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Peculiarities of mass exchange between components of binary systems in the dynamic mode: V694 Mon and SS 433

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Abstract. We observe events of dynamic mass transfer in the systems V694 Mon and SS 433. In V694 Mon, accretion occurs from an M5–M6 giant onto a white dwarf, while in SS 433 it occurs from an A4–A7 giant onto a neutron star. Both systems exhibit jets, with SS 433 having relativistic ones. In the symbiotic system V694 Mon, we observed the cessation of the disk accretion over three months in 2018. This was followed by the filling of the white dwarf's Roche lobe over the next three years, leading to the formation of an A4 I star within the Roche lobe by 2024, when hydrodynamic equilibrium was reached. The system is no longer considered symbiotic. In the SS 433 system, the Roche lobe of the neutron star is overfilled, resulting in the formation of a star with a neutron core and a convective envelope, known as a Thorne–Żytkow object. Rare powerful explosions occur accompanied by strong infrared radiation excesses. We interprete these explosions as ejections of the envelope of the neutron star or part of this envelope, these ejections are associated with magnetic activity of the neutron star, specifically a magnetar. Based on the wind speed from the system, we estimate the surface temperature of the newly formed star to be 1.5 million K. The star with the neutron core is the source of the power-law spectrum in optics. This object also causes the ellipsoidal effect in the light curves, and the nutation tidal wave that deflects the relativistic jets.

Keywords: stars: white dwarfs, neutron, binaries: general, mass transfer; individual: V694 Mon, SS 433

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1 Introduction

Podsiadlowski (2014)[1] described events of dynamic mass transfer in binary systems. When the radius of the donor star's Roche lobe decreases as the mass is transferred from a more massive star to a less massive one, the donor star overfills its Roche lobe by an increasingly larger amount, leading to runaway mass transfer on a dynamic time scale. The transferred material forms a common envelope of the system. This typically occurs when the donor star is a giant or supergiant with a convective envelope, as such stars tend to expand rather than shrink when they lose mass rapidly, while the Roche-lobe radius shrinks when the mass is transferred from a more massive to a less massive star. These events can occur in binaries when the massive companion expands while evolving towards a red giant.

We have traced such an event in the symbiotic system V694 Mon (MWC 560) between 2018 and 2024. This system comprised an M4–M5 III giant pulsating with the period of 331–339 days and an accreting white dwarf (Gromadzki et al. 2007; Munari et al. 2016). In the spectra of V694 Mon, the absorption components appeared in Balmer lines at radial velocities up to −6500 km/s. This phenomenon was explained by collimated ejections of matter directed along the line of sight. The inclination of the orbital axis of this system is small. Photometric history shows light brightenings with a period of 1875–1930 days (Munari et al. 2016; Doroshenko et al. 1993). The same period was found in variations of the outflow velocities (Iijima 2002), suggesting that this periodicity is related to the precession of the accretion disk. Thus, T. Iijima characterized V694 Mon as an "SS 433 type object with a white dwarf". However, we observed a break in the disk accretion and the filling of the white dwarf's Roche lobe with the accreting matter, leading to the formation of an A4 I star in the white dwarf's lobe (Goranskij et al. 2018, 2021). The phenomena we observe in this event in V694 Mon prompted us to revise the current conception of the relativistic binary SS 433.

2 Observations

Medium-resolution spectroscopic observations of V694 Mon were conducted by us between January 2, 2011 and March 8, 2024, primarily using SAO 1-m Zeiss telescope and UAGS spectrograph. A few spectra were obtained with the 6-m BTA telescope equiped with the SCORPIO-1 and SCORPIO-2 multimode focal reducers (Afanasiev & Moiseev 2005). The spectral resolution ranged from 2.3 Å to 14.8 Å. We also obtained three high-resolution spectra of V694 Mon in 2019, 2022 and 2023 with the BTA and MSS spectrograph, with a resolution of 0.29 Å. In total, we have

[1] https://www-astro.physics.ox.ac.uk/~podsi/binaries.pdf

53 spectra. Additionaly, we collected photometric data, encompassing 4777 epochs including photographic B, photoelectric UBV, Straizys $WBVR$, and CCD Johnson and Cousins $UBVRI$. The earliest plates of V694 Mon, found in the SAI plate collection, were taken at the Moscow Observatory in 1899 and 1900, these plates were suitable for microphotometry and electronic reduction, revealing that the brightness of V694 Mon in the blue band of the spectrum increased by 100 times between 1899 and 2024. We also observed SS 433 using the instruments and devices of the Moscow University and SAO RAS observatories, in addition to collected published photometric data since its discovery in 1978. Moreover, we have results of 21 years of synoptic monitoring of SS 433 using a 25-cm reflector equipped with an electronic image tube with a microchannel plate.

