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possible solutions, are not too specialized. One can expect that its application to the analysis of presently existing brightness distributions for stars with extended envelopes will permit the obtainment of important information about the structure of their atmospheres. This pertains primarily to stars of the Wolf–Rayet type included in eclipsing systems, for which the brightness distributions and the depth dependence of the absorption coefficient have been found directly from observations without the use of any model assumptions.

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Parameters of the x-ray binary system HD 153919 = 4U 1700-37

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A consistent model of the x-ray binary system HD 153919 = 4U 1700-37 is constructed, on the basis of which the optical light curve, corrected for eclipse effects, is interpreted. The possible values of the parameters of the system are determined within the framework of this model. It is shown that the degree of filling of the Roche lobe by the O6*f* visible star is $\mu < 1$. Allowance for the eclipse of the visible star by the accretion disk made it possible to describe the observed amplitude of the optical light curve of the HD 153919 system and the difference in the depths of the minima.

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INTRODUCTION

The x-ray binary system HD 153919 = 4U 1700-37 ($P_{orb} = 3^d.4118$) consists of an O6f visible star and a compact object, the x-ray source ($L_x \simeq 3 \cdot 10^{36}$ erg/sec), with a possible period of x-ray pulsations[1] of 97 min. The long duration of the x-ray eclipse of this system ($\Delta T/P_{orb} = 0.14$–0.18) does not agree with the amplitude of the optical variability ($\sim 0^m.05$) within the framework of the standard Roche model for the visible star if it is treated as an effect of the ellipsoidality of the visible star. Therefore, a satisfactory determination of the parameters of the HD 153919 system from photometric data has not been made until recently.

The first analysis of the parameters of the system from optical light curves was made by Hutchings.[2] It was found that to reconcile the observed duration of the x-ray eclipse (the angle of the start of the eclipse is $\theta_e = 58°$) with the value of the shallower optical minimum at the phase $\varphi = 0.0$ of the orbital period ($\sim 0^m.04$; the x-ray source is eclipsed by the visible star) requires one to assume that the critical Roche lobe of the visible star overflows, i.e., the degree of filling of the Roche lobe is $\mu > 1$.

Calculations of the parameters of the HD 153919 system by Avni and Bahcall[3] confirmed Hutchings's conclusions. Neither allowance for gravitational darkening nor allowance for possible asynchronism in the rotation of the visible component allowed the authors to reconcile the duration of the x-ray eclipse with the observed amplitude of the optical variability.

Paradijs et al.[4] made an independent attempt to determine the parameters of the HD 153919 system. For the duration of the x-ray eclipse they took a value of $\Delta\varphi_x = \Delta T/P_{orb} = 0.138 \pm 0.032$, obtained as twice the time between the instant of the middle of the eclipse at the phase $\varphi = 0.0$, determined from photometric and spectral data, and the observed instant of emergence of the compact source from the x-ray eclipse. Even in this case ($\theta_e = 25°$), however, the authors could not remove the inconsistency between the theoretical and observed light curves, which, in their opinion, indicates the inadmissibility of the description of the shape of the visible star in this system by a Roche figure; the hypothesis of oscillations of the surface of the visible star was also discussed.

Recently it was shown[5] that the HD 153919 system is an eclipsing variable in the optical range with an eclipse depth of $\sim 0^m.04$ and an amplitude of $\sim 0^m.03$ for the effect of ellipsoidality of the O6f visible star. To interpret these effects a model was employed in which the optical eclipses are caused by an accretion structure and a gas jet which trace the forced precession of the axis

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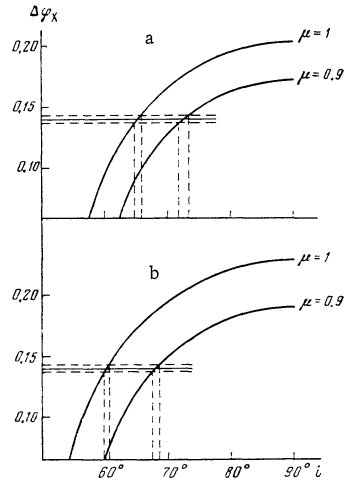

FIG. 1. Duration $\Delta\varphi_x$ of the x-ray eclipse as a function of the parameters i and μ for q = 0.10 (a) and q = 0.05 (b). A change in $\Delta\varphi_x$ by 0.006 results in a change in i by 1°-5°.

