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# Evolution of Red Nova V4332 Sagittarii Remnant

**E. A. Barsukova[1*], V. P. Goranskij[2], A. F. Valeev[1], and A. V. Zharova[2]**

[1] *Special Astrophysical Observatory, Russian Academy of Sciences, Nizhnii Arkhyz, 369167 Russia*
[2] *Sternberg State Astronomical Institute, Lomonosov Moscow State University, Moscow, 119992 Russia*
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**Abstract**—We present the multicolor $BVRI$ photometry and BTA/SCORPIO spectroscopy for the red nova V4332 Sgr, performed in 2005–2012. We have analyzed the behaviour of the nova remnant, considering our observations along with all the published observations and archival photographic photometry. The atomic and molecular emission spectra show an exponential weakening. Since 2003, the line fluxes have on the average decreased 30-fold. The continuum of the M-type giant in the spectrum has weakened abruptly between 2006 and 2008, twice in the red and by 4 times in the blue range. The variations in the spectral energy distribution of the stellar continuum after the outburst correspond to a decrease in the surface temperature of the M-type giant by 1000 K. The presence of a faint star of about $20^{\rm m}$ is possible. The star can be either a member of the system or a field star. It is found that the phenomenon of the red nova in this system is not related with the M-type star. The progenitor of the explosion could be a blue straggler, which has disappeared from the spectral energy distribution after the explosion of 1994. It is most likely that this object was a contact binary system. To explain the "cold explosion" of V4332 Sgr, we have accepted the hypothesis of merging components of a contact binary star in a hierarchical triple or multiple system. There are evidences of dynamical destruction of the outburst remnant and accretion of its matter to the M-type giant. The cause of the red nova phenomenon is thought to be a sudden explosive energy release in the center of a star having a massive envelope, and a subsequent expansion of the envelope in the conditions close to adiabatic. As a result of the explosion, thermal energy reaches the surface of the envelope a year or a few years after the outburst, whereas the envelope already has a large surface area. The cause of the explosion in the center of the star can be both a merger event of the nuclei of two stars in the contact system with a formed common massive envelope and instability in the core of a single massive star. Thus, the red novae can be heterogeneous objects at different evolutionary stages.

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## 1. INTRODUCTION

The outburst of the Nova Sagittarii 1994 (V4332 Sgr) was discovered on February 24, 1994 by M. Yamamoto [1]. The brightness of the star at the time was $8\overset{\rm m}{.}9$. The first spectroscopic observations of R. Bertram [2] revealed a very cold continuum and H$\alpha$ emission in the outburst which is quite atypical for the classical novae. The outburst was discovered at the time when the object was located at the side of the Sun and therefore could not be totally observed. The spectroscopic and photometric investigation of V4332 Sgr in the outburst and at the brightness decline is laid out in the study of Martini et al. [3]. As soon as 20 days after the discovery a rapid brightness decline has started, while the spectral class varied from K3–K4 III—I to M8–M9 III with the TiO and VO molecular bands. Then the emissions have appeared: first, the Balmer lines; and later, Na I, Fe I, Fe II, [O I], and a strong line of Mg I $\lambda$ 4571. Further evidence of the presence of a source of high-temperature ionizing radiation, forbidden [Fe II] lines, in the spectrum of June 5, 1994 are noted in [4].

Having the cold continuum in the spectrum of the outburst and its specific development, V4332 Sgr resembled a red variable star RV (McD 88 No. 1, V1006/7), which appeared in the bulge of the Andromeda nebula M 31 in 1988 [5–7]. At the maximum brightness, it reached the absolute magnitude of $M_V = -9\overset{\rm m}{.}1$ which exceeds the absolute magnitudes of the classical novae in M 31. Then three more Galactic objects with the K–M spectral types in the outbursts were discovered: V838 Mon 2002 [8, 9], V1309 Sco 2008 [10, 11], and OGLE-2002-BLG-360 [12]. Reliably determined

*E-mail: bars@sao.ru

now is the distance to V838 Mon ($6.1 \pm 0.6$ kpc) and the absolute magnitude of this star in the maximum outburst ($M_V = -9^{\mathrm{m}}\!.8$) [13]. Another Galactic object of this class was found in the archives, this is V1148 Sgr [14, 15]; however, the data about it is extremely scarce. Two more extragalactic objects became known: M 85 OT 2006-1 [16] and PTF 10fqs in the galaxy M 99 [17], which may possibly relate to this class. Their absolute magnitudes at maximum brightness are $M_R = -12^{\mathrm{m}}$ and $M_V = -13^{\mathrm{m}}$ respectively. Therefore, V4332 Sgr proved to be a representative of a new class of astrophysical objects, namely, the Stars Erupting into Cool Supergiants (SECS) [18], or red novae. With their maximum luminosities, the red novae fall in the gap between the classical novae and the supernovae ($-8^{\mathrm{m}}$ and $-17^{\mathrm{m}}$) [19]. They are yet called the Intermediate-Luminosity Red Transients (ILRT). Among the red novae there are objects of different galaxy population types: both the old population of the bulge and the halo (V1006/7 in M 31, M 85 OT 2006-1) and the young population of the spiral branch of the Galaxy (V838 Mon).

V4332 Sgr, being a relatively well-studied object, conceals a lot of mysteries. It appeared at a high galactic latitude ($b = -9^\circ\!.4$) in the direction to the Galactic center ($l = 13^\circ\!.6$) and has a small interstellar reddening ($E(B-V) = 0^{\mathrm{m}}\!.32$). If we adopt for it the absolute magnitude in the outburst maximum, known for V1006/7 in M 31 or V838 Mon, it turns out that this is a very distant object ($d = 15$–$22$ kpc) located behind the Galactic center. According to other estimates, the distance was adopted as 0.3 kpc or less [3] or about 1.8 kpc [21]. Using the archival POSS-I photometry of 1950 in the $B$ and $R$ bands, the spectral types G2 (the $\pm 0.4$ subclass) [20] or G6V [21] were determined for the outburst progenitor, where it was considered a "solar type star." In the Moscow collection of the sky photos, we have discovered six photographs taken between 1980 and 1986 by the 50-cm meniscus Maksutov telescope in the $BV$ system, from which the following photometric parameters were found: $V = 17^{\mathrm{m}}\!.63$, $B - V = 0^{\mathrm{m}}\!.58 \pm 0^{\mathrm{m}}\!.11$, $(B-V)_0 = 0^{\mathrm{m}}\!.26$ [22]. Combined with the observation in the $R$ band on the plate obtained at the Schmidt telescope in the ESO in 1985 and in the $I$ band at the Palomar Schmidt telescope in 1987, it follows from the photographic observations that the precursor contained a blue and a red component. Besides, the observations from the sky surveys have shown that the brightness of the progenitor in the $B$ band increased by $1^{\mathrm{m}}$ between 1950 and 1986, while in the $R$ band it increased by $2^{\mathrm{m}}\!.6$ between 1950 and 1991 [20]. In 2005 the blue component was already absent in the spectral energy distribution of V4332 Sgr, and the spectra did not reveal any signs of an ionization source. However, in 2005 the red component remained roughly at the same brightness level as in 1985–1986. It was concluded from the photometric data in [22] that the progenitor of V4332 Sgr was a binary system in which an explosion of the hot component has occurred.

Spectroscopic observations of the 1994 explosion remnant have begun only in 2002, with a delay of eight years [20]. The spectrum of the V4332 Sgr remnant proved to be unusual: apart from the continuum of the cool K8–M0 type star, it reveals emission lines of low-excitation metals and molecular emissions of the rarefied cold gas with the temperature of 1050 K [20]. In 2003 the spectrum of the cool star was estimated as M2.7 I [21]. The spectrum shows a strong emission of the alkali metals Na, K, and Rb, and no Balmer lines. The emission reveals resonance Al I, Mn I, Cr I, Ca I, Sr I lines, Mg I, Fe I lines, molecular lines AlO, TiO, VO, ScO, and CrO [4, 20, 21, 23–25]. The mechanism of radiation of the gaseous nebula and molecular atomic emissions can be the radiative pumping from the continuum of the cool star [25].

