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UBVR OBSERVATION OF V1357 Cyg = Cyg X-I. SEARCH OF THE OPTICAL RADIATION OF THE ACCRETION DISK

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16. Abstract
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The viewpoint is widespread that the x-ray source Cyg X-1 that is included in the close double system with the star V 1357 Cyg is a black hole to which disk accretion goes. Below it will be shown that the accretion disk intercepts part of the ultraviolet and optic radiation of the visible star V 1357 Cyg, as well as part of the x-ray radiation of Cyg X-1. This energy is re-emitted by the disk in the optic range. Since the x-ray radiation is variable (Gursky and Schreier, 1975) and the disk dimensions can be altered in broad limits (Illarionov and Syunyayev, 1974, Shapiro et al., 1975), then the optic radiation of the disk must experience considerable irregular variability in time, i.e., must make a variable contribution to the complete optic luminosity of the double system, and result in fluctuations in its brightness. The extended disk in principle can appear

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*Numbers in margin indicate pagination in original foreign text.

also as a normal star eclipsed by the disk and a disk eclipsed by a normal star (Shakura and Syunyayev, 1972).

In order to find the observational manifestations of the disk at the high-mountain station of the Astronomical Institute of the Uzbek SSR Academy of Sciences UBVR observations were made of V 1357 Cyg. Below data are given on the optic observations, and the possible observational manifestations of the disk are discussed and a comparison is made of the data of observations and theory.

We recall that V 1357 Cyg is spectroscopically a double star with period $5^{d}.6$ (Webster and Murdin, 1972; Bolton, 1972). Lyutyy (1972) discovered the photometric variability of this /4
object with a two times smaller period $2^{d}.8$, while Lyutyy et al. (1973) interpreted it as a consequence of the effect of ellipsoidality--distortions in the shape of the visible star (practically filling its Rosh cavity) as a consequence of the tidal effect of the companion that is not visible in the optic rays. The complete amplitude of variability is about $0^{m}.05$. In the system there are no x-ray eclipses (Gursky and Schreier, 1975).

Observations of the variable V 1357 Cyg were made on Maydanak Mountain (Central Asia) on a 60-cm Zeiss reflector from 6 August to 11 September 1977 (25nights); and five nights from 21 July to 4 August 1977 on a 40-cm reflector.

A photomultiplier and electrophotometer were used as the reception apparatus for counting impulses with output to the REU-79 central command post. The apparatus is briefly described in the work of Kilyachkov and Shevchenko (1975). The observations were made in the UBVR system; the residual reduction coefficients in the Johnson system were less than $0^{m}.010$ in B and V, and less than $0^{m}.03$ in U and R. As the main comparison star the star "c" from the work of Lyutyy was used (1972). The control star was star "a." In each observation session the variable was measured 3-4 times, the star "c" 1-3 times, and the star "a" once in all four filters with accumulation time 50 s. The measurement results were removed to the central control post every 10 s for the possibility of determining an error. The background was measured 1-2 times with the same accumulation time. A round diaphragm 28" in diameter was used. Each session of measurements lasted from 28 to 70 minutes depending on the rate of change in the air mass. The moment of time was averaged with respect to the session. In 30 nights 49 measurment sessions were held. By transfer of the standard the amount R was determined of the comparison star "c" $R=9^m.0\,40 \pm 0^m.010$.

Observation Results /5

The moment of time and the values of the amounts B, U-B, B-V, V-R and the phases of the period Ψ are given in table 1. Figure 1 presents the brightness curves in the systems B and V, as well as the change in color of U-B depending on the phase. Observations on the 40-cm telescope are isolated by the white circles and are averaged for the dates of observations.

The formally computed root-mean-square error in the individual measurements is very small, on the order of $0^m.001+0^m.002$. Averaging for the session reduced the error even more. At the same time the spread of individual points during the session was $0^m.002-0^m.003$ in the B and V filters and was two times greater in the U and R filters. Most likely these amounts also determine the actual root-mean-square error in observations. It is possible, however, that they are determined by rapid fluctuations in the brightness of the system.

