Astrophysics, Vol. 49, No. 3, 2006

OBSERVATIONS OF THE BINARY STAR 61 Cyg ON THE 26 INCH REFRACTOR AT THE PULKOVO OBSERVATORY

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UDC: 524.38

Results from an analysis of a forty year series of photographic observations of the binary star 61 Cyg on the 26 inch refractor at the Pulkovo Observatory are presented. The orbit is constructed and the sum of the masses of the components is determined from the relative positions of the components. A study of the individual motions of the components of 61 Cyg relative to the surrounding stars yields their mass ratio and the masses of the main and secondary components, 0.74 and 0.46 solar masses, respectively. The relative motion of the components is found to have a fluctuating component with a period of 6.5 years which may be caused, in particular, by the presence in the system of a dark, low-mass companion.

Keywords: *stars: double: masses - individual: 61 Cygni*

1. Introduction

The visual binary star 61 Cyg (ADS 14636 = WDS 21069 + 3845 = Gliese 820 = HR 8085 + HR 8086 = HD 201091 + HD 201092) is part of a Pulkovo program to observe stars with suspected invisible companion and has been observed on the normal astrograph since 1895 and on the 26 inch refractor since 1958. Its main parameters are the following: equatorial coordinates $\alpha_{2000} = 21^h 06^m.9$, $\delta_{2000} = 38^o 45'$; trigonometric parallax $\pi_{tr} = 0''.296$; V brightnesses of the components $5^m.4$, $6^m.1$; spectral classes of the components K5V, K7V; relative polar coordinates $\rho_{2000} = 30''.5$, $\theta_{2000} = 150^o$; and, proper motion $\mu_\alpha = 0^s.35107/\text{year}$, $\mu_\delta = 3''.2589/\text{year}$.

In this paper the term *invisible companion* means an object of low luminosity and low mass which perturbs the orbital motion of the star being studied. In our case, this effect can be detected through periodic deviations from its apparent orbital motion.

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Original article submitted March 29, 2006; accepted for publication June 9, 2006. Translated from Astrofizika, Vol. 49, No. 3, pp. 453-465 (August 2006).

 0571-7256/06/4903-0386

2. Historical information

One of the closest stars to the sun, 61 Cyg has been the object of study for many years by several generations of astronomers. At present its motion and physical nature are well known, based on astrometric, as well as astrophysical, observations. Here we provide some historical information including the research results used in this paper.

Data on the position of this star in the sky were first published by Hevelius in his catalog of 1500 stars observed without the aid of a telescope in the middle of the 17th century. Flamsteed was the first to note it as a binary with the number 61 in the constellation Cygnus in his catalog of 3000 stars published in 1725.

The relative orbit was determined by various authors in the 19th century, as well as from more modern data [1,2].

The idea that the star 61 Cyg has a companion was advanced in 1893 by Wilsing [3], who discovered periodic oscillations in the distance between the paired stars. Although these results were later explained by instrumental errors, Wilsing's work excited new interest in 61 Cyg. Subsequently, based on astrometric observations attempts were repeatedly made to discover the effect of a third body by studying deviations from the orbital motion of the pair or from rectilinear motion of each component against the background of reference stars. In several cases observational data made it possible to isolate a periodic component quite reliably, as well as to construct a model for the orbit of the possible companion and estimate its mass [1,4].

At Pulkovo this star has been observed on the normal astrograph since 1895 and in 1958 systematic observations of this star were begun with the 26 inch refractor in the framework of the Pulkovo program of research on stars with invisible companions.

According to the paper by Deich and Orlova [5] based on many years of observations on the two Pulkovo astrographs and observations at the MacCormick and Sproul observatories, there are periodic distortions in the orbital motion of this star which can be interpreted as perturbations from two invisible companions with orbital periods of 6 and 12 years. Here the most reliable period of 6 years offered the possibility of constructing a model for the orbit of the photocenter, described under the influence of this hypothetical companion by: $T = 1957.0$, $e = 0.2$, $a = 0''.006$, $i = \pm 34^{\circ}$, $\Omega = 108^{\circ}$, $\omega = 301^{\circ}$. The lower limit for the mass of the proposed companion was $0.004\,M_{\odot}$.

