The first three years of the outburst and light-echo evolution of V838 Mon and the nature of its progenitor

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Abstract. V838 Mon has undergone one of the most mysterious stellar outbursts on record, with (a) a large amplitude ($\Delta B \sim 10$ mag) and multi-maxima photometric pattern, (b) a cool spectral type at maximum becoming cooler and cooler with time during the descent, until it reached the never-seen-before realm of L-type supergiants, never passing through optically thin or nebular stages, (c) the development of a spectacular, monotonically expanding light-echo in the circumstellar material, and (d) the identification of a massive and young B3V companion, unaffected by the outburst. In this talk we review the photometric and spectroscopic evolution during the first three full years of outburst, the light-echo development and infer the nature of the progenitor, which was brighter and hotter in quiescence than the B3V companion and with an inferred ZAMS mass of $\sim 65 M_\odot$.

Keywords V838 Mon, novae, light-echo, massive star evolution, outburst, L-type supergiants

The outburst evolution

V838 Mon made headlines in early January 2002, when it was discovered in outburst by \cite{1}. The unusually cool spectrum (completely unlike that of a classical nova) and the multi-maxima light-curve helped to keep attention focused on the object for the next three months, until the discovery in late March by \cite{2} of a light-echo rapidly developing around V838 Mon. The presence of the first Galactic light echo in $\sim 70$ years fostered a massive, multi-wavelength observing campaign for V838 Mon. A high spatial resolution imaging series of the light-echo expansion and evolution was collected with HST by \cite{3}, which has been expanded by new images secured within the Hubble Heritage Program\textsuperscript{1}. An account of the spectroscopic, photometric and polarimetric evolution of V838 Mon during the first season of visibility was presented by \cite{4,5,6,7,8,9,10,11}. A major observational constraint was the discovery by \cite{12} and \cite{13} that V838 Mon is a binary system containing a normal B3V star, implying that the outbursting component is young and massive. BaII, LiI and $s$-element lines were prominent in the outburst spectra, while Balmer lines emerged with modest emission only during the central phase of the outburst. The outburst never reached optically thin conditions and the spectra never went through a nebular stage.

An updated optical and infrared lightcurve of the eruption of V838 Mon is presented in Figure 1 and the general spectral evolution is highlighted in Figure 2. The outburst lightcurve and spectral evolution can be easily divided into three distinctive phases: the K, M and L supergiant spectrum phases.

\textsuperscript{1}http://heritage.stsci.edu
Figure 1: Optical and infrared lightcurves of V838 Mon from 2002-2004 observations with the USNO 1.0 and 1.55m telescopes.
Figure 2: Spectral evolution of V838 Mon (sample spectra from an extensive monitoring of the whole event performed with the 1.82 m Asiago telescope, to be reported in detail by Munari et al. elsewhere).
During the first 90 days of the outburst, the star went through three maxima and its spectrum moved back and forth within the K supergiant types. The monotonic cooling during this phase (from $B-I_C \sim 3.5$ to $\sim 5.0$, cf. Figure 1) was interrupted by warming at each of three optical brightness maxima. This K-supergiant phase was characterized by a cool wind that gave rise to P-Cyg profiles with terminal velocities of $\sim 500$ km sec$^{-1}$ that progressively diminished to $\sim 250$ km sec$^{-1}$ by day $+90$.

Around day 90, the star entered an M-supergiant phase almost identical to that displayed by the M31-RV stellar eruption observed in 1988 in the Andromeda Galaxy as described by [14] and [15]. [16] investigated in detail the similarities, highlighting how in both events the transition to an M-supergiant spectrum was marked by a free-fall drop in optical brightness not accompanied by dust formation. The outbursting component in a matter of few weeks swept through the whole sequence of M spectral types while the $B$ band brightness of V838 Mon dropped by 6 mag, stopped only by the emergence of the $B=16.73$ mag spectrum of the B3V companion by day $\sim 120$.

By day $\sim 130$, the photosphere of the outbursting component had cooled so much to enter the realm of L supergiant spectral types, a type of star never seen before anywhere in the Galaxy ([12], [17]). Very strong H$_2$O, CO and AlO absorption bands dominate the infrared, while huge VO and TiO shape the optical. Since the time of coolest temperature reached around day 180, the temperature of the L-supergiant has been smoothly and constantly increasing even if by small amounts (cf. $J-K$ and $B-I$ in Figure 2). As a result, the optical spectra that in Oct 2002 were dominated by the B3V companion...
Figure 4: Comparison of the pre-outburst photometry of the two components of V838 Mon with Padova isochrones $Z=0.004$ and three ages scaled to the system distance (10 kpc) and reddening ($E_{B-V}=0.87$). The isochrones include the effect of mass loss and reddening-induced distortion.

The light-echo evolution

The light-echo was first discovered by [2] on U-band images taken in February, 2002, about 10 days after the first large outburst (a hundred-fold increase in brightness with a relatively sharp peak). The initial shell was circularly symmetric, showing obvious structure that later HST images by [3] resolved into concentric rings, each giving a photometric snapshot of the light curve variations. These rings expanded, with the rate of expansion of the outermost ring shown in Figure 3. Note the dramatic break in the expansion rate, with the early expansion proceeding at about 800mas per day, while the later expansion proceeding at about 90mas per day. The early expansion is probably coming from a light sheet in front of the outbursting star, and is very nearly symmetric, with axial ratios at most 10% different. The later

even in the $V$ band, are now again showing the molecular absorptions down to $\sim 4800$ Å.
expansion may be evidence of the light echo proceeding through circumstellar material, and shows more than 20% asymmetry. The light-echo has also faded, now difficult to image even at R-band, and has become more extended in the east-west direction than north-south. An inner void appeared about 70 days after the main outburst, matching the rapid decline from the last photometric peak. The bright cloud to the north has remained in all images. More detailed analysis of the ring expansion and structure evolution is in progress.

The progenitor

The energy distribution of V838 Mon in quiescence has been thoroughly investigated by [18], clearly showing how the progenitor of the outbursting component was brighter and hotter than the B3 V companion. The best fit to the V838 Mon quiescence data is the B3 V plus a 50,000 K star with $V=15.55$ and $B-V=+0.535$, both equally reddened by $E_{B-V}=0.87$. The location of the components of the binary is compared with Padova theoretical isochrones in Figure 4 (scaled to the system $E_{B-V}=0.87$ reddening and 10 kpc distance), for the $[\text{Fe/H}]=-0.7$ metallicity appropriate to the galacto-centric distance of V838 Mon. The Padova theoretical isochrones (that include the effect of mass loss) are corrected for reddening dependent deformation following [19].

The isochrone fitting the position of the two components indicates a system age of 4 million yr and a mass of ~65 $M_\odot$ on the ZAMS for the progenitor of the outbursting component. The outburst experienced in 2002 does not appear to be the terminal event in the life of the massive progenitor, but instead more probably was a thermonuclear shell flash in the outer layers of the star as could be expected in the case of He after most of the H-rich outer envelope has been blown away by the strong wind that characterize the Wolf-Rayet type of stars that occupy this part of the HR diagram.

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