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# Historical Light Curves of Peculiar Red Novae V838 Mon and V4332 Sgr

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**Abstract.** On the basis of archive photographic plates, we established that both stars were binaries containing at least one blue star which is responsible for a nova-like explosion.

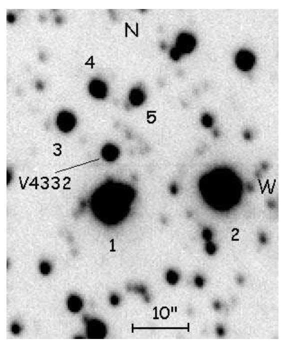
## 1. Introduction

V838 Mon and V4332 Sgr along with V1006/7 (McD Nova 88 No.1, RV) in M31 galaxy form a new class of eruptive variable stars which we call peculiar red novae with K-M type spectra in outbursts, or simply red novae. These stars have nothing in common with classical novae which flare up due to a thermonuclear explosion of the accreted hydrogen on the surfaces of their white dwarfs, and nothing in common with dwarf or X-ray novae having other outburst mechanisms. We use the term *nova* in the ancient sense as 'new star' that was not seen before its appearance. The nature of these stars is not yet known.

The aim of our investigation was to revise the archive photographic observations and modern multicolor CCD photometry using common and uniform standard photometric sequences and establish the changes in spectral energy distributions (SEDs) of these stars due to outbursts. The calibrations of V838 Mon were based on $UBVR_CI_C$ standard sequence by Munari et al. (2002a). We have not found photometric standards for V4332 Sgr in the literature and created such standards ourselves. The results are given in Fig. 1. V4332 Sgr is observable at only very high airmasses (in excess of 2.3) from our Observatory. We calibrated the photometric sequence four times in good photometric nights using different source standards. To plot the characteristic curves for photographic plates, we created secondary star sequences including about a dozen stars in the close vicinity of the targets.

The plate archive observations of V838 Mon contain 118 Sonneberg plates taken between JD 2425322 and 2448329 and 26 Moscow plates taken between JD 2433184 and 2449394 using 40-cm astrographs. Eye estimates of these plates done by one of us (S.Yu.Sh.) are already published (Goranskij et al. 2002, 2004).

So, V838 Mon was followed in the $B$ band during 66 years between 1928 and 1994. On the way to the La Palma Conference, V.P.G. found an additional 50 measurable plates (field centered on 20 Mon) in the Moscow collection, taken in the $V$ band with the 50-cm Maksutov telescope AZT-5 of SAI Crimean Station between JD 2442805 and 2443935. (No other pre-outburst $V$ band image is known of in the world). A search of the Moscow plate archive for V4332 Sgr images was successful too. We found 3 pairs of deep $B$ and $V$ band AZT-5 plates taken between JD 2443311 and 2446596 (centered on the globular cluster NGC 6717). All the AZT-5 plates were taken in the correct Johnson $BV$ system using specially designed and tested filters with astronomical emulsions AGFA ZU-21 ($B$), and Kodak 103aD, 103aG ($V$). Most of the Moscow collection $B$ and $V$ plates were digitized using SAI CCD scanners or a digital camera. These plates, and Digitized Sky Surveys' images were reduced using special software written for star photometry by V.P.G. and operating with Windows BITMAP images. This software provides special algorithms to remove nearby interfering companions from the measured star profile and its surroundings to improve the photometry, and this facility was used for both objects.




| Star | $U$ | $B$ | $V$ | $R_C$ | $I_C$ |
|---|---|---|---|---|---|
| 1 | 15.68 | 14.69 | 13.30 | 12.56 | 11.40 |
| 2 | 14.81 | 14.08 | 12.94 | 12.31 | 11.33 |
| 3 | 18.52 | 17.98 | 16.66 | 15.97 | 14.85 |
| 4 | 18.55 | 18.33 | 17.09 | 16.43 | 15.32 |
| 5 | 18.42 | 18.36 | 17.29 | 16.80 | 15.84 |
| $\sigma$ | 0.10 | 0.03 | 0.02 | 0.03 | 0.05 |

Figure 7. Map of V4332 Sgr and comparison stars.