However, it is known that speckle interferometric studies have not confirmed the existence of companions near the main and secondary components of 61 Cyg [6]. But, Ref. 6 speaks of companions of a stellar type with a brightness that differs from that of the visible components by no more than 2^{m} and lying at least $0''.038$ away from them. Astrometric observations at the Naval Observatory in the USA have also not detected periodic oscillations in the mutual distances between the components of 61 Cyg greater than the noise level [7]. Marcy and Chen [8] concluded that the history of the star's evolution and the low rotation velocity of both its components around its axis do not allow the formation of companions.

At the same time, theoretical celestial-mechanics calculations [9] show that planetary orbits in binary systems can be quasistable, i.e., vary over certain ranges of their parameters: eccentricity, semiaxis lengths, etc. This fact may make it difficult to discover planets in such systems. If we assume that the invisible companion in the 61 Cyg system is in a quasistationary orbit, this may explain the varying amplitude of the oscillations in the motion of the visible components and the difficulties of determining their period, based on our data (see below).

A study of the radial velocity of component A [10] showed no change in it by more than 50 m/s, which indicates the absence near the main component of any companions with values of *M*sin*i* equal to several times the mass of Jupiter. However, proof of a cyclical chromospheric activity in both components of 61 Cyg with a period of about 7 years has been obtained [10,11].

Observations of 61 Cyg with the Hubble Space Telescope revealed no companions, including planetary ones [12]. However, these observations extended only over a relatively short period (about a year and a half).

Because our series of observations is quite extended and uniform, the main task in this paper is a dynamic study of the motion of 61 Cyg and to determine the parameters of the relative orbit and estimate the masses of the components. Theoretical calculations and observational experience on the 26 inch refractor have shown that over a sufficiently extended interval of observations of nearby stars such as 61 Cyg it is possible to detect oscillations in their motion caused by the gravitation of a companion with a mass greater than 0.01 $M_{\odot}$ and orbital periods of 3-20 years. Therefore, we have the additional task of verifying the hypothesis that a companion is present with parameters that match the capabilities and accuracy of our observations.

3. Observations and measurements

61 Cyg has been observed photographically with the 26 inch refractor at the Pulkovo observatory (objective diameter 65 cm, focal distance 10.412 m, scale in the focal plane 19.807"/mm) from 1958 through the present. Every year during the observation season, which lasts from August to November for this star, about 10 photographic plates are obtained, each with an average of about 20 exposures of this pair against the background of the surrounding stars.

As a control, since 1976, every night the known distant visual binary star ADS 14710 ($\alpha_{2000} = 21^h 10^m.5$; $\delta_{2000} = 22^o 27'$; $\mu_\alpha = 0^s.0017$; $\mu_\delta = 0''.013$; $\pi_{tr} = 0''.002$; $\rho_{2000} = 18''.1$; $\theta_{2000} = 119^o$; $6^m.9$, $7^m.7$; A1V, A0) is observed immediately after 61 Cyg. We have also processed the observations of this star [13]. In addition, we have also processed a series of observations of the binary star ADS 7251 ($\alpha_{2000} = 9^h 14^m.4$; $\delta_{2000} = +52^o 41'$; $\mu_\alpha = -0^s.1714$; $\mu_\delta = -0''.615$; $\pi_{tr} = 0''.166$; $\rho_{2000} = 17''.3$; $\theta_{2000} = 82^o$; $7^m.8$, $7^m.9$; K2, K2), which has observed almost as long (since 1962) as 61 Cyg. Detection of identical periods in the motion of the components of these three binary stars would be evidence that they have a common instrumental or astroclimatic origin, and would force abandonment of the hypothesis that 61 Cyg has a companion.

At the end of the 1990's the plates from these series were measured on the automatic measurement system "Fantaziya" at the Pulkovo Observatory [13]. The average error in the measurements in a single exposure was 0".028. The errors in the one-year-average position were 0".007, 0".008, and 0".004 for 61 Cyg, ADS 14710, and ADS 7251, respectively. The measurements of the photographic plates for obtaining the distance ρ and position angle θ were processed in the standard way [14].

The series of relative positions of the components obtained from this analysis were used to construct the orbit of the binary star and identify possible periodic deviations from the orbital motion. The relative distances ρ and position angles θ of 61 Cyg obtained from the observations at Pulkovo over 1958-1997 and preliminary values of the mass ratio of the components A and B, well as the relevant techniques, have been described in our earlier papers [13,15].

