

## The Planets-Capture Model of V838 Monocerotis

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**Abstract.** The planets capture model for the eruption of V838 Mon is discussed. We used three methods to estimate the location where the planets were consumed. There is a nice consistency for the results of the three different methods, and we find that the typical stopping / slowing radius for the planets is about  $1R_{\odot}$ . The three peaks in the optical light curve of V838 Mon are either explained by the swallowing of three planets at different radii or by three steps in the slowing down process of a single planet. We discuss the other models offered for the outburst of V838 Mon, and conclude that the binary merger model and the planet/s scenario seem to be the most promising. These two models have several similarities, and the main differences are the stellar evolutionary stage, and the mass of the accreted material. We show that the energy emitted in the V838 Mon event is consistent with the planets scenario. We suggest a few explanations for the trigger for the outburst and for the double structure of the optical peaks in the light curve of V838 Mon.

## 1. Introduction

V838 Mon had an extraordinary multi-stage outburst during the beginning of 2002. Imaging revealed the presence of a spectacular light echo around this object (Bond et al. 2003). The amplitude of the outburst in the optical band was about 9.5 mag. The post-outburst spectroscopic observations of V838 Mon

showed that it was very red throughout the eruption and long after it ended (Munari et al. 2002; Banerjee & Ashok 2002; Kimeswenger et al. 2002; Evans et al. 2003; Kaminsky & Pavlenko 2005; Tylanda 2005). This is inconsistent with an exposed hot white dwarf in novae.

Evans et al. (2003) and Retter & Marom (2003) concluded that the progenitor star of V838 Mon probably had a radius of  $\sim 8R_{\odot}$ , a temperature of  $\sim 7,300$  K and a luminosity of  $\sim 100 - 160L_{\odot}$ . Tylanda, Soker & Szczerba (2005b) presented a detailed analysis of the progenitor. They argued that V838 Mon is likely a young binary system that consists of two  $5 - 10M_{\odot}$  B stars and that the erupting component is a main-sequence or pre-main sequence star. They also estimated for the progenitor a temperature of  $\sim 4,700 - 30,000$  K and a luminosity of  $\sim 550 - 5,000L_{\odot}$ . Tylanda (2005) adopted a mass of  $\sim 8M_{\odot}$  and a radius of  $\sim 5R_{\odot}$  for the progenitor of V838 Mon. There is additional supporting evidence that the erupting star belongs to a binary system with a hot B secondary star (Munari & Desidera 2002; Wagner & Starrfield 2002; Munari et al. 2005).

Spectral fitting suggested that V838 Mon had a significant expansion from a few hundreds to several thousands stellar radii in a couple of months during the outburst (Soker & Tylanda 2003; Retter & Marom 2003; Tylanda 2005; Rushton et al. 2005). Interferometric observations at the end of 2004 with the Palomar Testbed Interferometer confirmed the huge radius of the post-outburst star with an estimate of  $1,570 \pm 400R_{\odot}$  and suggested some asymmetric structure (Lane et al. 2005). There are only very rough estimates on the mass of the ejecta (Rushton et al. 2003; Lynch et al. 2004; Tylanda 2005).

### 1.1. Models for the outburst

Soon after its outburst, V838 Mon was recognized as the prototype of a new class of stars (Munari et al. 2002; Bond et al. 2003), which currently consists of three objects: 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 V838 Mon (Peculiar Red Variable in 2002), plus three candidates – CK Vul, which was identified with an object that had a nova-like event in the year 1670 (Shara & Moffat 1982; Shara, Moffat & Webbink 1985; Kato 2003; Retter & Marom 2003), V1148 Sgr, which had a nova outburst in 1943 and was reported to have a late type spectrum (Mayall 1949; Bond & Siegel 2006), and the peculiar variable in Crux that erupted in 2003 (Della Valle et al. 2003).

So far, seven explanations for the eruption of these objects have been supplied. The first invokes a nova outburst from a compact object, which is embedded inside a common red giant envelope (Mould et al. 1990). In the second model, an atypical nova explosion on the surface of a cold white dwarf was suggested (Iben & Tutukov 1992; Boschi & Munari 2004). Soker & Tylanda (2003) proposed a scenario in which a main sequence star merged with a low-mass star. This model was lately revised by Tylanda & Soker (2006), and summarized by Soker & Tylanda (2006). Van-Loon et al. (2004) argued that the eruption was a thermal pulse of an AGB star. Munari et al. (2005) explained the outburst of V838 Mon by a shell thermonuclear event in the outer envelope of an extremely massive ( $M \sim 65M_{\odot}$ ) B star. Lawlor (2005, 2006) proposed another mechanism

for the eruption of V838 Mon. He invoked the born-again phenomenon to explain the first peak in the light curve and altered the model by adding accretion from a secondary main-sequence star in close orbit to explain the second peak in the optical light curve of V838 Mon.