In 2009 the photospheric spectrum of the cool star was estimated as M6.2 III [25]. By this time the spectrum has changed to become more late-type as compared with the spectrum of 2003. This is due to the photometric weakening of the star between 2006 and 2008. At the same time it was noted that the spectrum of the cool star differed from the spectra of normal stars like M6 III by the additional absorption bands VO 7334–7534 Å and TiO 6985–7050 Å. These bands are only observed in M-type stars of earlier subclasses. These bands may indicate the low metallicity of the cool star.

In 2003 significant changes have occurred in the infrared (IR) spectrum of V4332 Sgr: in addition to the energy distribution of the cool star, which could be described by the distribution with the blackbody temperature of 3250 K, there has appeared a strong IR emission excess in the $JHK$ system bands with the temperature of 900 K [26]. The brightness increase in the IR range was also noted in [21]. This excess has probably appeared in a short while, since in 1998, according to the 2MASS, it was not there and a year later it was noticed within the DENIS survey. The radiation excess may be associated with the dust envelope, the lower mass limit of which is $3.7 \times 10^{12} M_\odot$. The data of different sky surveys in the range of 0.4–105 $\mu$m, summarized in [25], in the period from 2005 to 2009 show two spectral components with blackbody temperatures of 950 K and 200 K, the sum of which exceeded the luminosity of cool stars by about 50 times. Kaminski et al. [25] assumed that this energy distribution may indicate an M5–6-type giant surrounded by a thick gas and dust disk inclined to the line of sight by an angle close to 90°. Hence, the central giant star is immersed in this disk, and only a tiny fraction of the radiation of this star gets to the observer, being scattered on the dust particles. The authors of this paper compare V4332 Sgr with the object IRAS 1809-3211 (known as the "Gomez's Hamburger"), the energy distribution of which is similar to the energy distribution of V4332 Sgr. The light of the central star there, which is shielded and is hence not directly visible, is scattered on the dust particles at the outer edge of the disk. Within this hypothesis, the problem of the formation of the atomic and molecular spectrum of the cold gas remains unsolved as the radiation of the central star does not reach this edge. In addition, low rotational temperatures, measured by molecular emissions, suggest considerable distances from the central star to the cloud of cold gas which implies that the gas is not related to the thick disk but rather was ejected in the past, at the outburst of 1994 or later, with the stellar wind. As the profiles of the atomic lines are not bifurcated, it was believed that the outflow of gas is concentrated towards the axis perpendicular to the line of sight. Kaminski and Tylenda [27] have measured the linear polarization of V4332 Sgr. The degree of polarization was approximately 26% and 11% in the $V$ and $R$ bands respectively. Assuming that only the emission of the central star is polarized and the contribution of atomic and molecular emission to both bands amounts to about 40%, the degree of polarization of the continuum has to be within 40% and 20% in the $V$ and $R$ bands respectively. Such high polarization degrees have to testify in favor of the model with a red giant fully immersed in the thick dust disk and with possible outflows of molecular and atomic gas along the axis of this disk.

Note that presently there are at least three hypotheses explaining the phenomenon of red novae. This may be "a nuclear event in a single, evolved star, causing a slow shock that drove the photosphere of the star outward and resulting in the evolution to low temperatures" [3]. This is how the outburst of V4332 Sgr was explained for the first time. We understand this "event" as an explosion or a sudden transient increase of the energy output from the center of the star for different reasons. In case of V838 Mon we may be dealing with the central explosion of a young star on the zero-age main sequence of the B3 V type in the system with a B3 V-type companion. Then, the companion found itself inside the expanding supergiant—the explosion remnant [28]. Another explanation of the phenomenon of red novae is a collision or merger of stars in binary or multiple systems [29]. The merger of components of a contact system with the formation of a common envelope was observed in the red nova V1309 Sco in the archival images of the sky within the OGLE experiment [11]. The third hypothesis considers the red novae as an extreme case of classical novae—dwarf systems similar to the novae but with low-mass and cool white dwarfs possessing slow accretion rates [30, 31]. At that, the outburst of the nova is related to the thermonuclear explosion of hydrogen on the surface of a white dwarf and with a subsequent expansion of its photosphere. The latter hypothesis faces difficulties: white dwarfs or dwarf systems in the red nova progenitors are yet to be discovered.

In our opinion, not only the archival studies of the red nova progenitors but the studies of their remnants can as well provide valuable information about the nature of this phenomenon.

## 2. OBSERVATIONS AND RESULTS

Spectroscopic observations of V4332 Sgr were carried out in the SAO RAS at the 6-m BTA telescope with the SCORPIO focal reducer [32] between June 8, 2005 and August 17, 2012. The data on the spectra obtained are given in the table. The spectra were reduced in Linux, using the LONG context of the ESO MIDAS environment. From the SAO location, V4332 Sgr can only be observed at large zenith distances—in all cases it exceeded 65°. To reduce the losses of light due to the atmospheric differential refraction in the short-wave part of the spectrum, the camera slit was oriented perpendicular to the horizon. Nine seconds south of V4332 Sgr, there is a star with the brightness of $V = 13\overset{\mathrm{m}}{.}30$ [22], which was partially or completely captured by the slit. Its brightness in the $V$ filter exceeded the brightness of V4332 Sgr by 600 times. For this reason, some of the spectra of V4332 Sgr were distorted by the effect of the scattered light of this bright star. The signal-to-noise ratio in the spectra of V4332 Sgr varies in the $V$ and $R$ bands (in the continuum around 5500 Å and 6400 Å) within 25–100. In the $\lambda > 6800$ Å region the spectra are distorted by the fringes, and we did not manage to compensate them in all cases. In the digital form, the spectra are available online at: `http://jet.sao.ru/~bars/spectra/v4332sgr/`.

Multi-color photometric observations of V4332 Sgr in the Johnson $UBVRI$ and Cousins $RI$ filters were conducted for ten years from May 28, 2003 to July 13, 2013 at different telescopes and CCD photometers. In the SAO RAS the observations were made on the 1-m Zeiss telescope with the photometer operating in the $UBV(RI)_C$ system. The photometer is equipped with a EEV 42–40 CCD, which is cooled by liquid nitrogen to the temperature of −135°C. The observations were also made at the Crimean Station of the SAI MSU (Ukraine), using a 60-cm Zeiss telescope with a photometer operating

Log of spectroscopic observations of V4332 Sgr at the BTA/SCORPIO

| Date | HJD 2400000+ | Exposure, s | Range, Å | Resolution, Å | Grism |
|---|---|---|---|---|---|
| June 08, 2005 | 53530.486 | 2700 | 3900–5619 | 4.6 | VPHG 1200g |
| June 09, 2005 | 53531.489 | 2700 | 3900–5616 | 4.6 | VPHG 1200g |
| August 04, 2006 | 53896.472 | 2400 | 5630–7366 | 5.0 | VPHG 1200r |
| July 19, 2007 | 54301.337 | 1200 | 5640–7361 | 5.0 | VPHG 1200r |
| | 54301.395 | 3000 | 3802–7556 | 10.0 | VPHG 500g |
| June 05, 2011 | 55718.466 | 2400 | 5744–7299 | 5.0 | VPHG 1200r |
| June 06, 2011 | 55719.453 | 2400 | 3900–7897 | 10.0 | VPHG 500g |
| August 17, 2012 | 56157.332 | 4500 | 3883–7910 | 10.0 | VPHG 500g |

in the $BVR_CR_JI_J$ system with the SBIG ST-7 and Apogee-47 CCDs in the Cassegrain focus, and a 50-cm Maksutov meniscus telescope AZT-5 with the Meade Pictor-416 CCD and a filter in the $V$ system, mounted in the prime focus. The reduction of Crimean observations was made accounting for the flat field, bias, and dark frames. To reduce the observations obtained in the SAO, we only used the flat field and bias frames, since while cooling with nitrogen to low temperatures the dark signal did not differ from zero. We have also used for the photometry the frames in the $BVR_C$ bands obtained at the BTA with the SCORPIO focal reducer in the spectroscopic mode. All the observations were processed using the WinFITS code written by V. P. Goranskij in Windows. During the photometric reduction, the nearby star located 9″ south did not pose any problems. The background of this star was measured at the same distance from its center at which the studied object is located. In some cases, when the images were close to 3″ or larger, the halo around the star was fitted with the radially symmetric brightness function and then subtracted. From the simultaneous observations we have found for V4332 Sgr the corrections for the transition from the Johnson system to the Cousins system: $R_C = R_J + 0\overset{m}{.}40$ and $I_C = I_J + 0\overset{m}{.}60$, not depending on the color indices. Hence, all the observations in the $R$ and $I$ filters here are reduced to the Cousins system.

