A model of an expanding giant that swallowed planets for the eruption of V838 Monocerotis

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ABSTRACT

In early 2002 V838 Monocerotis had an extraordinary outburst whose nature is still unclear. The optical light curve showed at least three peaks and imaging revealed a light echo around the object – evidence for a dust shell which was emitted several thousand years ago and now reflecting light from the eruption. Spectral analysis suggests that the object was relatively cold throughout the event, which was characterized by an expansion to extremely large radii. We show that the three peaks in the light curve have a similar shape and thus it seems likely that a certain phenomenon was three times repeated. Our suggestion that the outburst was caused by the expansion of a red giant, followed by the successive swallowing of three relatively massive planets in close orbits, supplies a simple explanation to all observed peculiarities of this intriguing object.

Key words: stars: evolution – stars: individuals: V838 Mon – planetary systems

1 INTRODUCTION

The outburst of V838 Mon was discovered in 2002 January (Brown 2002). The object was about 6 mag brighter than its presumable quiescent brightness level (Munari et al. 2002a). After a short phase of slow decline it had a second episode of fast brightening by nearly the same factor. V838 Mon gradually faded again in February, but in March a third peak was observed. Figs. 1 & 2 display the visual light curve of the outburst compiled from various sources. To our knowledge such a light curve has never been observed before.

Spectra of V838 Mon taken by several groups (Munari et al. 2002a; Goranskii et al. 2002; Banerjee & Ashok 2002; Wisniewski et al. 2003) suggested a very cool and extended photosphere throughout the eruption. V838 Mon became redder during the outburst and the following decline. The spectrum near the peak of the outburst was fitted with a K5 giant while several months later an M10 giant can be concluded (Munari et al. 2002b; Munari & Desidera 2002). Later infrared observations in 2002 October led to the suggestion that this star is the first L-supergiant (Evans et al. 2003). This evolution in time corresponds to a gradual decrease in the effective temperature from \( \sim 2300 \) K (Munari et al. 2002b; Kimeswenger et al. 2002).

The light echo observed around V838 Mon is an indication of high mass loss, which occurred several thousand years ago (Munari et al. 2002a; Bond et al. 2003). The distance to the object is still uncertain. Initial estimates varied from 0.64 kpc (Kimeswenger et al. 2002) to \( \sim 10 \) kpc (Munari & Desidera 2002). Later and more detailed analysis suggests that the distance is at least 5-8 kpc (Bond et al. 2003; Crause et al. 2003a; Tylenda 2003). Assuming a distance around 8 kpc, the estimated maximum expansion radius of V838 Mon (Soker & Tylenda 2003) is \( \sim 3200 \) R\(_\odot\) (\( \sim 15 \) AU).

Evans et al. (2003) used IRAS and 2MASS data to conclude that the temperature of the progenitor of V838 Mon was \( \sim 7300 \) K. Its luminosity at 8 kpc is then \( \sim 160 \) L\(_\odot\). Combining these two parameters, we find a stellar radius of \( \sim 8 \) R\(_\odot\) for the progenitor of V838 Mon, which would suit a star on the red giant branch (RGB).

The overall observed behaviour of V838 Mon is very different from nova outbursts and hard to be understood by any of the known astronomical events. A bold suggestion that this outburst was caused by the release of gravitational energy during a binary merger event has been put forth (Soker & Tylenda 2003). According to this scenario, the first brightening was caused by the merger of the outer layers of the two stars. Then, after about a month, the cores collided generating more energy and causing the second burst. The third
Figure 1. The optical light curve of V838 Mon in the visual band compiled from various sources. The light curve comprises more than one thousand CCD measurements. The outburst occurred during the first four months of 2002, after which the object settled to V~16.

Figure 2. The structure of the peaks (same as Fig. 1 zoomed into the event of the outburst). In January (JD~2452275-305), February (JD~2452310-335) and March (JD~2452340-370) the light curve showed three peaks with a complicated structure, which can be described as composed of an early bright peak accompanied by a secondary weak bump about 10-20 days later.
peak was ascribed to changes in luminosity as the system settled into equilibrium. The analysis shows that the gravitational energy released by an accreted mass of \( \sim 0.05 \, M_{\odot} \) is sufficient to inflate the envelope of a 1.5 \( M_{\odot} \) main-sequence star to \( \sim 500 \, R_{\odot} \).

A careful inspection of the light curve of V838 Mon (Figs. 1 & 2) shows that the three peaks have a similar structure, namely each maximum is followed by a decline and a very weak secondary peak. In our opinion this characteristic of the light curve is inconsistent with the binary merger model mentioned above. The shape of the light curve prompts us to argue that V838 Mon had three events of similar nature, but probably of different strengths. The obvious candidate for such behaviour is the swallowing of massive planets in close orbits around a parent star.

