Historical light curve of the black hole binary V4641 Sgr based on the Moscow and Sonneberg plate archives

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Abstract

We performed digital processing of a large set of photographic plates for the X-ray binary system V4641 Sgr containing a black hole. A total of 277 plates were found in archives dated between 1960 and 1992. Photographic observations revealed lower level of outburst activity if to compare with CCD data after the large 1999 outburst. Only single outburst which happened in 1978 was confirmed. If archive photographic data are used along with contemporary CCD observations, the orbital period may be improved, and its value is 2.81728 ±0.00004 day.

Keywords: photometry, X-ray binaries, black holes; individual: V4641 Sgr

Introduction

V4641 Sgr is a system containing a B9–A0 III star with the mass of 2.9 ± 0.4 $M_{\odot}$ and a black hole of 6.2 ± 0.7 $M_{\odot}$ [1]. The orbital period of the system is P = 2.81678 day [2]. Its distance is 6.2 ±0.7 kpc [1]. The star was discovered by Goranskij [3] during the 1978 outburst but at first it was misidentified with Luyten's variable GM Sgr, a Mira type star [4]. At the beginning of 1999, V4641 Sgr was detected in X-rays as SAX 1819.3–2525, and later, in 1999 September it experienced a large outburst in all ranges of electromagnetic wavelengths and reached magnitude of $8^{m}.9$ in *V* band. In this event, relativistic jets were detected with the VLA radio interferometer [5]. The orbital period was improved in [6] by using photometry. Photometric observations show active states and outbursts, short-time flaring in the scale of seconds, a temporal appearance of the reflection effect [7,8,9]. Spectroscopy reveals changes in the profiles of Balmer lines and other manifestation of the black hole activity.

Archive search

We found 266 plates of V4641 Sgr in the Moscow plate collection of the Sternberg Astronomical Institute taken with 40 cm astrograph of SAI Crimean Station which are dated between 1960 and 1992. Typical exposures were of 45 minutes. The photographic observations were ended in 1992 as the production of astronomical plates was stopped. Partially, the star was estimated by eye on the basis of this set [4]. Additionally, 11 plates were found in the Sonneberg collection. Plates were taken between 1984 and 1988 with the similar astrograph. The exposure time of these plates were 30 minutes. All the plates were produced by AGFA/ORWO factory in Germany. Plates are sensible to blue light and realize Johnson *B* band well. The region of the variable star in these plates including close outskirts with comparison stars was digitized using a simple convex lens and FinePix-10 FujiFilm camera in the grey mode. This camera is self-focused on each frame, and it is sensible enough to take sharp and clear images with small exposures without any support stand. The frames in JPEG format given by the camera were transformed to BITMAP files, and reduced with the WinPG software developed by V. Goranskij. We used 17 comparison stars. Characteristic curves were fitted with the first or second order polynomial. The accuracy of the fit calculated as mean-squire residual from the polinomial varies between $0^m.03$ and $0^m.20$, mean value is $0^m.08$. Since 1994, we continued photoelectric and CCD observations with different telescopes and devices. CCD observations are performed up to now. So, our time set of V4641 Sgr continues about half century.

Results

The total light curve of V4641 Sgr in the *B* band is presented in Fig. 1. In the period between 1972 and 1992, only single 1978 outburst was detected, this is the outburst which led to the discovery of the star. In the peak of the 1978 outburst, the star reached $12^m.12$ *B*, and subsequent decay continued about 2 days. Additionally, a short-time outburst of V4641 Sgr with the 5.87 day decay in 1901 is found by J. Grindley and colleagues based on the Harvard collection, and an episode of bright state on June 28, 1965 is caught by R. Hudec and his colleagues using the Bamberg archive. The last two events were reported at this workshop. It is necessary to notice that the object was not detected in X-rays before the outburst in 1999. After the strong 1999 outburst, the optical outbursts became frequent. They repeated in 2002, 2003, and 2004. Object appeared in X-rays also in 2008, 2010, and in 2014.

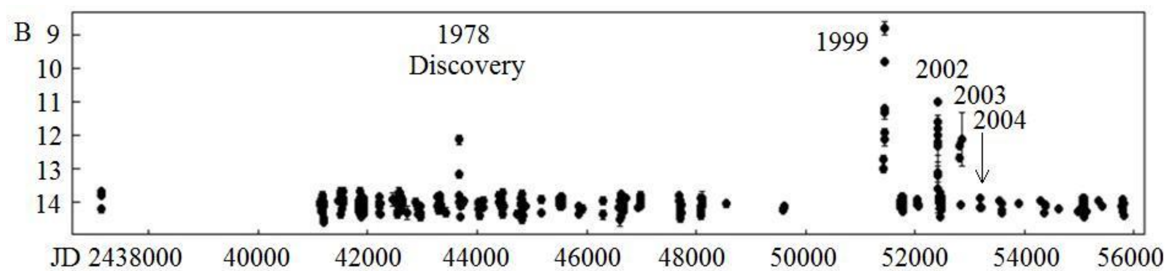

Figure 1. Historical half-century light curve of V4641 Sgr

Frequency analysis with the phase-dispersion minimization method [10] gives the best period $2^d.81728 \pm 0^d.00004$, and the double-wave light curve with unequal minima depths. The deepest minimum coincides with the black hole inferior conjunction. The date of conjunction is JD Hel. 2451764.337 ±0.005. The light curve plotted versus phase of this period is given in Fig. 2. The averaged orbital light curve with the amplitude of $0^m.45$ in the primary minimum demonstrates the greatest observed ellipsoidal effect of stellar component. The depth of the secondary minimum is $0^m.28$.

