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Optical observations of the x-ray sources Cygnus X-2 and Scorpius X-1

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Optical observations of V1341 Cyg (Cyg X-2) from July 1974 to April 1975 indicate a possible regular component of the light variation. Both the brightness and the amplitude of the regular variability were lower during May–October 1975. Observations of V818 Sco (Sco X-1) confirm the presence of regular periodicity in the light curve.

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Photoelectric observations of the variable star V1341 Cygni, identified[1] with the x-ray source Cygnus X-2, were carried out in the U, B, V system at the Shternberg Astronomical Institute's Southern Station in the Crimea by one of us (Lyutyi) from July 1974 to November 1975. The instrument used was mainly the 60-cm telescope equipped with a photon-counting photometer. Altogether 341 brightness measurements were made.[2] Photographic observations[3] of the variable star V1341 Cyg were obtained concurrently by two of us (Goranskii and Shugarov) at the Southern Station, using the 50-cm meniscus astrograph and the 40-cm astrograph, and also at Moscow with the 70-cm reflector. A total of 610 photographs of V1341 Cyg (509 in the B band and 101 in the V band) were measured with the iris-diaphragm microphotometer of the Shternberg Astronomical Institute. These were tied to a photoelectric standard, which was taken to be six stars whose color index is similar to that of V1341 Cyg.

The star V1341 Cyg (Cyg X-2) is an irregular variable with excess ultraviolet radiation.[4] According to our observations its brightness varies randomly with an amplitude slightly greater than 1^{m} (range of brightness variation: $14^{m}.6$-$15^{m}.7$). In the V and U bands the amplitudes are $0^{m}.8$ ($14^{m}.1$-$15^{m}.0$ V) and $1^{m}.4$ ($14^{m}.1$-$15^{m}.5$ U), respectively. The B − V color index is practically independent of the brightness of the star and is equal to $+0^{m}.43$, on the average. The U − B color index typically shows a slight decrease with increasing brightness; it ranges from $-0^{m}.5$ to $+0^{m}.1$.

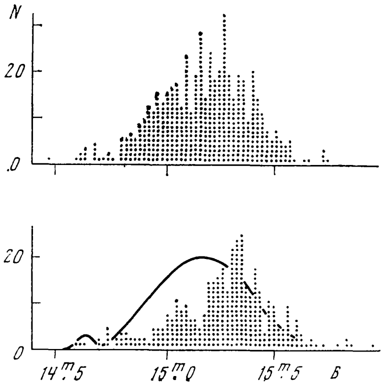

FIG. 1. Histograms for the brightness of the x-ray star V1341 Cyg (Cyg X-2): top, before mid-April 1975 (JD< 2442520); bottom, after that epoch. Notice the decline in the brightness of the star after mid-April.

TABLE I

Period	Semiamplitude of periodic component
$5^{d}.92 \pm 0^{d}.05$	$0^{m}.137$
1.2034 ± 0.002	0 .130
0.8528 ± 0.001	0 .131
0.5452 ± 0.0005	0 .099
0.4603 ± 0.0003	0 .098

The photoelectric observations exhibit rapid random variability (about $0^{m}.04$ within a minute) in the U band. More gradual light variations (up to $0^{m}.5$) occur over time spans of a few hours. Another interesting feature is the marked change in the photometric behavior of the star in mid-April 1975. Figure 1 shows histograms of the B brightness before and after epoch JD 2442520. On the average the brightness of the star dropped by $0^{m}.1$, and the amplitude of the light variations also diminished.

The problem of discriminating a periodic component in the optical radiation of Cyg X-2 is of interest. The presence of a periodic component in the brightness function of an x-ray source or in the radial velocities affords direct evidence that the x-ray star belongs to a binary stellar system. The optical brightness of a binary system containing an x-ray source may vary due to orbital motion for two reasons.[5] In the first place, a hot spot heated by x rays may be present on the surface of the ordinary star facing the x-ray star. In this event the orbital and photometric periods will coincide. The other factor is the ellipsoidal shape of the ordinary star due to tidal action on it by the x-ray star; in this event the orbital period will be twice the photometric period.