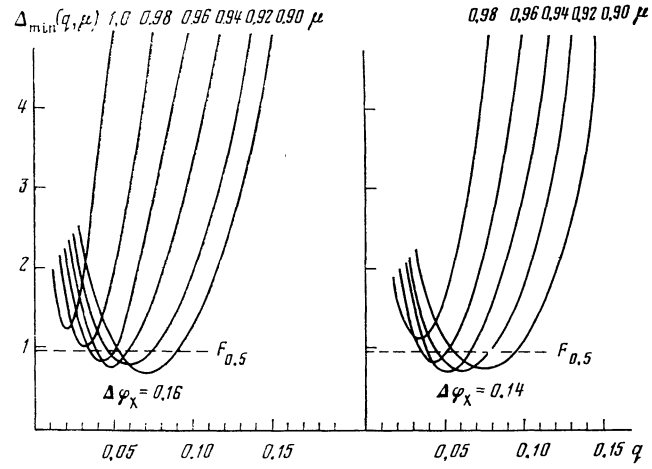

FIG. 2. Discrepancy $\Delta_{min}(q, \mu)$, defined by Eq. (2), for durations $\Delta\varphi_x$ = 0.16 and 0.14 of the x-ray eclipse. The dashed line indicates the critical discrepancy for the significance level α = 0.5.

of rotation of the visible star (P_{prec} = $32^d.46$), not oriented perpendicular to the orbital plane because of a supernova explosion which took place in the binary system.[6] It was also shown[7] that the duration of the x-ray eclipse in the 2-10 keV range in the HD 153919 system varies with the precessional period of $32^d.46$, and the minimum duration is $\sim 0^P.14$. This quantity agrees well with the values of $\Delta\varphi_x = 0.14 \pm 0.03$ found by Dolan et al.[8] from observations in the hard x-ray range of 20-80 keV. It is natural to assume that the variation in the duration $\Delta\varphi_x$ of x-ray eclipse from 0.18 to 0.14 is caused by variable absorption in gas streams and the stellar wind and that the minimum value of $\Delta\varphi_x = 0.14$ reflects the eclipse of the x-ray source by the body of the O6f "star proper."

In the present article we lay out the results of an interpretation of optical light curves of the HD 153919 system with allowance for eclipse effects. It is shown that the optical light curve of this system corrected for eclipse effects agrees well with the duration $\Delta\varphi_x = 0.14$ of the x-ray eclipse. The inverse problem of finding the parameters of the HD 153919 system is solved and it is shown that the O6f visible star does not entirely fill its Roche lobe, which is important for the current theory of the evolution of x-ray binary systems.[9,10]

INTERPRETATION OF THE "PURELY" ELLIPSOIDAL LIGHT CURVE

The "purely" ellipsoidal V light curve of the HD 153919 system, constructed in the report of Cherepashchuk and Khruzina,[5] is interpreted within the framework of the "standard" model of Refs. 3 and 11. In this model the system consists of a visible star, the shape of which is described by a Roche figure, and a point x-ray source in a circular orbit. Within the framework of such a model the theoretical light curve of the system is determined by the assignment of three parameters: the mass ratio q =

TABLE I. Discrepancy Δ_{min} (2) as a Function of the Parameters i, q, and μ for the "Purely" Ellipsoidal Light Curve of HD 153919

μ	Parameters	$q=M_X/M_v$						
		0.04	0.05	0.06	0.07	0.08	0.09	0.10
1.00	Δ_{min}	2.80	4.84	7.28	9.27	12.66	15.03	18.01
	i	60	60	62	62	64	64	65
	$M_v(M_\odot)$	86	45	25	16	10	7	5
0.98	Δ_{min}	1.30	1.65	2.54	3.76	5.12	6.70	8.12
	i	61	62	63	64	65	66	66
	$M_v(M_\odot)$	83	42	24	15	10	7	5
0.96	Δ_{min}	0.86	*0.84	1.28	1.78	2.59	3.68	4.92
	i	62	63	65	65	66	67	68
	$M_v(M_\odot)$	81	41	23	15	10	7	5
0.94	Δ_{min}	0.92	*0.74	*0.77	1.08	1.61	2.12	2.88
	i	64	65	66	67	68	68	69
	$M_v(M_\odot)$	77	39	23	14	9	7	5
0.92	Δ_{min}	1.20	*0.81	*0.74	0.79	1.02	1.35	1.81
	i	66	67	68	68	69	70	71
	$M_v(M_\odot)$	73	37	22	14	9	6	5
0.90	Δ_{min}	2.10	1.10	*0.87	0.76	0.78	0.89	1.09
	i	69	68	70	71	71	73	73
	$M_v(M_\odot)$	70	37	21	13	9	6	5

