I. M. Kopylov. *Spectral observations of binary systems with relativistic companions using the six-meter telescope.* Preparations for the program of spectral studies of x-ray pairs with massive optical companions were begun at the Special Astrophysical Observatory in 1975–1976. Regular observations were performed in 1978–1983 using camera No. 2 of the main stellar spectrograph (OZSP) of the BTA with a dispersion of 9 and 28 Å/mm, and some observations (for weaker objects) were performed at the prime focus of the BTA on the UAGS spectrograph with an image tube (dispersion of 56 Å/mm). The working wavelength range was λ 3700–6700 Å. Information about the objects studied is presented in Table I. The goal of the investigations was as follows: for bright objects—to determine all physical parameters of the optical companions, the structure and nonstationarity of their atmospheres, rates of mass loss, and the determination or refinement of the orbits and models of systems and estimates of the masses of the relativistic companions; for weak objects—to determine, primarily, the physical parameters of the optical companions. Each object was studied with a different degree of completeness, depending on the importance of new information about the object for the problem of evolution of close binary systems, rates of loss of matter by such systems, and the determination of the nature of the relativistic satellites. The basic results of the investigations have been published. Only the two most interesting systems—Cygnus X-1 and SS433 are discussed in the report.

1. Cygnus X-1 (4U 1956 + 35). This system was studied in greatest detail because of the fact that its invisible component is the most likely candidate for a black hole. The spectral class of the supergiant was determined—optical component of the system $\overline{\mathrm{Sp}} = 09.54 \pm 0.05(\overline{T}_e = 29\,500$ K), absolute stellar magnitude $\overline{M_V(\mathrm{Sp})} = -6^m{,}33 \pm 0^m{,}03$ and distance to the system $v = 2.30 \pm 0.12$ kpc$^{1/2}$. It was established that the spectrum of the supergiant varies significantly with an orbital period

TABLE I.

Object	Star	B	V	Number of spectrograms	
				OZSP	UAGS
4U 1956+35	HDE 226868	$9^m{,}7$	$8^m{,}9$	62	—
A 0535+26	HDE 245770	9,4	8,9	67	43
4U 0352+30	X Perseus	6,8	6,7	44	—
2S 0114+650	LSI+65°,010	12,2	11,7	9	18
X 0236+610	LSI+61°,303	11,6	10,8	7	17
2A 1052+606	BD+61°,1211	10,0	8,8	6	10
4U 0115+63	v635Cas	17,1	15,6	6	8
SS 433	v1347Aql	16,7	14,5	See text	

$P_0 = 5^d,6$: the intensities of all spectral lines, Sp, T_e, and M_V vary. The radius of the supergiant $\overline{R}_X = 22 \pm 0.5\ R_\odot$ and the acceleration of gravity $\log g = 3.07 \pm 0.07$ were determined, and their periodic variations as a function of time were also determined.[1-3] The amplitudes of all these variations in general agree with the photometric variability,[4] determined by the rotation of the ellipsoidal supergiant.[6]

It was established that the intensities of the lines of the elements N, C, and O of the supergiant are definitely higher than those of isolated supergiants.[1,2] The kinematic profile of the atmosphere of the supergiant Cygnus X-1 (the dependence of the rate of expansion v_r on the optical depth τ) revealed[6] that the atmosphere is expanding in an accelerated fashion, and $\Delta v_r/\Delta\tau$ varies with the orbital period.

The long-period variations of the brightness in the U,B,V system, the polarization of the radiation, and the x-ray flux of Cygnus X-1[7] suggest that the rotational axis of the optical component precesses with a possible period of ~ 39 or 78 days. The angle of precession was estimated ($\Delta i \geqslant 2\times 8^0$) from the observed amplitudes ΔU, ΔB, and ΔV.[8] Analysis of the spectroscopic consequences of the precession of the supergiant revealed that the spectral class Sp(T_e) and the observed rotational velocity ($150 \geqslant V_e \sin i \geqslant 75$ km/s) vary in a synchronous fashion with a precessional period of $39^d,39 \pm 0^d,22$ and the predicted angle Δi^8, as well as periodic variations in the intensities of the lines of N, C, and O (the nonuniformity of the latitude distribution of C, N, and O on the star as a consequence of the characteristics of the evolution of the supergiant in this system).

