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PHOTOMETRIC OBSERVATIONS OF HIGH MASS X-RAY BINARY HD 226868

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The results of photometric observations of the high mass X-ray binary HD 226868 = Cyg X-1 have been presented. The observations of this star were performed at 60-cm telescope of ShAO named after N.Tusi by using CCD photometer. This star is a binary system consisting of a black hole and a massive giant component star. Black hole and optical giant component masses are $\mathrm{M} = 20 \pm 5\mathrm{M}_{\odot}$ and $\mathrm{M}_{\mathsf{opt}} = 40 \pm 5\mathrm{M}_{\odot}$, respectively. The blue supergiant orbiting the black hole is HDE 226868 and its spectral type is O9.7 Iab. Our aim was investigating variability of this star in the V filter of the BVRI photometric system. Together with our photometric observations we used also AAVSO photometric database for the star HD 226868. Short-term and long-term photometric variability of this star has been revealed. The low luminosity state of star HD 226868 was discovered by analyzing the AAVSO photometric database, where V magnitude changes in the interval between $\sim 9^{\rm m}.1$ and $9^{\rm m}.2$. The lower luminosity state was observed on November 16, 2021, from $19^{\mathsf{h}}\,55^{\mathsf{m}}\,12^{\mathsf{s}}$ to $20^{\mathsf{h}}\,11^{\mathsf{m}}\,02^{\mathsf{s}}$. This state may be related to the supergiant wind instability as well as changes in the supergiant's mass transfer rate.

Keywords: high-mass X-ray binary – binary star systems – photometric variability – HD 226868

1. INTRODUCTION

The star HD 226868 = Cyg X-1 is a High-Mass X-ray Binary (HMXB), which was the first identified bright X-ray source [5, 19, 29]. HMXBs were among the

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very first bright X-ray sources detected in the 1970s. The identification of the single-lined supergiant star HD 226868 with the X-ray source Cyg X-1 was reason to believe that this star is a binary system where the secondary component is a neutron star or a black hole. Cyg X-1 was the first close binary system in which the presence of a black hole was revealed [5, 29] and it was the only object of that type for about a decade. Its studies are important for the understanding of the evolutionary properties of massive stars, the formation of black holes and neutron stars in these systems, processes of accretion onto black holes in close binary systems and also for the testing massive stars evolution models. Another high importance investigation of these objects is connected with the fact that, the HMXBs are potential progenitors of gravitational wave sources. Studying the Galactic HMXB population can provide valuable insights into their formation and evolution.

HMXBs are binary systems consisting of a compact object, either a black hole or a neutron star, and a high-mass optical component (supergiant) with a mass greater than $8M_\odot$ [7]. These systems emit X-rays due to the accretion of material from the optic companion star, which heats up as it falls onto the compact object. The material transfer can occur via stellar winds or Roche-lobe overflow, producing X-ray luminosities ranging from 10^{35} to 10^{38}erg/s [7].

The star HD 226868 consists of supergiant optic component with the spectral type O9.7 Iab. [28] and a black hole. Although many different models were proposed for this star to avoid the presence of a black hole, at present, there are no doubts about the presence of a black hole in this system. The orbital period of this binary system is $\sim 5.6^d$ [5,29]. The spectral type of this star was determined for the first time in [28] as O9.7 Iab and confirmed by the authors of [10,13,20]. In [13] by using the atmosphere models obtained the value 32000 K for the effective temperature of HD 226868.

Although more than three decades discovering of the star Cyg X-1, the masses of the components in this binary system are still a subject of controversy, there is still substantial uncertainty concerning the masses of both components. The most recent and precise value of mass function of optical component is $f\,(M_x) = 0.251 \pm 0.007 M_\odot$ [12]. Although the mass function of the optical star is relatively small, it is tens of times larger than the mass function values for the corresponding binary systems with X-ray pulsars [7].