4. Relative orbit and the sum of the masses of the components of 61 Cyg

The relative orbit (motion of component B relative to A) was determined by the apparent motion parameters (AMP) method developed at the Pulkovo Observatory [16,17]. This method makes it possible to construct the orbit over a short arc of observations drawing on one point that is distant in time and one measurement of the difference in the radial velocities near the center of the observed arc.

The initial data for 61 Cyg were five parameters of the apparent motion determined from the orbital arc available to us at the midtime of the observations (t_0 = 1978.3). They include: the distance ρ between the components, the position angle θ, the relative motion μ, its direction ψ, and the radius of curvature ρ_c of the arc. Of these quantities, the radius of curvature ρ_c is the least reliably determined from the observations.

Additional parameters required for determining the orbit are the trigonometric parallax π_{tr}, the relative radial velocity ΔV_r (the difference in the radial velocities of the components), and the sum M_{A+B} of the masses of the components. Of these, the most reliable are the parallax of this pair determined from observations on HIPPARCOS. The relative radial velocity was determined from data of recent decades. Ref. 18 lists the results of several such measurements for several wide binary stars, including 61 Cyg, as well as the results obtained by the paper's authors in the mid 1980's with the 6-m BTA telescope. Besides determining the radial velocities of the stars by the standard method (*), they used a special method for a more accurate direct measurement of the difference in the radial velocities of the components (**). Table 1 is a summary of the results from that article, supplemented by the result from Ref. 10.

A preliminary estimate of the masses of the components can be obtained from their spectral classes [19]: the primary A–K5V-0.7 $M_\odot$ and the secondary B–K7V-0.6 $M_\odot$. Hence, the estimated sum of the masses of the components is $M_{A+B} = 1.3\, M_\odot$.

Using observations that are distant in time from the arc of our observations allows us to make a choice between two equivalent orbits derived by the AMP method for the orbital arc at hand and differencing by geometrical elements (but identical from a dynamical standpoint). If, on the other hand, there is a set of such observations that are distant in time, then, despite their nonuniformity and, perhaps, lower accuracy, a comparison of the derived orbit with them may provide a more precise estimate of the correctness of the chosen values for the input parameters. The best agreement of

TABLE 1. Determinations of the Relative Radial Velocity of 61 Cyg

Measurements in years	V_{rA} (km/s)	V_{rB} (km/s)	ΔV_r (km/s)	Authors
1982	-66.08	-65.01	1.07	Kiselev, et al., 1987
1983-1985	-64.96 ± 0.05	-63.88 ± 0.04	1.08 ± 0.06	Marcy, Benits, 1989
1982-1987	-65.14	-64.07	1.07 ± 0.12 (*) 1.10 ± 0.08 (**)	Romanenko, Chentsov, 1994
1986.5			1.169 ± 0.118	Campbell, et al., 1988
1989-1992	-66.06 ± 0.12	-64.58 ± 0.17	1.48 ± 0.21	Tokovinin, 1994

the constructed orbit with all the known observations can be obtained by varying these parameters.

Thus, we have the following initial values for the parameters: $\rho_c = 20''.5$, $\Delta V_r = 1.1$ km/s, $M_{A+B} = 1.3\,M_{\odot}$. These parameters were varied about the indicated initial values, and the constructed orbits were compared with the whole set of position observations of 61 Cyg made around the world and collected at the website of the WDS catalog of the Naval Observatory in Washington, USA (*http://ad.usno.navy.mil/ad/wds/wds.html*). Distant outliers were eliminated from these data and corrections for the proper motion and precession were introduced into the values of the position angle to bring them to the epoch and equinox of 2000.0. Then for each time from the general list of observations the ephemeredes of the distances and position angles were computed from the resulting orbit; the differences O-C were determined from these calculations and the observed values. The three parameters for the AMP method mentioned above were chosen so as to minimize the average value of O-C for all the available observations.

