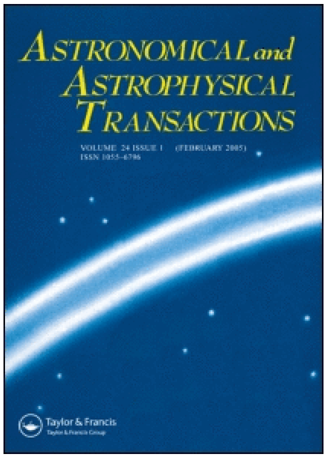

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A STUDY OF THE MOTION OF THE STAR GLIESE 623 WITH A LOW-MASS DARK COMPANION ON THE BASIS OF OBSERVATIONS AT PULKOVO

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Photographic observations of the nearby star Gliese 623 (AC 48° 1595/1589) with an optically invisible companion of extremely low stellar mass have been made during the years 1979–1995 by means of 26-inch refractor at Pulkovo. The relative proper motion and relative parallax have been obtained on the basis of 89 plates (580 individual positions). The residuals with a mean error of ±0.011 arcsec have been calculated. The motion of the photocentre evoked by the companion has been estimated by means of these residuals. The following dynamic elements are chosen for the photocentric orbit: $P = 3.76$ years, $e = 0.51$, $T_0 = 1984.3$. The most stable geometrical element is the great semi-axis of the photocentre α which equals 0.052 ± 0.007 arcsec (m.e.). The values of i, ω and Ω have shown some change for different intervals of observations and are due to systems of reference stars. The lower limit of the mass of the companion is estimated as 0.09 ± 0.03 solar masses. The positions of the main star on the each plate are given.

KEY WORDS Stars: binaries, dark companions, individual (Gliese 623)

1 INTRODUCTION

The principal programme performed by means of the Pulkovo 26-inch refractor ($F = 10.4$ m, $D = 65$ cm, $M = 19.81$ arcsec in mm) is the determination of the trigonometric parallaxes of the selected stars with suspected unseen companions. Some of these companions may possess small masses near to substellar ones. For the majority of these stars there are long-term sets of observations (see, for instance, Shakht, 1992; Shakht and Kiyaeva, 1992).

The stars for the programme of objects with unseen components have been chosen on the basis of geographical position ($\varphi = +59°46'$, $\lambda = -02^h01^m.3$) and seeing conditions at Pulkovo.

The Pulkovo programme consisted of single and multiple stars of the late spectral classes, the majority of which are red dwarfes, as described by Kiselev *et al.* (1992).

Thanks to the specific conditions we have the possibility to observe these stars close to a meridian over a limited interval of time. This circumstance exerts an influence on the weight and the precision of parallax determinations for these objects. That is way we often prefer to exclude the parallax displacement by means of its certain catalogue value from the observational positions of star which may be named geocentrical and then we use the corrected geliocentrical positions for determinations of motion free from parallax.

2 THE HISTORY OF OBSERVATIONS OF THE STAR GLIESE 623

As is already known the star Gliese 623 (AC 48°1595/1589) (RA = $16^{h}22^{m}.6$, Dec. = +48°28′ (1950.0), m 10.3 sp dM3) is a binary (Gliese 623 A and B). The second component of this system is an optically invisible one and its mass is near to the substellar mass. The first astrometric study of the motion of Gliese 623 A was made by Lippincott and Borgman (1978, hereafter LB) on the basis of observations at Sproul Observatory during 1938–1977. The first estimate of the lower limit of the mass of the dark companion was 0.06–0.08 solar masses and was made by these authors too. Subsequently, other methods have been applied to improve the parameters of photocentric orbit and estimates of the mass of Gliese 623 B (see, e.g., McCarthy and Henry, 1987 (MH); Marcy and Moore, 1989 (MM)).

The numerous estimates of the low limit of this mass yield it in the range 0.067–0.087 solar masses if the primary has a mass of 0.31 solar masses as found by MM. Nevertheless, some difficulties remain in the determination of parallax and hence in the estimates of mass of the component.

