Expansion of the light echo from the outburst of the unique variable star V838 Mon

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Abstract. New measurements of the outer radius of the light echo two years after the peculiar outburst of V838 Mon are presented. Since the outburst maximum (Feb 06 2002) the angular radius ρ of the echo increases with the time t as $\rho \sim t^{0.537}$, which is close to the theoretically expected law $\rho \sim t^{0.5}$. However, the up to now available data cannot allow an evaluation of the location of the scattering matter and, especially, the distance to V838 Mon. The lower limits for the distance of V838 Mon from the Earth and the distance of the interstellar slab from the star can be estimated at about 6 kpc and 2 pc, respectively.

Key words: stars: individual: V838 Mon – stars: distances – ISM:reflection nebulae

Разпространение на светлинното ехо от избухването на уникалната променлива звезда V838 Mon

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Представени са нови измервания на външния радиус на светлинното ехо две години след пекулярното избухване на V838 Mon. След максимума на избухването (06.02.2002 г) ъгловият радиус ρ на ехото се расте с времето t като $\rho \sim t^{0.5}$, което е близко до теоретично очакваното $\rho \sim t^{0.5}$. Обаче, достъпните до сега данни не позволяват да се оцени местоположението на центъра на разпръскващата се материя, и оттам - на разстоянието до V838 Mon. Долните граници на отстоянието на обекта от Земята и на ехото от звездата са съответно 6 kpc и 2 pc.

1 Introduction: The outburst of V838 Mon and its "echo"

The unusual eruption activity of V838 Mon after its discovery in early January 2002 (Brown N. J. [2002]) was a subject of numerous papers and communications during the last two years (e.g., see Munari U. et al. [2002], Banerjee D.P.K. et al. [2002], Goranskij V.P. et al. [2002], Wisniewski J.P. et al. [2003] and the references there). Briefly speaking, this 16-mag star underwent at least 3 outbursts, the second of which, reaching maximum of $V \approx 6.5$ on Feb. 6, 2002, was the biggest and the "sharpest" one. A circular light echo around the central object was observed during a dozen days after this maximum Henden A. et al. [2002]. Considered to be Nova or Nova-like, V838 Mon has demonstrated a peculiar behavior and has converted into an extremely red cool object.

Besides the unusual spectral evolution, the light echoś rapid development is what poses additional puzzles. The astrophysical echo is an extremely rare event — only $2 \div 3$ "Nova" — and $5 \div 6$ "Supernova"–echoes are known. It is rather a tool for studying the circumstellar and interstellar matter, but it can provide a reasonable estimate for the distance in certain cases. The crucial estimate when studying the event V838 Mon is the evaluation of the distance d to the object because the final luminosity of the outburst depends on that. The early estimations, based on different methods (reddening, interstellar lines, polarimetry and wrong interpretation of the echo expansion) placed the star from 0.6–0.8 kpc (Wisniewski J.P. et al. [2003], Henden A.et al. [2002], Kimeswenger S. et al. [2002]) to more than 3 kpc Zwitter T. [2002], while Bond et al. [2003], using the fine HST–ACS pictures (resolution $0.03''$/pxl), evaluated $d \sim 6$ kpc. Finally, Tylenda R. [2004] analyzing the HST–frames obtained until the end of 2002, derived an even greater distance: $8 \div 9$ kpc. The problem of the distance increases dramatically as far as the maximum luminosity can reach in the latter case a huge value, turning V838 Mon into the brightest star in our Galaxy during its outburst!

Here we present new measurements of the outer radius of the light echo during two years after the peculiar outburst of V838 Mon.

2 Observations and measurements

We collected the set of original CCD images in different filters using three telescopes: 2m RCC telescope at the Bulgarian National Astronomical Observatory (NAO) "Rozhen", 2.1m telescope at Observatorio Astronomico Nacional San Pedro Martir, Mexico (SPM) and 10m Hobby-Eberly telescope (McDonald Observatory, USA). We also used the available on the web-sites (http://www.starstuff.org/Articles/1241.asp; http://hubblesite.org/newscenter/archive) pictures of the V838 Mon echo, obtained with HST and different ground-based telescopes and measurements available from the literature (see Table 1). The scale for every frame was established using one and the same set of nearby stars. The full color pictures from HST were used as "reference points" for all others frames.