Because of the uncertainty of the orbital inclination, the mass of the secondary component was unknown. However, the minimum mass estimates in [12,13] make it reasonable to suggest that the secondary component is a black hole. The masses of the components have been determined as $17.8M_\odot$ for the supergiant and $10.1M_\odot$ for the black hole [13].

By analyzing the emission lines of the stellar wind, the rotational broadening of the absorption lines of the optical component and the photometric V-band light curve, authors of [10, 11] conclude that the optical component is close to filling its Roche lobe, the fill-out factor is close to 1 and according to [31] the best value for the fill-out factor is in the range 0.95-1 [31].

From the analysis of rotational broadening of the absorption lines of the optical component and the ellipsoidal light variations of V-band light curve the authors of [10, 11] received the value of $33^0 \pm 5^0$ for the inclination of the orbit.

If the distance to the HD 226868 is in the range of $1.95 - 2.35\,\mathrm{kpc}$ and the effective temperature is in the range $30000 - 31000$ K , then the mass of optical component has to be in the range of $40 \pm 5\mathrm{M}_\odot$ [31]. By analyzing the profiles of the emission lines, rotational broadening of the absorption lines and the ellipsoidal light variations, obtained the value of $20 \pm 5\mathrm{M}_\odot$ for the mass of the black hole component [31].

The light variations with the small amplitude ($\Delta\mathrm{V} \sim 0^{\mathrm{m}}.04$) with a $\sim$ 5.6-day orbital period were revealed in [17, 18, 26]. The light curve of star HD 226868 can be explained by tidal deformation of the supergiant component by the gravitational field of black hole, which is surrounded by an accretion disk [18].

The different longer periods (294 days, 150 days, and 4.5 years) were revealed for the Cyg X-1, which is thought to originate from an oblique accretion disk precession due to gravitational torques from the supergiant component [15, 21, 29]. However, the $\sim$ 5.6 day orbital period is the only one that is confirmed in all wavebands by most authors. It has been suggested that the 294 day period is aliasing of the true 150 day period [21].

Authors of [13] during the high (soft) state of the X-ray source of Cyg X-1 in April-May 1975, revealed the oscillations in the light curve with a period of 61.9 minutes. $39^{\mathrm{d}}.2, 78^{\mathrm{d}}.4$, $149^{\mathrm{d}}.4$ and $53^{\mathrm{d}}.3$ periodicities were also detected in [15, 27].

Light periodicity analysis of HD 226868 is complicated because the optical light variations are small and irregular variability is superimposed on the light curve. The photometric behavior of star HD 226868 is quite complex. The light curve is similar to the light curve of distorted binaries, with the considerable additional intrinsic variability. The large scatter in light variations explains with the intrinsic variability of supergiant component. But may be takes place also variable obscuration by irregular gas streams. The intrinsic variability of supergiant component is recognized as a characteristic of this star by all observers and some of the unusual photometric features may be connected with this. In [13] another peculiarity of the light curve was revealed: an extremely rapid rise in brightness on the ascending side of both light minima.

High X-ray luminosity ($2-5.5\cdot10^{37}$erg/s) and significant emission of gamma rays are the observational facts that favor for the presence of an accretion disk harboring Cyg X-1 [2,4,25]. The X-ray spectrum of Cyg X-1 is consists of black-body and power law components. The blackbody component comes from the accreting disc and power law component generates by Compton scattering of disc emission by either a hot corona of electrons or at the base of a jet [3,6,23]. The existence of highly collimated jet observed in [24] and confirmed in [8].