Our collection of photometric observations also uses the data from the papers [3, 20, 21, 33]. These data have been corrected to bring them to the photometric system close to the system of the SAO RAS photometer. The corrections for the transition to the uniform system (SAO RAS) were found from simultaneous or closely spaced observations. The collection of observations is available online at `http://jet.sao.ru/~goray/v4332sgr.ne3`. The light curves can be considered in detail at the same website with a Java compatible browser, using the link `http://jet.sao.ru/~goray/v4332sgr.htm`.

The light curves of V4332 Sgr for ten years (2003–2013) in the $BVR_CI_C$ bands are presented in Fig. 1. The dominant feature of the curves in the optical range is the brightness decline, which has occurred between 2006 and 2008. In the $B$ band the brightness has dropped from $19\overset{m}{.}4$ to $21\overset{m}{.}4$, i.e., by $2\overset{m}{.}0$; in the $V$ band—from $17\overset{m}{.}4$ to $19\overset{m}{.}8$, by $2\overset{m}{.}4$; in the $R_C$ band—from $16\overset{m}{.}2$ to $18\overset{m}{.}0$, by $1\overset{m}{.}8$. In the near-IR range, in the $I_C$ band, the brightness decline at that time is much smaller and amounts to not more than $0\overset{m}{.}4$. There exists an observation in this filter, made in 1999 [20]. Accounting for this observation, we can conclude on a gradual brightness decrease $I$ from 1999 to 2010 by $1\overset{m}{.}1$. Then a brightness increase by about $0\overset{m}{.}2$ is noticeable. A small brightness rise between 2011–2013 by $0\overset{m}{.}4$–$0\overset{m}{.}5$ is also visible in the $V$ and $R_C$ filters. During the brightness decay and in the low state, the fluctuations of brightness are observed with an amplitude up to $0\overset{m}{.}8$ with a characteristic time of 200–300 days. The amplitude of these relatively rapid variations increases with the decreasing brightness of the star. However, a slight brightness increase in 2011–2013 can be explained by the fact that new observations randomly captured the times close to the cycle maxima of these rapid fluctuations. However, this trend of increasing brightness may prove to be important to understand the nature of the remnant and therefore requires further monitoring of V4332 Sgr.

Figure 2 shows the variations of color indices in V4332 Sgr. Since 2003, the color indices $V - R_C$ and $R_C - I_C$ reveal a general trend of reddening of the star with a decreasing brightness, while $B - V$ remains constant within the accuracy of measurements or even becomes slightly blue. We explain this behavior of the color indices by the fact that at the gradual

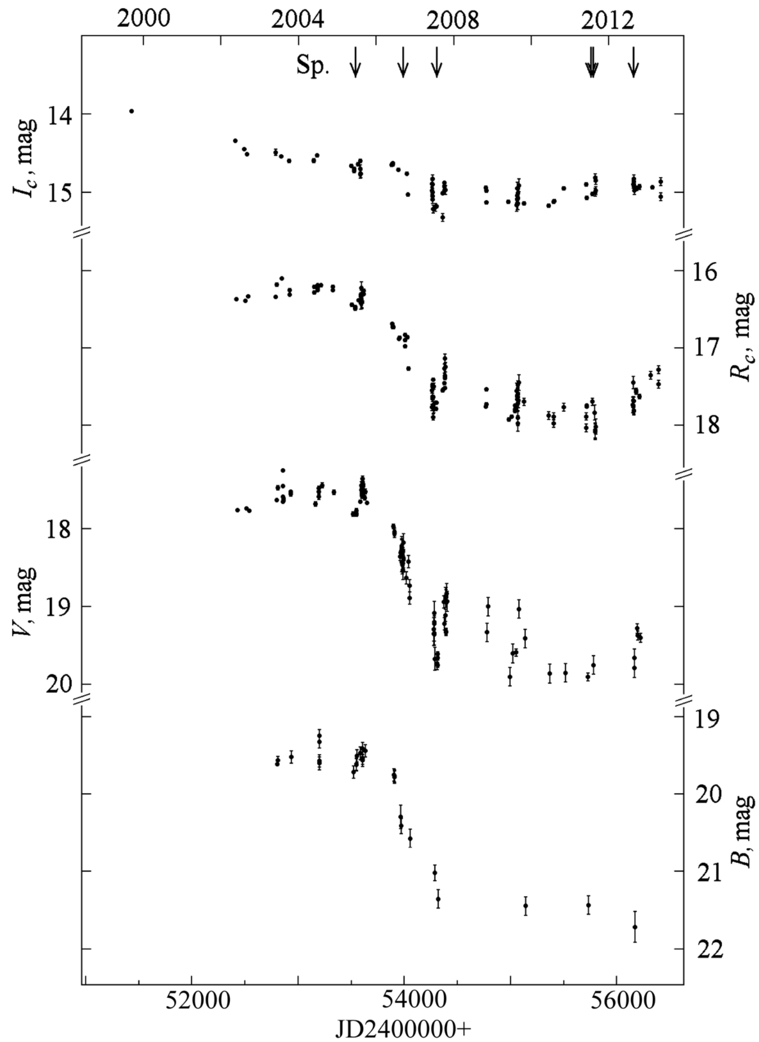


**Fig. 1.** Light curves of V4332 Sgr in the $BV(RI)_C$ system. The arrows on the top indicate the time of spectra acquisition at the BTA telescope.

brightness decrease and reddening of the continuum of the M-type star in the blue and yellow regions of the spectrum, the fraction of radiation of another faint and hotter star may possibly be increasing. The same trend is observed on the color–magnitude diagrams in Fig. 3. At the brightness decrease, the $V - R_C$ and $R_C - I_C$ color indices of V4332 Sgr become redder, while the $B - V$ indices become bluer. The amplitude of variation of the $V - R_C$ and $R_C - I_C$ color indices amounted to $0\overset{m}{.}7$–$0\overset{m}{.}8$ and $1\overset{m}{.}5$ respectively. The trend of increasing brightness of the object during the last three years (2011–2013) is accompanied by a decrease in the $R_C - I_C$ color index.

The BTA spectra of V4332 Sgr are demonstrated in Fig. 4 (in the blue region) and Fig. 5 (in the red region). These spectra were calibrated, and the fluxes were expressed in physical units using simultaneous or closely spaced in time photometric data. Identifications of atomic or molecular emission lines are made according to [4, 20, 24] in the blue region of the spectrum and [25] in the red region. An important problem of identifying the atomic lines in the blue part of the 2005 spectrum is the presence or absence of the Fe I emission. This was already observed in [4]. The Fe I emissions were identified by Martini et al. [3] in the spectrum of the star obtained in June 1994 immediately after the outburst, when the temperature of the radiation source was significantly higher [3]. At that time the Fe I emissions were observed simultaneously with the forbidden lines of the [Fe II] ions [4]. The 5164.3 Å line that was identified in [21] with Fe I $\lambda\lambda$ 5166.3, 5168.9 is more reliably identified in our spectrum with the molecular emission TiO $\lambda$ 5167.0. The corresponding TiO band is visible in the continuum of the M star in the absorption. The TiO emission is close in wavelength to the Cr I $\lambda$ 5166.2 emission, and this line may make a significant contribution