A promising model for the peculiar eruption of V838 Mon was suggested by Retter & Marom (2003) and was further developed by Retter et al. (2006). This paper summarizes this model for V838 Mon and similar objects.

The peculiar and enigmatic outburst of V838 Mon led to a specific meeting dedicated to this phenomenon that was held in La Palma, Spain on 2006 May, in which the first author of this paper presented the planets-swallowing model of V838 Mon. The most important result that was presented in the conference is probably two new very reliable distance estimates that are consistent with a distance of about 6 kpc to V838 Mon (Sparks 2006; Afsar & Bond 2006). This is somewhat smaller than what was previously believed (e.g., Bond et al. 2003), and thus it has some impact on the energy emitted in the outburst.

## 2. The planets capture model of V838 Mon

Retter & Marom (2003) showed that the three peaks in the optical light curve of V838 Mon have a similar double-shaped structure and interpreted them as the devouring of three Jupiter-like massive planets by an expanding host star that leaves the main sequence. They proposed that it is either a red giant branch (RGB) or an AGB star. The planets-swallowing scenario had been analyzed in detail by Siess & Livio (1999a, b).

Retter & Marom (2003) calculated that the gravitational energy released by a Jupiter-like planet that reaches a distance of one solar radius from the center of a solar-like parent star is sufficient to explain the observed eruption. In addition, they found that the time scales of the outburst of V838 Mon could be explained by this process. Retter & Marom (2003), therefore, argued that the planets-devouring model is generally consistent with the observed properties of this object, including its possible binary nature mentioned above. This is since planets have been observed in binary systems (e.g., Marcy et al. 2005; Mugrauer et al. 2005; Schneider 2006).

It was found that the progenitor of V838 Mon is very likely a B star (Section 1). The planets-swallowing scenario is consistent with a B-type progenitor as well. The initial slow expansion of the parent star may occur as a result of the natural stellar evolution after leaving the main sequence.

### 2.1. Where are the planets consumed?

Within the planets-devouring model for V838 Mon, Retter et al. (2006) estimated the distance from the center of the host star where the swallowing process takes place. They used three different methods in their calculations: (1) checking the energy budget by comparing the observed luminosity with the gravitational energy of a Jupiter-like planet that falls towards the center of its host star. (2) by assuming that a stellar envelope mass of the order of the planetary mass is required to stop it or slow it down significantly. The resulting timescale was compared with the rise times of the peaks in the optical light curve. This method led to the conclusion that the critical stellar density, where most of the planetary

energy is released, is of the order of  $\sim 10^{-3} \text{ gr cm}^{-3}$ . From density profiles of B stars, the consumption radius was then calculated. (3) using the Roche Lobe geometry. The planet will overflow its Roche Lobe only very close to the center of its parent star.

The results from the three methods were consistent with each other and suggested that the typical stopping / slowing radius is about  $1R_{\odot}$ . A careful inspection of the stellar profiles presented in fig. 2 in Retter et al. (2006) yielded another insight to this process. The observed expansion of V838 Mon changed the density profile, and therefore, the critical density shifted deeper into the star and closer to its core. Thus, the first planet was stopped far away from the stellar core, while the two other planets had to go deeper. This can explain the observed fact that the first peak in the optical light curve is the weakest among the three peaks.

Retter et al. (2006) also suggested an alternative version to the three-planets model. They proposed to explain each peak in the optical light curve of V838 Mon by a single step in the falling process of a single planet. This idea can explain the similar duration of the three events.

### 3. The signature of planets in stellar envelopes

Retter et al. (2006) asked the question what would happen to planets that have recently entered the envelope of their host stars and started their fall towards its core. They concluded that the planets may show quasi-periodic oscillations at the start of this process. When they penetrate deeper into the stellar envelope, the amplitude of the variations becomes larger, but they are smeared over a longer interval of time, and deep inside the parent star the opacity is too large for the oscillations to be seen from outside the star. Thus, the falling planets can only be detected at the start of the process and at the end when they presumably cause an eruption event. This process can explain the observed slow rise in brightness in V4332 Sgr before outburst (Kimeswenger 2006). In addition, Retter (2005, 2006) proposed to explain the long secondary periods, which are observed in red giant stars, and whose origin is still unclear (Wood, Olivier & Kawaler 2004), by planets.