3 THE OBSERVATIONS OF GLIESE 623 AT PULKOVO

We present the results of astrometric observations over the interval 1979–1995. The following Pulkovo astronomers have taken part in these observations: A. A. Kiselev (20 plates), N. A. Shakht (19 plates), O. A. Kalinichenko (18 plates), T. P. Kiseleva (14 plates), O. P. Bykov (11 plates) and others. During these observations NP–27 plates were used.

The number of plates obtained is about 100 with six exposures on each plate on average. We are observing this star for 3 months during the course of the spring season. The relative positions of the star have been determined in the system of reference stars. These stars with magnitudes and colours near to the object have been choisen by means of the Palomar Atlas. Information about the reference stars used is given in Table 1, where x, y are rectangular coordinates of the reference stars with respect to the object on the standard plate 1987.3 with orientation to 2000.0, μ_{xy} are relative proper motions calculated in this reference system, sp-spectral class of the star.

Table 1. Data about reference stars for Gliese 623

No.		m_{vis} (*m*)	*Sp*	x (*mm*)	y (*mm*)	μ_x (*arcsec*)	μ_y (*arcsec*)
1	*	10.5	G5	−24.14	+14.35	+0.008	−0.001
2		11.1		−24.81	+27.38	+0.024	−0.017
3	*	11.0		+11.36	−40.01	−0.017	−0.004
4		9.1		+31.56	−22.82	+0.008	+0.006
5		11.7		+15.75	+33.76	+0.001	−0.003
6	*	10.2	KO	+24.57	+52.99	−0.008	−0.001
7		11.3		−32.18	+30.59	−0.029	+0.001
8	*	9.0	KO	−17.16	−54.76	+0.014	−0.003
9		11.5		+03.34	−13.97	+0.018	−0.001

Note. *Reference stars of LB.

The data about control star No. 9 whose motion has been studied as the motion of the main star are given in the bottom line. In spite of some variations of seeing conditions and modification of the ocular part of the telescope with a change of shutter we kept a constant system of five stars for 89 plates which we analyse here. The positions of Gliese 623 A in this system are given in Table 2. The additional stars Nos. 6–8 were measured on the plates 1979–1990, the stars marked with an asterisk are the reference stars of LB and the positions in this system 1979–1990 have been used to compare the Sproul and Pulkovo observational series.

4 MEASUREMENTS AND TREATMENT OF THE DATA

The measurements of all plates have been made by the author of this paper with the semi-automatic Zeisse measure-machine Ascorecord. The method of six constants and the standard plate has been applied for the treatment of the plates according to the practice of parallactic determinations at Pulkovo. The following equations are used:

$$\begin{aligned} x_i - x_i(st) &= a_j x_i + b_j y_i + X_j, \\ y_i - y_i(st) &= c_j x_i + d_j y_i + Y_j, \end{aligned} \qquad (1)$$

where x_i, y_i are measured coordinates of reference stars on each plate, $x_i(st)$ and $y_i(st)$ are measured coordinates of reference stars on the standard plate, a_j, b_j, c_j, d_j are constants of plate, X_j, Y_j are relative positions of the object in the reference frame with respect to the standard plate. The value i changes from 1 to N, where N is the number of reference stars and j changes from 1 to M, where M is the number of plates.

The values of geocentric positions X_j, Y_j of Gliese 623 A determined with respect to a standard plate on the moment 1987.28, on the basis of the system of five reference stars (1–5) are given in mm for 89 plates in Table 2.

Table 2. Moments of observations $(t_j - t_c)$, parallactic factors P_x, P_y, relative positions X_j, Y_j and residuals R_x, R_y obtained after excluding proper motion and parallax