The resultant minimum average O-C was found for the following values of these parameters (at time $t_0 = 1978.3$): $\rho_c = 24''.5$, $M_{A+B} = 1.2\,M_{\odot}$, and $\Delta V_r = 0.9$. (Linear extrapolation of the values of ΔV_r from Table 1 gives a close value

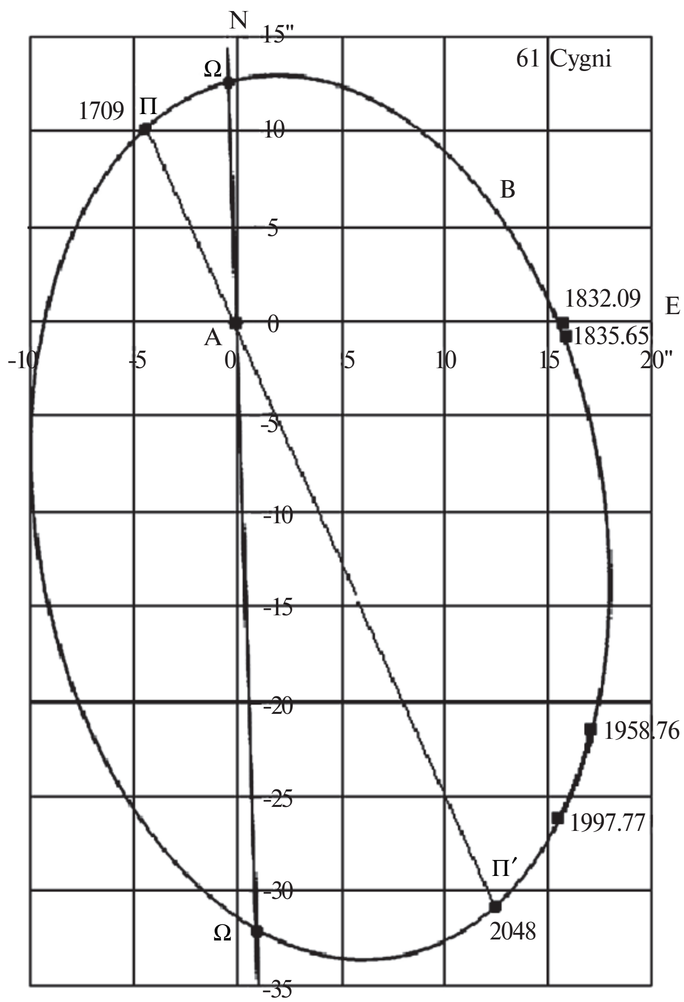

Fig. 1. The apparent relative orbit of 61 Cyg constructed from observations on the 26 inch refractor at the Pulkovo Observatory using the apparent motion parameters method.

of $\Delta V_r = 0.8$ km/s.) These values correspond to the following orbital elements: a = 82 ± 2 a.u., eccentricity $e = 0.49 \pm$ 0.03, inclination $i = 129^o \pm 2^o$, periastron longitude $\omega = 149^o \pm 6^o$, longitude of the ascending node $\Omega = 178^o \pm 2^o$, period P = 678 ±34 years, and time of passage for the periastron T_0 = 1709±16 years. Figure 1 is a sketch of the orbit corresponding to these elements. The arc corresponding to the Pulkovo observations is indicated and, as an example, two points from the list of earlier observations of 61 Cyg (from the WDS catalog) are shown as a check on our calculated orbit.

Thus, the method described here has made it possible to construct a new version of the relative orbit of the components of 61 Cyg and to estimate the sum of their masses. The error in the sum of the masses was $\pm 0.15\, M_{\odot}$. The resulting value of the sum of the masses does not exceed the estimate based on the spectral classes of the components. This is evidence that there is no hidden mass on the order of 0.1 times the sun's mass or more.

5. Study of deviations from the orbital motion

After the parameters of the orbit were determined, the ephemeredes of the positions at each observation time and then the differences O-C in the sense of "observation minus ephemeris" were obtained. These differences were analyzed and studied, in particular, using the Scargle periodogram method [20] and the CLEAN method [21].

The O-C for the control stars ADS 14710 and ADS 7251 were studied along with 61 Cyg. Significant peaks appeared only in the periodograms for the binary star 61 Cyg in the X coordinate (projected on the right ascension: $X = \rho \sin\theta$). There were two peaks, corresponding to periods of 6.5 and 11.2 years (Fig. 2). The dashed line corresponds to the level of significance of the periods. When the first and second halves of our series were studied separately, the peaks remained. These periods are close to the results of Deich and Orlova [5]. However, it may be that the smaller peak (about 12 years) can be explained by instrumental or astroclimatic effects which produce tiny periodic oscillations in the instrument scale [22].

