High-mass X-ray Binaries: Illuminating the Passage from Massive Binaries to Merging Compact Objects
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Rapid evolution of the relativistic jet system SS 433

V. P. Goranskij[1], E. A. Barsukova[2], A. N. Burenkov[2], A. F. Valeev[2], S. A. Trushkin[2], I. M. Volkov[1,3], V. F. Esipov[1], T. R. Irsmambetova[1] and A. V. Zharova[1]

[1]Sternberg Astronomical Institute, Moscow State University,
Universitetskii prospect, 13, Moscow, 119234, Russia

[2]Special Astrophysical Observatory, Russian Academy of Sciences,
Nizhnij Arkhyz, Karachai-Cherkesia, 369167, Russia

[3]Institute of Astronomy, Russian Academy of Sciences,
Pyatnitskaya Street, 48, Moscow, 119017, Russia

Abstract. We analyzed a 40-year set of multicolor photometry and a 15-year set of synoptic monitoring of SS 433 along with fragmentary spectral and radio data. This system contains a neutron star and an A3–A7 I giant. The system is found to be either close, in contact, or it has a common envelope from time to time. The A-type giant is now in transition to the dynamical mass transfer.

Keywords. accretion, dense matter, X-rays: binaries; individual (SS 433, V1343 Aql)

SS 433 is an eclipsing system with moving emission lines in the spectrum. The moving components of Balmer and He I lines are formed by a pair of oppositely directed, highly collimated and precessing relativistic gaseous jets moving with a velocity of $0.26c$. The orbital period of 13.082 day, the jet precession period of 162 days, and jet nodding period of 6.28 day are all represented in photometric data. Components of the system are A3–A7 I giant (Gies *et al.* 2002; Hillwig *et al.* 2004) and a neutron star (Goranskij 2011, 2013). The mass of the A type star was estimated in the range between 9.4 and 12.7 $M_\odot$ (Kubota *et al.* 2010) or between 8.3 and 11.0 $M_\odot$ (Goranskij 2011, 2013), the absolute magnitude $-5^m.9 \leq M_V \leq -5^m.0$, and reddening $E(B-V) = 2^m.65 \pm 0^m.03$. The mass of the neutron star was limited by 1.25 and 1.65 $M_\odot$ (Goranskij 2011, 2013). Based on these data, with the Stephan-Boltzmann law and Kepler's Third law, we may conclude that the system is in contact, or overcontact, it may have a common envelope, and the Roche lobe of the neutron star may be filled by matter. The system is located in the center of the radio structure W50 interpreted as a 10000-year old supernova remnant. The distance to SS 433 is well known from radio interferometry to be of 5.12 ± 0.27 kpc.

To verify the proximity of the system components, we analyzed a 40-year photometry and perform special synoptic observations with a small 25-cm telescope and electronic image tube equipped with a microchannel plate.

First, we confirmed the assumption by Barnes *et al.* (2006) that the photometric 162-day periodicity is caused mostly by precession of an expanding circumstellar disc masking the binary in the certain phases. The binary is well presented in the light curve only near precession T_3 phases, the phases of the largest divergence of moving emission lines. However, its contribution is distorted or completely invisible in other precession phases (Fig. 1). Other confirmation facts of such a disk are the following: (a) the lag of photometric precession maximum in the Rc band relative to spectroscopic T_3 phase for

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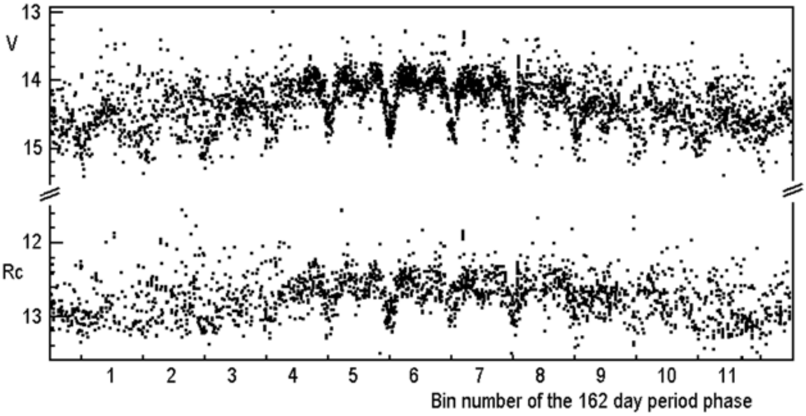

Figure 1. Evolution of the orbital light curve of SS433 depending on the phase of precession 162-day period. In this figure, 13-day light curves calculated in small phase bins are connected in order to increase precession phase. The T_3 moment corresponds to the bin No. 6.