No.	$t_j - t_0$	P_x	X_j	R_x	P_y	Y_j	R_y
1	−8.129	0.969	−0.4663	+28	0.078	0.1803	−9
2	−7.997	0.563	−0.4616	+26	0.746	0.1811	−16
3	−7.105	0.939	−0.4078	+22	0.218	0.1593	+2
4	−7.091	0.912	−0.4076	+17	0.297	0.1590	−3
5	−7.075	0.871	−0.4045	+42	0.388	0.1583	−12
6	−7.023	0.682	−0.4032	+39	0.644	0.1615	+13
7	−7.020	0.670	−0.4045	+24	0.656	0.1599	−2
8	−6.127	0.968	−0.3587	−54	0.086	0.1368	+7
9	−6.114	0.953	−0.3534	−8	0.167	0.1379	+15
10	−6.070	0.857	−0.3498	+8	0.414	0.1414	+43
11	−6.048	0.784	−0.3522	−24	0.526	0.1396	+22
12	−6.029	0.709	−0.3505	−12	0.617	0.1397	+21
13	−5.996	0.556	−0.3498	−14	0.751	0.1385	+7
14	−5.068	0.851	−0.2950	−24	0.425	0.1136	−10
15	−5.002	0.586	−0.2907	−11	0.728	0.1135	−16
16	−4.998	0.558	−0.2926	−20	0.749	0.1111	−41
17	−4.994	0.545	−0.2925	−21	0.759	0.1143	−8
18	−4.991	0.531	−0.2919	−15	0.768	0.1127	−25
19	−4.958	0.353	−0.2907	−10	0.867	0.1130	−21
20	−4.950	0.305	−0.2891	+4	0.886	0.1104	−46
21	−4.121	0.961	−0.2362	+10	0.127	0.0892	−22
22	−4.118	0.958	−0.2360	+9	0.143	0.0900	−12
23	−4.115	0.955	−0.2380	−12	0.159	0.0915	+2
24	−4.019	0.667	−0.2331	+1	0.659	0.0910	−16
25	−4.016	0.654	−0.2335	−5	0.671	0.0920	−5
26	−4.014	0.642	−0.2342	−12	0.682	0.0922	−4
27	−4.011	0.629	−0.2321	+8	0.694	0.0917	−9
28	−3.997	0.562	−0.2291	+34	0.746	0.0934	+8
29	−3.028	0.705	−0.1725	+30	0.620	0.0734	+35
30	−3.006	0.606	−0.1744	+4	0.713	0.0744	+44
31	−3.004	0.593	−0.1747	+2	0.723	0.0715	+14
32	−2.982	0.481	−0.1722	+22	0.801	0.0730	+29
33	−2.081	0.887	−0.1222	−27	0.355	0.0481	+13
34	−2.048	0.784	−0.1211	−28	0.527	0.0484	+12
35	−2.026	0.696	−0.1182	−6	0.630	0.0479	+5
36	−1.988	0.513	−0.1168	+2	0.780	0.0477	+1
37	−1.985	0.499	−0.1184	−17	0.790	0.0463	−12
38	−1.982	0.484	−0.1198	−33	0.799	0.0503	+28
39	−1.963	0.379	−0.1165	−4	0.855	0.0473	−2
40	−1.098	0.926	−0.0638	−14	0.289	0.0235	−7
41	−1.090	0.909	−0.0633	−13	0.305	0.0231	−10
42	−1.087	0.902	−0.0611	+8	0.321	0.0230	−12
43	−1.084	0.896	−0.0636	−18	0.336	0.0234	−8
44	−0.112	0.951	−0.0031	+20	0.156	0.0018	+8
45	−0.110	0.947	−0.0065	−15	0.192	−0.0017	−29
46	−0.104	0.938	−0.0020	+27	0.223	−0.0008	−21
47	−0.096	0.922	−0.0032	+12	0.270	0.0021	+7
48	−0.058	0.818	−0.0004	+25	0.479	0.0015	−5
49	−0.052	0.799	−0.0015	+11	0.507	0.0026	+6
50	−0.046	0.779	−0.0014	+10	0.534	0.0013	−8
51	−0.033	0.725	0.0020	+40	0.599	0.0023	+1