### 4. The trigger for the outburst

The values that Retter et al. (2006) derived for the location of the accretion process compare very well with the numbers estimated from the Virial temperature by Siess & Livio (1999a). At such a close proximity to the stellar core, the temperature of the stellar envelope exceeds  $10^6 \text{ K}$ . Therefore, the eruption may be triggered by extra energy received from the nuclear burning of deuterium brought by the falling planets. Another option is that the outburst occurred once the planet reached the critical stellar density, which is required to significantly slow it down. Hitting denser material causes higher energy release and increasing radial acceleration component. At a density of  $\rho \sim 10^{-3} \text{ gr cm}^{-3}$  and a distance of a few solar radii from the stellar core, the opacity,  $\kappa$ , becomes larger than one. Therefore, the trigger for the event could be when the luminosity released by the planet is larger than the local Eddington limit. Alternatively, the

outburst could be triggered by a sudden inward fall of the first planet, maybe because of some kind of tidal instability, perhaps due to the proximity of the three planets to the parent star and / or to each other, or maybe because of eccentric orbits or due to some gravitational influence by the secondary star. The consumption of the inner planet and the subsequent expansion of the host star led to the engulfment and the swallowing of the two other planets. This idea may supply a simple solution to the question ‘how three planets in close orbits around their host star can be stable for a long interval of time?’, by speculating that they were actually unstable. A different idea was presented in Section 2.1.

## 5. The double structure of the peaks

Retter & Marom (2003) showed that the three peaks in the optical light curve of V838 Mon have a similar double-shaped structure (see their fig. 1), and each of the three peaks is accompanied by a shallower peak a few days later. If the trigger for the outburst in V838 Mon is when the planet reached the critical stellar density (previous section), we may suggest that the three peaks are explained by super-Eddington events, when photons are radiated away, while the secondary flares can be understood by the material that is ejected away at lower velocities and is seen once the opacity is lower than a certain limit. This seems like a simple explanation for the time lags between the primary and secondary peaks. According to this idea, the observed fact that the intervals between the primary and secondary peaks get longer reflects the stellar expansion.

## 6. The rate of planet-swallowing events

Retter et al. (2006) estimated the rate of V838 Mon-like outbursts within the planets-capture model for this phenomenon. They assumed that this is a natural step in the stellar evolution and that no unique trigger mechanism is required for this process. They first started with solar-like stars. The number of stars in the Milky Way is about  $10^{11}$ . The age of a  $1M_{\odot}$  expanding RGB or an AGB star (there is a small difference of  $\sim 10^8$  years between the two phases) is about  $1.2 \times 10^{10}$  years (Sackmann, Boothroyd & Kraemer 1993). Thus they obtained a number to age ratio of about 8 per year for these stars. The number of B type stars with masses of  $\sim 5-10M_{\odot}$  (see Section 1) in our galaxy can be estimated as about 1% of the whole population from the initial mass function (e.g. Lucatello et al. 2005). Their evolution is, however, much faster than solar-like stars, and their age on the main sequence is estimated as about  $2 - 9 \times 10^7$  years (Siess 2006). Therefore, about 10 – 50 massive stars in the Milky Way leave the main sequence every year.

The estimate of the frequency of V838-like outbursts in our galaxy should take into account the ratio of stars with Jupiter-like planets in close orbits. Marcy et al. (2005) concluded that about 12% of FGK stars have Jupiter-like planets. Assuming that about 5% of all stars host planets at the relevant range of masses and separations and devour them, we thus expect about 0.4 such events per year in our galaxy for solar-like stars and  $\sim 0.5 - 2.5$  outbursts in massive stars.

Many V838 Mon-like eruptions are probably missed. This effect can be accounted for by a comparison with nova outbursts because the observational bias for these two types of events is similar. About 5 – 10 novae are detected in our galaxy each year while estimates for the actual occurrence number of these eruptions range between 11 and 260 (Shafter 1997). Adopting a reasonable value of 50 galactic novae per year, we estimate that a single V838 Mon-like event should be detected every  $\sim 2 - 10$  years in all stars. These values are in agreement with the current three members and one candidate in this group that erupted in the past 20 years (Section 1.1). Note that the wealth of poorly studied novae may hide more V838 Mon-like systems. The number of galactic novae that are discovered every year is rising fast thanks to many new variability surveys. Therefore, we should expect an increase in the frequency of the detection of V838 Mon-like events as well.

## 7. A Comparison between the different models

So far seven models have been suggested for the new phenomenon, which is defined by V838 Mon (Section 1.1). The binary merger and the planet/s-swallowing models seem to have two main advantages over the other models. The first is that they can explain an outburst in three stages as the optical light curve indicates. In addition, both can invoke different types of stars, which is consistent with the observations that suggest that a B star responsible for the eruption of V838 Mon, while the progenitors of M31RV and V4332 Sgr seem to be red giants (Tylenda et al. 2005a; Bond & Siegel 2006). More arguments against the other models can be found in Tylenda & Soker (2006) and Retter et al. (2006).

Tylenda & Soker (2006) and Soker & Tylenda (2006) argued that only a merger model fits all observed features of the V838 Mon-like stars. In their scenario, a low mass ( $M \sim 0.1 - 0.3M_{\odot}$ ) star merged with the massive B star, and a third unseen star was probably ejected away from the system. This would mean that V838 Mon is a rare quadrupole system, because of the massive B companion (Section 1).