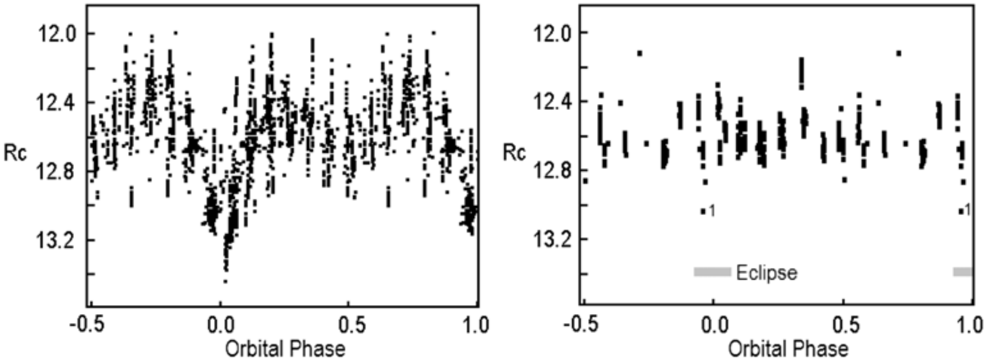

Figure 2. Light curves of SS 433 plotted in the precession phase range between −0.02 and 0.24 versus phase of the orbital elements Min I = JD 2450023.83 + 13.082454·E. Left: typical light curve. Right: observations in the common envelope episode without eclipses related to the time range between August 26 and October 8, 2016. We marked with “1” the first shallow eclipse during this time interval.

~10 days; (b) the infrared excess in the R and I bands (Goranskij 2011) which is radiated by the external parts of this disk; (c) the equatorial outflow seen at radio interferometry (Paragi *et al.* 1999).

Second, we observed episodes of complete disappearance of the eclipses. The photometry usually shows the variability of widths and depths of the eclipses depending on the precession phase, outbursts and active states. Our synoptic monitoring revealed an episode of disappearing of eclipses near the T_3 phase in September – October 2016 which began with a shallow eclipse on September 6. The following two eclipses were absent. Fig. 2 shows the non-eclipsing orbital phase light curve compared with the typical eclipsing light curve. In this figure, neither the typical “ellipsoidal variations” out of eclipses nor other orbital periodic variations are seen.

We explain this episode as a formation of the common envelope of the A-type star with the neutron star inside. The envelope radius was larger than the radius of the A-star’s Roche lobe, and therefore the envelope could not be masked by the external circumstellar disk at the wide range of precessing phases around T_3. When the neutron star is inside the common envelope with the A-star, there is nothing to eclipse. On 2016 October 8.76

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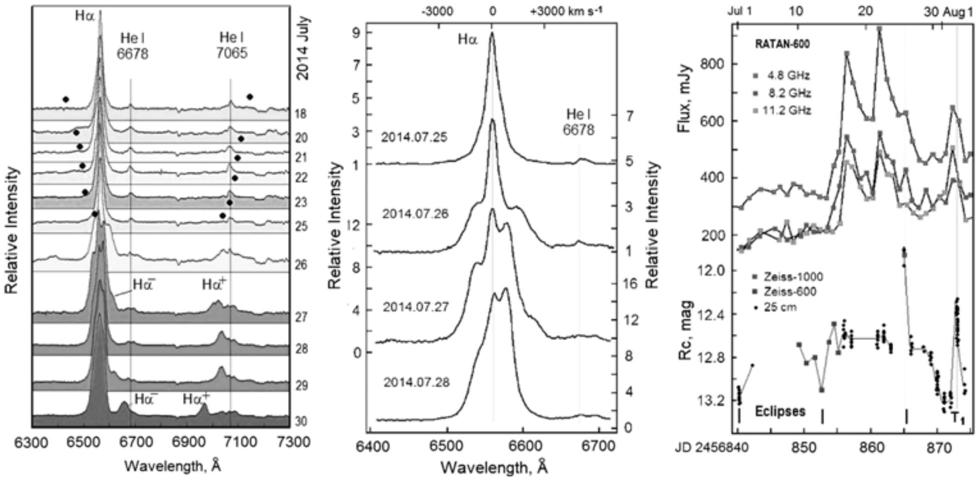

Figure 3. Left: Spectra of Hα region with the relativistic components. The forthcoming places of invisible components are marked with black points. Center: Hα-line profiles before the July 26 explosion, and during explosion (from top to bottom). Right: RATAN radio flux curves in three frequency bands (top); optical light curve in the Rc band (bottom). Note, that radio fluxes were strong and flaring before the optical outburst, when the relativisic jet components were invisible.

