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The planets capture model of V838 Monocerotis: conclusions for the penetration depth of the planet(s)

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ABSTRACT

V838 Mon is the prototype of a new class of objects. Understanding the nature of its multistage outburst and similar systems is challenging. So far, several scenarios have been invoked to explain this group of stars. In this work, the planets-swallowing model for V838 Mon is further investigated, taking into account the findings that the progenitor is most likely a massive B-type star. We find that the super-Eddington luminosity during the eruption can explain the fast rising times of the three peaks in the optical light curve. We used two different methods to estimate the location where the planets were consumed. There is a nice agreement between the values obtained from the luminosities of the peaks and from their rising time-scale. We estimate that the planets were stopped at a typical distance of one solar radius from the centre of the host giant star. The planets-devouring model seems to give a satisfying explanation to the differences in the luminosities and rising times of the three peaks in the optical light curve of V838 Mon. The peaks may be explained by the consumption of three planets or alternatively by three steps in the terminal falling process of a single planet. We argue that only the binary merger and the planets-swallowing models are consistent with the observations of the new type of stars defined by V838 Mon.

Key words: accretion, accretion discs – stars: AGB and post-AGB – stars: individual: V838 Mon – planetary systems.

1 INTRODUCTION

V838 Mon had an extraordinary multistage outburst during the beginning of 2002. Fig. 1 taken from Retter & Marom (2003) displays its optical light curve zoomed on the three months of the eruption. 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 – at the low range of nova outbursts. Novae are thermonuclear-runaway events in which a white dwarf ejects its outer shell, which was accreted from its main-sequence secondary star over several thousand years. The post-outburst spectroscopic observations of V838 Mon showed, however, that it was very red throughout the eruption and long after it ended (Banerjee & Ashok 2002; Kimeswenger et al. 2002; Munari et al. 2002; Evans et al. 2003; Kaminsky & Pavlenko 2005; Tylenda 2005). This is inconsistent with an exposed hot white dwarf in novae.

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Initial estimates of the distance to V838 Mon were below 1 kpc. In recent papers, there is, however, a general consensus that it is in the range 6–10 kpc (Bond et al. 2003; Lynch et al. 2004; Tylenda 2004; Van Loon et al. 2004; Crause et al. 2005; Deguchi, Matsunaga & Fukushi 2005; Munari et al. 2005). Evans et al. (2003) and Retter & Marom (2003) concluded that the progenitor star of V838 Mon probably had a radius of $\sim 8\ R_{\odot}$, a temperature of ∼7300 K and a luminosity of $\sim$100–160 $L_{\odot}$. Tylenda, Soker & Szszerba (2005b) presented a detailed analysis of the progenitor. They argued that V838 Mon is likely a young binary system that consists of two 5–10 $M_{\odot}$ 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 ∼4700–30 000 K and a luminosity of $\sim$550–5000 $L_{\odot}$. Tylenda (2005) adopted a mass of $\sim 8\ M_{\odot}$ and a radius of $\sim 5\ R_{\odot}$ 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

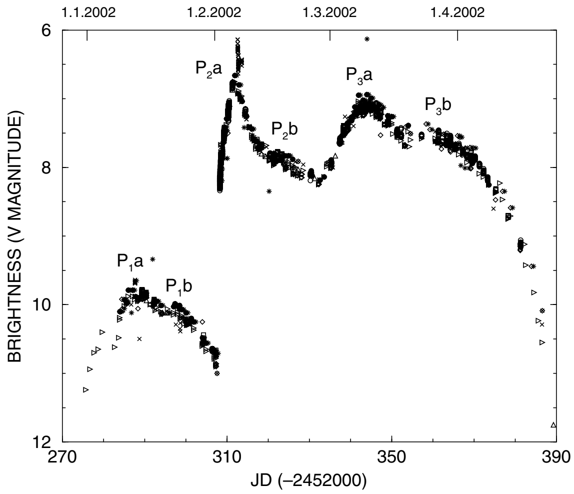

Figure 1. The visual light curve of V838 Mon during the first three months after discovery, taken from Retter & Marom (2003). The object showed three peaks separated by about a month. Retter & Marom (2003) argued that the three local maxima (P_i a, $i = 1, 2, 3$) are accompanied by secondary shallower spikes (P_i b, $i = 1, 2, 3$), supporting the idea that the star experienced three similar events, which presumably are the swallowing of three planets. An alternative possibility, which we propose in this work, is that the three peaks represent three steps in the falling process of a single planet at different radii.

couple of months during the outburst (Retter & Marom 2003; Soker & Tylenda 2003; Tylenda 2005; Rushton et al. 2005b). 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 $1570 \pm 400\,R_{\odot}$ (Lane et al. 2005).