Table 2. Continued

No.	$t_j - t_0$	P_x	X_j	R_x	P_y	Y_j	R_y
52	−0.014	0.641	−0.0015	+1	0.683	0.0033	+9
53	0.000	0.576	−0.0000	+12	0.737	0.0001	−26
54	0.942	0.820	0.0554	+4	0.476	−0.0172	+35
55	0.969	0.716	0.0566	+6	0.608	−0.0176	+27
56	0.977	0.681	0.0575	+14	0.645	−0.0199	+2
57	0.991	0.619	0.0585	+20	0.702	−0.0218	−16
58	1.040	0.360	0.0558	−18	0.864	−0.0173	+29
59	1.054	0.280	0.0568	−10	0.895	−0.0174	+29
60	1.938	0.831	0.1092	−36	0.458	−0.0405	+26
61	1.949	0.794	0.1082	−50	0.514	−0.0398	+32
62	1.952	0.784	0.1110	−22	0.527	−0.0418	+11
63	1.969	0.719	0.1130	−8	0.606	−0.0423	+5
64	2.010	0.527	0.1121	−28	0.771	−0.0441	−15
65	2.954	0.776	0.1701	−10	0.538	−0.0667	−12
66	2.957	0.766	0.1692	−21	0.551	−0.0654	+1
67	2.973	0.699	0.1698	−20	0.627	−0.0660	−6
68	2.976	0.687	0.1713	−5	0.639	−0.0697	−44
69	3.009	0.530	0.1708	−20	0.769	−0.0628	+23
70	3.017	0.487	0.1725	−4	0.797	−0.0713**	−
71	3.028	0.428	0.1731	−1	0.830	−0.0674	−22
72	3.036	0.382	0.1725	−8	0.853	−0.0657	−5
73	4.074	0.162	0.2338	+19	0.928	−0.0888	−7
74	4.121	−0.121	0.2361*	+33	0.953	−0.0925	−34
75	5.057	0.264	0.2879	−16	0.900	−0.1086	+18
76	5.087	0.083	0.2908*	+8	0.943	−0.1067	+41
77	6.010	0.526	0.3451	−14	0.772	−0.1337	−9
78	6.021	0.469	0.3430	−37	0.608	−0.1326	+16
79	6.023	0.454	0.3468	+1	0.816	−0.1345	−17
80	6.974	0.698	0.4044	+10	0.628	−0.1563	−7
81	7.006	0.544	0.4440	+2	0.760	−0.1620**	−
82	7.039	0.366	0.4070	+20	0.860	−0.1565	−11
83	7.937	0.835	0.4618	+18	0.452	−0.1793	−9
84	7.940	0.826	0.4615	+10	0.466	−0.1775	+8
85	7.981	0.665	0.4601	−13	0.660	−0.1802	−22
86	8.085	0.095	0.4658*	+22	0.941	−0.1783	+1
87	8.085	0.095	0.4673*	+37	0.941	−0.1783	+1
88	8.093	0.045	0.4682*	+44	0.948	−0.1803	−17
89	8.102	−0.005	0.4632*	−8	0.952	−0.1766	+22

The moments of observations $t_j - t_0$, and parallactic factors P_x, P_y and residuals R_x, R_y in 0.1 microns obtained from equations (3), see Section 5, are also given.

5 DETERMINATIONS OF THE PROPER MOTION AND ESTIMATION OF THE PARALLAX OF GLIESE 623

For the study of the motion of this object the following equations are used:

$$
\begin{aligned}
X_j &= C_x + \mu_x(t_j - t_0) + P_x\pi_x, \\
Y_j &= C_y + \mu_y(t_j - t_0) + P_y\pi_y,
\end{aligned}
\qquad (2)
$$

where C_{xy} are the constants which are due to the errors of the standard plate, t_j is the moment of observations, t_0 is the moment of observations of the standard plate equal to 1987.28, μ_{xy} are the relative proper motion, P_{xy} are parallactic factors, π_{xy} are the values of the relative parallax.

As one can see from Table 2 the majority of parallactic factors P_{xy} have only a positive sign. This corresponds to the narrow interval of time accessible for the observations of this star. In consequence we do not aim at exact determinations of the parallax and equations (2) have been solved in the first study only to estimate the precision of our series and any possible correlations between unknowns.