We have limited ourselves here to investigate only the expansion of the outer edge of the echo. We have measured the angular radius ρ averaging the size of the outer rim in N–S, E–W, NE–SW and SE–NW directions at different epochs t (in days) since the outburst. We accepted the moment of the second flash maximum (Feb 6 2002, JD 2452313) as zero–point. The echo brightness decreases differently in different bands. Beginning to be brightest in U, now the echo is considerably "red". However, in all the cases when we measured the echo size in different bands, the results practically coincided, so we accepted a single mean value for the radius in a given epoch (Table.1).

Table 1. Shapes of some countries

Date	t [days]	Telescope	ρ [arcmin]	ρ [arcsec]	$d\rho/dt$ [marcsec/day]	Image source	Data source
23.03.2002	45	1m USNO	0.225	13.5	-	-	[6]
04.04.2002	57	1m USNO	0.25	15.0	75	-	[2]
30.04.2002	83	2.4m HST	0.36	21.6	-	-	[15]
20.05.2002	102	2.4m HST	0.32	19.2	60	[14]	this work
02.09.2002	206	2.4m HST	0.48	28.8	92	[14]	this work
28.10.2002	263	2.4m HST	0.56	33.6	84	[14]	this work
10.12.2002	307	10m HET	0.60	36.0	55	this work	this work
17.12.2002	314	2.4m HST	0.60	36.0	-	-	[9]
27.01.2003	355	10m HET	0.645	38.8	66	this work	this work
25.02.2003	384	2.0m NAO	0.67	40.2	62	this work	this work
24.03.2003	411	10m HET	0.69	41.4	45	this work	this work
18.10.2003	620	2.1m SPM	0.86	51.6	49	this work	this work
22.11.2003	653	2.2m NAO	0.87	52.2	18	this work	this work
21.12.2003	684	2.0m NAO	0.91	54.6	58	this work	this work
26.01.2004	720	2.0m NAO	0.94	56.4	50	this work	this work
08.02.2004	732	2.4m HST	0.95	57.0	33	[13]	this work
15.03.2004	767	2.0m NAO	0.97	58.2	27	this work	this work

Figure 1 represents some examples of the frames that we have used for measurements. Some asymmetry of the late echo-images exists but nevertheless it is possible to outline a complete oval figure. As a result, the size in SE-NW direction is measured less certainly (see also Tylenda R. [2004]). Despite the tenfold worse resolution of our images in comparison with the published HST pictures, the main structures in the echo are well distinguished on our frames as well. The outer rim is sharp enough to be measured. We have not measured the angular distance of the echo center from the source.

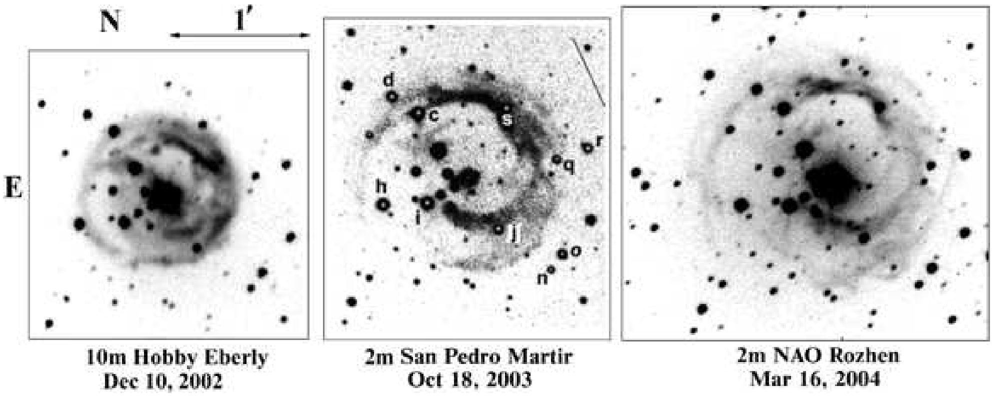

Fig. 1. Examples of the light echo from V838 Mon images obtained in different epochs and with different telescopes. The letters on the second image designate a set of reference stars.