Rushton et al. (2003) set an upper limit of $0.01\,M_{\odot}$ for the ejecta from the absence of molecular emission from V838 Mon. Using infrared observations and assuming a model of a spherically symmetric shell, Lynch et al. (2004) estimated, however, that the mass ejected in the outburst of V838 Mon is about $0.04\,M_{\odot}$. Tylenda (2005) concluded that the total mass lost by V838 Mon is $\sim$0.001–$0.6\,M_{\odot}$, and Tylenda & Soker (2006) adopted a range of $0.01 - 0.1\,M_{\odot}$. The high infrared excess indicates multiple episodes of ejection of large amounts of material during the outburst of V838 Mon (e.g. Crause et al. 2003). It seems that the mass of the matter ejected during the eruption event is well above the typical values in nova outbursts, which are about 10^{-5} to $10^{-4}\,M_{\odot}$ (e.g. Warner 1995).

The estimates of the expansion velocities of the ejecta of about 50–500 km s^{-1} (Crause et al. 2003; Osiwala et al. 2003; Kipper et al. 2004; Rushton et al. 2005a) are at the low range of nova outbursts. Rushton et al. (2005a) inferred from infrared observations that some material began falling back into the star in 2003 December, and Tylenda (2005) described the decline of V838 Mon by a collapsing envelope of $\sim 0.2\,M_{\odot}$. Banerjee et al. (2005) found water lines in near-infrared spectra of V838 Mon, and related them with a region around the star, with a temperature of $\sim$750–900 K, which appears to be cooling in time. SiO maser emission from V838 Mon was detected by Rushton et al. (2005a), Deguchi et al. (2005) and Claussen et al. (2005).

Van Loon et al. (2004) announced a weak detection of multiple shells around V838 Mon using archival *IRAS* and *MSX* infrared data. They thus proposed that it is a low-mass asymptotic giant branch (AGB) star that had several thermal pulses in the past. They argued that this result is, however, inconsistent with the presence of a young B companion star. Tylenda (2004) investigated the structure of the dust distribution in the vicinity of V838 Mon. Near the central object, he detected a strongly asymmetric dust-free region, which he interpreted as produced by a fast wind from the central system. Tylenda (2004) proposed that the asymmetry implies that V838 Mon is moving relative to the dusty medium, and concluded that the dust illuminated by the light echo is of interstellar origin rather than produced by mass loss from V838 Mon in the past. Crause et al. (2005) stated that the dust is likely in the form of a thin sheet distant from the star, and thus supported the idea that this material is interstellar. Tylenda, Soker & Szszerba (2005b) criticized and questioned Van-Loon et al.'s (2004) results and further argued that V838 Mon is made of a binary system with two hot stars, and that the progenitor cannot be a red star.

To summarize, V838 Mon had a spectacular outburst, which has attracted many researchers (both observers and theoreticians), but several features of this unique object are still controversial and somewhat confusing.

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 & Tylenda (2003) proposed a scenario in which a main-sequence star merged with a low-mass star. This model was lately revised by Tylenda & Soker (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 ($M \sim 65\,M_{\odot}$) B star. Recently, Lawlor (2005) 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). They showed that the three peaks in its optical light curve have a similar double-shaped structure (see Fig. 1) 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 analysed in detail by Siess & Livio (1999a,b); however, their simulations indicate relatively long time-scales for the process.

Retter & Marom (2003) calculated that the gravitational energy released by a Jupiter-like planet that reaches a distance of one solar radius from the centre 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). As discussed above, it was found that the progenitor of V838 Mon is very likely a young B star. 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.

In the following, we adopt the planets-swallowing model for V838 Mon and further explore this scenario and its implications. The progenitor of V838 Mon is very likely a massive B-type star. It should be kept in mind, however, that other types of giant stars, namely RGB and AGB stars, are very likely applicable to the other members in this group.