Note: Here M_V is the mass of the visible component for a mass function $f_V(M)$ = $0.0033M_\odot$ and i is the orbital inclination (in degrees) found from the condition that the duration of the x-ray eclipse is $\Delta\varphi_x(i, q, \mu) = 0.14$. Sets of possible values of the parameters of the system for the significance level $F_{0.5}$ = 0.96 and M_V = 15-40 $M_\odot$ are marked by asterisks.

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TABLE II. Region of Possible Parameters of the HD 153919 = 4U 1700-37 System at the Significance Level α = 0.5 for M_V = 15-40 $M_\odot$

Parameters	Eclipse duration $\Delta\varphi_X$	
	0.14	0.16
$f_v(M)$ $(M_\odot)$	0.0033±0.0007	0.0033±0.0007
i (deg)	63÷72	65–77
μ	0.89÷0.97	0.89÷0.97
q	0.045–0.072	0.045–0.071
$M_x(M_\odot)$	0.95–2.08	0.93÷2.04
$M_x(M_\odot)$ *	1.43±0.12	1.40±0.12

*This value of M_x was calculated for the case when M_V = 25 $M_\odot$.

M_x/M_V, the orbital inclination i, and the degree of filling of the Roche lobe μ. An analysis of radial-velocity curves of the system, constructed from lines with high ionization potentials (He II), leads to the conclusion that the orbit of the HD 153919 system is nearly circular.[12]

In calculating the emission flux from an elementary small area on the surface of the visible star the effect of gravitational darkening was taken into account through the law $T \approx \overline{T}_0[g(r)/|g(r)|]^\beta$, where β = 0.25 for an O6f star whose envelope is in radiative equilibrium while $\overline{T}_0$ = T_{ef} = 36,000°K and $|g(r)|$ are the values of the effective temperature and the acceleration of gravity averaged over the stellar surface. The effect of heating of the surface of the visible star by the x-ray emission of the compact object was also taken into account. This effect is very small for the HD 153919 system, since the ratio of bolometric luminosities is[1] $L_X/L_V \simeq 5\cdot10^{-4}$. The angular dependence of the radiation rescaping from each small area was described in the approximation of a linear limb-darkening law. The value of the limb-darkening coefficient u for an O6f star was taken as[13] 0.3; the variation of u(T) at different points of the tidally deformed surface of the O6f was neglected. Control calculations with a value of u = 0.6 showed that the corresponding theoretical curves differ by no more than $0^m.003$.

The unknown parameters of the problem are the parameters i, q, and μ. The use of information about the duration $\Delta\varphi_X(q, \mu, i)$ of the x-ray eclipse made it possible to eliminate the parameter i and obtain the function i = i(q, μ). The inverse problem was solved by trial and error with respect to the parameters q and μ in the region of their possible values. The error in $\Delta\varphi_X$ results in uncertainty in the value of i for fixed values of q and μ. In Fig. 1 we present theoretical values of the durations of x-ray eclipses for fixed q and μ as a function of the orbital incliation i.[1)] It is seen that an error of $\sim 0^P.01$ in the eclipse duration results in an uncertainty of $\sim 2°$ in the orbital inclination.

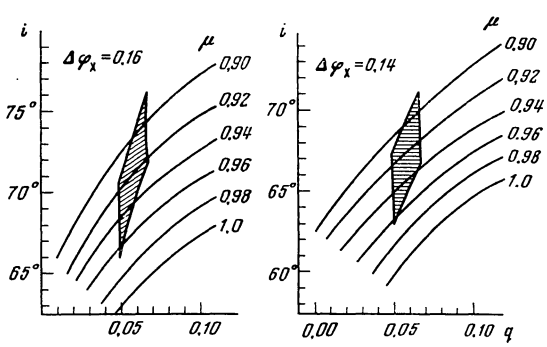

FIG. 3. Region of possible values of the parameters of the HD 153919 system (hatched shapes) at the significance level α = 0.5 for M_V = 15-40 $M_\odot$ and for values of the duration of the x-ray eclipse $\Delta\varphi_X$ = 0.14 and 0.16.