During the past decade radial velocity studies of nearby stars have been very successful in finding planets. So far more than one hundred candidates for extrasolar planets have been discovered. Massive planets of Jupiter’s mass (\( M_{J} \)) or larger have been seen to be common around many stars at very close orbits (Livio & Soker 2002; Schneider 2003).

The fate of a planet in close orbit to an expanding RGB or asymptotic giant branch (AGB) star has been investigated by several authors (Livio & Soker 1984; Harpaz & Soker 1994; Soker 1996a,b; 1998; Siess & Livio 1999a,b). It is generally accepted that some of the inner planets surrounding a star should be engulfed and swallowed as it expands after leaving the main-sequence. It was shown that the inner planets in the solar system, up to and including Earth are likely to be eventually swallowed by the Sun (Rybicki & Denis 2001). There were also numerous reports of signs that many giant stars have in fact swallowed planets during their evolution (Siess & Livio 1999a,b). It was estimated that at least 3.5-9% of stars should experience enhanced mass loss as a result of planets and brown dwarf companions spiralling into their envelopes (Livio & Soker 2002).

Even before being engulfed, planets can be affected by enhanced solar-like winds and tidal interaction which becomes the dominant effect at a close range. The engulfed planet may be evaporated inside the envelope or overflow its Roche Lobe while spiralling inwards (Harpaz & Soker 1994; Soker 1996b, 1998), but there is a range of masses for which the planet can survive and expel the envelope and a range (around 1-10 \( M_{J} \)) where it can survive up to reaching the stellar core (Livio & Soker 1984; Soker 1998; Siess & Livio 1999a,b). We note that Sandquist et al. (1998) have conducted 3D hydrodynamic simulations of Jupiter-like planets entering the envelope of main-sequence stars. They have found the results to be sensitive to the stellar mass and to the details of planetary interior models. They concluded that in some cases planets less massive than Jupiter can survive through to the base of the convective zone (see also Sandquist et al. 2002).

## 2 OUR MODEL

We would like to propose then that the multi-stage eruption of V838 Mon was the swallowing of three planets in succession. In our scenario, in addition to the gravitational energy generated by the process, there may also be a rapid release of nuclear energy as ‘fresh’ hydrogen is driven into the hydrogen burning shell of a post main-sequence star. The material arrives from the outer convective stellar region as a shock wave is formed by the infalling supersonic body. This will be augmented by material from the incoming planet itself if it is massive enough (probably several \( M_{J} \), around 0.01 \( M_{\odot} \)) to avoid being evaporated away before reaching the nuclear burning region. The replenishment of the dwindling hydrogen abundance in the burning shell can cause a significant increase in the rate of nuclear reactions. This should be even more enhanced if the incoming hydrogen manages to penetrate deeper into the star where temperatures are higher.

A rather similar situation has been investigated and the effects of a large planet or a brown dwarf companion being swallowed by an AGB or RGB star were calculated (Siess & Livio 1999a,b). It was found that the accretion can be accompanied by substantial expansion and subsequent ejection of matter, infrared emission, increase in surface metallicity (especially Lithium abundance) and a spin-up of the star. The case considered was where the planet’s mass is deposited into the interior of the star at a slow rate and this was represented as an internal accretion process. A spherically symmetric stellar evolution code was used and accretion rates of only \( 10^{-5} - 10^{-4} \, M_{\odot} \, \text{yr}^{-1} \) were assumed. Even then, completing the rather complicated evolution and following the increase in luminosity for the higher mass transfer rate used was difficult. The situation we are describing calls for matter to enter the hydrogen burning region at higher rates and the entire process terminating much sooner than in the above mentioned calculations.

The gravitational energy released by an infalling planet of several \( M_{J} \) is very large. If we consider a planet with 5 \( M_{J} \) that spirals-in into a host star with a core mass of 1 \( M_{\odot} \) within a time scale of one month, the rate at which gravitational energy is released is:

\[
L \sim \frac{G(1M_{\odot})(5 \times 0.001M_{\odot})}{1R_{\odot}} / 30 \text{d} \sim 2 \times 10^{6}L_{\odot}
\]

(1)

This is much larger than the luminosity emitted in the first peak, which is \( \sim 3 \times 10^{3}L_{\odot} \) for a distance of 8 kpc (Soker & Tylenda 2003), and even bigger than the luminosity of the entire outburst (\( \sim 6 \times 10^{4}L_{\odot} \)). On the other hand, the enormous expansion of the stellar envelope might require the utilization of most, if not all the released gravitational energy. In this case, we conclude that most of the gravitational energy was probably used to throw away the ejecta and the luminosity rise was due to nuclear energy.

While the scenario we are promoting could occur in any of the post main-sequence stages from the RGB to the AGB phase, it appears to most likely happen at the RGB stage. At this phase, stars with masses up to 2 \( M_{\odot} \) (i.e. most stars) will expand to almost the same radius they will reach later during the AGB phase and the thermal pulses (Siess & Livio 1999a,b; Rybicki & Denis 2001). Thus, any planet that is eventually engulfed by its host star is likely to be accreted at this earlier phase. We note that as stated in Section 1, the estimated radius of V838 Mon prior to the eruption is suitable for the RGB phase.