3 Simplest models: perpendicular plane slab and spherical shell

Let the distance to the object be d. In an epoch $t_0 = 0$ an outburst is registered and in epoch $t > 0$ a scattered light around the source — echo — is observed. The theory of the astrophysical echo (Tylenda R. [2004], Couderc P. [1939] gives (for $d \gg x,\ y$) a paraboloid as a shape of the illuminated surface at a given epoch t. Its intersection with an interstellar cloud gives a light echo at the projected for the sky distance ξ from the center. Let us consider two simplest cases of echo in a coordinate system (x,y,z) with z along the line of sight: a) — a thin dust plane slab placed perpendicular to the line of sight at a distance zo from the light source ($z = 0$); and b) — a thin spherical shell with a radius ro centered on $z = 0$. For both cases the shape of the echo will be a concentric ring with a linear radius ξ and an expansion velocity v:

$$\xi = \left[x^2 + y^2\right]^{0.5} = \left[2z_0(ct)^2\right]^{0.5}, \tag{1}$$

and

$$\nu = \frac{d\xi}{dt} = \frac{c[z_0 + ct]}{[2z_0 ct + (ct)^2]^{0.5}} \tag{2}$$

for the dust plane slab, and:

$$\xi = \left[x^2 + y^2\right]^{0.5} = \left[2r_0 ct - (ct)^2\right]^{0.5}, \tag{3}$$

and

$$\nu = \frac{c(r_0 - ct)}{[2r_0ct - (ct)^2]^{0.5}} \tag{4}$$

for the spherical case. Only the spherical case allows to measure directly the distance when ξ reaches the shell–radius ro (in the known moment $t = \frac{r_0}{c}$). In all other cases there are two unknown parameters – zo and d – and the distance can be estimated only roughly. The light echo is usually superluminal, i.e., the apparent speed $\nu = \frac{d\xi}{dt} > c$. The speed at epoch to=0 is infinite and then drops. It is not a speed of matter, of course, but only the light–spot movement. The apparent expansion rate approaches c in late epochs (when $ct \gg z_0$). Then, using the observed rate of the angular expansion $\frac{d\rho}{dt}$ and considering $d \gg z_0$, one can evaluate d.

4 Discussion

The known galactic echo is that from Nova Per 1901A (GK Per). Couderc [1939] have derived for the angular radius a relation $\rho = 0'.863t^{0.5}$. The GK Per echo reached a radius of about 16′ one year after the outburst onset (Feb 22 1901). The circumstellar nebula, caused by the mass-loss of 1200 km/sec, was detected 15 years later with a radius of only 8″.