3 V694 Mon = MWC 560

Our photometry and spectroscopy indicate that in 2018 significant changes occured in the star behaviour:

(1) the star ceased its flickering;

(2) the stellar brightness increased 500 days before the end of the 1930-day flare circle, these changes occurred during the conjunction of the star with the Sun;

(3) in the spectra, high-velocity absorption components in Balmer lines disappeared, suggesting the cessation of the accretion into the disk and disappearance of collimated jets.

Our spectroscopy since October 17, 2018 has traced in details the history of filling white dwarf's Roche lobe and formation of an A star photosphere there. From 2018 to 2020, Balmer and metal-line emissions with absorption components evolve with increasing intensities. In November 2021, we registered the absorption spectrum of an A star with unusually strong absorption lines, indicating the presence of an extensive atmosphere. Alongside the deep absorption spectrum, a weak emission-line spectrum appeared. This emission was confirmed by the high-resolution BTA/MSS spectrum taken on February 17, 2022. Notably, these emission lines were absent in the previous high-resolutuon spectrum taken on March 8, 2019.

We identified these emissions with the ions of Y, Zr, Nb, Ba, La, Ce and Nd, with cerium being particulary prevalent. These elements are associated with the s-process (neutron capture), which is believed to occur in AGB stars. Recently, Klochkova & Panchuk (2022) studied strong absorption lines of these elements in the photosphere of the cool post-AGB supergiant GSC 04050−02366. However these lines were not observed in any of the early phases of V694 Mon. This suggests that the donor star was a red giant or an AGB star. We interpret the appearance of such a spectrum as a manifestation of the lower level of the discarded donor's envelope. We identify the newly formed companion as a A4 I star. With a known distance to V694 Mon $d = 2.36$ kpc ($\pi = 0.424 \pm 0.035$ mas, Gaia) and the recent photometric data $U = 8^{\rm m}\!\!.54$, $B = 8^{\rm m}\!\!.59$, $V = 8^{\rm m}\!\!.34$, $E(B{-}V) = 0^{\rm m}\!\!.17$, $A_V = 0^{\rm m}\!\!.52$, we calculated parameters of the star $M_{\rm bol} = -4^{\rm m}\!\!.02 \pm 0^{\rm m}\!\!.03$, $T_{\rm eff} = 8600$ K. The A star formed in the Roche lobe is now as luminous, as a post-main sequence A star with a mass of $6.5\,M_\odot$. Previously, the accretor was considered to be a white dwarf.

4 SS 433 = V1343 Aql

SS 433 is an eclipsing system with $P_{\rm orb} = 13^{\rm d}\!\!.082$ and moving emission components of H and He I lines due to precession of relativistic jets with the period $P_{\rm prec} = 162^{\rm d}\!\!.8$. The inclination of its orbital axis is $78^\circ\!\!.83$. The velocity of the ejected matter is $0.26\,c$. The jets also show nutation periodic variations with $P_{\rm nut} = 6^{\rm d}\!\!.28$ superimposed on the precession velocity curve. A weak stellar absorption lines in the spectrum of SS 433 were discovered by Hillwig & Gies (2008) and confirmed by subsequent studies. The contribution of this star in the common light in eclipse was 36% if measured in the precession phase T_3. Otherwise, the presence of the A star was called into question by Barnes et al. (2006). They found that the strength of these lines outside an eclipse in the phase "where the accretion disk is close to edge on" is equivalent to the donor contribution of 77%. So the "lines may originate in a clumpy, accretion driven outflow", not in an A star. Note, that the A4 I star we observe now in V694 Mon system is an accretor, while the A4 Iab star in SS 433 is a donor of accretion.

In accurate $UBVRI$ photometry, we deal with a strong Balmer jump, rather than weak absorption lines, confirming the presence of an A4 star in SS 433 system; however, we do not confirm the presence of any accretion disk. The example of V694 Mon suggests, that the strong absorption spectrum may be formed in an extensive envelope of an A star when it has acquired the envelope from the donor but has not yet reached the hydrodynamic equilibrium. Conversely, the A-type donor star with the envelope, overflowing beyond the bounds of its Roche lobe, can have an expanded low-density atmosphere, which was observed by Barnes et al. (2006). Therefore these lines belong to an A star, not to any outflow. The spectroscopic method of measuring the contribution of a star to the total light of a binary, based on the comparison of its spectrum with that of a normal star, may sometimes yield false results.