A search for a periodic component in the optical variability of Cyg X-2 within the period range $0^{d}.1 < P < 100^{d}$ has been carried out with a BÉSM-6 computer, using a program compiled by one of us (Basko[6]) on the basis of two independent algorithms.[7,8] The photoelectric observations during the interval JD 2442247-570 (250 observations by May 1975) exhibit a group of diurnally conjugate periods related by expressions of the form $P_1^{-1} = P_2^{-1} \pm (1^{d})^{-1}$. The periodic component may be repre-

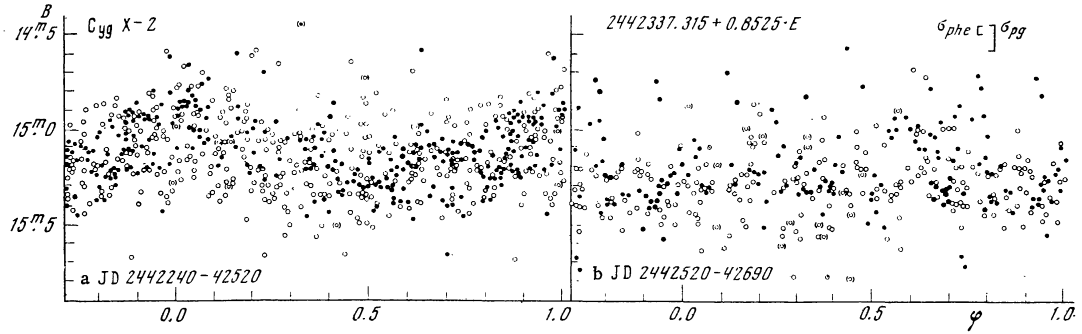

FIG. 2. Composite light curves of V1341 Cyg with period P = $0^d.8525$: a) before April 1975; b) after April 1975. Dots, photoelectric observations; circles, photographic observations.

sented in the form $a \cos(2\pi t/P)$, and the coefficient a determines the semiamplitude of the regular variability. The first three values of the period given in Table I have the greatest reliability, but it is hard to choose one over another. By including later observations (up to JD 2442684), we find a significantly lower reliability for each of the periods in this group, although they still stand out within the period range investigated.

An analysis of the complete series of photographic observations does not yield the group of conjugate periods presented in Table I. The character of the variability of V1341 Cyg changed markedly in April-May 1975. According to the photoelectric obsevations prior to this time, there was a definite group of diurnally conjugate periods, as indicated in the table. It is interesting to note that the photographic observations made at that time give best agreement with the third period, $P_3 = 0^d.8528$. Figure 2 displays a graph of the composite light curve with a period of $0^d.8525$, close to P_3, according to the observations up to mid-April 1975. The early observations (Fig. 2a) manifest a periodic component with a semiamplitude of about $0^m.13$. The late observations (Fig. 2b) do not show a periodic component with $0^d.8528$ period, and the mean brightness of the star has declined to the average minimum brightness prior to April 1975.

Evidently certain changes in the physical conditions occurred in April 1975, resulting in a decrease in the optical brightness and a sharp drop in the amplitude of the regular variability.

The presence of strong (up to 1^m) random brightness fluctuations and the weakness of the periodic component may be understood in terms of the hypothesis of an accretion nature for the x-ray star Cyg X-2. For example, if the orbital inclination $i \approx 30°$ and there are equal contributions to the luminosity of the system from the optical radiation of the accretion disk, the hot spot, and the unheated side of the normal star, then the semiamplitude of the regular variability will be considerably smaller than $0^m.1$. This circumstance is due to the small contribution of the radiation of the hot spot and the weak variation of the observed spot area as a function of the phase of the orbital period. It is natural to ascribe the irregular rapid variability to rapid variations in the x-ray flux heating the outer regions of the accretion disk and the hot spot.

A search for periodicity in the light curve of Scorpius X-1 has been initiated by Lyutyi and Efremov,[9] who have called attention to a possible weak regular component in the light curve, with a $3^d.9$ period. An analysis[10] has shown that the most probable values of the period are approximately $3^d.8$ and $0^d.8$. These values are clearly conjugate to each other. A subsequent analysis[11] of more extensive observational material has yielded periods of $0^d.787$ and $3^d.74$. The $0^d.787$ period is further confirmed by spectroscopic data.[12]

We have performed a mathematical reduction of the U, B, V observations of Sco X-1 obtained by one of us (Lyutyi) in 1972-1975 with the 60-cm reflector of the Southern station.[13,2] The search for periods has covered the range $0^d.6 < P < 100^d$. The three values for a period warranting highest confidence are $3^d.740 \pm 0^d.005$, $1^d.1245 \pm 0^d.0005$, and $0^d.7872 \pm 0^d.0003$, although the reliability of these periods is fairly low. Nevertheless, it apparently is no accident that two of the three most probable values for a period agree exactly with the two best values for the period of optical variability of Sco X-1 found previously by Gottlieb et al.[11] from different observational material.