2 WHERE ARE THE PLANETS STOPPED?

Within the planets-devouring model for V838 Mon, we can estimate the distance from the centre of the host star where the swallowing process takes place. The planet is assumed to be engulfed by the stellar envelope. The consumption is defined as the point in space and time where and when the impacting planet has come to rest relative to the stellar envelope, i.e. when it has transferred all (or most of) its kinetic energy to the parent star.

The motion of a secondary star that orbits inside the envelope of a primary giant star was discussed in detail by Livio & Soker (1984), Soker (1998) and Siess & Livio (1999a,b). It is generally accepted that there is a limit for the secondary mass of $\sim$1–10 $M_{\rm J}$, where $M_{\rm J}$ is the Jovian mass, above which the planet can survive and reach the stellar core before evaporation. The physics of the spiraling process are extremely complex and are outside the scope of this paper. Therefore, in this work we simply assume that the planet manages to arrive to the stellar core and that it does not dissolve earlier. The planetary mass is assumed to be constant, and we ignore a few possible effects in the inward-falling process such as evaporation, mass loss, mass accretion, stellar expansion, influence of the propagating shocks and energy deposition by the planet.

Let $M_{\rm p}$ denote the mass of a planet that starts from a large radius (say from the stellar edge) and reaches a distance $r_{\rm o}$ from the centre of a parent star in a time-scale t. $M_{\rm in}$ represents the stellar mass enclosed within this radius. The luminosity emitted by the planet is then approximately

$$L = \alpha \frac{G M_{\rm in} M_{\rm p}}{r_{\rm o}} \Big/ t, \quad (1)$$

where G is the gravitational constant and $0 \leqslant \alpha \leqslant 1$ is the energy efficiency. In this equation, we neglected the kinetic energy of the ejected matter and the gravitational energy of the expanded shell or took them into account in the α parameter. We note that the estimates of these values (Section 1) are highly uncertain. The stopping radius can be expressed by

$$r_{\rm o} \sim 1 \left(\frac{\alpha}{0.25}\right) \left(\frac{M_{\rm in}}{{\rm M}_\odot}\right) \left(\frac{M_{\rm p}}{M_{\rm J}}\right) \left(\frac{L}{10^5\,{\rm L}_\odot}\right)^{-1} \left(\frac{t}{30\,{\rm d}}\right)^{-1} {\rm R}_\odot \quad (2)$$

where ${\rm M}_\odot$, ${\rm L}_\odot$ and ${\rm R}_\odot$ are the solar mass, luminosity and radius, respectively.

It is assumed that the energy released during the eruption event dominates the process. Using a distance of 8 kpc (Section 1), for the first peak in the outburst of V838 Mon $L \sim 3$–$9 \times 10^4\,{\rm L}_\odot$ (Retter & Marom 2003; Rushton et al. 2005b; Tylenda 2005), and $t \sim 30$ d (Fig. 1). Assuming $\alpha = 0.25$, for a host star with a mass of $\sim$8 ${\rm M}_\odot$ (Section 1), we obtain a stopping radius of about 8–26$m_{\rm p}$ ${\rm R}_\odot$ where $m_{\rm p} = M_{\rm p}/M_{\rm J}$. For the second peak, $L \sim 6$–$13 \times 10^5\,{\rm L}_\odot$ and $t \sim 25$ d, so $r_{\rm o} \sim 0.7$–$1.6\,m_{\rm p}\,{\rm R}_\odot$. For the third peak, $L \sim 3$–$11 \times 10^5\,{\rm L}_\odot$ and $t \sim 40$ d and we find $r_{\rm o} \sim 0.5$–$2\,m_{\rm p}\,{\rm R}_\odot$. The gravitational energy of the inner planet at its initial radius, which is presumably about 5 ${\rm R}_\odot$ (Section 1), cannot be neglected. Taking this effect into account, we find a final radius of 4–4.5 ${\rm R}_\odot$ for the first peak for $m_{\rm p} = 1$. Note that for simplicity we used $M_{\rm in} = 8\,{\rm M}_\odot$, but since $M_{\rm in}$ is lower than the stellar mass, the correct numbers are somewhat smaller. We conclude that the planets are probably stopped at a typical distance of about one stellar radius from the centre of the host star.

