998.0	154.0	3.27	− 6.7

With the present result added, the weighted mean reduced to absolute parallax becomes

$$\pi = +0.''203 \pm 0.''004 .$$

Mass ratio determinations have been listed by Schilt (1944) and Strand (1952). From the present paper, the Sproul astrometric result $f = 0.445 \pm 0.003$ and the revised spectroscopic value 0.403 are added. For an orbit as large as this, the GC value of 0.478 from a long interval of transit observations is determined to better than 10 percent, and also warrants inclusion. As a weighted mean, $f = 0.442$ with an estimated error less than ± 0.01 is adopted, which gives the component masses $A = 0.81 \pm 0.05\, M_\odot$ and $B = 0.64 \pm 0.04\, M_\odot$.

Plate measurements and computer reductions in the present paper were made by the first author with support from the National Science Foundation, and the orbit analysis by the second author.

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