The outburst and subsequent data of V838 Mon include $UBV$ photoelectric photometry taken by N.V.M. at the SAI Crimean station, and by A.V. Kusakin at Tien-Shan Observatory, CCD $UBV$, Cousins $R_C I_C$ and Johnson $R_J I_J$ photometry taken by V.P.G. and E.A.B. at the Special Astrophysical Observatory and SAI Crimean Station with different devices and telescopes. Our data were published by Goranskij et al. (2002, 2004). In our collection, the literature sources by Crause et al. (2003, 2005); Kimeswenger et al. (2002); Munari et al. (2002a) and single observations published in IAUCs and VSNET are included. The outburst and post-outburst photometry of V4332 Sgr includes the data published by Banergee & Ashok (2004); Bond & Siegel (2006); Gilmore (1994); Martini et al. (1999); Kimeswenger (2006), and our CCD observations taken at SAO and SAI Crimean Station.

All the observations were scaled to a uniform system, that of SAI Crimean Station and SAO. Systematical shifts between different sets were eliminated. A few discrepant observations were ignored. A single problem was not solved, to reduce Johnson $R_J$ to Cousins $R_C$ in the post-outburst data of V838 Mon.

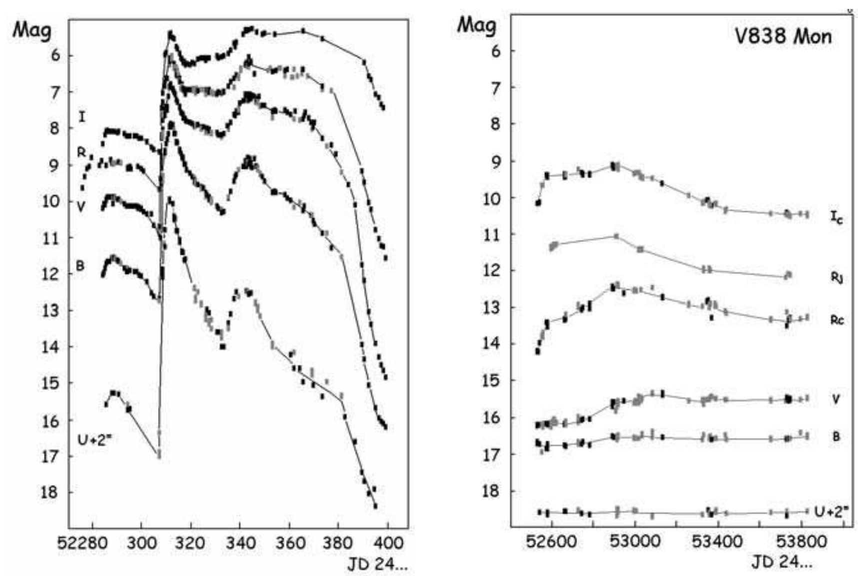



Figure 8. The light curves of V838 Mon in the main outburst (left) and rebrightening (right).

The data are given separately here for these bands. The all-filter outburst and post-outburst light curves of V838 Mon are shown in Fig. 2. Our observations are marked with light signs, and those ones taken from literature by dark signs. The historical light curves of V838 Mon (excluding ourbursts) in $B$ and $V$ bands are given in Fig. 3, and that of V4332 Sgr in $B$ band is given in Fig. 5. The full light and color curves and their details can be seen with a Java compatible browser on our Internet page http://jet.sao.ru/∼goray/. All reduced digital data including our current photometry are accessible in the files http://jet.sao.ru/∼goray/v838mon.ne3, and .../v4332sgr.ne3, where the order of filters in the columns is $V, B, U, R, I$.