3 THE SLOWING TIME-SCALE

The luminosities reached in the three peaks in the optical light curve of V838 Mon were $L \sim 0.3$–0.9, 6–13 and 3–11 $\times 10^5\,{\rm L}_\odot$ (Section 2). Thus, the last two peaks were certainly brighter than the Eddington luminosity, which is $(4\pi c G M)/\kappa \sim 1 \times 10^5\,{\rm L}_\odot$ for an 8 ${\rm M}_\odot$ star (Section 1), where c is the speed of light and κ, the opacity, is taken to be of the order of unity. The first faintest peak may also be super-Eddington, taking into account all uncertainties. We conclude that at least the two brightest peaks in the outburst of V838 Mon were super-Eddington, which is consistent with the findings of Tylenda (2005). Therefore, the radiative pressure was larger than the gravitational force and the material was thrown away at a high speed, which is governed by the unbalance between the radiative and gravity forces. This implies that the photons reach the outer envelope of the giant star very fast, and the long-term diffusion Kelvin–Helmholtz time-scale is irrelevant for the outburst process. Thus, the slowing time-scale of the planets, which is the time it takes them to lose most of their orbital energy, should power the light curve.

Consider a planet with mass $M_{\rm p}$ and radius $R_{\rm p}$ moving at an orbital radius r_o inside a stellar envelope with a local stellar density of $\rho_{\rm o}$. The relative velocity between the planet and the envelope is of the order of the Keplerian velocity. Thus, for a circular orbit, the planet velocity is given by

$$v_p \sim \left(\frac{G M_{\rm in}}{r_{\rm o}}\right)^{1/2} \sim 400 \left(\frac{M_{\rm in}}{{\rm M}_\odot}\right)^{1/2} \left(\frac{r_{\rm o}}{{\rm R}_\odot}\right)^{-1/2} {\rm km\,s^{-1}}. \quad (3)$$

The corresponding orbital period is

$$t_p = \frac{2\pi r_{\rm o}}{v_p} \sim 0.1 \left(\frac{M_{\rm in}}{{\rm M}_\odot}\right)^{-1/2} \left(\frac{r_{\rm o}}{{\rm R}_\odot}\right)^{3/2} {\rm d}. \quad (4)$$

In Fig. 2, we plot several profiles of B-type stars on the main sequence when $r < 30\,{\rm R}_\odot$, and later when they become red giants i.e. when $r > 100\,{\rm R}_\odot$ (top panels), and of RGB (middle panels) and AGB stars (bottom panels) at different locations along their giant branch as characterized by their radii. These models were calculated by the code of Siess, Livio & Lattanzio (2002). We find that for most cases, the planet velocity is larger than the sound speed at the relevant part of the stellar envelope. In regions where the planet moves supersonically, it will drive a shock, which propagates into the envelope and eventually slows down the planet. The planet will be significantly slowed down and spiral into an inner orbit or stopped when it encounters an envelope mass of the order of its own mass.