The solutions of systems (2) on a different interval of observations have shown that parallactic displacement is distinguished since the first five years with 30 plates. The value of π_x changes in the range 0.110–0.140 arcsec for the different variations of plates, just as π_y remains constantly near to 0.136 arcsec. Finally we have obtained

$$\mu_x = +1.1480 \pm 0.0010 \text{ arcsec (m.e.)}, \qquad \mu_y = -0.4462 \pm 0.0010 \text{ arcsec},$$
$$\pi_x = +0.126 \pm 0.020 \text{ arcsec}, \qquad \pi_y = +0.136 \pm 0.020 \text{ arcsec},$$

using all plates except these marked by an asterisk in Table 2 with small P_x and by double asterisks with residuals R_y which are more than 3σ.

In should be noted that although the weight of the parallax is not considerable owing to the geographical position of Pulkovo, our data give values of π_{xy} near to those of the catalogue's (0.138 arcsec, Gliese, 1969) and near to π_{abs} equal 0.134 arcsec according to LB.

It the subsequent stage of the treatment we used the following systems of equations:

$$\begin{aligned} X' &= C_x + \mu_x(t_j - t_0), \\ Y' &= C_y + \mu_y(t_j - t_0), \end{aligned} \tag{3}$$

where X', Y' are the relative positions of stars corrected by means of π_{abs} LB. The values of μ_{xy} obtained for the main star on the basis of all data and μ_{xy} obtained for the control object by means of 76 plates are given in Table 3.

6 COMPARISON OF THE MAIN STAR AND THE CONTROL OBJECT

Some control objects are observed with a 26″ refractor on the same nights as the stars of the Pulkovo programme of objects with the suspected unseen components.

Table 3. Relative proper motion for Gliese 623 and control star

	Gliese 623	*Control star*
μ_x	+1.1480 arcsec	+0.0184
	±10	±11 arcsec
μ_y	−0.4466 arcsec	−0.0011
	±9	±10 arcsec

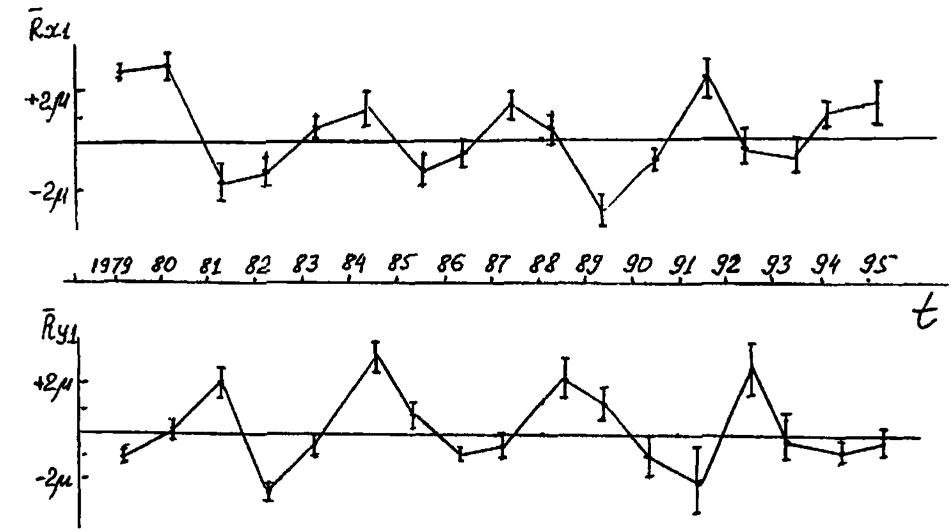

Figure 1 The residuals R_{x1}, R_{y1} with their mean errors obtained after the exclusion of proper motion and parallactic displacement in the movement of the star Gliese 623 A, where 1 μ equals 0.02 arcsec.

As a rule they are the remote far stars whose motion is investigated with the purpose of controlling false perturbations of an astroclimatic or instrumental character. In this case we make the same analysis of the motions for the control star obtained on the same plates as the main star.