The solution of the inverse problem[11,14] is a random set of parameters (q, μ) for which the discrepancy Δ is less than Fischer's critical level F_α for the chosen significance level α,

$$\Delta(q,\mu) < F_{M,\ \sum_{j=1}^{M}(n_j-1),\ \alpha}. \tag{1}$$

The discrepancy Δ was calculated in accordance with Ref. 15,

$$\Delta(q,\mu) = \frac{\sum_{j=1}^{M}(n_j-1)\ \sum_{j=1}^{M} n_j(l_j^0-l_j^t)^2}{M\ \sum_{j=1}^{M} n_j(n_j-1)\bar{\sigma}_j^2}, \tag{2}$$

where l_j^t is the theoretical brightness at the j-th point of the orbital phase φ (j = 1,..., M) of the light curve, l_j^0 is the average observed brightness of the system at the j-th point, obtained by averaging n_j individual observations, and $\bar{\sigma}_j^2$ is the estimate of the square of the dispersion of the mean value at the j-th point.

The existence of uncertainty in i for fixed q and μ results in the fact that the value corresponding to the minimum discrepancy Δ_{min} was chosen out of all the orbital inclinations satisfying the duration of the x-ray eclipse.

To find the parameters of the system we used the "purely" ellipsoidal light curve of the HD 153919 system in the V filter, obtained by eliminating the effects of eclipses and absorption by the gas stream from the observed optical light curve,[5] which was represented by 12 standard points in the region of orbital phases φ = 0.0-0.5. For the duration of the eclipse we took values of

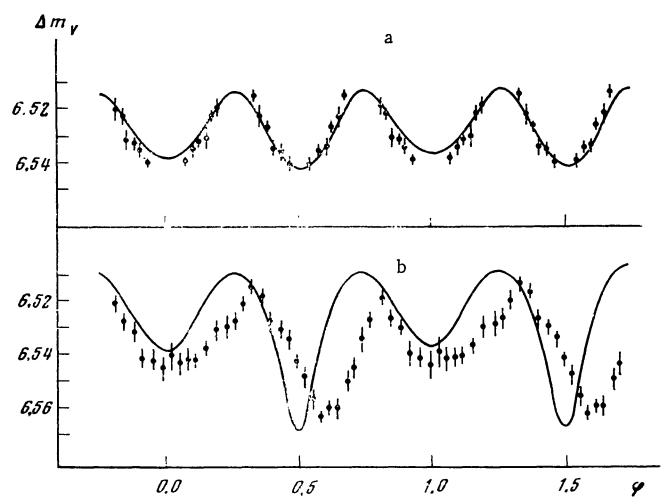

FIG. 4. Theoretical light curves of the HD 153919 system for the parameters M_V = 25 $M_\odot$, i = 68°, and q = 0.058, and μ = 0.92; a) describing the "purely" ellipsoidal light curve; b) observed light curve with allowance for the effect of eclipse by the accretion disk.

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$\Delta\varphi_x = 0.14$ as the most probable and $\Delta\varphi_x = 0.16$ to estimate the influence of a change in $\Delta\varphi_x$ on the solution of the problem.

The discrepancies Δ_{min} as a function of the mass ratio q of the components for different degrees of filling of the Roche lobe μ are shown in Fig. 2. The discrepancy F = 0.96 (Ref. 15) corresponding to the critical significance level for $\alpha = 0.5$ is marked by a dashed line. The weak dependence of Δ_{min} on μ prevents a significant narrowing of the region of possible values of the parameters. Since information about the mass function of the compact object is absent for the HD 153919 system, and only its value for the normal component is known,[12] $f_V(M) = (0.0033 \pm 0.0007)\ M_\odot$, to limit the possible values of the mass ratio q in the system we must draw upon additional information, such as data on the possible values of the mass M_V of the visible star, determined from its spectral class. The mass of the visible star for the spectral class 06f cannot exceed 40 $M_\odot$ (Ref. 16), and its minimum value for single stars is 25 $M_\odot$. With allowance for mass exchange in the system and the intense stellar wind, this value can be reduced to 15 $M_\odot$ (Ref. 17).