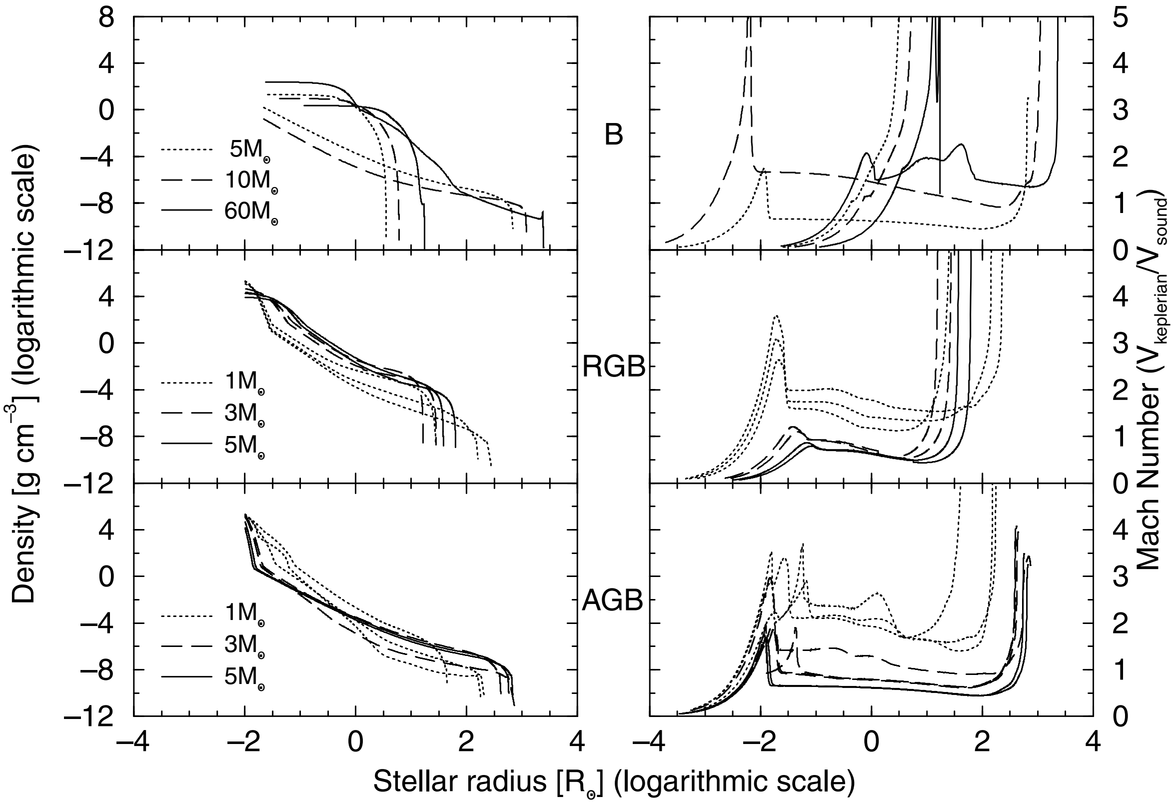

Figure 2. Left-hand graphs: sample density profiles of B, RGB and AGB stars (top, middle and bottom panels, respectively) during different stages in their stellar evolution using the code of Siess et al. (2002). For B stars, plots for 5, 10 and 60 $M_\odot$ are marked with dotted, long-dashed and solid lines. For RGB and AGB stars, data for masses of 1, 3 and 5 $M_\odot$ are, respectively, shown with dotted, long-dashed and solid lines. The right-hand panels display the Mach number as a function of radius for the same models. The density required to stop Jupiter-like planets ($\rho \sim 10^{-3}$ g cm^{-3}) is obtained at a typical distance of $r \sim 1\,R_\odot$ from the centre of the host star.

Therefore, the slowing range is approximately given by

$$l = \frac{M_{\rm p}}{\left(\pi R_{\rm p}^2\right)\rho_{\rm o}} = \frac{4}{3} R_{\rm p}\left(\frac{\rho_{\rm p}}{\rho_{\rm o}}\right) \sim 10^{10}\left(\frac{R_{\rm p}}{R_{\rm J}}\right)\left(\frac{\rho_{\rm p}}{\rho_{\rm o}}\right)\ {\rm cm}, \qquad (5)$$

where $R_{\rm J}$ represents the Jovian radius and $\rho_{\rm p}$ the mean planet density. The corresponding slowing time is

$$t_{\rm slow} = \frac{l}{v_{\rm p}} \sim 4\left(\frac{R_{\rm p}}{R_{\rm J}}\right)\left(\frac{\rho_{\rm p}}{\rho_{\rm J}}\right)\left(\frac{\rho_{\rm o}}{10^{-3}}\right)^{-1}\left(\frac{r_{\rm o}}{{\rm R}_\odot}\right)^{1/2}\left(\frac{M_{\rm in}}{{\rm M}_\odot}\right)^{-1/2} {\rm d}, \qquad (6)$$

where $\rho_{\rm J}$ denotes the Jovian mean density.

The slowing time-scale corresponds to the time length when the planet loses a significant fraction of the orbital energy. In the light curve, this should be expressed by the rise times of the peaks. The rising times of the three peaks in the optical light curve of V838 Mon can be respectively estimated as about 12, 4 and 10 d (Fig. 1). Thus, a local stellar density of the order of $\rho_{\rm o} \sim 10^{-3}$ g cm^{-3} is required at the location where the planets are consumed. From Fig. 2, we find that this value is obtained in the range $r \sim 0.1$–$12\,{\rm R}_\odot$ for B stars. The upper limit corresponds to a mass of $60\,{\rm M}_\odot$, which was proposed by Munari et al. (2005), but it is very likely unrealistic for V838 Mon. For a B star with a more reasonable mass in the range 5–$10\,{\rm M}_\odot$ (see Tylenda 2005; Tylenda et al. 2005), the required density occurs at $r \sim 0.1$–$4.5\,{\rm R}_\odot$, and if V838 Mon is a B star with a mass of $\sim 8\,{\rm M}_\odot$ (see Section 1), we find $r \sim 0.2$–$4\,{\rm R}_\odot$. Note that higher values are obtained for lower stellar radii, and that the expansion leads to a shift of the 'critical' density closer to the stellar core. For RGB and AGB stars, the required density is respectively found at $r \sim 0.5$–10 and $r \sim 0.2$–$8\,{\rm R}_\odot$. These values are in excellent agreement with the conclusion that the planets are swallowed at a characteristic distance of one solar radius from the centre of the host star using the luminosities of the peaks assuming a reasonable energy efficiency (Section 2).