The mean yearly residuals $\bar{R}_{x1}$, $\bar{R}_{y1}$ with their mean errors for the main star are given in the Figure 1, the corresponding residuals for the control object are given in Figure 2. As seen from Figure 1, the residuals R_{x1}, R_{y1} are periodic in two coordinates, with the annual mean errors being under the residual amplitudes. On the contrary, the residuals R_{x2}, R_{y2} for the control object are randomly distributed with residual errors comparable with annual mean ones. On the basis of these pictures we can say that the gravitational influence of the unseen companion on Gliese 623 A is confirmed by means of our astrometrical series.

For the control the residuals smoothed using weights due to mean yearly errors have been studied by means of the spectral analysis method described by Godisov (1970) using the formula:

$$S(k) = 1/m \sum_{\tau=0}^{m-1} \delta_k B(\tau)(1 + \cos \pi\tau/m) \cos[(\pi\tau/m)k], \qquad (4)$$

where $B(\tau)$ is the autocorrelational function, m is the number of the ordinates of $B(\tau)$, k is the parameter of frequency ($k = 0, 1, \ldots, m$), $\delta_k = 1/2$ for $k = 0$ or m, if m is an even quantity and $\delta_k = 1$ for the remaining k; $S(k)$ is the ordinate of the spectrum of power in relative units.

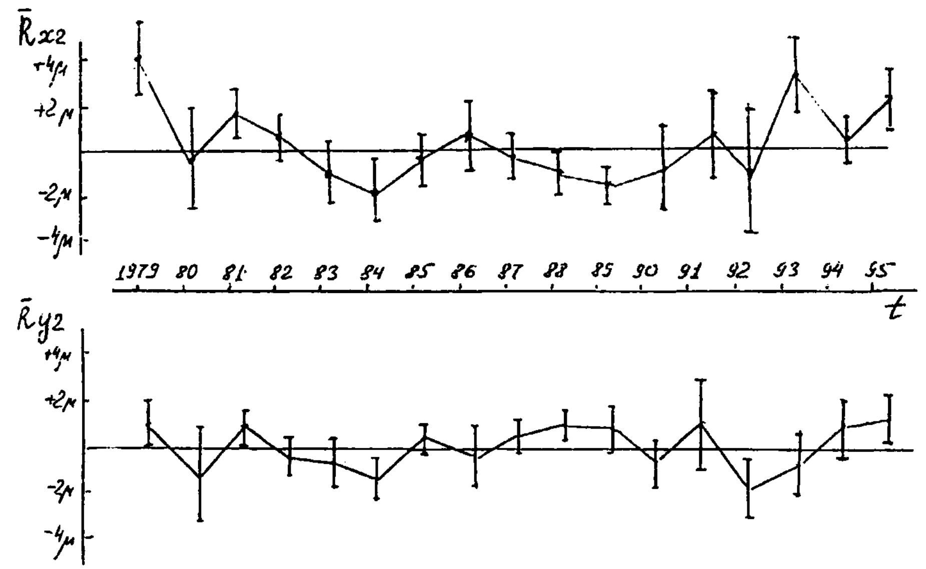

Figure 2 The residuals R_{x2}, R_{y2} with their mean errors obtained after exclusion of the proper motion for the control object.