The predominant content in the SS 433 spectra is a power-low spectrum of a very hot source with a linear distribution of intensity versus wavelength diagram in the logarithmic scale. The maximum of this distribution is in the soft X-rays. $UBVRI$ photometry is useless to measure the temperature of this source. However, the temperature can be roughly estimated using the velocity of the stellar wind from the source in the hydrogen line with the formula $mv^2/2 = kT$, where m is the mass of a proton, k is a Boltzmann constant. This yelds about 1.5 million K. The power-law spectrum distribution in optical range is close to the spectra of the hottest massive O-type stars. If we attempt to solve the light curve of SS 433 as a binary with an O-type donor in the precession phase −0.20 to +0.20, then we will obtain accurate but erroneous solution involving a black hole. Goranskij (2011) extracted the spectral distribution of the A star from common light of SS 433 in the mid-eclipse, and confirmed spectral result by Hillwig & Gies (2008) using Balmer jump of the A star. Its bolometric luminosity is between $-5\overset{\mathrm{m}}{.}9$ and $-5\overset{\mathrm{m}}{.}0$, and the mass ranges from $8.3\,M_\odot$ and $11.0\,M_\odot$. The contribution of its Balmer jump is also evident in the $(U–B)–B$ diagram. With a contribution so small as 36%, the donor cannot be responsible for the observed large ellipsoidal effect in the light curve. This effect is due to the filling or overfilling of the Roche lobe of the compact companion, along with the tidal effect on jets. The accretion disk is excluded because its axisymmetric structure cannot cause the ellipsoidal effect. The supercritical accretion disk is also ruled out.

Using mass ratio $q = 0.1496$ found by Brinkman et al. (1989) based on Ginga X-ray observations of eclipse in May 1987, we obtained the mass of the compact companion as $1.45 \pm 0.20\,M_\odot$. Considering that SS 433 is located at the center of the radio nebula W50, and is believed to be a 10 000 years old supernova remnant, the compact companion should be a neutron star. As noted by Brinkman et al. (1989), the Roshe lobe of the companion is totally eclipsed. The presence of the power spectrum in totality suggests that its Roshe lobe is overfilled. Our photometry shows a strong red and infrared excess over the power-low spectrum, indicating the presence of a massive circumstellar disk resulting from extensive mass exchange between components. Therefore, we observe a star with a neutron core in this system.

The properties of stars with the neutron core are predicted based on theoretical assumptions and model calculations in several investigations, with some predictions that their existence is impossible. Thorne & Żytkow (1977) describe them as M giants with a thin leyer (40 meters) around a compact core, called a halo (Thorne–Żytkow Objects, TŻO). In the halo, gravitational energy is released, and thermonuclear burning occurs in thin layers, with a convection zone extending from the outer edge of the halo up to the photosphere. These objects can originate only in binary systems when the neutron star acquires its envelope from a donor star and later merges with the core of the donor. In SS 433, we can observe and study a real TŻO within the system. In case of SS 433, the convection zone is limited by its Roche lobe, and there are indications of a magnetic field in the neutron star. In SS 433 we have observed three types of photospheric conditions.

1. The most frequent occurance is a wind photosphere above the Roche lobe with weak irregular variability in photometric bands.
2. Rare brightenings last for several orbits with increasing rapid variability of a few tenths of a magnitude, sometimes accompanied by the low-amplitude orbital light variations and even the disappearance of eclipses. We interpret this as a convection zone above the Roche lobe.
3. Large outbursts, characterized by strong IR excesses and the appearance of shoulders in Hα emission lines, are very rare. We attribute these outbursts to the energetic events of a young magnetic neutron star, or magnetar. These events involve the resetting of the envelope or part of it. We assume that the magnetar prevents merger of the neutron star with the donor's core, thereby forming the predicted M giant TŻO, and redirects matter into a circumstellar disk.

5 Summary

This investigation demonstrates that mass transfer in the dynamic mode ultimately results in cessation of accretion through a disk, either by filling or by overfilling the Roche lobe of the accretor, and in subsequent loss of matter into the circumstellar disk, rather than in the formation of a supercritical accretion disc around the accretor. This transfer can occur unexpectedly rapidly and may last only a few years.

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