It should be emphasised that the initial engulfment could be as a result of the very slow expansion of the giant star and then a rapid eruption consequently taking place, or a stellar flare (shell hydrogen burning tends to be unstable)
that is greatly enhanced by the swallowed planet (or brown dwarf). The induced eruption causes additional planets to be engulfed and swallowed. The material that was seen to have been previously ejected from the star (the light echo, Section 1), could well have been a result of an even inner planet that had been accreted at an earlier stage. That event should not have been strong and extensive enough to totally engulf the planets that were swallowed during the present outburst, but may have started their spiralling-in process a long time ago.

The free fall time for a planet with an initial separation, $a$, into a star with a mass $M$ is given by:

$$t_{ff} = \frac{7.5d}{2M\cdot} \left(\frac{a}{0.3AU}\right)^{3/2}$$

Assuming that V838 Mon has a mass in the range of 1-3 $M_\odot$ and that the actual spiralling-in time is within an order of magnitude of this obvious lower limit, the timing of the second and third peaks relative to the actual outburst would constrain all three planets to be within about 0.5 AU from the star just prior to the outburst (which is obtained assuming the actual falling-in time is about 4 times the free-fall time and taking into account that the last peak was about two months after the initial burst). Returning once again to the estimated value of the progenitor’s radius, being within the range expected for a star in the RGB (Section 1), we find that this value is also consistent with what would be expected for a strong tidal interaction with planets in the range described by Eq. 2 (Soker, private communication) and is thus in line with our model.

It is believed that Lithium is destroyed at early stages in stars as it is convected into hot nuclear burning regions. The accretion of planets could cause a significant enhancement of this and other elements on the surface of stars. While several other mechanisms have been offered to explain the Lithium enrichment observed in many evolved giant stars, there are problems with these scenarios. Therefore, the presence of this element in several giant stars was taken as an indication that these objects have swallowed planets in the past (Siess & Livio 1999a,b). In fact, the reported detection of the isotop Li$^6$ in the atmosphere of HD 82943, which hosts two planetary systems, was interpreted as evidence for accretion of planet/s (Israelian et al. 2001; 2003), but see also Reddy et al. (2002). Lithium was actually observed in the spectra of V838 Mon during the outburst (Munari et al. 2002a; Goranskii el. 2002). These observations, together with the evidence for ejected matter, infrared emission excess, the radius of the progenitor and its significant expansion during the outburst (Munari et al. 2002a; Banerjee & Ashok 2002; Kimeswenger et al. 2002; Bond et al. 2003; Crause et al. 2003b; Evans et al. 2003), are consistent with the predictions of the models (Siess & Livio 1999a,b) and thus strongly support the proposed scenario for V838 Mon.

3 OTHER CONSIDERATIONS

The second brightening in the light curve of V838 Mon (Figs. 1 & 2) was extremely fast and strong compared with the third peak (the information on the first maximum is limited as there are no magnitude estimates just before the onset of the outburst). The difference between the two peaks may be attributed to planets of different masses, compositions or even to a solid planet (compared with a gaseous one).

Recent spectra (Munari & Desidera 2002; Wagner & Starrfield 2002), taken after the decline from outburst, revealed a weak blue continuum that may point to the presence of a hot B-type star in addition to the cool outbursting object. We note, however, that since the field of V838 Mon is quite crowded, the possible companion may actually be a background star unrelated with the erupting object. In addition, even if V838 Mon is a member in a binary system, it may have no effect on the scenario suggested above. Indeed planets in close orbits have been observed in binary systems (Dvorak et al. 2003) and investigations have shown that they can be stable for a long period of time despite the presence of a binary companion (Dvorak et al. 2003; David et al. 2003).

The peculiar outburst of V838 Mon may not be unique. A few other stars have shown several observational similarities to V838 Mon, and in particular similar colour evolution, but the observational data of these objects are relatively scarce. The list includes M31RV (Red Variable in M31 in 1988) (Rich et al. 1989; Mould et al. 1990; Bryan & Royer 1992), V4332 Sgr (Luminous Variable in Sgr, 1994) (Martini et al. 1999) and maybe also CK Vul (Nova? Vul 1670) (Shara, Moffat & Webbink 1985; Kato 2003). It was thus suggested that V838 Mon is the prototype of a new class of objects (Munari et al. 2002a,b; Bond et al. 2003), which we propose may all have been expanding giants who were observed in the act of swallowing planets. V838 Mon is presumably an extreme case of this new group, in which three relatively massive planets were consumed during the outburst. According to our ideas, there should be more examples of expanding giants that swallow less and lighter planets thus showing weaker and less spectacular eruptions.

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