We are inclined to consider the real deviations to be more than $0^m.012$ of the mean brightness curve observed near the phases $\Psi=0.036$ (17 August) and $\Psi=0.838$ (10 August), as well as the

TABLE 1

1 2443	2 V	3 U–B	4 B–V	5 V–R	6 0
346.575	8.84	– 0.32	0.82	0.81	0.305
356.612	8.87	– 0.31	0.81	0.83	0.097
357.225	8.84	– 0.33	0.82	0.81	0.205
258	8.84	– 0.30	0.82	0.82	0.212
358.236	8.86	– 0.33	0.81	0.82	0.386
360.271	8.84	– 0.32	0.81	0.83	0.750
426	8.84	– 0.32	0.82	0.82	0.777
362.396	8.854	– 0.307	0.816	0.82	0.134
465	8.846	– 0.312	0.827	0.83	0.141
363.453	8.840	– 0.309	0.818	0.83	0.330
364.373	8.876	– 0.314	0.817	0.81	0.481
365.375	8.851	– 0.304	0.813	0.82	0.660
366.369	8.870	– 0.319	0.811	0.82	0.838
367.221	8.889	– 0.306	0.819	0.83	0.992
341	8.892	– 0.315	0.815	0.83	0.011
368.219	8.842	– 0.321	0.820	0.83	0.167
308	8.841	– 0.319	0.819	0.82	0.184
369.348	8.858	– 0.317	0.820	0.82	0.370
370.235	8.869	– 0.322	0.820	0.82	0.528
392	8.863	– 0.324	0.821	0.83	0.557
372.215	8.864	– 0.318	0.819	0.82	0.883
368	8.860	– 0.312	0.824	0.81	0.909
373.366	8.863	– 0.308	0.812	0.82	0.036
374.341	8.843	– 0.318	0.813	0.83	0.261
377.237	8.842	– 0.321	0.812	0.82	0.777
307	8.841	– 0.318	0.814	0.82	0.791
378.347	8.876	– 0.315	0.820	0.81	0.974
382.351	8.744	– 0.318	0.818	0.82	0.689
388.193	8.837	– 0.320	0.822	0.82	0.734
319	8.839	– 0.321	0.815	0.83	0.755
389.212	8.864	– 0.311	0.819	0.82	0.915
390.170	8.864	– 0.320	0.820	0.82	0.087
314	8.862	– 0.315	0.824	0.83	0.112
391.235	8.837	– 0.317	0.821	0.82	0.276
419	8.840	– 0.320	0.818	0.82	0.309
392.228	8.870	– 0.320	0.820	0.81	0.454
264	8.868	– 0.326	0.820	0.82	0.460
393.198	8.853	– 0.316	0.817	0.82	0.627
247	8.860	– 0.318	0.822	0.83	0.635
300	8.852	– 0.315	0.819	0.82	0.638
360	8.843	– 0.320	0.823	0.82	0.656
395.295	8.885	– 0.312	0.819	0.82	0.998
346	8.882	– 0.304	0.816	0.82	0.009
396.183	8.846	– 0.321	0.816	0.83	0.160
332	8.844	– 0.314	0.819	0.82	0.186
451	8.840	– 0.318	0.817	0.82	0.207
397.340	8.855	– 0.320	0.816	0.82	0.367
418	8.857	– 0.311	0.825	0.82	0.391
398.210	8.882	– 0.318	0.819	0.82	0.521

difference in the depth of the main and secondary minimums by $0^m.008-0^m.010$.

Our observations satisfy in the best way the following elements JD 2443395.295∓0.013+5^d. 601092P±0.000008. In refinement of the period the moment of the minimum (JD 2441166.06) is