Fig. 2 shows that the stellar expansion, which occurs as a natural step in its evolution, leads to a strong change in the density profile. The observed expansion during the outburst of V838 Mon probably causes a similar structural change in the density profile. For V838 Mon, the expansion of the stellar structure induced by the dissipation process will shift the critical density to smaller radii inside the star (e.g. Siess & Livio 1999a,b). Therefore, the expansion of the envelope implies that a distant planet has to penetrate closer to the stellar core than a close planet in order to hit the critical density and to stop. Thus, it makes sense that the inner planet was consumed at a larger distance from the centre of the host star than the two other planets (Section 2).

4 THE SIGNATURE OF PLANETS IN STELLAR ENVELOPES

The rate at which the planet loses energy is given by its kinetic energy divided by the slowing time:

$$\dot{E} = \frac{0.5 M_{\rm p} v_{\rm p}^2}{t_{\rm slow}} \sim 10\left(\frac{\rho_{\rm o}}{10^{-6}}\right)\left(\frac{R_{\rm p}}{R_{\rm J}}\right)^2\left(\frac{M_{\rm in}}{{\rm M}_\odot}\right)^{3/2}\left(\frac{r_{\rm o}}{30{\rm R}_\odot}\right)^{-3/2} {\rm L}_\odot. \qquad (7)$$

This energy deposit rate is adequate to explain the observed luminosity in the eruption of V838 Mon even given a moderate radiative efficiency.

Prior to the outburst, if the planet is well inside the envelope of a host giant star, this luminosity will be smeared out because of the long diffusion time-scale of the photons. In giant stars, variations can be seen at the start of the process, near the stellar radius, but then their amplitude would be much smaller. However, even when the planet is far away from the core of the parent star (say at $r_o \sim 30\,\mathrm{R}_\odot$ and $\rho_o \sim 10^{-6}$ g cm^{-3}) about $10\,\mathrm{L}_\odot$ can be produced by the falling process. This would be a fraction of the luminosity of the giant star, which is typically a few hundreds–thousands solar luminosities, but it is still detectable. The deeper the planet is found inside the stellar envelope, the larger the amplitude of the variation becomes; however, it is smeared over a longer interval of time. Therefore, we expect to observe quasi-periodic variations in giant stars only when their planets start the inwards spiraling process. Based on this idea, Retter (2005, 2006) recently proposed to explain the long secondary periods, which are observed in the light curves of RGB and AGB stars and whose nature is unknown (Wood, Olivier & Kawaler 2004), by the presence of planets that orbit at the outer edges of their host stars.

For the progenitor of V838 Mon, the following parameters were estimated: $M \sim 8\,\mathrm{M}_\odot$, $R \sim 5\,\mathrm{R}_\odot$ and $L \sim 550$–$5000\,\mathrm{L}_\odot$ (Section 1). For these values, the expected quasi-periodicity is 0.4 d (see equation 4), and we find that the amplitude of the variations before the outburst could have been of the order of the stellar luminosity. Goranskij et al. (2004) checked archival photographic observations of the progenitor of V838 Mon during 1928–1994. They could not find any significant variability in the *B*-band images. However, their measurements are based on eye estimates that are accurate to about 0.2 mag, and therefore variations with smaller amplitudes or such that are stronger in the red could have been missed. In addition, we comment that the radial acceleration is neglected in our calculations, so the fall could be quite fast. The density profile of main-sequence B stars is very steep, and there is a sharp rise of about 10 orders in a fraction of a stellar radius (Fig. 2, upper left panel). Thus, the falling planet penetrates higher densities quite fast, so the swallowing of the inner planet could have been very rapid. Based on our estimates, only a fall of $\sim$0.5–1 $\mathrm{R}_\odot$ is necessary to stop a planet that orbits at the edge of a massive B star with a radius of $\sim 5\,\mathrm{R}_\odot$ (Section 2). On the other hand, the density profiles of giant stars is much shallower, so a planet that orbits in their outer envelopes slowly falls inwards and can show the quasi-periodic variations discussed above. In this context, we note that the steep profiles of main-sequence B stars imply that the inner planet was very likely consumed near the edge of the host star. Therefore, the luminosity emitted in the first peak did not have to be super-Eddington (see Section 3) for the outburst to be observed.