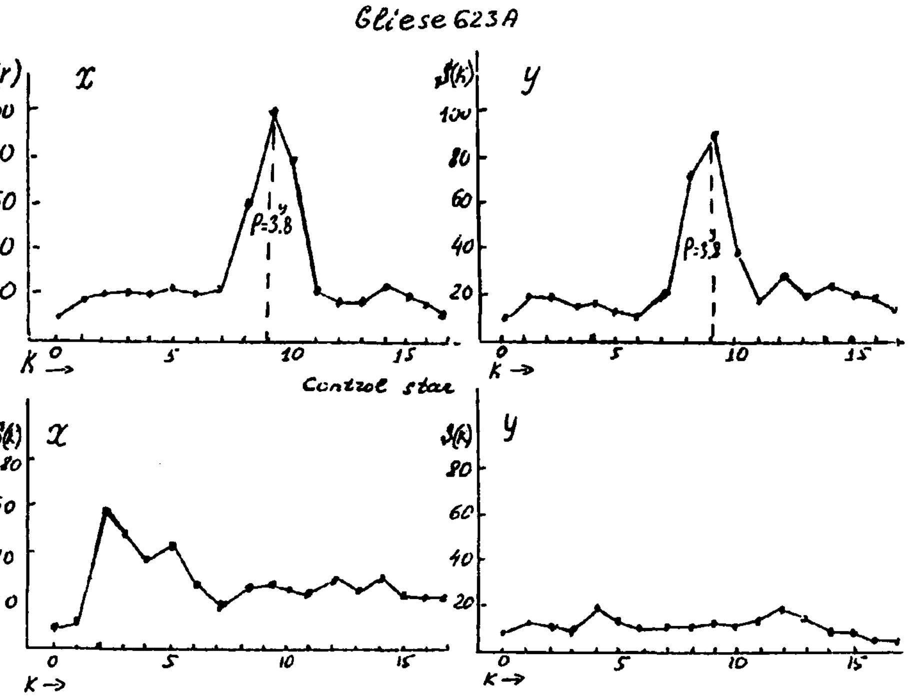

Figure 3 The spectrum of power for R_{x1}, R_{y1} and for R_{x2}, R_{y2}.

As our series consists of only 17 equally distributed in time mean yearly points and thus is insufficient for the determination of a precise period, we have used this analysis only for comparison of the residuals of two objects.

By means of the formula $P = 2T_m/k$, where P is the period and T_m is the duration of the series and k is the argument of $S(k)_{\max}$ one can estimate the certain presence of a period near to 3.8 years for the main object and some accidental fluctuation of a non-gravitational character for the control object.

The corresponding ordinates of the spectrum of power are given in Figure 3.

7 DETERMINATION OF THE ELEMENTS OF PHOTOCENTRIC ORBIT AND ESTIMATION OF THE MASS OF THE COMPANION

On the basis of the residuals R_x, R_y we estimated the dynamical elements of the preliminary photocentric orbit P, e and T and then the rectangular coordinates of the ellipse of the photocentric orbit have been calculated in units of the great semi-axis:

$$x = \cos E - e; \quad y = \sin E(1 - e^2)^{1/2}, \tag{5}$$

where E is the excentric anomaly.

We have made some attempts to estimate the dynamic elements of the photocentric orbit by means of the graphical method of Zurhellen modified by Shain (1936) and by Van de Kamp (1981).

Then the following equations have been solved:

$$\begin{aligned} X'_j &= C_x + (t_j - t_0)\mu_x + x(B) + y(G), \\ Y'_j &= C_y + (t_j - t_0)\mu_y + x(A) + y(F), \end{aligned} \tag{6}$$

where (B), (G), (A), (F) are the Thiele–Innes constants obtained with respect to the photocentre.

We have made many versions of the solutions for the systems (6) with the assumed values of dynamic elements P, e, T_0 in the following ranges respectively: 3.70–3.80 years, 0.50–0.58 and 1984.1–1984.5 for different systems of the reference stars and for different intervals of observations. The first stage of the analysis has shown that the value of our period is possibly greater than the period of LB (3.72) and near to 3.80 years.

Then solutions with different dynamic elements and with different systems of reference stars have shown that the great semi-axis α is the most stable parameter and it is also slightly more than α of LB (0.049 arcsec) and remains in the range 0.051–0.52 arcsec.

Finally, we adopted the following dynamic elements:

$$P = 3.76 \pm 0.10\,\text{yr}, \quad e = 0.51, \quad T_0 = 1984.3.$$

The solution of equations (6) with these elements gives the minimum of the error on the unit of weight and the relation between external precision on X, Y