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The possibility of explosive helium burning in low-mass stars

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A simplified calculation is performed for the evolution of an accreting helium dwarf. If $\dot{M} < 10^{-8}\ M_{\odot}/\mathrm{yr}$, the density at which helium burning sets in will exceed $10^7\ \mathrm{g/cm^3}$. At such high densities the helium-flash process may be explosive in character.

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Type I supernovae are often ascribed to stars of low mass. However, calculations[1] of the evolution of individual stars with mass $M \leq M_{\odot}$ show that no strong eruptive processes would take place in such stars that might some manner result in a supernova outburst. The sole hydrodynamic calculation[2] of a helium flash, based on Härm and Schwarzschild's evolutionary calculations[3] as an initial model, indicates the possibility of an explosion in a helium core with an energy release of $\approx 5 \cdot 10^{48}$ erg. Helium burning in the cores of single stars would take place at a density of $\approx 5 \cdot 10^5\ \mathrm{g/cm^3}$ if neutrino losses are neglected, and at $\approx 10^6\ \mathrm{g/cm^3}$ if they are taken into account.[1] The explosive energy release can rise considerably if the density at the epoch of onset of helium burning is higher. In principle, such a situation can be realized in close binary systems.

Let us take a binary star whose primary component has a mass $M \lesssim 2.0\ M_{\odot}$, and whose secondary has $M \lesssim 1\ M_{\odot}$, (the time scale for nuclear evolution of such a star will be comparable to the lifetime of the Galaxy). If the primary component loses matter at the time of hydrogen burning in a shell and prior to helium burning in the core, then it will turn into a helium dwarf with a thin hydrogen envelope. The rate of increase of the mass within the core of the dwarf will be determined by the rate of hydrogen depletion in the shell source. The change in the central temperature T_c and density ρ_c of the helium dwarf will be determined by the change in the mass of the core and its adiabatic contraction. After $\approx 10^{10}$ yr the secondary star in the system will have expanded and have begun to lose mass, some of which will be captured by the degenerate helium dwarf. If the rate of hydrogen depletion in the shell source of the accreting star is determined solely by the accretion rate, the firing of helium would be expected to take place at a higher density.

In this letter we report the results of a simplified calculation of the evolution of a helium dwarf in a close binary system, with allowance for the increase in its mass due to accretion.

1. Equations describing evolution of T_c and ρ_c.

According to published calculations,[1,4] for stars with a degenerate helium core and a shell source of hydrogen burning, as well as for carbon–oxygen cores, the following relation exists between the mass of the core and the luminosity of the star:

$$L / L_{\odot} = 14286\,(M_c / M_{\odot} - 0.32) \text{ for } 0.35 < M_c / M_{\odot} < 0.45. \tag{1}$$

The rate of increase of the core mass is proportional to the luminosity of the star:

$$dM_c/dt = L/X \cdot E_{\mathrm{H}}, \tag{2}$$

where

$$E_{\mathrm{H}} = E_{\mathrm{CNO}} = 6.0 \cdot 10^{18}\ \mathrm{erg/g},\ X = 0.71.$$

Hence the rate of increase of the helium-core mass becomes

$$\frac{d}{dt}\frac{M_c}{M_{\odot}} = 0.207 \cdot 10^{-6}\,(M_c / M_{\odot} - 0.32)\,M_{\odot}/\mathrm{yr}. \tag{3}$$

For a helium dwarf the number of protons per free electron is $\mu_e = 2$ (just as in carbon–oxygen cores), and the matter in the core is strongly degenerate. We may therefore expect the central density to vary with time in the same manner as in carbon–oxygen cores[5]:

$$d \ln \rho / dt = 2.16 \cdot 10^{-17}\,\rho^{0.4725}. \tag{4}$$

To a first approximation the following expression holds for a degenerate core:

$$\frac{d \ln \rho}{d \ln M_c / M_{\odot}} = \beta, \text{ where } \beta\text{-const}. \tag{5}$$

With Eq. (3) we have

$$\frac{d \ln \rho}{dt} = -\frac{\beta}{M_c}\frac{dM_c}{dt}. \tag{6}$$

The rate of growth of a helium core belonging to a binary