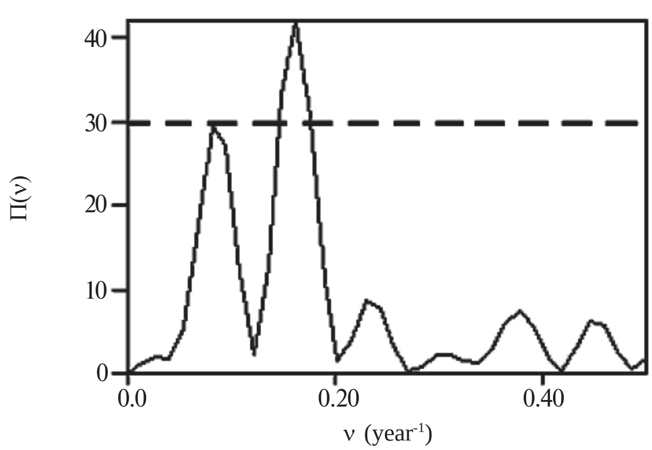

Fig. 2. A periodogram constructed from the $(O\text{-}C)_x$ deviations from the relative orbital motoin of 61 Cyg.

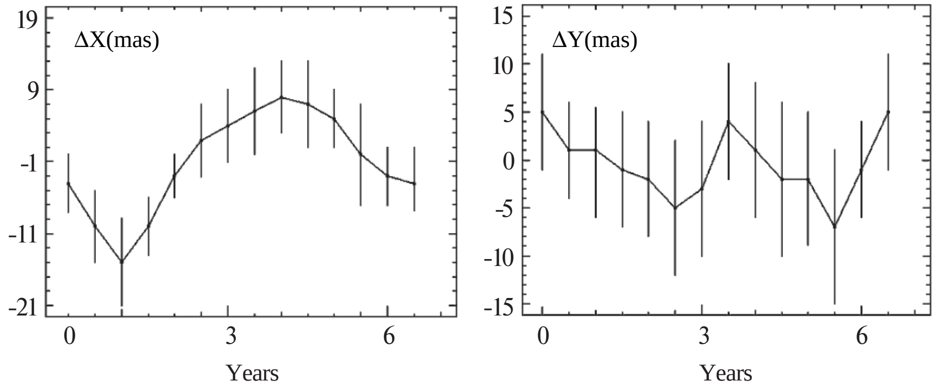

Fig. 3. The deviations (O-C) in the relative motion of the components of 61 Cyg with respect to the coordinates *X* and *Y* averaged over the phases of a 6.5-year period. The error bars indicate the mean square errors for the individual points.

The explanation for the 6.5-year period may be the presence of an invisible low-mass companion, possibly rotating in a quastationary orbit around one of the components. If we accept this proposition, then it is possible to average our discrepancies over this period and attempt to construct the ellipse described by the photocenter. Figure 3 shows the result of this kind of averaging. Since a wave with a period of 6.5 years appears only in the coordinate X, the construction of the ellipse for the photocentric motion is uncertain. Figure 4 shows one variant of the smoothed curve obtained from the observations. The labelled points in this figure correspond to observations, but they are determined with large errors. Nevertheless, we have tried to construct a model and compute the parameters of the photocentric orbit [23], whose major semiaxis was equal to 0".018, so that the lower bound on the mass of the proposed companion was $0.014\,M_{\odot}$.