### 1.1. V838 Mon

In the light curves of V838 Mon (Fig. 2), three peaks are seen in the main outburst. These peaks repeated with a period of about 30 days. Retter & Marom (2003) treated them as the swallowing of three massive planets by an expanding red giant. We suggest a more natural explanation for this phenomenon, as shock waves arriving at the star's surface due to pulsations (Barsukova, et al. 2002). The dip before the brightness rise is a characteristic feature of a shock wave, and it is observed often in pulsating variables. In V838 Mon, this dip is most prominent before the steepest rise to the 2nd highest peak, in the time range between JD 2452303 and 2452307. In the high-amplitude RRab type variables, such a dip precedes the appearance of a steep shock wave front. Christy (1966) (p.165) finds from his RR Lyrae model calculations that 'the dip in luminosity is associated with the time of maximum compression and with the time of velocity reversal in the photosphere and is due to a temporary increase in opacity in

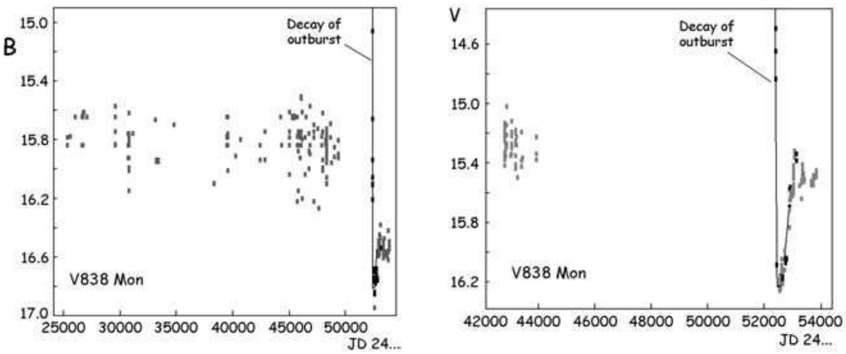



Figure 9. The historical light curves of V838 Mon in the $B$ (left) and $V$ (right) bands.

the sub-photosphere'. The compressed gas in the front of a steep shock wave, mostly hydrogen and helium is not transparent being totally ionised, and therefore such a dramatic flare is seen when the shock wave arrives. The following smaller amplitude peak in the main outburst has also a typical shape of the pulsation wave. Fig. 2, right, shows rebrightening of V838 Mon following the main outburst. This rebrightening is absolutely not seen in the $U$ band, and its amplitude increases with the band wavelength. Spectroscopic observations show that this phenomenon is connected with the formation of 'brown' L supergiant (Evans et al. 2003), the remnant of outburst, which is seen in the spectra along with normal B3V type companion (Munari et al. 2002b). In the autumn of 2002, the contribution of L supergiant into $B$ and $V$ bands is negligibly small as seen in the spectra by Munari et al. (2005). The blackbody temperature of this star is about 1200°K as follows from our multicolor photometry. Subsequent temperature increase and luminosity decrease are the main tendencies, so the details of its spectrum expand into the photometric yellow and blue bands. We suppose that these photometric changes are concerned with chemical evolution. V838 Mon is an oxygen rich star (Lynch et al. 2004), and sudden cooling of its material gives rise to burning of carbon and metals in the oxygen. In the simple sense, it is a very large conflagration in the body of the supergiant star.

The progenitor of V838 Mon was a blue star (Goranskij et al. 2002; Barsukova, et al. 2002). Munari et al. (2002b) noted that V838 Mon has a B3V companion in the post-outburst spectra. In the $B$ band this companion is about $1^m$ fainter than the star seen before outburst. Goranskij et al. (2004) show that the pre-outburst SED of V838 Mon may well be fitted with the same B3V type spectrum in the large wavelength range from $B$ to $K$ band. They assumed that the progenitor might be also a blue star which mimicked B3V companion in the pre-outburst SED of a binary system. Munari et al. (2005) regard the progenitor as a hot star with $M \sim 65 M_{\odot}$, $T = 50000°K$ which was $0\overset{\mathrm{m}}{.}5$ brighter than its B3V companion. Tylenda et al. (2005a) considered the progenitor as a B1.5 main sequence or PMS star with $M \sim 5 - 10 M_{\odot}$.