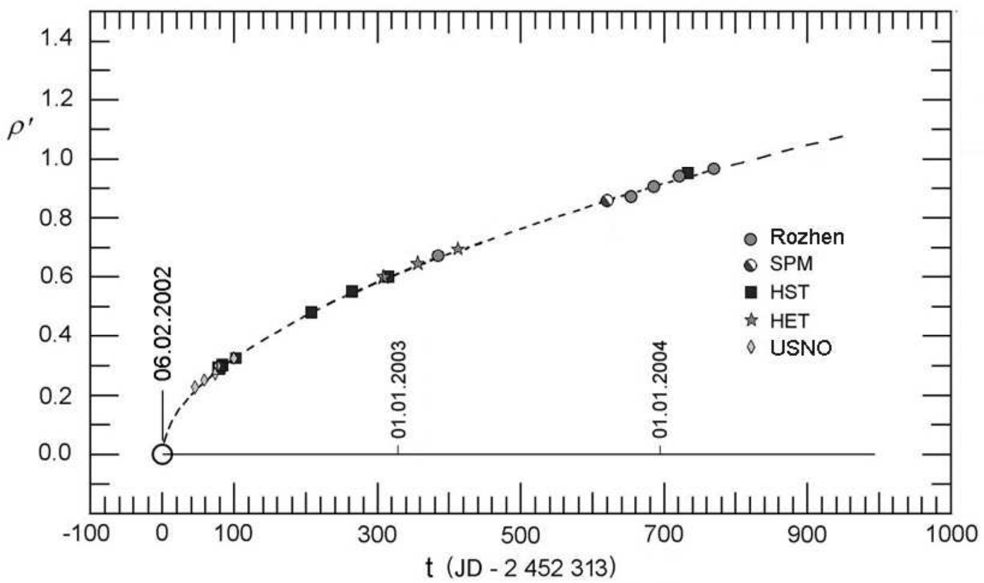

Fig. 2. The echo–radius in the course of time.

Figure 2 represents the apparent angular radius ρ (in angular minutes) of the V838 Mon echo in the course of time (in days from the maximum). The least square power fit gives $\rho = 0.027t^{0.537}$, which is close enough to the "square root–law". Formally, the "exact" relation $\rho = 0.034t^{0.5}$ is obtained for an epoch earlier by several days from Feb 6, 2002. This moment precedes the most energetic outburst.

Comparing the curve for V838 Mon with this for GK Per we can note the following: V838 Mon echo develops much more slowly (radius of only 0.6′ one year after the onset). It can reflect either the great difference in distances to both objects (GK Per is at $d \approx 0.6$ kpc) or the different natures of the echoes (interstellar plane dust sheet at 14 pc before GK Per. The Nova Per echo shows very thin, highly fractured arcs on the photographs while V838 Mon-echo looks more "united" up to now, with relatively wide "rings". The last can be explained by the longer duration of the high luminosity-phase in V838 Mon in comparison with GK Per. Indeed, GK Per faded by 4 mag a month after the onset, while V838 Mon, having at least two–staged outburst with a total of 9 mag amplitude, kept a luminosity of only $\sim 1.5 \div 2$ mag below the maximum for about 3 months. Another possible explanation needs very thick scattering matter along the line of sight.

The expansion rate of the V838 Mon echo (in $\frac{mas}{day}$) for several epochs as well as the curve calculated by the empirical relation $\rho = 0.03t^{0.5}$, are plotted against the radius (in arcsec) in Figure 3. The speed is far from approaching the near constant value and the last observed angular speed $\frac{d\rho}{dt}$ is about $35 \div 40$ $\frac{mas}{day}$.

An estimate for the lower limit of the distance for superluminal motion is:

$$d = \frac{\frac{d\xi}{dt}}{\frac{d\rho}{dt}} > \frac{c}{\frac{d\rho}{dt}} = \frac{173kpc}{\frac{d\rho}{dt}}, \tag{5}$$

where $c = 0.84 \times 10^{-6} \frac{kpc}{day}$ and $\frac{d\rho}{dt}$ is in $\frac{mas}{day}$. For observed rate of about 35–40 $\frac{mas}{day}$ for $t = 770$ days the lower limit for the distance is almost 6 kpc, which determines the distance of the plane slab from the star of almost 2pc. If the observed speed law will be kept, we will obtain lesser and lesser values for $\frac{d\rho}{dt}$ and, consequently, a greater and greater distance limit to V838 Mon, however the most probable distances for V838 Mon and the scattering plane slab are $d \approx 9kpc$ and $z_0 \approx 5pc$, respectively.

The angular radius, according to (1), can be written also as

$$\rho = \frac{\xi}{d} = \left[\left(1 + \frac{2z_0}{ct}\right) \left(\frac{ct}{d}\right)^2 \right]^{0.5} \tag{6}$$