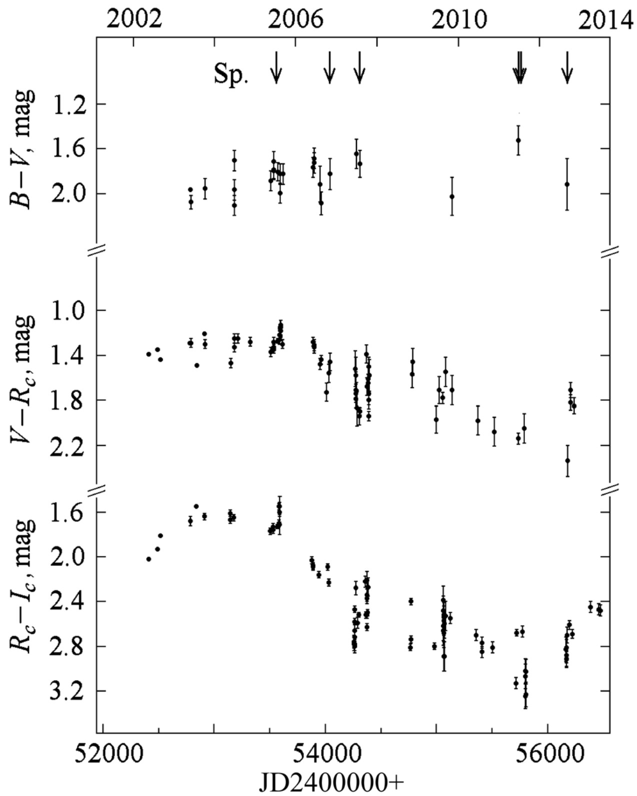


**Fig. 2.** Color index variations of V4332 Sgr. The arrows on the top indicate the time of spectra acquisition at the BTA telescope.

to the blend. The Fe I $\lambda$ 4376 emission from [20] fully coincides in wavelength and radial velocity with the AlO(6,3) molecular emission. No other identifications were found for the Fe I $\lambda$ 5110 line [20] (which is a blend of the AlO(1,2) and is reliably resolved). The emergence of this Fe I line is perhaps related to the fluorescence.

The main feature of the spectra in the range of 3900–5600 Å is the weakening of intensity of emission lines and stellar continuum between 2003 and 2011. The same weakening is visible in the photometric data as well. The resonance lines Al I $\lambda$ 3961, Mn I $\lambda$ 4030, Ca I $\lambda$ 4227, the triplet Cr I $\lambda\lambda$ 4254.3, 4274.8, 4289.7, and molecular lines AlO TiO are still visible in 2007, and in the later spectra they are lost in the noise. In the 2007 spectrum and in the later spectra, the intercombination line Mg I $\lambda$ 4571 is not visible, and the resonance line Sr I $\lambda$ 4607 that was stronger in 2005 has disappeared.

The spectrum of the M star with its TiO absorption bands is not visible in this range, although a weak continuum is noticeable. This is possibly the spectrum of another star, which is fainter and hotter, whose contribution is also observed in the photometry. While the M star gets weaker, the contribution of this faint star in the total brightness increases, especially in the shortwave range of the optical spectrum. From the spectrum and the photometry, the contribution of the faint star can be roughly estimated as $V \sim 20^{\mathrm{m}}$, $B - V \sim 1\overset{\mathrm{m}}{.}4$ [34]. This faint component can be both a stellar remnant of the 1994 explosion and a background or foreground star, randomly superimposed onto the image of V4332 Sgr. Indeed, the object is visible against the dense background of faint stars. A more reliable confirmation of the existence of this faint stellar component, its membership in the V4332 Sgr system, and an establishment of its nature requires observations with high angular resolution at a large telescope.

The 5700–7500 Å range (Fig. 6) also reveals a significant reduction in the emission intensity of atoms and molecules with time between 2006 and 2012. In the lower spectrum the brightness of the Na I $D_2D_1$ emission has again notably increased reflecting a weak trend of increasing brightness in the period of 2011–2013, observed in the photometry. At the same time, the continuum variations of the M star around 6700–7400 Å are significantly smaller than those occurring in the blue range. In the presence of photometric data, the radiation fluxes in the emissions and in the continuum can be separated which was done in our work [34]. Figure 6 shows the variations of fluxes in the atomic lines of Cr I, the blend Na I $D_2D_1$, Ca I blend, and in the molecular TiO and ScO lines. Apart from the BTA data, we used the flux measurements from the papers by Kimeswenger [20] (date 2003.5) and Kaminski et al. [25] (date 2009.5). Obviously, starting from 2003, there occurs a gradual exponential flux weakening over time (represented by a linear function in the logarithmic scale). Figure 6 shows some deviations in the fluxes of individual lines from the exponential law against this weakening. However, these deviations do not exceed the errors of observations and calibrations by more than three times. Unlike the photometric data and flux densities in the continuum in different photometric bands, the fluxes in the emission lines do not reveal any jump-like brightness drop between 2006 and 2008. Besides, the amplitudes of flux drop in the lines are significantly greater than in the continuum. This implies that the brightness drop in the period of 2006–2008 refers to the M star, and the atomic and molecular emissions vary independently. The general trend of the atomic and molecular emission flux weakening (a solid gray line in Fig. 6) corresponds to the flux weakening by about 30 times between 2003 and 2012.

Studying the continuum level jump of the M star, we have subtracted from the photometric data in the $UBVR_CI_C$ bands the contribution of the atomic and molecular emission. The energy distribution calculations in the continuum spectrum of the M star