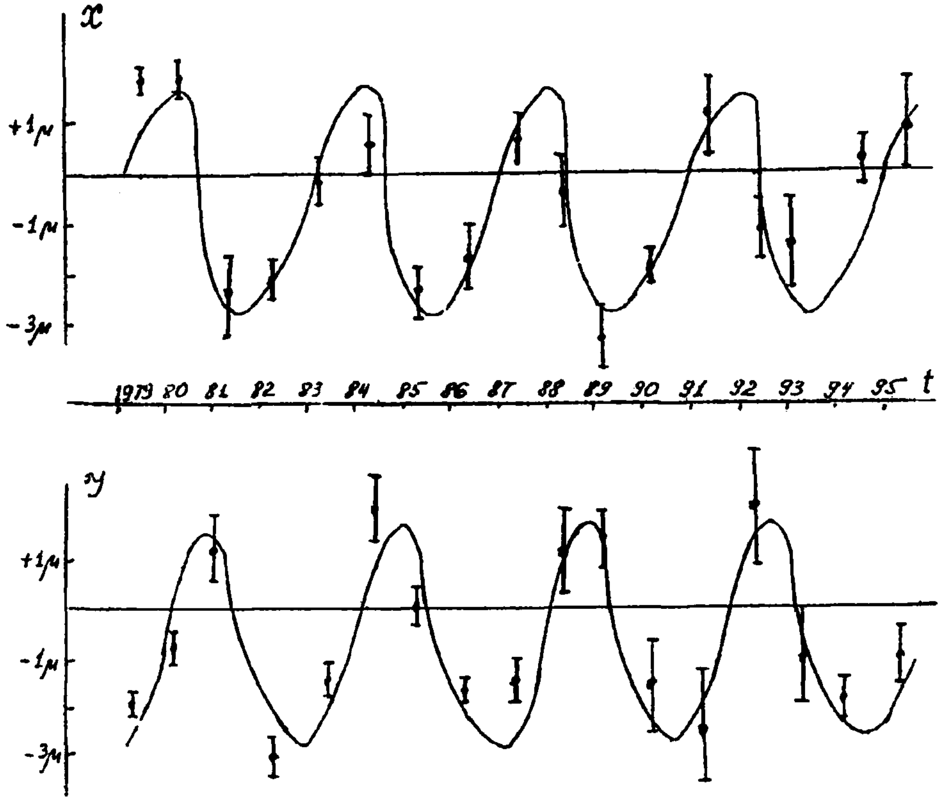

Figure 4 Comparison of the ephemerides of the photocentric orbit with the results of the observations.

coordinates corresponds to the same relation in other longterm observational series of similar stars.

The use of the dynamic elements of LB for our series gives the same precision but in this case the constants obtained from equation (6) yield geometric elements which are markedly different from those obtained by LB, MM and MH. With our dynamic elements we have determined geometric elements i, ω, Ω, α which are equal to 134°, 265°, 134°, 0.052 ± 0.007 arcsec respectively. The value of ephemerdes are given in Figure 4.

Taking into account our value of α, the parallax π (LB) and the mass of the main star equal to 0.31 solar masses (MM) we have estimated the low limit of the mass of the satellite as 0.09 ± 0.03 solar masses, and thus this value is near to the mass of the substellar object.

We have only a preliminary estimate of the precision of the orbital elements.

The error of P is obtained by graphical estimation, the precision of the constants corresponds to the errors obtained by means of the least-squares method. The value of i is in the range $\pm 5°$, and the values of ω and Ω have the greatest dependence on the different dynamic elements and different reference systems and may have a scatter of more than 10°.

The treatment of the series 1979–1990 with four reference stars LB and with eight reference stars (Table 1) gives similar results but with a little better precision in the latter case.

The precision of such a series is estimated by means of error on the unit of weight on the basis of the solution of equations (2) or (3). This error equals 0.040 arcsec for the solution with five reference stars.

The similar error is slightly smaller for the system with eight reference stars and for the plates 1979–1990 which were of a better quality. Its marked decrease is impossible in this case for it reflects not only errors of observations and emulsion but the orbital motion too.

8 CONCLUSIONS

This study is founded on the classical technique of solution of equations (6). This method has been applied since in this case we have had difficulties in determining the projection of the focus for the apparent ellipse.

However this choice may not be adequate either because of the probable correlations between unknowns in equations (6), and thus some other methods must be found for the correction of this photocentric orbit.

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