Rarefied Gaseous Disk Around Black Hole in the System of V4641 Sgr

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Abstract. The results of photometric CCD monitoring and spectral observations of the black hole binary and microquasar V4641 Sgr in the quiet state are presented. The ellipsoidal light curve with large amplitude of 0".36 in R band suggests the influence of a massive object orbiting around a normal B9 star. In the spectra taken with the 6-m telescope one hour before black hole inferior conjunction, an absorption component in the red wing of Hα line is visible. It is formed by gaseous stream moving in the direction to the normal star. That suggests the grazing conjunction in this system. Maximum velocity of the stream is of 650 km/s. Assuming that the stream is moving through the circular Keplerian orbit around black hole, the mass of the black hole is determined to be $M_{BH} = 7.1 - 9.5 \, M_\odot$, what confirms the model by Orosz et al.

V4641 Sgr is a detached stellar system including black hole with the mass of $8.73 \leq M_{BH} \leq 11.70 \, M_\odot$ and a normal B9III type star [1]. In the quiet state, the brightness of the star is of about 13".6 V. The elements for the inferior conjunction of the black hole are the following [2]:

$$T_c = 2451764.298 + 2^d.81728 \cdot E.$$ 

The secondary B9 companion shows a strong tidal distortion due to gravitational influence of the black hole. The system is known to have a relativistic jet source [3]. Three historical outbursts of V4641 Sgr are known, in June 1978, in September 1999, and in May 2002. In the peak of 1999 outburst, the star reached brightness of 8".9 V. The high state of 2002 was characterized by light flickering in the time scale of seconds and minutes with the amplitude up to 1".5 and dips [4]. The amplitude of flickering decreased in the dips. Here we present the results of optical monitoring and spectroscopy of V4641 Sgr in the quiet state.

CCD monitoring of V4641 Sgr was done in V and R bands with 60-cm telescope of SAI Crimean station and with 38-cm telescope of Crimean Astrophysical Observatory in July-August 2000 and May 2001. SBIG ST-7 CCD was used. In the R band, the observations continued about 4 hours each night and covered well all the phases of orbital period. Fig. 1 shows light curve of V4641 Sgr, magnitudes are given relative to comparison star e [2]. The accuracy of observations is equal to 0".02. The ellipsoidal variations of high amplitude predominate, and two light minima of unequal depth are visible. The deepest minimum coinciding with the phase of superior conjunction of the normal star has amplitude of 0".36, the secondary one having only 0".27. This extreme amplitude suggests that the system is highly inclined. The system is considered to be non-eclipsing because no eclipses are seen in X-ray data. Due to strong gravitational influence of the black hole, the surface of the normal star is elongated mostly in the direction of
black hole, and is heated by central energy source non-uniformly. This may be the cause of inequality of minima in the light curve. There is no irradiation effect due to reprocessing of X-rays by normal star seen in the light curve. There are no features in the primary minimum which would give evidence of the partial eclipse of the normal star by the accretion disk, like contacts or light drops. To ascertain, if surrounding matter exists around the black hole to absorb light in the spectral lines, we performed the special spectral observations of V4641 Sgr in the orbital phases nearby to the inferior conjunction of the black hole.

![Figure 1. The light curve of V4641 Sgr in R band.](image)

Spectra of V4641 Sgr were taken with 6-m telescope BTA of Special Astrophysical Observatory on July 11, 2001 at the orbital phases of \(0^\circ.9841 - 0^\circ.0006\). The wavelength ranges were 5800 - 7100 Å to check H\(\alpha\) region, and 4630 - 5880 Å to overlap H\(\beta\) and He II \(\lambda 4686\) Å regions. The dispersion was 1.25 Å/pixel, and S/N=200. Air mass was about 3 atmospheres for this low declination star, and we observed the nearby A2 type star HD 315568 to control the Earth atmosphere transparency in the line profiles. We analysed also few spectra of V4641 Sgr taken with 6-m telescope on August 21, 1996 and on September 17, 1999 in the other orbital phases.

One hour before the conjunction on July 11, 2001 the depression with EW = 0.5 Å was observed in the red wing of H\(\alpha\) absorption line (Fig. 2) in two of our spectra. This suggests the absorption by a gaseous stream moving along the line of site to the normal star. No such depressions were observed in the H\(\alpha\) line profile of the control star, no ones in the line profile of V4641 Sgr on August 1996.

The gaseous stream is assumed to be a part of a rarefied disk located in the orbital plane (this idea was proposed by S.N. Fabrika). It is optically thick only in H\(\alpha\) line. Note, that the highest velocity part of the disk may cover the normal star at the phase of observation, as follows from a high inclination model of this binary system. With the absence of X-ray eclipses, the observation of the stream presumes a "stargrizing" conjunction and extreme orbit inclination angle of about \(i = 70.7^\circ\). No trace of accretion stream moving from normal star to black hole is seen in the blue wing of H\(\alpha\) profile. The observed maximum heliocentric velocity
of the stream of 642 km/s and the center-of-mass velocity of the system of 110 km/s suggest the calculated velocity \( v \) on the circular Keplerian orbit around the black hole of 650 km/s at the distance of \( R = 0.15 - 0.20a \), \( a \) being the distance between components. The orbital inclination of 70.7°, and the angle between the circular flow direction and the projection of the line of sight onto orbital plane of about 30° in the region of the star limb covered by the maximum velocity flow were taken into account in calculations. Assuming \( M_{BH} = \frac{v^2 R}{G} \) for mass of central black hole we have value in the range of 7.1 – 9.5\( M_{\odot} \) what overlaps well the mass range given by Orosz et al. [1].

More symmetric line profiles in \( \text{H} \beta \) line were found in the exact zero phase in the conjunction, but a weak absorption component may be revealed by Gaussian analysis at the same velocity as that of \( \text{H} \alpha \). Modelling predicts that the disk's streams overlapping the light of the secondary star are visible at large projection angles in zero phase, and the line profile should be more symmetric. Model predicts also depression in the blue wing of Balmer lines one hour after the conjunction. Unfortunately we have no observations in this orbital phase. There are no traces of \( \text{He II} \lambda 4686 \)A line in absorption what suggests, that the disk is not exposed by X-rays from the black hole in quiescence.

The rarefied gaseous disk discovered in this study may be responsible for supercritical accretion events accompanied with strong outbursts, when enough matter is accumulated in it to get the disk instability.

References
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