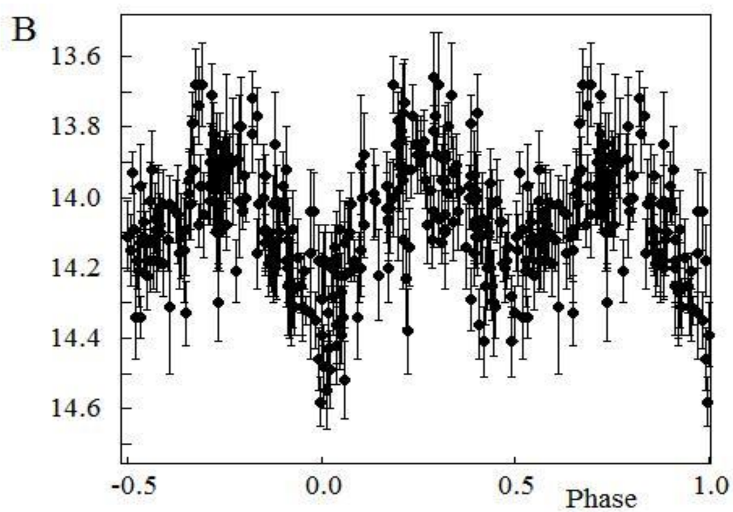

Figure 2. Photographic light curve of V4641 Sgr plotted versus the orbital phase. A primary minimum corresponds with the inferior conjunction of the black hole.

We performed CCD *B*, *V* and R_C monitoring of V4641 Sgr in 16 nights between June 5 and 25, 2007 using SAI Crimean Station 60-cm telescope and SAO 1-m telescope [9]. These observations (Fig. 3) show essential light excess over the quiet light level, visible only in the orbital phases between –0.25 and +0.25 with the maximum value of 0.15 mag in the *V* band at the black hole inferior conjunction. The excess is absent in other orbital phases. This phenomenon has not been observed previously. We explain it as an irradiation of the area of A0 type star facing to the black hole. The area re-emits weak X-ray radiation of the black hole to optical bands. At the same time with the reflection effect the radiation at 0.5–10 keV was detected by Swift XRT at the level of $(1.2–2.1) \cdot 10^{-11}$ ergs/cm^2/s [11].

On July 11, 2001, near the inferior conjunction of the black hole, we carried out the spectroscopic observations of V4641 Sgr with the Russian 6-m telescope in order to view the black-hole surroundings against the stellar disk of the normal component. A depression with equivalent width EW = 0.5 A was observed in the red wing of the Hα profile with the maximum absorption at the heliocentric velocity of 642 km/s [8]. We suggested that this gas stream could be a part of a rarefied gaseous disk around the black hole, in the system’s orbital plane. Assuming that the flow is moving through the circular Keplerian orbit around the black hole, the mass of the black hole is determined as M_{BH} =7.1− 9.5 $M_{\odot}$, what overlaps the mass range given by Orosz et al. [2].

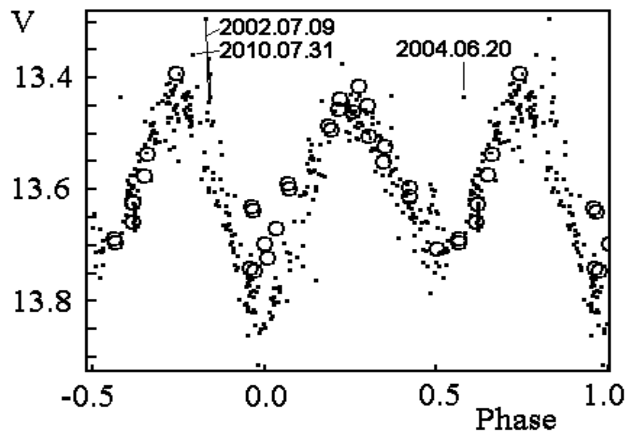

Figure 3. Appearance of the reflection effect in May 2007 (blank circles) in the *V* band. Swift detected a weak and variable X-ray radiation. Short solid lines mark splashes of an optical radiation.

We explain the deeper minimum in the light curve at the phase of the black-hole inferior conjunction as an extreme case of fon Zeipel effect at the surface of the optical companion faced to the black hole due to very low gravity at this area of the star. This effect is clearly recorded with our photographic observations. Photographic observations revealed lower level of outburst activity compared with CCD data after the large 1999 outburst. Unfortunately, such low-amplitude effects as X-ray irradiation and rapid flaring in the scale of seconds are lost due to errors of photographic observations and long-time exposures.

Reference.

[1] R.K.D. MacDonald, C.D. Bailyn, M. Buxton, et al., Astrophys. J., **784**, 2 (2014).
[2] J.A. Orosz, E. Kuulkers, M. van der Klis, et al., Astrophys. J. **555**, 489 (2001).
[3] V.P. Goranskij, Astronomicheskij Tsirkular, No. 1024, 3 (1978).
[4] V.P. Goranskij, Inform. Bull. Variable Stars, No. 3464 (1990).
[5] R.M. Hjellming, M.P. Rupen, R.W. Hunstead, et al., Astrophys.J. **544**, 977 (2000).
[6] V.P. Goranskij, Inform. Bull. Variable Stars, No. 5068 (2001).
[7] M.Uemura, T. Kato, R. Ishioka, et al., Publ. Astron. Soc. Japan, **56**, 61 (2004).
[8] V.P. Goranskij, E.A. Barsukova, A.N. Burenkov, Astronomy Reports, **47**, 740 (2003).
[9] V.P. Goranskij, E.A. Barsukova, A.N. Burenkov, ATel No.1134 (2007).
[10] J. Lafler, T.D. Kinman, Astrophys. J. Suppl. **11**, 216 (1965).
[11] E.M. Cackett, J.M. Miller, ATel No.1135 (2007).