The perfect square-root law is fulfilled for $\frac{2z_0}{ct} \gg 1$, so we can estimate for ρ (in arcminutes) $\rho \approx 3437.75[(\frac{2z_0c}{d})^2 t]^{0.5} = 0.034t^{0.5}$. Taking $c = 0.84 \times 10^{-6} \frac{kpc}{day}$ we derive for z_0 a relation $z_0 \approx 0.58 \times 10^{-4} d^2$ (d in kpc). Such a strong dependence of z_0 from d confirms a rather great distance to V838 Mon: indeed, for $d = 1$ kpc the distance of the plane slab is only 0.06 pc (only 71 lightdays), while a tenfold larger d gives the more reasonable value of 6 pc. At the same time the term $z_0 \gg \frac{ct}{2} = 0.84 \times 10^{-6} t \approx 0.58 \times 10^{-4} d^2$ (t in days, z_0, d in kpc) gives an "absolute" lower limit for the distance to V838 Mon $d > 2.36$ kpc as far as we can apply the square-root law for $t = 770^d$.

On the other hand, according to Tylenda R. [2004], the time-stable bright rim between the stars "i" and "j" in Figure 1 can be explained as compressed rim of a circumstellar spherical shell. Tylenda R. [2004] note the appearance of an illumination of the dust behind the star since the end of October 2002. Thus one could conclude that, if a circumstellar spherical shell exists, we must see the reaching of the maximum of the echo radius r_0. The light path for this time interval (since the end of Jan 2002) is about $250 \div 300$ lightdays $\approx 0.20 \div 0.25$ pc and must be taken as $2r_0$ in formulae (3) – (4). Assuming ro to be connected with the above noted rim at angular distance to the star of $0.4' \div 0.5\prime$, one can obtain for the distance to V838 Mon $d \approx 0.7 \div 1.5$kps – a value much less than the estimate derived by the outer rim expansion rate!

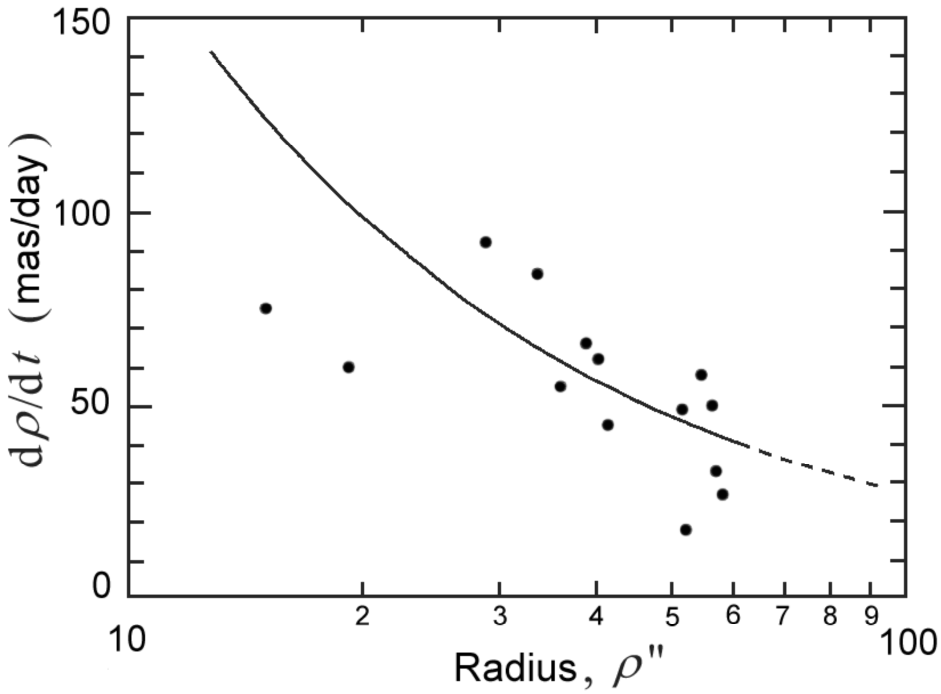

Fig. 3. The echo expansion speed as a function of the radius. The curve represents the function $\frac{d\rho}{dt} = 3 \times 10^4 \frac{\rho}{t}$.

5 Conclusions

Our measurements of the radius of the outer rim of the echo from V838 Mon outburst show that most probably the event arises in an interstellar dust slab placed at several parsec from the star. The distance to V838 Mon must be greater than $\approx$ 2.5kpc and most probably exceeds 6 kpc.

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