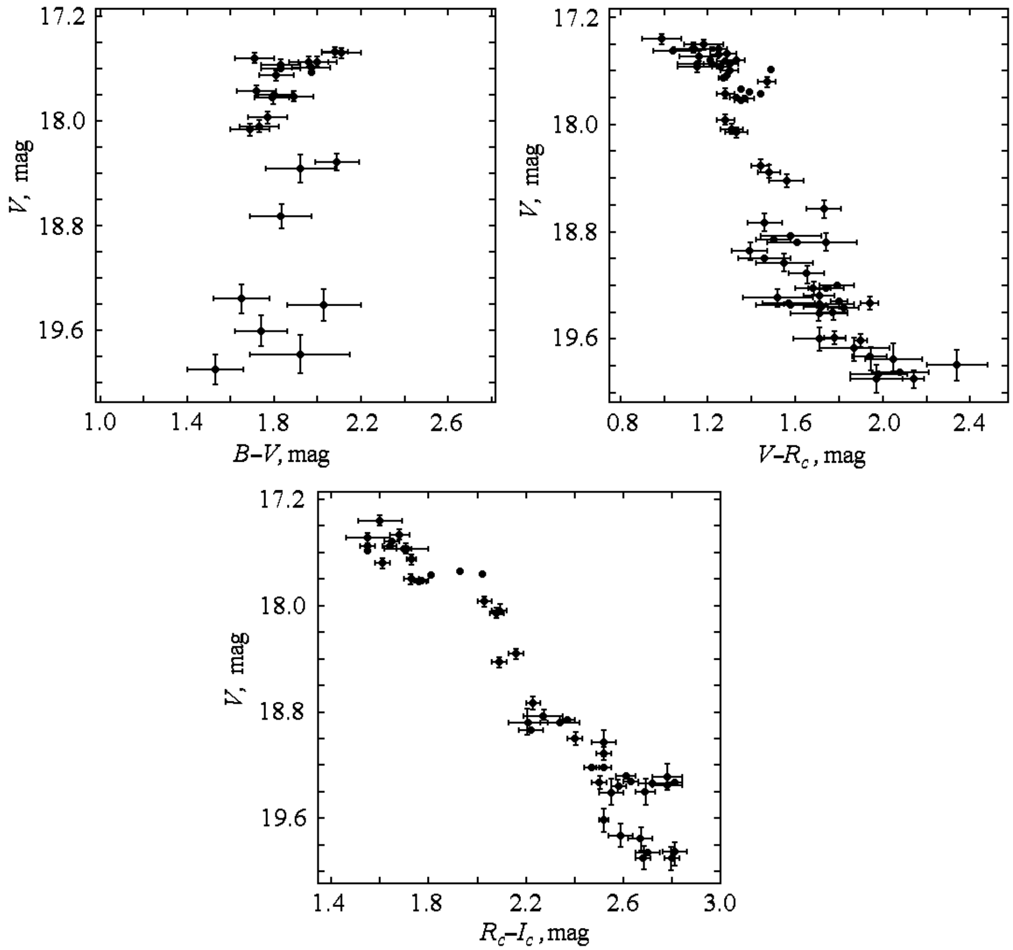


**Fig. 3.** Color—magnitude diagrams for V4332 Sgr.

before and after the jump were performed for two epochs: 2003—2005 and 2011. The results are shown in Fig. 7 by the black circles (2003—2005) and rectangles (2011). The signs of each spectral distribution are connected by a broken line. We have supplemented the optical data by the observations in the infrared range from [26, 35], which are for 2003 and 2011 respectively. The IR range also reveals emission lines, mainly molecular AlO, the contribution of which was not taken into account. According to the IR spectra (Fig. 1 from [26]), the relative contribution of the emission is considerably smaller than that in the bands of the optical spectrum. The energy distributions are built taking into account the interstellar reddening with $E(B-V) = 0\overset{m}{.}32$. Both energy distributions were approximated by the Planck function. The energy distribution of 2003—2005 in a broad wavelength range corresponds to the blackbody temperature of 2800 K, and the distribution of 2011—to 1780 K. Black body approximations indicate the change of surface temperature of the M star by about 1000 K. The radiation excess in the shortwave and longwave sections of the continuum are observed in the first and second epochs. The excess in the $H$ and $K$ bands is related with the dust component, and in the of $U$ and $B$ bands—with a faint star which is detected from the photometric and spectroscopic data.

On the same diagram (Fig.7) we have plotted the archival observations of V4332 Sgr, obtained prior to the outburst. Empty rectangles mark the observations in the $B$- and $R$ bands from the Palomar Sky Survey (POSS-I), obtained in 1950, the circles represent the photographic observations in the $B$ and $V$ system obtained with the AZT-5 50-cm meniscus telescope of the SAI MSU Crimean Station, and the images in the $R$ system obtained with the ESO Schmidt telescope in 1985 and in the $I$ system with the Palomar Schmidt telescope in 1987 (POSS-II). All the observations were reduced with the same photometric standard [22] and published in [24]. There is no information on the spectral composition of the radiation of the star before the outburst. In 1980—1986 the spectrum revealed the radiation of the same M star the continuum of which

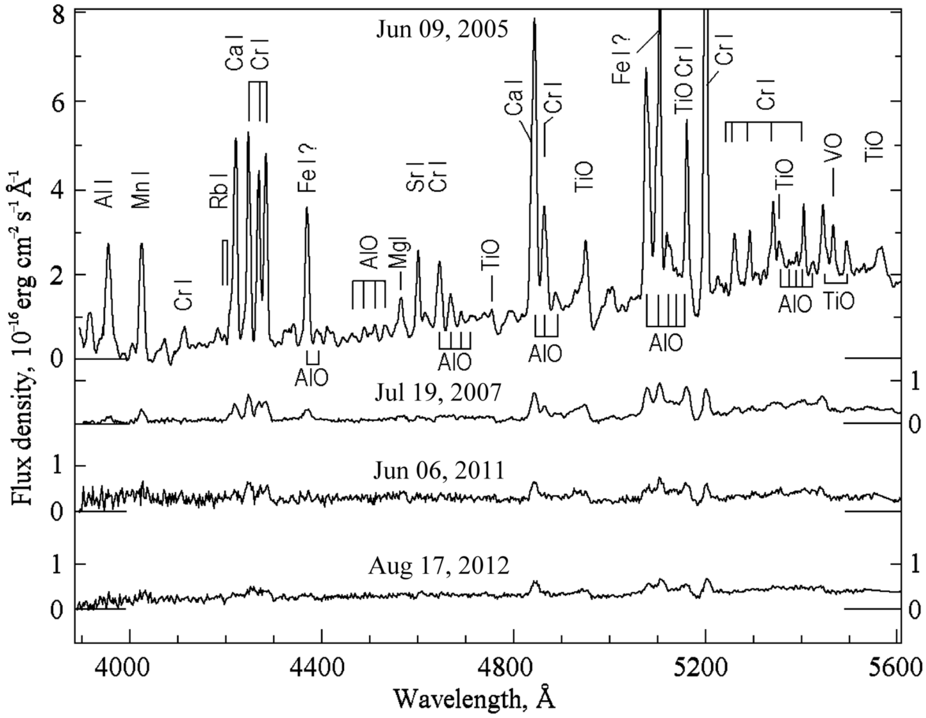


**Fig. 4.** The BTA/SCORPIO spectra calibrated using photometry, the blue region.

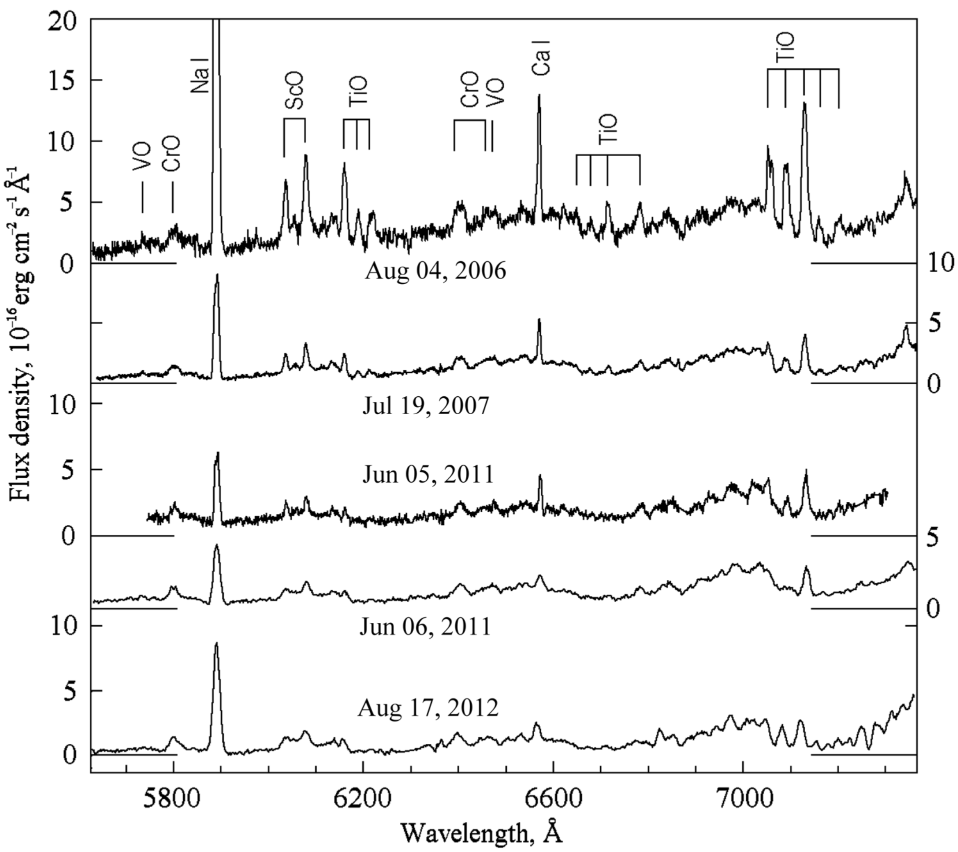


**Fig. 5.** The BTA/SCORPIO spectra calibrated using photometry, the red region.

was visible in 2003–2005; and apart from this, the spectrum has revealed a blue component which is missing after the outburst [22, 24]. Of course, the first conclusion depends on the assumption that before the outburst the spectrum consisted of stellar components only. The Palomar observations in 1950 are located significantly below and show a gradual brightness increase of the M star or its rapid variability. But these observations also indicate the radiation excess in the blue region of the spectrum compared to energy distributions observed after the 1994 outburst. The conclusion about the presence of the blue component in 1980–1986 does not depend on the variability of the M star. It is based on two pairs of plates in the $B$ and $V$ rays, where each pair is obtained at neighboring nights. During the day, the $M$ star could not change its brightness so drastically that it would affect the $B - V$ color index. The fluxes in these bands were obtained by averaging the observations in these nights.