The X-ray luminosity of Cyg X-1 observed in two spectral states: low (hard) and high (soft). The star Cygnus X-1 about 90% of the time is in low (hard) state [9]. To the low (hard) state corresponds relatively low accretion rate from the supergiant component and because relatively low X-ray luminosity. The low accretion rate in the low (hard) state allows the optically thick, but geometrically thin disk to be evaporated more efficiently. An optically thin, hot corona of electrons flows from the disk inner radius to the event horizon of black hole component. This corona generates the power law low (hard) spectrum [9]. Occasionally, the mass accretion rate from the supergiant component slightly increases, by only $\sim$ 15% [17], which causes an increase in X-ray luminosity of about 10% to 20% [6]. Evaporation of the disk proceeds less efficiently in the high/soft state, and the disk inner radius advances to the last stable orbit of the black hole. This causes the disk blackbody emission to dominate over the power law radiation from the corona [6].

It should be note that the complexity in the Cygnus X-1 system is very high, even during the low (hard) state and during the high (soft) state, additional events are introduced.

2. OBSERVATIONAL DATA, THEIR REDUCTION AND RESULTS

Photometric observations of the HMXB star HD 226868 were carried out during 2020-2022 years, at the 60-cm Zeiss telescope of the Shamakhy Astrophysical Observatory (ShAO) named after N. Tusi, equipped with a CCD photometer, in the V filter of the BVRI photometric system [1]. The MaxIM DL program was used to process the obtained CCD images. The standard star HD 226867($V = 10^{m}.7$) and two control stars, HD 226938 ($V = 10^{m}.14$) and HD 226919 ($V = 9^{m}.56$), were used. The root mean square error of photometric observations determined by using the control star is 0.007 . Table 1 presents information concerning our photometric CCD observations of HD 226868. In this table were shown: the date of observations, number of received CCD images obtained during one night (N), exposure time in seconds. Obtained also flat field, dark and bias images for the processing CCD images of star HD 226868.

Table 1. The photometric CCD observations of HD 226868 at 60-cm telescope of ShAO.

2020	N	Exp (sec.)	2021	N	exp	2022	N	Exp (sec.)
06 23/24	300	8	05 12/13	50	10	07 08/09	150	7
0624/25	180	6	05 15/16	300	10	07 17/18	100	10
07 17/18	250	12	06 01/02	100	10	07 18/19	150	10
07 24/25	188	10	06 17/18	150	15	07 19/20	100	10
07 26/27	258	10	06 18/19	150	8			
07 27/28	200	10	06 19/20	150	13			
			07 04/05	150	10			
			07 18/19	150	10			
			09 02/03	50	20			
			09 13/14	157	10			
			09 16/17	120	8			
			11 09/10	200	8			

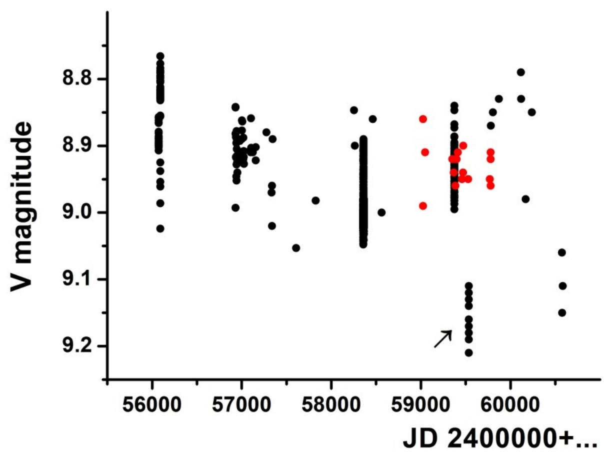

Fig. 1. V magnitude variations of star HD 226868 from May 26, 2012 to September 30, 2024. The red and black dots represent our and AAVSO dates, respectively..

The American Association of the Variable Stars Observations (AAVSO) [32] high accuracy photometric database of HD 226868 was used to reveal short-term and long-term photometric variations (Fig. 1-Fig. 3).