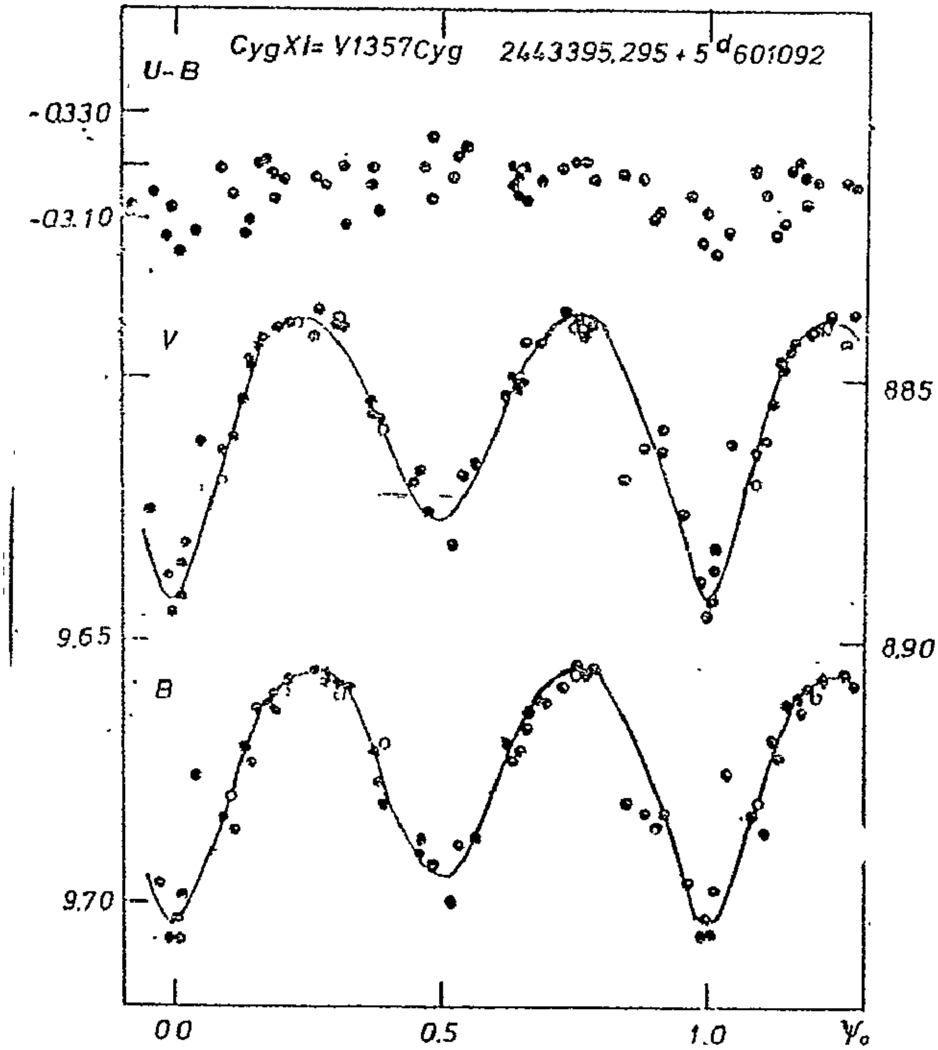

Figure 1. Brightness Curves of V 1357 Cyg in B and V Filters. White Dots--observations on 40-cm telescope.

taken as starting epoch from the work of Lyutyy (1972).

We will note the main features of the brightness curve obtained from the observations on Maydanak Mountain.

1. The brightness curve has a 3-10 times lower dispersion as compared to the curves obtained by Lyutyy (1972), Walker (1972), Lyutyy et al (1973, 1974), Khaliullin (1975), Walker and Quintamilla (1974), and Lester et al. (1976). It is most probable that the difference in the curves of brightness was produced by the

change in activity of the x-ray source Cyg X-1. Optic observations were made in the same period that x-ray observations of /6 Cyg X-1 were planned from the satellite OGO-8, therefore extra-atmospheric observations will make it possible to verify this hypothesis.

2. The brightness curve is more symmetrical in relation to both minimums than the curves of Lyutyy (1972), Walker (1972), Walker and Quintamilla (1974) and Lester et al. (1976).

3. The amplitude of changes in brightness is closer to the data of Walker (1972) and Walker and Quintamilla (1974), less than that of Lyutyy (1972), and Lyutyy et al. (1973, 1974), and Lester et al. (1976) by 1.3-1.4 times. The mean level of the brightness curve coincides with the result of averaging all data, as well as with the observations of Walker (1972). The mean level of the brightness curve of Walker and Quintamilla (1974) is by $0^m.02$ brighter than that of our observers.