The accurate magnitudes of this binary system before outburst based on digitized images (50 in $V$ and 20 in $B$ band) are given in Table 1. Digitally reduced

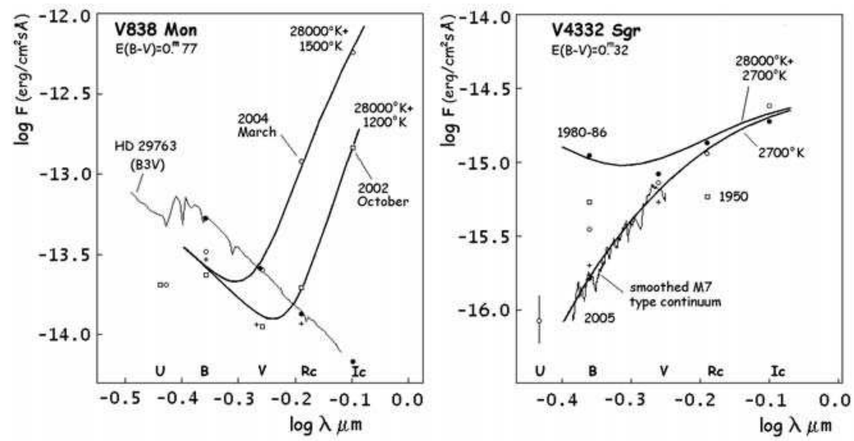



Figure 10. Pre- and post-outburst SEDs of V838 Mon (left) and V4332 Sgr (right). Blackbody models and component temperatures are given.

$B$ magnitudes agree well with the eye estimates made by S.Yu.Sh. The light curves show that this binary was not variable during 66 years of observations since 1928 (Fig. 3). The brightness and color of B3V companion refer to 2002 October, when the contribution of a cool star in the $B$ and $V$ filters was negligible. The progenitor's magnitudes are extracted from the common light. It was brighter than its companion by factor of 1.36±0.03, and it had the same and undistinguishable color, and most probably the same spectrum of B3V as its companion. Now we can say that the downward level jump after the outburst in $B$ and $V$ light curves is due to the disappearance of the exploded star from the summary SED of the binary, and the later rebrightening is due to the appearance of its remnant in these wavebands.

Table 1. Photometry of V838 Mon components

| Star | $V$ | $B$ | $B-V$ |
|---|---|---|---|
| Pre-outburst binary | $15^{\rm m}_{.}27\pm0^{\rm m}_{.}01$ | $15^{\rm m}_{.}87\pm0^{\rm m}_{.}03$ | $0^{\rm m}_{.}60\pm0^{\rm m}_{.}03$ |
| B3V companion | 16.21±0.03 | 16.79±0.03 | 0.58±0.04 |
| Exploded star | 15.86±0.03 | 16.48±0.04 | 0.62±0.05 |

The pre- and post-outburst SEDs of V838 Mon are shown in Fig. 4 (left). Pre-outburst photometry (filled circles) includes now $V$ band point. Pre-outburst SED fitted with a B3V star is shown. Spectroscopy allows us to separate the contribution of the hot star. SED of the hot star on 2004 March is plotted by crosses. Fitting the post-outburst SEDs shows increase of blackbody temperature of L supergiant from 1200 to 1500°K between 2002 October and 2004 March.

### 1.2. V4332 Sgr

On the basis of Digitized Sky Surveys, Tylenda et al. (2005b) assumed that V4332 Sgr was a solar type star before its 1994 outburst. Kimeswenger (2006) estimated its spectrum as G2($\pm$0.4 subclass) using only POSS-I survey. He noted that 'the object started to rise years before the 1994 event', and the star brightened by a factor 10 in $R$ band between the epochs of 1950.53 and 1991.59.