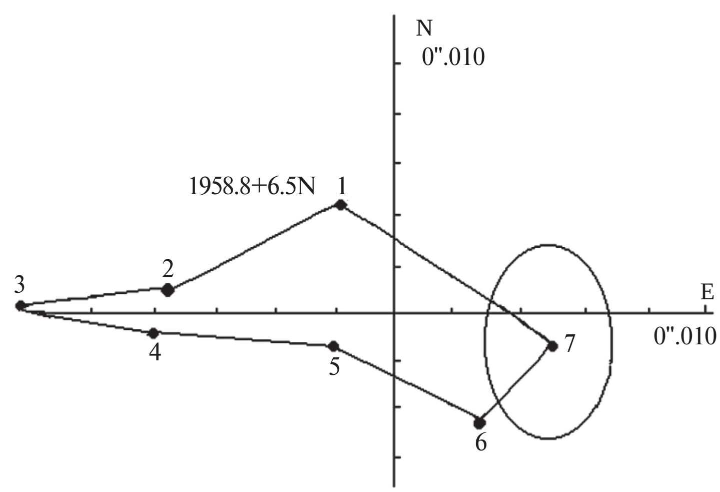

Fig. 4. A smoothed curve representing the possible motion of the photocenter of a "61 Cyg+ companion" system with a period of 6.5 years. An error ellipse is shown around point 7.

6. Study of the motion of 61 Cyg relative to the background stars, determination of the mass ratio

Images of surrounding stars were also obtained on the photographic plates with images of the star 61 Cyg. Using them, it was possible to study the motion of each component separately, which may allow us to determine which component is the one undergoing periodic motions. It should be noted that the accuracy of this sort of study is, of course, affected by the measurements of the components of the binary, but also by errors in the measurements of the reference stars and by their proper motions.

The chosen plates contained six background stars, close in spectral class to the object under study and with small proper motions. Using the method of six constants and these stars, the coordinates of the pair on all the plates were reduced to the coordinate system of one of the plates selected to be in the middle of the series. X_{Ai}, Y_{Ai} and X_{Bi}, Y_{Bi} , the relative coordinates of each component relative to the zero point of the standard plane, were obtained for times t_i, where $i = 1, 2, \ldots, N$. These coordinates contain the proper motion μ_X , μ_Y , the parallactic shift $\pi_{tr}\ P_X$, $\pi_{tr}\ P_Y$, the quadratic term Q, and a term that depends on the mass ratio. Q is the perspective acceleration, which can be calculated using the formula $Q = -1''.024 \cdot 10^{-6} \mu_\alpha \pi_{tr} V_r$. After these quantities were eliminated, the residual differences were studied using Scargle's method to discover the possible periods. Figure 5 shows periodograms for the series of coordinates X and Y of both the components. A small peak corresponding to a period of 6.2 years shows up in the periodogram for coordinate X of the main component of the pair. In the Y coordinate, both components have peaks near 11-12 years which, as in the analysis of the relative motion of the components (see above), we have explained in terms of instrumental effects.

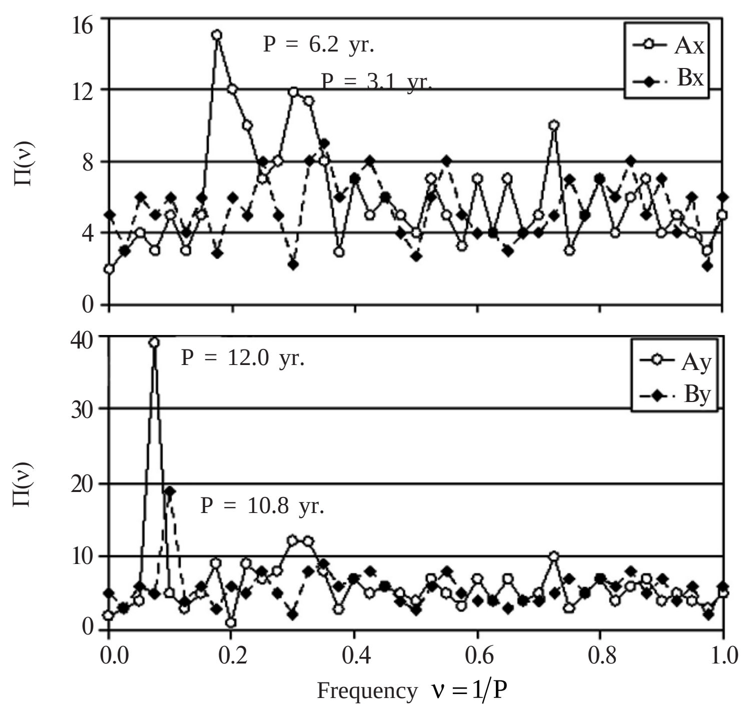

Fig. 5. Periodograms for the series of residual differences in the motion of the principal (A) and secondary (B) components of 61 Cyg with respect to the coordinates X and Y.