4. Changes in the color indices of B-V, and V-R lie in the limits of the measurement errors. The mean color indices $\overline{B-V}=0^m.818$, $\overline{V-R}=0^m.82$. Apparently, as yet it is impossible to draw an unambiguous conclusion about the changes in the color indices U-B with phase (fig. 1). The mean color index $\overline{U-B}= -0^m.317 \pm 0^m.001$.

5. The minimum that corresponds to the lower connection of the secondary x-ray source is by $0^m.01$ brighter than the minimum of the upper connection (see fig. 2). The difference in the depth of the main and secondary minimum follows distinctly only from the brightness curve of Lester et al. (1976).

On figure 2, on our brightness curve in filter B (dotted line and white circles) the curve (solid line) is plotted that was computed by Avni and Bacall (1975) for the change in brightness by means of the ellipsoidality of the supergiant. The

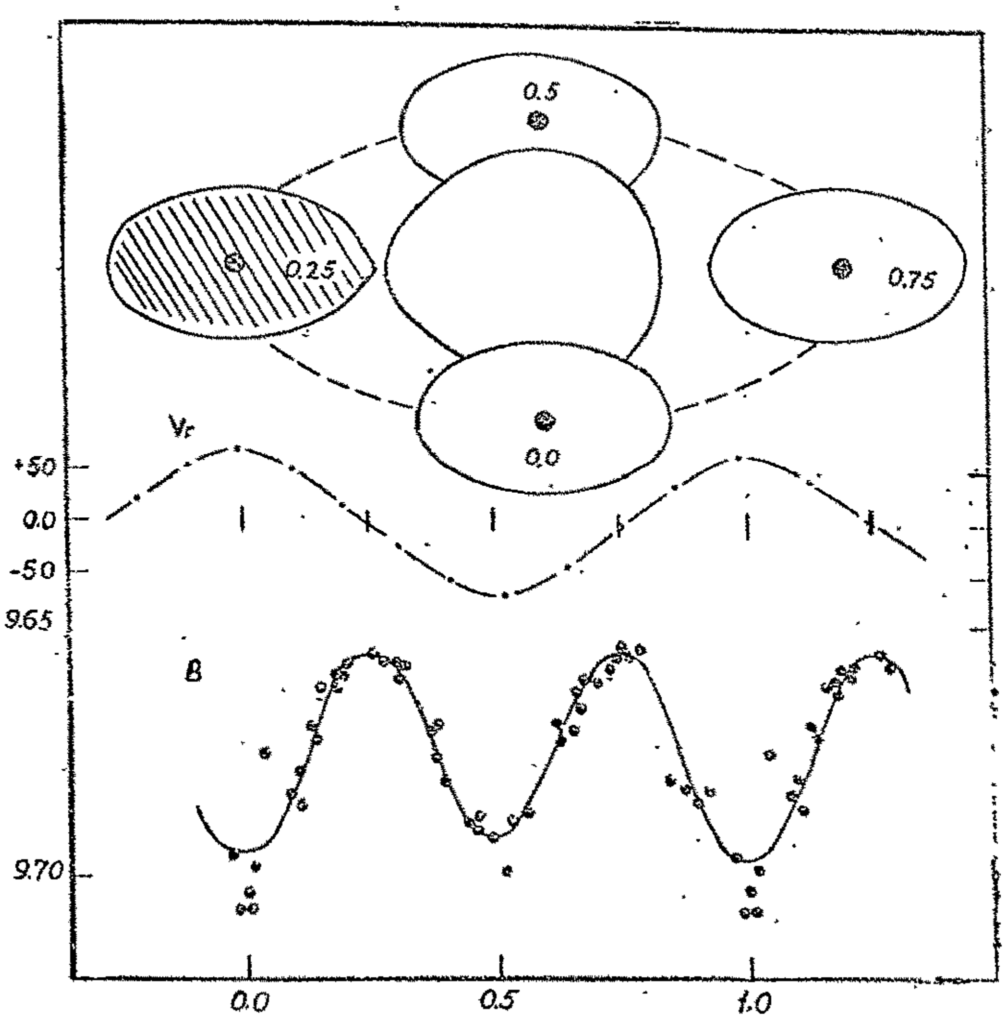

Figure 2. Variability in Brightness of System
a--scheme of system illustrating possibility of eclipses of star and disk; b--curve of radiation velocities of V 1357 Cyg from work of Mason et al. (1974); c--comparison of observational data with theoretical curve of Avni and Bacall (1975).

maximums of both curves in the phases 0.25p and 0.75p are superposed. Avni and Bacall (1975) assume that the appearance of their curve does not contradict the observations of Lester (1976) and Walker and Quintamilla (1974).