In Table I we present the discrepancies $\Delta_{min}(q, \mu)$ for an eclipse duration of $0^p.14$. Those sets of parameters (q, μ) which satisfy the condition (1) for the significance level $\alpha = 0.5$ and the limits of $15\ M_\odot \le M_V \le 40\ M_\odot$ on the mass of the visible star are marked by an asterisk. A summary of the possible values of the parameters of the HD 153919 system at the significance level $\alpha = 0.5$ is given in Table II and in Fig. 3. The theoretical light curve of the system in the V filter for the parameters i = 68°, q = 0.058, $\mu = 0.92$, and $M_V = 25\ M_\odot$ from the region of possible values is shown in Fig. 4a. The good agreement between the theoretical and the "purely" ellipsoidal light curves is seen.

INTERPRETATION OF THE OBSERVED OPTICAL LIGHT CURVE OF THE HD 153919 SYSTEM WITH ECLIPSE EFFECTS

Along with the calculation of the ellipsoidal light curve for the HD 153919 system, we investigated the applicability of it to a model with a disk.[14] In this model it is assumed that there is a flat, circular, optically opaque, luminous disk around the relativistic object. Since optical light curves of the HD 153919 system averaged over the precession cycle are used in the analysis, it is natural to assume that the disk lies in the orbital plane on the average. For angles of orbital inclination i close to 90° one observes optical eclipses of the star by the disk and of the disk by the star, i.e., in summing the fluxes from elementary small areas of the star and disk we allowed for only those of them which were not eclipsed. The radius R_d of an accretion disk is, according to Paczyński,[18] half the radius of the Roche lobe of the compact star, $R_d = 0.5(1 - \xi^*)$, where ξ^* is the maximum size of the Roche lobe of the visible star. Since the luminosity of the x-ray source in the HD 153919 system is relatively low, the optical luminosity of the accretion disk is due mainly to the "reflection" of light of the visible star[19] and was taken as $K_1 = 0.01$ of the luminosity of the visible star. To estimate the influence of eclipse effects we used the average observed light curve of the HD 153919 system in the V filter uncorrected for eclipse effects.[5] An investigation of the region of possible values of the parameters in this case using the method described above for ellipsoidal variability with values of $\Delta\varphi_x = 0.14$ and 0.16 showed that this curve cannot be described consistently within the framework of the Roche model without effects of eclipses by the accretion disk. The use of the Roche model with an accretion disk for the analysis with the best parameters found for "purely" ellipsoidal variability allowed us to reconcile the difference in depths and the amplitude of the observed light curve (Fig. 4b). Here the minimum correspond to the case of the "x-ray source in front" is observed at the phase $\varphi = 0.6$, as already mentioned. A more complicated model in which the visible star is eclipsed by a gas stream located at an angle to the line of centers of the components is needed to eliminate this discrepancy.

DISCUSSION OF RESULTS

An analysis of the "purely" ellipsoidal light curve allowed us to find the parameters of the HD 153919 system; in particular, for the first time we obtained reliable estimates for the values of the orbital inclination i and the degree of filling of the Roche lobe μ (see Table II). It was shown that the degree of filling of the Roche lobe in this system is $\mu < 1$, which agrees with present concepts on the evolution of x-ray binary systems.[9,10]

The existence of precessional motion of the axis of rotation of the visible star distorts its shape. In a nonprocessing model the departures of the Roche figure from the critical equipotential surface for systems containing a precessing visible star depend on the angle η between its axis of rotation and the normal to the orbital plane, the mass ratio q of the components, and the degree of asynchronism Ω of the rotation.[20] An analysis of the generalized model of a Roche figure in the case of $\eta \neq 0$ and $\Omega = 1$ made by Avni and Schiller[20] showed that whereas the physical volume of the star is practically constant in the course of precessional motions, the volume of its critical lobe varies with the phase of the orbital period and is smallest at the times when the secondary component lies on the line of intersection of the orbital plane with the equatorial plane of the visible star, and hence the degree of filling of the Roche lobe μ is greatest here. Our analysis of the parameters of the HD 153919 system yields an estimate of the minimum value of μ. The degree of increase in μ at the time of passage of the compact object through the line of intersection of the planes is ~5% for $\eta \approx 25°$, $\Omega = 1$, and q = 0.06 (Ref. 20), i.e., the degree of filling of the Roche lobe reaches ~0.97 in these periods, which can result in an enhanced outflow of material from the Roche lobe of the visible star at these phases. Further investigations are needed for quantitative estimates of this effect.

[1)] $\Delta\varphi_x = \theta_e/\pi$, where θ_e is the phase angle at which the straight line parallel to the line of sight and passing through the x-ray source is tangent to the Roche surface.

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