The results of our photometry in $B$ band relative to our new standard are shown in Fig. 5. The star became much brighter in $B$ band by a magnitude in 1980-s relative to 1950. Using 2 best $V$ and 3 $B$ AZT-5 plates we derived $V = 17^{\rm m}.63 \pm 0^{\rm m}.08$, $B = 18^{\rm m}.21 \pm 0^{\rm m}.09$ and $B-V = 0^{\rm m}.58 \pm 0^{\rm m}.11$. Remeasuring POSS-I images with our new standard, we have $B - R_C = 1^{\rm m}.8$ (Kimeswenger (2006, Table 1) gives $B - R = 1^{\rm m}.51$). Our pre-outburst $R_C$ band photometry is $0^{\rm m}.5$ brighter than that by Kimeswenger (2006), but the post-outburst one agrees well. Using ESO $R$ image taken at JD 2446255 and AZT-5 $B$ plate taken at JD 2446588 we have $B - R_C = 2^{\rm m}.0$. $B-V$ and $B - R_C$ indices do not correspond to a normal single star and indicate that this star was a binary before outburst.

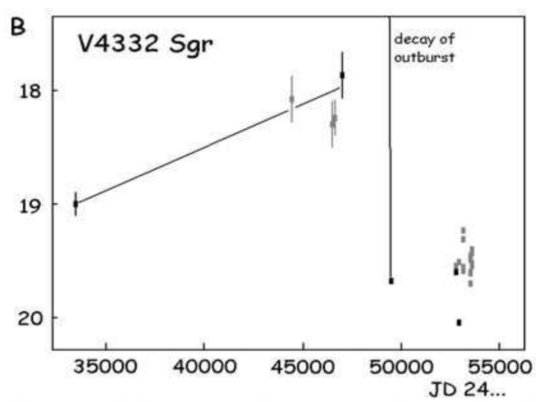



Figure 11. Historical light curve of V4332 Sgr in the $B$ band.

Like in V838 Mon, the brightness of V4332 Sgr in the $B$ band dropped to a level lower than that before the outburst, and even lower than the 1950 level (Fig. 5). Otherwise, the brightness in the $V$ and $R$ bands stayed at the same level as before the outburst, in 1980s.

The uniform CCD observations taken with 1-m telescope of SAO RAS in 2003 – 2006 show the rapid variability ($R_C$ band light curve is presented in Fig. 6). In 2006 June, after the Conference, we find the star weakened by $0^{\rm m}.5$ in $V$ and $R$ relative to 2003 – 2004 level. The nature of this variability is a subject of future study.

SEDs of V4332 Sgr are drawn in Fig. 4 (right) using 1950 and 1980s photometry, and modern photometry and spectroscopy. Archive photometry shows strong excess in $B$ band, the evidence of a blue companion. Pre-outburst SED of 1980s (filled circles) is two-fold and contains a hot B type star and an M7 type companion. Dealing with post-outburst photometry (open circles), we should remember that this star has strong emission line spectrum, and that the stel-

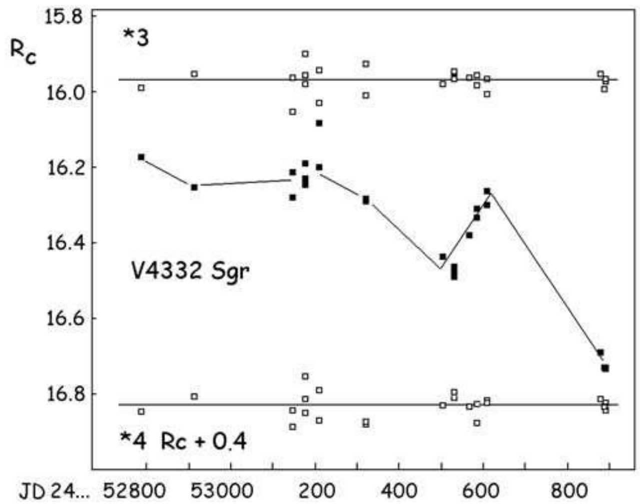



Figure 12. Recent rapid variability V4332 Sgr in the $R_C$ band. Stars 3 and 4 are check stars.