Discussion of Results

It is apparent from fig. 2 that deep acute minimums near /7 the phases 0 and 0.5 fall from the mean brightness curve. The same acute deep minimums can be found in the data of Lyutyy, Walker (1972) and Cherpashuk et al. (1974), see also Sykes (1977). It is tempting to explain these dips by the eclipses of the star by the accretion disk, gas jet or gas ring surrounding the system, and vice versa by the eclipses of these formations by the star. It is clear that the precession of the disk plane (as is discussed in the case of the system Her X-1=HZ Her)and many other effects will result in irregular eclipses. It is natural that the most probable is eclipses near phases 0.25 and 0.75. The simplest model of eclipses is given in fig. 2. If this hypothesis is true, then one can draw the conclusion that a reduction in brightness and the duration of the eclipses are small, i.e., practically only a small part of the stellar surface occurs. Here it is important that the disk is significantly colder than the star (see below). This must result in a difference in the depth of the acute minimums.

To verify this hypothesis more detailed and longer observations are needed. We will pass to theoretical estimates.

Condition of Eclipses

From the fact of the absence of x-ray eclipses follows (see fig. 2)

$$R < A \cos i,$$

where R--radius of visible star, A--distance between centers of masses of two stars in the system, i--angle of inclination of the system. We assume that in the system there is an accretion disk of radius z. The eclipse of the disk by the star (or of the star by the disk) can occur with

$$R + Z \cos i > A \cos i.$$

Consequently, with

$$\frac{R}{A} < \cos i < \frac{R}{A-z}$$

there will not be any x-ray eclipses in the system, but optic eclipses must be observed. /8

Computations of the parameters in the system Cyg X-1= V1357 Cyg that take into consideration the data on radiation velocities (function of mass) of the visible star, the amplitude of ellipsoidal changes in brightness and the absence of x-ray eclipses, and as the most probable angle of inclination provide $i=40\div45°$ (Avni and Bacall, 1975, Bochkarev et al., 1975) Until now such computations did not consider the possibility of eclipses of the star by the disk and the disk by the star. The estimates that do not consider the true shape of the star (it is non-spherical) and the disk (orbits of particles on the periphery of the disk) are not circular due to the tidal effect of the visible star (Paczynski, 1977) show that eclipses are possible only with comparatively large i angles. Assuming that the star fills its critical Rosh cavity, i.e., that $R/A=0.38-0.2 \lg q \approx 0.46$ (Paczynski, 1971), and assigning the disk radius z, it is easy to find the angle at which the surfaces of the disk and star touch (see fig. 2). With $z=0.2A$ the eclipses occure with $i > 55°$, with $z=0.3A$ with $i > 49°$ (see below for a discussion of the disk dimensions). These estimates force us to refer seriously to the idea about the possibility of eclipses in the Cyg X-1 system.

We recall that in the system Her X-1 eclipses of an extended disk by the star were found already a long time ago (Lyutyy et al. 1974, Lyutyy, Syunyayev, 1976, Bionovatyy-Kogan et al., 1977). One should also note the possibility of deviation of the outer parts of the disk from the plane of the system. In this case the optic eclipses can be observed also with smaller values of the i angle. A change in the disk radius can result in disappearance of the eclipses and their appearance again. Even the firmly established fact of the absence of optic eclipses in the system Cyg X-1=V 1357 Cyg yields useful information: we obtain additional limitations on the disk dimensions and the angle. The question as to whether in the system V 1357 Cyg=Cyg X-1 /9 eclipses are actually observed is problematic. It is easier to obtain a response to another question. A comparison of our data with the results of the simultaneously made x-ray observations from the satellite OGO-8 most likely will make it possible to obtain an answer to another question: why was V 1357 Cyg so quiet during our observations. Was the x-ray source Cyg X-1 "quiet" during this time? As yet we can merely note a significant difference between our curve of brightness and the brightness curve obtained by Khaliullin (1975) on the same telescope and in a comparable observation time. Khaliullin (1975) observed a rapid (several hours) and strong (with amplitude $\lesssim 0^m.03$) irregular variability in brightnes on the background of which it is impossible to look for fine effects of the type of possibility of eclipses discussed above. If it happens that the x-ray source was relatively stable during our observations then an explanation of the difference in dispersion of the observation points in relation to the mean brightness curve in these two series of observations can be very simple. The accretion disk provides a noticeable and variable contribution to the optic brightness of the system. The super giant V 1357 Cyg most likely is a stable star and does not alter its brightness in several hours. All the fluctuations in the brightness are linked to the accretion disk. In observing them, we observe the radiation of the disk and other unstable formations--gas jet, hot point in the zone of intersection of the jet and the disk, and gas ring possibly surrounding the system. It is simplest of all to evaluate the optic luminosity of the disk.