The rate of mass loss $\dot{M}$ was estimated from the spectra based on models of atmospheres calculated with extremely low (for fixed T_e) values of $\log g$ for the supergiant Cygnus X-1 and the star α Camelopardalis ("runaway" supergiant 09.51a with an invisible satellite with a small mass), based on the computed behavior of the density n_e and observed velocity gradient $\Delta v_r/\Delta\tau$ in the atmosphere. For Cygnus X-1 $\dot{M} = 5 - 6\cdot 10^{-6}\ M_\odot$/yr is in good agreement with exoatmospheric data. The mass of the supergiant ($M_* = 17 \pm 4 M_\odot$) and the mass of its relativistic companion ($9 \geqslant M_X \geqslant 5 M_\odot$) were determined for $\log g = 2.95$ for a model of the atmosphere which best describes the spectrum of the Cygnus X-1 supergiant.

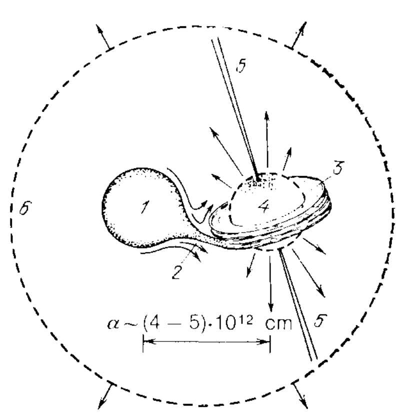

FIG. 1. Schematic model of the double system SS433.1) Optical star; 2) gas flow from the star to the accretion disk; 3) accretion disk; 4) expanding envelope of the disk; 5) relativistic jets; 6) overall expanding envelope of the system.

2. SS433. A schematic model of SS433 is shown in Fig. 1. This is a spectrally eclipsing binary system, consisting of a massive optical star, a relativistic object surrounded by a thick accretion disk perpendicular to whose plane two gas jets are ejected with a velocity of 0.27c, a gas flow from the star to the disk, and an overall expanding envelope. The spectral and eclipsing binary nature of SS433 were established in 1979[10,11] with an orbital period of $P_0 = 13^d,08$. The accretion disk precesses with a period of $P_p = 164^d$, and the rocking of the disk also exhibits a nutation with $P_n \approx 6^d,3$. The object emits energy at frequencies ranging from radio waves to gamma rays.

We have been studying SS433 on the BTA since 1980 with the help of a digital 1000-channel television scanner, developed at the Special Astrophysical Observatory in 1978–1979. The working wavelength range is λ 3700–8500 Å and the spectral resolution is 2–4 Å. A total of about 600 scans were obtained for SS433: 80 in 1980, 270 in 1981, approximately 170 in 1982, and 60 in 1984. The digital processing of the scans was completely automated.[12]

The behavior of the precessional and nutational periods of SS433 was studied in detail, and it was shown that phase shifts (disruptions), caused by the sharply variable rate of