Archival observations of V4332 Sgr also indicate a brightness increase of the blue component between 1950 and 1980–1986 (Fig. 7).

We have decided to check based on our data the assertion from [25] that the central object is now immersed in the dust disk and that the photospheric spectrum of this object observed in the optics is formed by the scattering of the radiation of the star on the dust particles of the circumstellar disk. In addition, it was found in the later paper [27] that the continuum emission is strongly polarized which occurs at large scattering angles. The question was, what was the cause of a sudden change in the distribution of the continuum of the star in 2006–2008 if not a drop of its surface temperature? Increased reddening of light due to the overlapping by the dust disk and/or scattered light during the full occultation of the star by the disk? When the light is scattered on small particles (Rayleigh scattering), the scattered light becomes bluer. This is contrary to our observations, which show a strong reddening of the spectrum. During the scattering on large particles, the distribution of energy in the spectrum of the reflected light would not change but the light would become polarized. Hence, these two hypotheses and intermediate states with a set of heterogeneous scattering particles are not suitable. Absorption of light of the star by large particles of the disk looks like an eclipse by an opaque screen and cannot change the shape of the continuum. Absorption by fine particles as well as interstellar extinction causes the reddening of the star. Using the law of interstellar extinction from [36], we tried to choose such a color excess value $E(B - V)$ for the energy distribution of 2011 at which the slope of this distribution would have approached the slope of the energy distribution in 2003–2005 (in the part of the spectrum where the

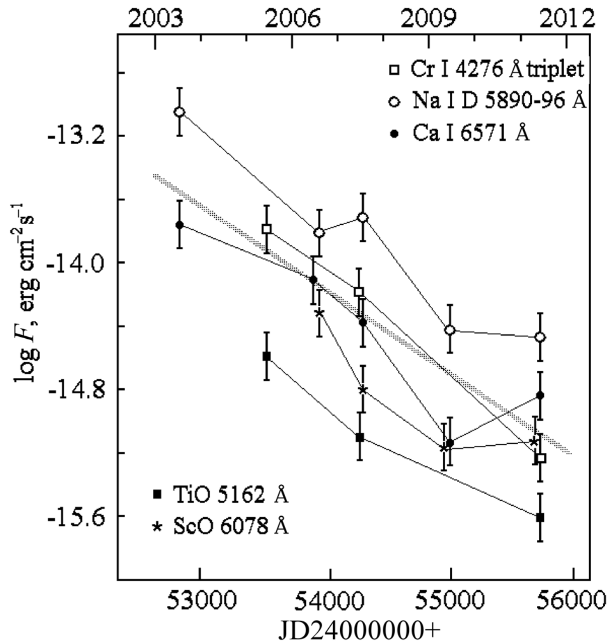


**Fig. 6.** Flux variations in the atomic and molecular emissions with time.

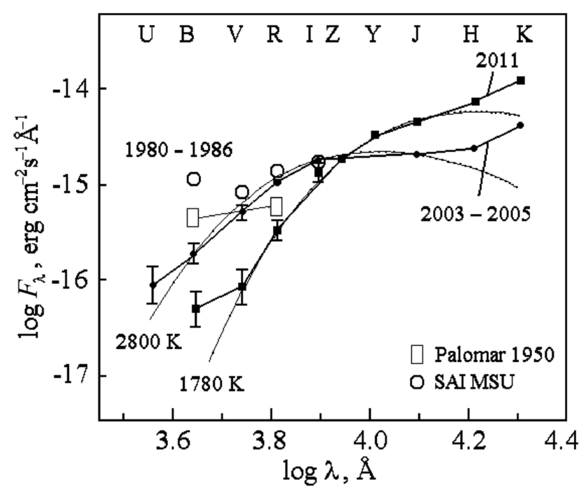


**Fig. 7.** The energy distributions in the continuum of V4332 Sgr at different times. Filled circles mark the observations of 2003–2005 before the abrupt brightness variation. Filled squares—the 2011 observations. The contribution of the emission component in the $UBVR_CI_C$ filters was subtracted here, and the errors of observations are shown. The energy distribution is approximated by the Planck function. The observations before the outburst are plotted by the blank signs. Rectangles—the 1950 observations based on the Palomar Sky Survey, the crosses—the observations in the $BV$ filters of 1980–1986 (Crimean Station of the SAI) and in the $R$ and $I$ filters from 1985–1987 (DSS).

distributions are not distorted by the blue and red radiation excesses). It turned out that such a color excess value exists, but this requires the assumption that the proper luminosity of the M star during the brightness drop of 2006–2008 was simultaneously increasing. Of course, such an event during the obscuration of the star by the edge of the disk is not very likely. Moreover, a significant brightness drop in 2006–2008 within the "Gomez's Hamburger" model can only be explained by the thickening of the dust disk itself, as it is assumed that the M star is the central object. Eventually we took up the hypothesis of reduction of the surface temperature of the star which at the same time related to the decrease in its luminosity, i.e., the hypothesis of variability of the M star.

The results of polarization observations [27] conducted in August 2010 in the $V$ and $R$ photometric bands (40% in $V$ and 20% in $R$) look particularly interesting when compared with our spectral data. According to [27], the contribution of the emission in both bands was about 40% (according to our data, the closest in time and relating to June 2011, the contribution of the emission is estimated as 4–6% in $V$ and 13–15% in $R_C$). At that, the spectrum of the M star has shifted red-wise from the $V$ band and is very weak in this band, although it can be traced by the TiO bands (Fig. 5). The spectrum of another, fainter and hotter, star dominates. It remains unclear which object possesses such a high polarization in the $V$ band. In our opinion, the results of polarimetry have to be verified.

## 3. NATURE OF V4332 SGR

Given its high Galactic latitude $|b| = 9.4°$, V4332 Sgr can be attributed to the objects of the Galactic bulge or thick disk, it also points to the great age of the system. Small interstellar reddening $E(B-V) = 0\overset{m}{.}32$ is not at all an indication of its proximity. The transparency in this region of Sagittarius is pretty good. Close, and even at a smaller Galactic latitude of −4.8°, a well-studied V4641 Sgr system with a black hole is located, the distance to which is estimated at 7.4–12.3 kpc; it has the same interstellar reddening [37]. Unlike the red nova V838 Mon, the progenitor of which was the system of young and massive B stars, V4332 Sgr is an old evolved object. The assumption of a large age confirms the presence of the M-type giant in the system before and after the outburst of 1994. This means that at least one star in this system has passed the main sequence stage. The radial velocity for the M star is $V_r = -56 \pm 16$ km s$^{-1}$, and for the gas component the radial velocity, determined from the atomic emission lines of metals, lies in the range from −58 to −75 km s$^{-1}$. This does not mean that V4332 Sgr belongs to the extreme population of type II, poor in metals. The continuous spectrum of V4332 Sgr indicates that the M star belongs to the oxygen branch of cool stars. And comparing the spectra of V4332 Sgr and V838 Mon in the blue region, in [28] the same resonance lines of metals Al I, Mn I, Ca I, and Cr I were found with the only difference that in V4332 Sgr they are in emission, while in V838 Mon they are in absorption. Hence, the difference between the outburst remnants consists only in the fact that the emission of the first object occurs in an optically thin medium, while in the second object there occurs absorption in an optically thick photosphere.

The question about the nature of the hot blue star observed in the V4332 Sgr system until 1994 remains open. Basically, the energy distribution of the V4332 Sgr progenitor is similar to the energy distribution of symbiotic stars. However, we cannot claim the existence of the symbiotic star, since there is no evidence on the line spectrum before the outburst which is indispensable for such a classification. Hot stars occur among the objects of the old population. These are the stars from the horizontal branch of globular clusters, namely, the stars with a double energy source (a central helium source plus a hydrogen shell source), which have already undergone the red giant phase. The hot stars of the horizontal branch occur in the globular clusters with low metal abundances. The probability of such an object in the V4332 Sgr system is small, because its spectrum has a large set of metal lines and their oxides.