Optic Radiation of Disk

We assume that in the system there is an accretion disk with radius on the order of dimensions of the critical Rosh cavity of an invisible component. The distance between the centers of the stars in the Lebed' system X-1 is close to

$$A = \frac{PV}{2\pi \sin i}\left(1 + 1/q\right) \simeq 4 \cdot 10^{12}\ \text{cм},$$

where $q=M_x/M_v=0.4$, angle of inclination i is taken as equal to 40-50°, v≈72 km/s--radiant velocity of visible component (Mason et al, 1974). The size of the disk can be on the order of z≈0.2A ≈8 10^{11} cm. (Paczynski, 1977), i.e., the area of the visible surface of the disk $\pi z^2 \cos i$ can be only slightly smaller than the area of the surface of the stellar disk πR^2, where R≈(0.38-0.2 lg q), A≈0.46A, if the star fills its critical Rosh cavity (Paczynski, 1971). /10

Paczynski (1977) noted that the closed Kepler orbits in the double system with q=0.4 can exist only with $z \leq 0.216A$. At the same time it is evident that the pressure in the disk can result in the existence of a stationary accretion disk with large dimensions, possibly all the way to z=0.3A.

The external zones of the disk radiate by means of 1) release in it of gravity energy during accretion, 2) reflection and reprocessing of ultraviolet and optic radiation of the close visible star, and what is most important for us, 3) by means of absorption and reprocessing of part of the x-ray radiation of the internal regions of the disk. Shakura and Syunyeyev (1973) showed that in the external regions of the disk the gravity release of energy $\left(Q = \frac{3}{8\pi}\frac{GMM}{R^3}\right)$ becomes small as compared to the third of the aforementioned energy sources. Therefore we will dwell in detail only on the second and third energy sources.

a). Reflection and Reprocessing of Radiation of Visible Star

Considering the star to be spherical, it is easy to find the brightness of the disk in any point of it. Assume the complete flow of energy from a unit of stellar surface to be equal to πF, then the stream of energy falling on a unit of disk surface at the point removed by distance P from the center of the star equals

$$\pi F' = F R^3 \int_0^{\arccos \frac{R}{\rho}} \frac{(\rho\cos\theta - R)\sin^2\theta\, d\theta}{(\rho^2 + R^2 - 2R\rho\cos\theta)^2} \int_0^{\pi} \sin\varphi\, d\varphi =$$

$$= F\left[\operatorname{arctg}\sqrt{\frac{\rho+R}{\rho-R}} - \frac{R}{\rho}\sqrt{1-\frac{R^2}{\rho^2}} - \frac{1}{2}\arccos\frac{R}{\rho}\right].$$

Here R--radius of star, θ--angle with top at center of star between radius-vector of radiating point on surface of the star and straight line connecting the center of the star and the given point on the disk (fig. 3), φ--angle between plane of disk and plane in which the vector $\vec{R}$ and $\vec{P}$ lies. This evaluation considers the effects of orientation of the emitting (on the star) and absorbing (on the disk) areas; the distance between them equals $D = \sqrt{\rho^2 + R^2 - 2\rho R\cos\theta}$; cosine of the angle between the direction to the given point of the disk and the perpendicular to the surface of the star equals $\frac{\rho\cos\theta - R}{D}$, while the cosine of the angle between the perpendicular to the disk and the direction to the assigned point on the stellar surface /11

evidently also depends on the angle φ. It does not take into account the effects of the ellipsoidality of the visible component which must increase the angle i and correspondingly reduce the stream of energy falling on the disk. Table 2 presents the numerical values for the ratios of the streams F'/F and the temperatures of the surfaces of the star and the disk depending on the ratio R/P. The scattering by the disk surface of the

TABLE 2.