Tylenda & Soker (2006) and Soker & Tylenda (2006) claimed that the energy released by a planet that falls onto a massive star is not sufficient to explain the observed eruption. However, as noted by Retter et al. (2006) the difference in mass between a low mass stellar companion and 1–3 massive Jupiter-like planets is only a factor of 3–10. In their calculations, Tylenda & Soker (2006) assumed that the falling planet reaches a final distance of about  $5R_{\odot}$  from the center of its  $\sim 8M_{\odot}$  host star. However, Retter et al. (2006) estimated that the consumption occurs much deeper, at a radius of  $\sim 1R_{\odot}$ . Thus, the energy released by the planet could easily be about five times larger than the estimates of Tylenda & Soker and even higher if the planet gets closer to the core of its host star, if it accretes some matter during the fall, or if the stellar mass is larger than  $8M_{\odot}$ . Therefore, it seems that the energy release by the swallowed planets can account for the observed outburst of V838 Mon. In addition, the new distance estimate of 6 kpc instead of the previous 8 kpc (Sparks 2006; Afsar & Bond 2006) decreases the observed energy by a factor of about 2. We also note that 90 percent of the energy emitted in the outburst of V838 Mon, estimated by Tylenda &

Soker (2006), comes from their estimate for the ejecta mass of  $\sim 0.2M_{\odot}$ . This is a very unreliable estimate, that could easily be 20 times smaller. It is enough to point out that most estimates for the ejecta mass assumes spherical symmetry, while the observations suggest a clear asymmetry (Lane et al. 2005; Wisniewski 2006). We note that asymmetric ejection of material is likely to occur both in the binary merger and planets-capture models, where a clear preference in the orbital plane should take place. Finally, we may speculate that since the B star in V838 Mon is very massive, it may have unusually massive planets.

An interesting point is that for V4332 Sgr, Tyllenda et al. (2005a) and Tyllenda & Soker (2006) calculated that its outburst can be explained by a merger of a solar-like star and a planet. What is a merger of a solar-like star and a planet, if not our scenario?

In summary, we think that only two models among the many offered so far for the V838 Mon phenomenon are consistent with the observations. These are the binary merger scenario and the planet(s)-swallowing model. These ideas are very similar because both invoke the accretion of a secondary mass as an explanation for the eruption. Two significant differences between the models are the energetics involved and the evolutionary status of the donor. The issue of energetics may be answered in the future with better modelling and / or observations.

## 8. How to distinguish between the models

As note above the binary merger and the planet(s)-capture models have many similarities. How can we distinguish between the two models? It is clear that good estimates for the ejecta mass are required. Large values would add support to the binary merger model, while low values will indicate that the planet(s) scenario is preferred. Other ways of obtaining this task are to examine carefully the other members in the V838 Mon group, and to find new similar stars. According to the binary merger model, the V838 Mon phenomenon should happen among all kinds of stars. The planet(s)-swallowing scenario is preferred in old stars, that have left the main-sequence – red giants and asymptotic giant branch stars. Note that V838 Mon could be a relatively old B star, especially if the dust, which is responsible to the illumination of the light echo, originated in previous mass loss episodes in its past. As a massive star, V838 Mon should have evolved very rapidly.

As a final side note, we comment that the planet capture model is consistent with a few of the other models offered for V838 Mon. It is possible that V838 Mon swallowed its planets during the large expansion in the thermal pulses phase of an asymptotic giant branch star. According to the calculations of Lawlor (2005, 2006) accretion of a mass of the order of Jupiter-like planet is enough to cause the observed eruption. Lawlor (2005, 2006) proposed that the accretion comes from a secondary star, but a planet seems like a nice alternative.

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## Discussion

*A. Evans:* One of your predictions was “infrared emission.” Can you be more specific?

*A. Retter:* This is a prediction by Siess & Livio (1999a,b). Check these papers for further details. The idea is basically that infrared emission will be a result of mass loss.

*R. Hirschi:* What speeds up the evolution to the red giant stage in the planets-capture scenario?

*A. Retter:* The release of gravitational energy by the falling planet that causes an expansion to large radii.

*V.P. Goraskij:* We observed planets captured during the main outburst when the star was bright, but later, the expansion of the star continued, and it became faint. In such a condition, the engulfing and swallowing of other planets should occur. Why didn’t we observe such events in the L-supergiant stage?

*A. Retter:* Do you want more than three massive Jupiter-like planets? It is clear that the falling process of distant planets will take longer.

*S. Kimeswenger:* As long as the planet is on the main sequence, the planet will get a lot of irradiation – why is it not evaporated at that time already?

*A. Retter:* We think that this will happen for planets with Earth-like masses, and that massive Jupiter-like planets should survive this radiation.