In the globular and old open clusters, one can discover the so-called "blue stragglers", the stars located on the main sequence significantly higher than the turn-off point of the evolution into the red giants on the color–magnitude diagram for cluster stars. Obviously, these are more massive stars left behind in their development from the main stellar population. In [38] Leonard and Linnel have developed the idea that the stragglers form in the collisions or mergers of stars and pass the stage of mixing to then begin their evolution on the main sequence anew. Mateo et al. [39] studied the blue stragglers in the globular cluster NGC 5466 and detected three variable stars, two of which were identified as W UMa-type contact systems. Binary systems were found among the stragglers in other studies, cited in [39]. In this work it was assumed that non-variable blue stragglers are the remnants of contact systems—single rapidly rotating stars. In 2008 in the case of a red nova V1309 Sco, direct observations of the merger of a contact system were obtained in [10, 11]. Before the outburst the light curve of this system was a double wave with the period $1\overset{d}{.}4$, which then turned into a solitary wave with a close decreasing period (formation of a common envelope). It is interesting to trace whether a blue straggler will form in this merger. The stragglers are also found in the old open clusters M 67 and NGC 188, and in M 67 they form a quasi-horizontal branch. One of these objects—ES Cnc (S 1082) is a hierarchical multiple system containing as much as two stragglers. One belongs to a close binary system with an orbital period of $1\overset{d}{.}07$ with a star on the main sequence near the turn-off point, and the other is in on an elliptical orbit around the binary system [40]. If we assume that before the explosion the V4332 Sgr system contained a straggler having the luminosity of a straggler from the quasi-horizontal branch of M 67, then the distance to V4332 Sgr may be estimated at 10–16 kpc.

Taking the hypothesis of a straggler in the V4332 Sgr system, we have three possible explanations of the 1994 event.

1. Convergence and collision of a single straggler star with a red giant, which has led to the explosion, expansion, and shedding of the envelope of the giant, followed by transformation of its structure. The collision has possibly occurred due to the orbital evolution under the influence of the third component.

2. A central explosion of an unknown origin of the straggler itself in the binary system with a red giant. Possibly, this system was already semidetached with an accretion disk or symbiotic. But it is known that the explosions of hydrogen that accumulates on the surfaces of white dwarfs or subdwarfs (symbiotic novae) do not lead to the red nova phenomenon.

3. The straggler was a contact system which was a part of a hierarchical triple system containing a red giant. The explosion occurred at the merger of components in the contact system. In this case we have a red nova phenomenon similar to V1309 Sco, in the presence of a red giant. If it happened this way indeed, in a certain period of time after the outburst maximum the system will have two red giants, where one is a remnant of the red nova explosion, and the other is the component of the system which was observed before the outburst. Hence, the third hypothesis can be tested.

The variations of physical parameters of V4332 Sgr in the 1994 outburst and during the brightness decay after the outburst were investigated by Tylenda et al. [21], based on the photometric and spectroscopic observations of Martini et al. [3] and Gilmore [41]. The observations were compared in [21] with a later photometry in the IR and optical bands of 1999 and 2003, and with the 2003 spectra. The results of analysis are the spectral classes, effective temperatures, radii, and luminosities of the star. They are listed in Table 3 of [21]. The blackbody temperature we have determined for the continuum of the M star from the 2005 observations turned out to be about 500–700 K lower than the temperature of the star in May–September 2003 from [21]. There may be a systematic error related with the account of the emission spectrum in the photometric bands. Besides, Tylenda et al. [21] took a clearly underestimated distance to V4332 Sgr of approximately 1.8 kpc, mistakenly assuming that the progenitor of the explosion is a main-sequence "solar-type star." However, the quantitative data from [21] can be viewed in comparison. Table 3 from [21] shows that the M2–M4 III–I spectrum was observed during the brightness decline from March 8 to March 11 1994 at the luminosity level of 154–66 $L_{\odot}$ after which in June 1994 the stellar spectrum became more late-type, namely, M8–M9 III–I at the luminosity level of 86–11 $L_{\odot}$. But in May–September 2003, the star proved to have the same early-type spectrum of M2–M4 III–I at a low luminosity level of 5.9–4.8 $L_{\odot}$. These observations can be interpreted in such a way that during the brightness decline of March 8–11, 1994 the radiation was dominated by the M2–M4 star—the explosion remnant, after which the temperature and luminosity of the remnant have dropped. But in May–September 2003 only the light of the M2–M4 star was left in the continuum, i.e., the component of the system which we have identified before the explosion in 1980–1986. Of course, during the brightness decline the observers could not distinguish a fainter star of the same spectral class. In 2003 the explosion remnant has manifested itself in the emission spectrum and IR excess, and the M2–M4 type component became visible. Hence, the third hypothesis is the most likely.

The subsequent evolution of the V4332 Sgr explosion remnant was traced from 2003 to 2013. Our observations have shown an exponential attenuation of fluxes in the atomic and molecular emission lines by about 30 times during ten years. In 2003 the IR observations have captured the dust formation in the form of powerful radiation excesses [23]. Significant variations of brightness and temperature of the M star in 2006–2008 do not reveal any apparent connection neither with the formation of dust nor with the gradual weakening of fluxes in the emissions. The "Gomez's Hamburger" model for V4332 Sgr, discussed in [25], which assumes that the central M-type giant star is completely hidden in the depth of the dust disk, looks unnecessarily complicated. It does not explain neither the radical 30-fold decay of the radiation fluxes in the lines nor the varying continuum spectrum of the M star. These variations cannot be explained neither by the circumstellar reddening nor by the reflection by dust or by the Rayleigh scattering. The variations of the continuum spectrum by 2–4 times depending on the wavelength had a jump-like character and were explained by the intrinsic variability of the M star. Therefore, in [34] we have suggested that there exists an explosion remnant separate from the M star that emits both in the emissions and in the infrared range. This remnant has formed dust, and it simply cools down after the explosion. The mass of this source may be a few solar masses, this is why it cools for a long time.

The problem of formation of an unusual cold spectrum was debated in [25], where the molecular and atomic spectra of V4332 Sgr were explained by the radiative pumping. The source of excitation radiation can be the continuum of the star of a spectral type M5–M6 III with the temperature of $T = 3200$ K (for 2003). Kaminski et al. [25] gave an argument against the assumptions about the cooling of a massive cloud as the cause of molecular radiation in the emission. This is the low temperature of the environment (about 120 K) at which no excitation of the optical lines by the collisions is possible. These arguments have to be taken into account. However, we cannot agree with the hypothesis that the M star is an explosion remnant (it was observed before the outburst). It is not the central object of the system and the source of a bipolar outflow of matter resulting from the 1994 explosion, which forms an unusual spectrum. Another hypothesis stating that the IR source is a dusty disk surrounding the M star also gives doubts.

If we compare the evolution of the V4332 Sgr remnant with the evolution of the remnant of a well-studied red nova V838 Mon, we can find significant differences. The progenitor of V838 Mon is a binary system of young and massive B stars. The remnant of V838 Mon is a cool M-type star, and its spectrum is dominated by its continuum. The component of the system—a B3 V type star—has approached this remnant in 2006 and plunged into it, passing through its envelope. Under the external layer there was a void, in which it was moving for more than two hundred days before disappearing completely. During the motion under the outer layer, its radiation was weakened by about five times and was highly variable. Such a shell structure was predicted from the infrared observations by Lynch et al. [42]. The spectrum with a cold continuum remains to this point (as of May 2013). This means that the remnant looks like a star for the past 11 years. It might soon be dynamically destroyed as a result of an approach with its B3 V-type companion, and henceforth even the stellar core can be rejected from it, if it exists.

In contrast to V838 Mon, the V4332 Sgr system revealed the traces of dynamic destruction of the explosion remnant immediately after the outburst. In the early spectra obtained in [3], both the permitted and forbidden Fe II emissions are visible which means that the system possessed a hot source of ionizing radiation and rarefied gas. This is possibly a result of uncovering of internal hotter layers in the destruction of the remnant or a result of formation of a shock wave during the interaction with the M star. A strong intercombination line Mg I $\lambda$ 4571 is visible. A large mass of gas in the rarefied state is required to form such a strong line. The gas could be swept out of the remnant during its destruction. In this rarefied part of the explosion, the emission spectrum may be formed by the radiative pumping by the M star. The variability of the M star indicates the interaction of the remnant and the M star. Its increased luminosity and surface temperature just before the outburst may be related with the accretion onto it from the binary system in the state of merging and formation of a common envelope, and after the outburst—from the expanding envelope.