UT, we have taken a spectrum of SS 433 with the SAO 1-m Zeiss telescope and UAGS spectrograph. The relativistic components of Hα line were visible in the spectrum, so the jets were not blocked in this episode.

On July 26, 2014, a powerful outburst of SS 433 was observed with an unusually strong infrared excess in eclipse (Goranskij & Spiridonova 2014; Charbonnel *et al.* 2014). Fortunately, simultaneous multi-frequency monitoring observations were taken with the RATAN-600 radio telescope, and spectroscopy provided by one of us, V. F. Esipov, with the 125-cm telescope at the SAI Crimean Station. The spectral observations began 6 days before the outburst when the relativistic lines were invisible. This indicates that the jets were blocked. The forthcoming locations of these lines are marked by black circles in Fig. 3. In the outburst, the Hα profile showed a narrow central component and wide pedestal with FWZI $\sim$ 7000 km s^{-1}. Charbonell *et al.* describe this profile as a three-component one, and note its rapid variability. At the time of the outburst, the relativistic lines reappeared at the forthcoming places. Fig. 3 (left) shows the Hα component superimposed on the Hα line profile, and its motion can explain the variability of the pedestal. In a few days, the intensity of the pedestal increased gradually with decreasing its width, the central component weakened, and then the brightness of the star fell down to the normal level for its proper precession phase (Fig. 3, right). Taking into account the strong IR excess in the outburst, it becomes clear that this event was the ejection of the large mass envelope accompanied by the recovery of jets. The expanding envelope interacted with the earlier released stellar wind.

And third, we have found a secular decrease of amplitudes of all three periodic variations during 40 years of observations. The amplitudes decrease due to the increasing donor's radius and brightness. Probably, this process is irregular and spasmodic.

The A-type star is on the way to red giants, and its shell expands being truncated by the Roche lobe. Mass transfer from the A-type donor passes into a dynamical timescale (Podsiadlowski 2014). This happens with an expanding supergiant having a convective envelope and losing its mass. Its Roche lobe shrinks when the mass is transferred to a less massive star, what makes the supergiant to overfill the Roche lobe in larger amount and

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increases the rate of mass transfer in a dynamic mode. Overfilling of the neutron star's Roche lobe and sporadic events of common envelope formation interrupted by ejections of a large mass volume become more frequent. When the Roche lobe of the neutron star is filled or overfilled, the accretion gainer represents a star with the neutron core, i.e. a Thorne & Zytkov (1977) object.

What can we assume about the past, present, and future of SS 433? The most massive primary star of a primordial binary with the main-sequence components had passed its way to a giant with a helium core. It filled and overfilled its Roche lobe, transferred most part of its mass to the less massive secondary companion, and it exploded as a SN Ia (the radio structure W50 is probably a remnant of this SN). As a result, there was a Be/X-ray binary. The evolution of the massive secondary star accelerated to fill its Roche lobe, and to become the donor of accreting matter toward the neutron star.

At present, the transfer of mass from the donor turns to dynamic mode filling and overfilling the Roche lobe of the neutron star from time to time. Jets are forming inside the neutron star's envelope created from the accreted matter, and burst through channels and nozzles, which are seen as bright spots on the surface of the photosphere. The visibility conditions of the nozzles provide an essential contribution in shaping the source lightcurve with the periodic nutation wave having an amplitude of 0.22 mag and a period P = 6.289 day. The system loses its mass through the external Lagrangian point L_2 and the stellar wind. This is a short-time stage associated with the approach of the neutron star with the expanding photosphere of the donor.

In the future, the neutron star will be absorbed inside the common envelope with the expanding A-type giant. Jets will be blocked and disappear completely. Then the neutron star will spiral to the center of this star and form a single star, a massive Thorne-Zhytkov object. Cherepashchuk (2013) has described two scenarios of this development depending on the accretion mode on the central neutron star: (1) The lower-temperature mode when neutrinos do not bring the accretion energy out. This will be a luminous star at the Eddington limit with the lifetime of about 10^6–10^8 years. (2) The high-temperature accretion mode with the energy carried away by neutrinos. Then, if the envelope is massive enough, a single black hole will arise. In this case, the lifetime of the envelope is very short, similar to the dynamical timescale. The other scenario is (3) the explosion of the donor as a supernova before the merger of its nucleus with a neutron star. The remnant may be a binary of two neutron stars or a black hole – neutron star binary.

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