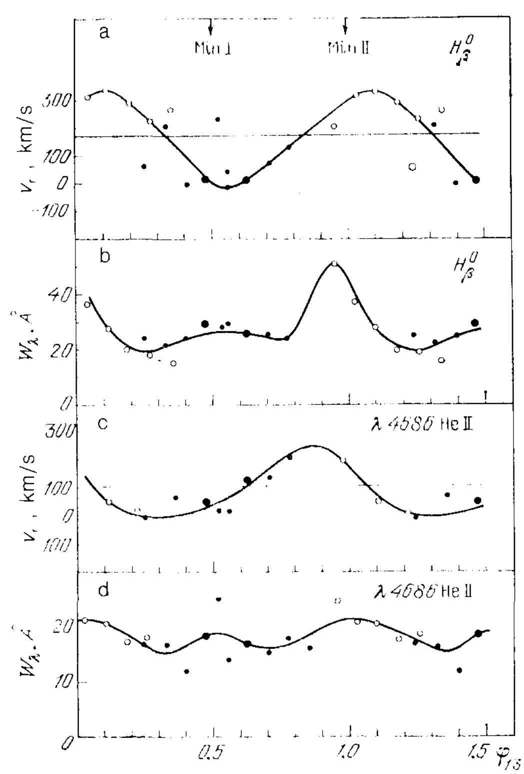

FIG. 2. Variation of the radial velocities with the phase of the orbital period (a) and of the equivalent widths of the "stationary" emission line H^0_β, arising in the gas flow (b); (c,d) same for the line HeII λ 4686, arising in the envelope of the disk. The arrows at the top mark the phases of the secondary (MinII) and principal (MinI) eclipses.

ejection of mass from the star, are observed in both periods from time to time. For example, the powerful second flash in July of 1980 over a period of the order of two weeks completely destroyed the regularity in the variations of z^+ and z^- with periods of P_p and P_n; in June 1981 the disruption of the phase in P_p reached $16^d,3$. However, there are no secular changes in P_p and P_n: for 1980–1982 $P_p = 163^d,34 \pm 0^d,05$ and $P_n = 6^d,284 \pm 0^d,001$.[13–15]

In July of 1980 a powerful optical flash occurred in the system (the emission increased by more than a factor of two), which substantially affected the physical and dynamical conditions in the system; the nature of the entire spectrum of SS433 changed radically. An amazing increase in the intensities of all emission lines occurred almost synchronously with the increase in brightness of the system (with a delay of 1^d–2^d): the intensities of all "relativistic" lines of H and HeI increased (prior to the onset of the flash they could hardly be observed in the spectrum), and at the same time the intensification of lines on the z^+ branch was several times greater than that of lines on the z^- branch, w_λ of the "stationary" lines of H^0 and HeI^0, arising in the gas flow from the star to the disk, increased enormously, and the intensities of all absorption (shell) lines increased with a delay of 2^d–4^d. It is presumed that all these events were caused by an explosion at the center of the accretion disk, adjacent to the relativistic companion.[16]

The shortest scale of rapid variability of w_λ and of the line profiles of the "relativistic" emissions and of the continuous spectrum of SS433 equals on the average 20^m (significant changes were observed over times of up to 4^m–5^m), and the changes in the lines are not synchronized with the change in the level of the continuum (July–August 1981).[17] Significant changes in w_λ and the profiles of H_α^+ and H_α^- with the nutation period ($6^d,3$) were observed and studied for the first time, their interpretation was given, and more accurate estimates of the basic physical and geometric parameters of the relativistic jets were made. The dependence of w_λ for the H^- and H^+ lines on the precession period was studied. The observed difference in $\overline{w}_\lambda$ for the H_α^- and H_α^- lines near the time T_3 (on the average by a factor of 3.0 ± 0.2) can be completely explained by relativistic effects.[18]

The angle of nutation $\theta_H = 3^0,5$ the half-width of the jet $\Delta\alpha_j \approx 0^0,5 - 1^0$, the ejection interval of clouds in the jet $\Delta t \approx 100^s$ the average size of a cloud $l \approx 2\cdot 10^{12}$ cm, the length of the jet $R_j \approx 3\cdot 10^{15}$ cm the number of clouds present simultaneously in the jet $N \approx 3000$, the density of clouds $n_e \approx 3\cdot 10^9$ cm^{-3} the porosity of the gas in the jets $q \approx 0.02$, and $\dot{M}$ in the jets $\sim 10^{-6}\ M_\odot$/yr were determined from the modeling of the profiles of the relativistic H_α lines. Study of the values of v_r and w_λ for the emission lines HeII, CIII + NIII, HeI^0, HI^0, and shell lines with P_0 showed that HeII and CIII + NIII lines appear in the expanding shell of the accretion disk, HI^0 and HeI^0 lines appear in different parts of the gas jet from the star to the disk, shell lines appear at the outer boundaries of the expanding jet, and in MinI the eclipsing of the disk by the star is incomplete.

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