## 4. ON THE NATURE OF COLD EXPLOSIONS

We believe that the nature of "cold" explosions of the red novae is related with the short-term energy release episode in the center of stars possessing massive envelopes. During the central explosions the envelope receives a slow shock inside and expands. The thermal explosion energy reaches the stellar surface several years later, when its surface has such a large area that this energy can no longer heat it to a high temperature. This idea was for the first time applied to the red novae by Martini et al. [3] without sufficient justification. The authors assumed that there was an explosion in the center of an evolved star, i.e., at a late stage of evolution. The nature of such explosions can be explained in the objects at the post-asymptotic stage of evolution (like, for example, FG Sge or V4334 Sgr also known under the name of the "Sakurai's Object"). These are carbon stars, which differ by their spectra and chemical composition as well as by the duration of flashes from the M star (an oxygen star) and the gas component of V4332 Sgr. However, in the case of V838 Mon we have a young object located on the initial main sequence. The possibility of a thermonuclear explosion of the hydrogen core in a young star in the late stage of gravitational contraction is rejected by modern theorists working with model calculations. They believe that the process of initiation of thermonuclear burning does not lead to an explosion, it is prolonged and "very gentle." However, the explosions in the cores of protostars in the late stages of gravitational contraction, when the hydrogen core is completely ionized, were predicted by the founders of the evolutionary theory of protostars C. Hayashi and T. Nakano [43] in 1965. Powerful bursts of young low-mass T Tau-type stars (FU Ori, V1504 Cyg, and other objects of the "fuor" class) are also known; however, they are more often interpreted as the episodic accretion events from massive circumstellar disks [44] rather than the initiation of thermonuclear burning in the centers of stars.

What happens in the event of a release of additional energy in the stellar core during the explosion or due to any other reason? The star loses its mechanical and thermal equilibrium, its envelope comes in motion, and then the equilibrium is gradually restored.

> As the information on the variation of gas pressure is transferred by the sound waves, the star recovers its lost mechanical equilibrium during the time it takes the sound waves to travel the diameter of the star. This time is quite short: for example, for Sun it takes about an hour...The characteristic times of thermal processes occurring in the star (e.g., the energy transfer time from the core to the surface...) is much longer, hundreds of thousands, millions, even billions of years [45].

The radiation transfer velocity is determined by the mean free path of a photon inside the star $S \approx (\kappa\rho)^{-1}$, where $\kappa$ is the opacity of matter, and $\rho$ is the matter density. For the core of the Sun, this length is 0.1 mm, and for massive stars it is even smaller. Hence, the case of explosion in the center will cause the shock wave to appear on the surface of the star, which will look like a short outburst. Then the envelope will expand, while the energy of the explosion will be focused on its bottom. In this case the convection would not be effective. At that, the energy density of the envelope in all its layers will decrease and the mean free path of a photon will increase so that the explosion energy would reach the surface of the star not in hundreds of thousands or millions of years but much faster, in a few years. Such an envelope expansion condition can be described as close to adiabatic. Since the thermal energy of the explosion is contained in the envelope, the energy outcome decreases, while the surface area increases. At the adiabatic expansion mode, first there occurs a fast envelope expansion, and then the energy of the explosion is carried over onto the surface. During the adiabatic expansion we would see a decline in the brightness of the star, continuing from the onset of the explosion until the time when the explosion energy would reach the surface. During the "gentle hydrogen ignition" in the center, we would not even see a shock wave. It is important to test this hypothesis in the dynamic calculations, which have not yet been conducted.

The OGLE observations of the V1309 Sco red nova demonstrate a brightness drop before the outburst due to the adiabatic expansion of the common envelope of the contact system. The drop was $1\overset{m}{.}0$-deep in the $I$ band and lasted about a year (Fig. 1 in [11]). In this case it was firmly established that the cause of the energy release in center of the star was a merger of cores of the contact system stars. The brightness decrease of another red nova, V838 Mon, in the $R$ band by $0\overset{m}{.}461$ was discovered in 1998 [46], four years before the outburst. After subtracting the contribution of the secondary component, the brightness decrease of the exploded star also amounts to $1\overset{m}{.}0$. In the case of V838 Mon we managed to reliably determine that the outburst of the red nova was preceded by an expansion of the envelope. Since the distance to the V838 Mon is correctly measured, we know the photometric contribution of the exploded component in the $BVRI$ filters before the outburst, the spectra in the early days of the appearance of the nova, and the bolometric corrections; and hence we can determine the temperature and luminosity. The radius of the star is determined from the Stefan-Boltzmann law with the formula $L = 4\pi R^2\sigma T^4$. On February 10, 1994, the explosion progenitor—the B3 V-type star—had a radius of $2.9\,R_\odot$, and on January 12, 2002 it was a K0 I supergiant with a radius of $327\,R_\odot$. About January 12 the brightness of the star has reached the first peak after the initial brightness increase. At the peak of the outburst on the crest of the shock wave on February 5, 2002, the radius of the supergiant already amounted to $425\,R_\odot$ with the spectrum of A7 I, and on October 14, 2012 it was equal to $442\,R_\odot$ with the M6 I spectrum. Hence, in January 2002 the radius of the star proved to be 112 times larger, and the surface area—by 12.5 thousand times greater than that of the explosion progenitor. These are the sound evidence of the fact that before the appearance of red novae the stars undergo a close to adiabatic expansion of the envelope, while the central explosion occurs a few years earlier. Unfortunately, the time of the envelope expansion of V4332 Sgr was missed and is not presented in the observations.

The discovery of the red nova V1309 Sco and unique OGLE observations of the merger of components of the contact system in this case show that the red nova phenomenon occurs in double or multiple systems. Conversely, for V838 Mon there is no evidence of the binarity of the exploded star. An approach of the explosion remnant with the hot component of the system and a further engulfment of the component by the remnant occurred three years after the explosion. Hence, this interaction of stars in the V838 Mon system was not the cause of the red nova phenomenon.

## 5. CONCLUSIONS

We have presented the results of multi-color photometric observations in the *BVRI* system and BTA/SCORPIO spectroscopy of the red nova V4332 Sgr, conducted in 2005–2013. The behavior of the nova remnant was studied according to our data along with all the published observations and archival photographic photometry. The atomic and molecular emission spectra weakened exponentially, and since 2003 the fluxes in the lines have decreased by an average of 30 times. The continuum of the M-type giant in the spectrum has weakened abruptly in 2006–2008 by 2–4 times, most noticeably in the blue range. The variations in the energy distribution of the spectrum correspond to a surface temperature decrease of the M-type giant by 1000 K. Spectroscopy and photometry reveal one more very faint star of about $20^{m}$, which may either be a member of the system or a field star.

It was found that the M star is neither the progenitor nor the remnant of the red nova in this system. The progenitor of the explosion may be a blue straggler, the emission of which has disappeared from the spectral energy distribution after the explosion of 1994. Most likely this object was a contact system. We are hence inclined to the hypothesis of the merger of components of the contact binary star in the hierarchical triple or multiple system to explain the red nova phenomenon in V4332 Sgr. The variability of the M-type giant before the explosion can be explained by its interaction with the progenitor—a close binary which was passing to the common envelope state with the loss of orbital angular momentum, and a part of its matter was outflowing onto the surface of the M-type giant. After the explosion, the expanding envelope was dynamically destroyed, and the accretion from it onto the M-type giant had continued for some time.

The reason of the phenomenon of red novae is a sudden explosive energy release in the center of a star with a massive envelope and a subsequent expansion of the envelope in the conditions close to adiabatic. As a result, the thermal energy of the explosion reaches the surface of the envelope in a year or several years. The reason of the explosion in the center of the star can be both an instability in the nucleus of a young massive star and a merger of the cores of two stars in a contact system with a formed common massive envelope. The red novae can therefore be heterogeneous objects at different stages of evolution.

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