Fig. 1 shows V magnitude variations of HD 226868 during 2012-2024. The red and black dots represent our and AAVSO dates, respectively. The arrow in Fig. 1 indicates the lower luminosity state of star HD 226868, where V magnitude changes in the interval between $\sim 9^{m}.1$ and $9^{m}.2$. Lower luminosity state was on

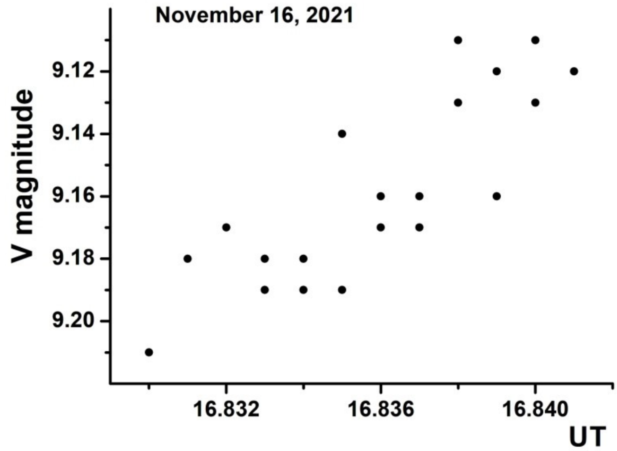

Fig. 2. V magnitude variation of star HD 226868 plotted by using AAVSO observations Database,on November 16, 2021.

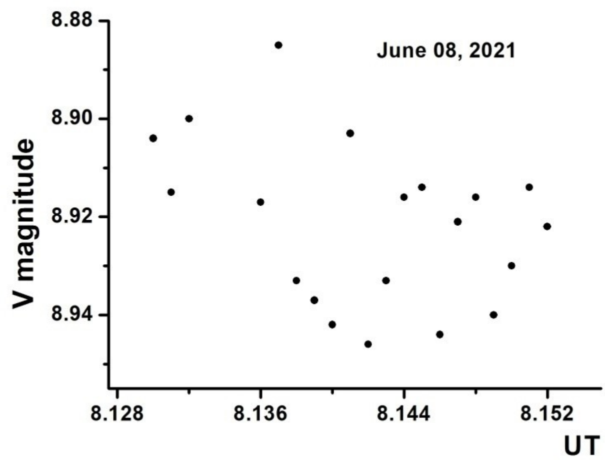

Fig. 3. V magnitude variation of star HD 226868 plotted by using AAVSO observations Database, on June 08, 2021.

November 16, 2021, from $19^h55^m12^s$ to $20^h11^m02^s$. ($\sigma = 0.012$). As seen in Fig. 1 the star HD 226868 was only once in this state during 2012-2024. Revealing the low luminosity state on November 16, 2021, is real because of the existence of high-precision ($\sigma = 0.012$) eight measurements. The low luminosity state may be connected with the long-term photometric variability or with the wind instability of the supergiant component.

Fig. 2 shows the V magnitude variation of star HD 226868 plotted by using AAVSO observations database ($\sigma = 0.012$) on November 16, 2021.

Fig. 3 shows the V magnitude variation of star HD 226868 plotted by using AAVSO observations database ($\sigma = 0.003$) of star HD 226868 on June 8, 2021, for 34 minutes, from $03^h04^m30^s$ to $03^h38^m46^s$ UT.

As seen from Fig. 2 and Fig. 3, the rapid photometric variations of star HD 226868 were observed. Revealed the low luminosity state of this star (arrow in Fig. 1) may be related to the supergiant wind instability as well as changes in the supergiant's mass transfer rate.

3. CONCLUSIONS

The main result of this research is revealing the low luminosity state of star HD 226868, where V magnitude changes in the interval between $\sim 9^m.1$ and $9^m.2 (\sigma = 0.012)$. The lower luminosity state was observed on November 16, 2021, from $19^h55^m12^s$ to $20^h11^m02^s$. In future research, it is reasonable to clarify the relation of this state to the low (hard) and high (soft) stages of X-ray luminosity of HD 226868. This observational fact is important in constructing the physical model of star HD 226868. Low luminosity state may be related to the supergiant wind instability as well as changes in the supergiant's mass transfer rate.

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