A study of the motion of both components of the binary star (against the background of the reference stars) may make it possible to determine the mass ratio of the components by comparing the curvatures of their trajectories in the celestial sphere. Our observations encompass a relatively small portion of the orbit of 61 Cyg with a very small curvature, so the curvatures of both components could not be compared directly in our case.

Here the mass ratio was determined by a method based on the assumption that the center of mass of a binary star moves in space uniformly and rectilinearly, i.e., its motion in the plane of the chart (after elimination of the perspective acceleration) will proceed along a straight line with a constant angular velocity. In this method redundant systems consisting of equations of the form

$$\begin{aligned} X_A(1-K_B)+X_B K_B-\pi_{tr}\, P_X &= C_X+\mu_X\, t+Q_X t^2\,, \\ Y_A(1-K_B)+Y_B K_B-\pi_{tr}\, P_Y &= C_Y+\mu_Y\, t+Q_Y t^2\,, \end{aligned} \tag{1}$$

are solved for C, μ, and Q, where X_A, Y_A and X_B, Y_B are the coordinates of the primary and secondary components obtained after reducing all the plates to the coordinate system of the standard plate by the method of six constant; π_{tr} is the trigonometric parallax from the HIPPARCOS catalog; P_X, P_Y are the parallax coefficients; C_X, C_Y is the position of the center of mass of the system relative to the zero point of the standard plate; μ_X, μ_Y is the motion of the center of mass of the system with respect to the reference stars; Q_X, Q_Y is the secular perspective acceleration of the star relative to the system of reference stars calculated using the formula with the known proper motions, parallax, and radial velocity; and K_B is the ratio of the mass of component B to the sum of the masses of the components, $K_B = M_B/(M_A+M_B)$. Here K_B is a free parameter. The criterion for its optimum value is minimal error in the unit weight σ_0 in solving Eq. (1). Table 2 lists the results.

Here all the equations for the coordinate X have been solved by this method and the σ_0 given here corresponds to its minimum value. However, it turned out that in our case the perspective acceleration projected onto the coordinate Y is correlated with the orbital motion and the unknowns K_B and Q_Y separate poorly. Thus, in solving Eq. (1) for Y we have used a fixed value of K_B, equal to that obtained for X and equal to 0.38. On eliminating K_B from the left hand side of the equations, we have determined the remaining quantities listed in the last column of Table 2.

We have estimated [15] the error in the mass ratio by directly calculating K_B from a system of equations similar to Eq. (1). The errors in the remaining unknowns were calculated in accordance with the least squares solution.

TABLE 2. Parameters of the center of mass motion and the ratio of the masses in the system 61 Cyg

	X	Y
C	6″.2107 ± 0″.0073	-9″.1541 ± 0″.0077
μ	+4″.1113 ± 0″.0005	+3″.2268 ± 0″.0006
Q	0″.00007 ± 0″.00005	0″.00012 ± 0″.00005
K_B	0.38 ± 0.04	0.38 ± 0.05
σ_0	0″.0829	0″.0869

A comparison of the resulting sum of the masses ($M_{A+B} = 1.20 \pm 0.15\, M_{\odot}$) and mass ratio ($K_B = 0.38 \pm 0.04$) of the components of 61 Cyg yields the masses of the two components: $M_A = 0.74 \pm 0.13\, M_{\odot}$ and $M_B = 0.46 \pm 0.07\, M_{\odot}$.

7. Conclusions

1. New observational data have been used to obtain the relative orbit and the dynamic and kinematic parameters of the binary star 61 Cyg, as well as the position and motion of its center of mass.

2. The sum and ratio of the masses of the components A and B have also been obtained; the mass of the secondary component turns out to be somewhat less than the estimate based on its spectral class.

3. In estimating the masses and studying the deviations from an orbital motion, we have found no effect from an invisible companion having a mass of more than 0.015 $M_{\odot}$ within the range of periods (3-20 years) accessible to us. The whole series yields a wave with a period of 6.5 years but with an amplitude of less than 0".015 over the observational interval of 1958-1976 which falls to 0".010 over 1977-1997.

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