DISTRIBUTION OF BRIGHTNESS AND TEMPERATURE OVER DISK ILLUMINATED BY NEIGHBORING STAR

$\frac{R}{\rho}$	$\frac{\pi F'}{\pi F}$	$\frac{T'}{T}$
I	I/2	0.84
0.9	0.23	0.69
0.8	0.I4	0.6I
0.7	0.088	0.54
0.6	0.052	0.48
0.5	0.028	0.4I
0.4	0.0I4	0.34
0.35	0.0094	0.3I
0.3	0.0059	0.28
0	0	0

ultraviolet radiation is assumed to be weak as compared to the true absorption. It is evident that the temperature is the same in all points of the disk removed by the same distance P from the center of the star, i.e., the lines of constant brightness on the disk represent arcs with circumferences of radius P, limited by the boundaries of the disk. In the limits of the disk with z=0.2A, when $0.4 < R/P < 0.6$, the ratio F'/F can be altered from 0.052 to 0.014. Here the stream falling on the unit of area of the disk surface drops with removal from the star. If the temperature of the stellar surface is close to 25000 K, then the temperature of the disk surface in the selected boundaries is altered from 12000 to 8500 K. Here the main portion of the disk area is at a temperature close to 10,000 K. The bolometric luminosity of the external regions /12 of the disk strongly depends on its dimensions and with z=0.2A can reach $2.5\cdot10^{-3}$ of the luminosity of a normal star, or $2.3\cdot10^{36}$ erg/s. Due to the lower temperature $T' < T$ a considerable part of this energy goes to the optic range, which increases the contribution of the disk to the luminosity of the system in the standard ranges UBV. We recall that the intensity of the radiation at wavelength λ 4400Å from two unit areas with T= 25,000 K and 10,000 K differs only 9.4-fold (and at wavelength λ5500 Å 6.9-fold), while the bolometric stream of radiation differs 39 times. With the selected parameters of the disk and the system the contribution of the disk to the observed stream at wavelengths λ4400 Å and λ5500 Å must be $\approx \left(\frac{z}{R}\right)^2 \cos i \frac{F_\nu(\lambda, T')}{F_\nu(\lambda, T)}$ $1.5 \cdot 10^{-2}$ and $2 \cdot 10^{-2}$ respectively, i.e., the contribution of the disk is $0^m.015$ in the filter B and $0^m.02$ in the V filter. Above it was already noted that the disk dimensions can exceed 0.2 A. With an increase in the dimensions of the disk its contribution to the optic luminosity of the system must also rise.

b. Reprocessing of X-Rays

The inner regions of the disk are not stable in relation to the secular (Lightman, Eardley 1974) and thermal (Shakur, Syunyayev, 1976) instabilities. Therefore the surface of the disk there is very distorted. The directivity of the x-ray radiation in this case is difficult to compute; we assume that this radiation is quasi-isotropic. The disk has the shape of two saucers applied by the bottom to each other. It is natural that it intercepts a noticeable part of the x-ray radiation of the central source. The estimates (Shakura, Syunyayev, 1973; Lyutyy Syunyayev, 1976) show that it can be intercepted and reprocessed into optic radiation up to 4% of the total x=ray stream. The complete x-ray luminosity of Lebed' X-1 in the range 100 ev $< h\nu <$ 1 mev depends on the time and lies in the interval 10^{37}- /13
10^{38} erg/s. Consequently, the contribution of the reprocessed x-ray radiation to the optic luminosity of the disk can reach $4 \cdot 10^{36}$ erg/s, which is close to the contribution from heating by ultraviolet radiation. Heating of the disk by x-ray and

ultraviolet radiation can result in its optic luminosity on the order of $6 \cdot 10^{36}$ erg/s. Here the contribution of the disk to the stream of optic radiation from the system at wavelength λ 4400 Å can reach $0^m.03$ and $0^m.04$ at wavelength λ 5500 Å. The temperature of the surface of the disk can reach 13,000 K.