lar continuum is very faint in the blue. Using BTA spectra, we estimate the emission line contribution of 43 per cent in $B$ band. If we subtract emission component from photometry (crosses), or plot pure smoothed continuum (as seen in Fig. 4, right), we see only M7 type star with blackbody temperature of 2700°K and photometric values $V = 18.^{m}1$, $B-V = 2.^{m}0$. This cool star can not be the remnant of the outburst because it is nonvariable in the SED before and after outburst. The hot star disappeared after the 1994 outburst. We did not find anything like a 'brown' L supergiant in V4332 Sgr, it was not present in the infrared 2MASS and DeNIS observations in 1998 and 1999 described by Tylenda et al. (2005b). The remnant may be the rarefied oxygen-rich gaseous cloud, the emission lines of which are well seen in the recent spectra. May be, such a large structure as a brown supergiant could not be formed in V4332 Sgr because this system was not so wide as V838 Mon, and it was tidally destroyed.

In 1950 the hot star was also seen, but fluxes in $B$ and $R$ filters (squares in the Fig. 4, right) were twice as small as in the 1980's. We haven't found an explanation for this phenomenon.

Table 2. Photometric parameters of peculiar red novae progenitors

| Star | Max $B$ | Quiet $B$ | Ampl. $B$ | Ouiet $M_B$ | Distance (Kpc) |
|---|---|---|---|---|---|
| V1006/7 M31 | $17.^{m}5$ | – | – | – | 770 |
| V838 Mon | 7.9 | $16.^{m}5$ | $8.^{m}6$ | $+1.^{m}5$ | 2.4 – 5.2 |
| V4332 Sgr | 10.0 | 19.0 | 9.0 | +1.9 | 15 – 22 |

We conclude that a hot star is responsible for both explosions, V838 Mon and V4332 Sgr. In Table 2, the photometric parameters of these hot companions are compared with those of V1006/7 in M31, distance and maximum absolute magnitudes of which are known (770 Kpc, $M_V = -9\overset{m}{.}1$, $M_B = -7\overset{m}{.}1$, Sharov 1993). The pre-outburst quiet $B$ absolute magnitudes of V838 Mon and V4332 Sgr and their distances are estimated on the basis of the assumption that all objects have the same absolute $V$ and $B$ magnitude in outburst maximum. We estimate the distance of V838 Mon from its light echo to be 3.2 Kpc.

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## Discussion

*Munari*: First we have to congratulate you on your archival plate work. You estimated the distance to V4332 Sgr is larger than 10 kpc and there is a young star in it. At galactic coordinates 13.63/-9.40 your assumed $E(B-V)$=0.32 seems somewhat low, but mainly it worries me that such a young object would lie so above and far away from the galactic disk. Could you comment on the galactic location of V4332 Sgr?

*Goranskij*: Thank you. It is an interesting question which is under investigation now. First, I can say that the Sun is located above the Galactic plane. I have found in APOD (http://antwrp.gsfc.nasa.gov/apod; 2005 June 5) an excellent wide-field color photo of Milky Way, where the gas-and-dust clouds are seen to be displaced mostly to its opposite side at this Galactic longitude, in the direction to Scorpio and Ophiuchus. And the direction to V4332 Sgr is very transparent. Additionally, I have discovered a black-hole binary, V4641 Sgr, which is located in the same direction behind the Galactic centrum at a distance of 9 Kpc. It is closer to the Galactic plane, but has a similar low reddening $E(B-V)=$ 0.32. In visual overview of color photo, I found two blue star clouds seen on the background of red bulge star population. But the nature of them is yet unknown. I plan to carry out a photometric investigation. They are located on the same Galactic latitude a few degrees north of V4332 Sgr. Some people say that the Galactic plane may be distorted by the tidal influence of Magellanic Clouds.

Second, the youth of V4332 Sgr is not so prominent as that of V838 Mon, and it is under question.

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