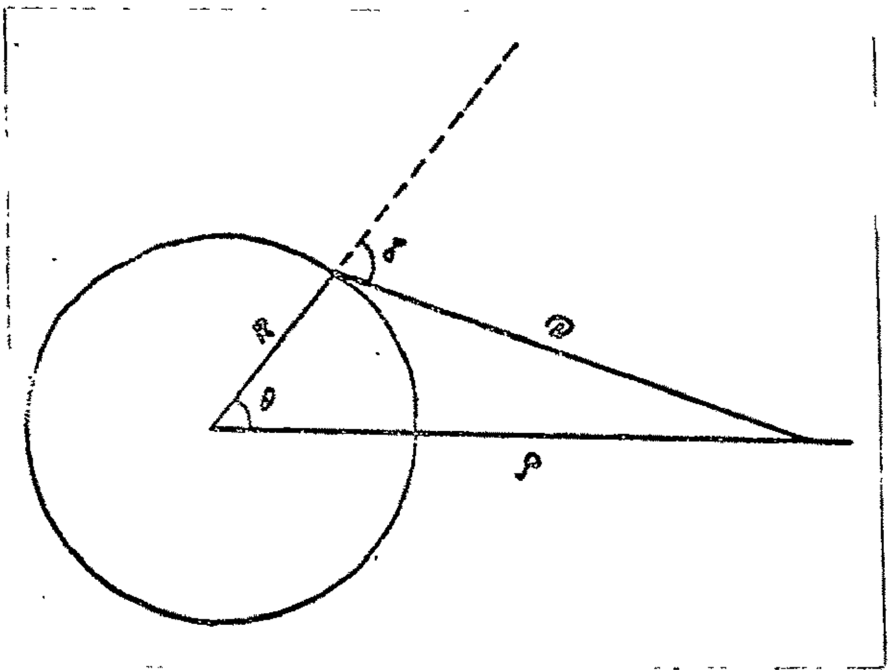

Figure 3. Geometry of Problem on Heating Surface of Disk by Radiation of Spherical Star
Figure corresponds to the case where the plane of the triangle OAB is perpendicular to the plane of the disk, i.e., angle $\gamma = \pi/2$.

Polarization

Radiation of the disk must be linearly polarized since we observe the disk at a noticeable angle to its perpendicular and the Thompson scattering must make a noticeable contribution to the nontransparency.

Variability in Optic Radiation of Disk

The optic radiation of the disk must be variable for two reasons. First, the x-ray radiation is variable. In the phase with it, but with a delay by $\Delta t \approx A/C \approx 2$ min the optic radiation of the disk must fluctuate. According to the estimates given above with a considerable change in the x-ray luminosity (or spectrum of x-ray radiation, which results in a change in the albedo) the complete amplitude of the optic variability in the system can reach $0^m.02$. Such a rapid stochastic variability plotted on the regular ellipsoidal variability of brightness can explain the considerable fluctuations in the brightness of the system in relation to the mean curve of brightness (Khaliullin, 1975).

Second, the dimensions of the disk can be altered. Here its area is altered and the optic luminosity. The effect can be great also with a constant x-ray stream.

Third, the external regions of the disk for different reasons can be deflected from its plane. This results in interception of a considerable portion of x-rays and increase in the luminosity of the disk, as well as an increase in the amplitude of the variability.

It is evident that the first of the listed reasons results in the shortest scale of variability, all the way to several minutes. Here the variability in the optic radiation reflects the dependence of x-ray luminosity on time.

The second and third reasons can hardly result in variability with the characteristic time less than the rotation period of the system.

As is known, the x-ray source of Cyg X-1 has two states--high and low. In the transitions between them the spectrum is radically altered, and possibly, the complete luminosity of the source (Gursky and Schreier, 1975). If the variability of the optic radiation of the system is linked to the reprocessing of x-rays, then not only the dispersion of the points must be altered in relation to the mean brigthness curve, but also the mean level of the system brightness (brightness averaged with respect to period).

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