According to the planets-devouring model of V838 Mon, prior to outburst, when the planet is at the edge of the stellar envelope of its parent star, the giant host star may show some quasi-periodic oscillations in its light curve imposed on a gradual increase in the luminosity. This is due to energy released by the inward-falling planet. Indeed, such a brightening has recently been detected in the light curve of the progenitor of V4332 Sgr, one of the stars in this new group (Kimeswenger 2006).

5 THE RATE OF PLANET-SWALLOWING EVENTS

We can estimate the rate of V838 Mon-like outbursts within the planets-capture model for this phenomenon. We assume that this is a natural step in the stellar evolution and that no unique trigger mechanism is required for this process. We first start with solar-like stars. The number of stars in the Milky Way is about 10^{11}. The age of a $1\,\mathrm{M}_\odot$ expanding RGB or an AGB star (There is a small difference of $\sim 10^8$ yr between the two phases.) is about 1.2×10^{10} yr (Sackmann, Boothroyd & Kraemer 1993). Thus, we obtain a number to age ratio of about 8 per year for these stars. The number of B-type stars with masses of $\sim$5–10 $\mathrm{M}_\odot$ (see Section 1) in our galaxy can be estimated as about 1 per cent 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 $\times 10^7$ yr (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 per cent of FGK stars have Jupiter-like planets. Assuming that about 5 per cent 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 yr 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 yr (Section 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.

6 DISCUSSION

Within the planets-swallowing model for V838 Mon, we used two different methods to find the location where the planets were swallowed inside the envelope of the host star. There is a nice consistency between the estimates obtained from the energy balance and from the stellar density that is required to stop the planets. We concluded that the planets were consumed at a characteristic distance of about one solar radius from the centre of their host star (Sections 2 and 3). This is consistent with the fact that a Jupiter-like planet overflows its Roche lobe about $2\,\mathrm{R}_\odot$ away from the core of a host star with a mass of $M \sim 8\,\mathrm{M}_\odot$ (see Eggleton 1983). This is a rough lower limit for the final radius because if the planet was not stopped earlier, it would then start transferring most of its mass to the host star and would quickly dissolve and cease to exist as an independent body.

The values we 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 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 $\rho \sim 10^{-3}$ gr cm^{-3} and a distance of a few solar radii from the stellar core, the opacity, κ, 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 inwards 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. Next, we explore a different idea.

6.1 One or three planets?

The planets-devouring scenario for the outburst of V838 Mon can explain the rising time-scale of the peaks and their strengths. However, one difficulty of this model is that equation (6) probably implies that the three planets should be relatively close to each other in order to fall within a couple of months as observed; unless the swallowing of the inner planets, the subsequent mass ejection and stellar expansion, or eccentric orbits somehow boosted this process. One would expect that the time between episodes of falling planets may be of the order of several years, thousands of years, or even more. We comment though that the radial acceleration is neglected in our simple approach, and that hydrodynamic simulations are required to better describe the falling process of the planets.

An alternative scenario to the multiple planets model is that all three peaks were produced by the same planet at different radii, which seems to be consistent with our estimates (Sections 2 and 3). The captured planet reaches some critical density in the envelope of the host star and triggers an initial event that gives rise to super-radiant bubbles, perhaps driven by some convective instability that quickly propagates out and then cools radiatively over rather short time-scales. As a result of the large energy release of the first event, the star expands and the density of the material surrounding the planet falls below the limit. The on-going fall of the planet brings it again into higher densities, and another super-Eddington event is triggered. The resulting adjustment of the envelope is driving the planet out of the critical density value again, etc. The planet finally reaches the nuclear burning shell and dissolves or just evaporates as argued in Livio & Soker (1984). By this process, the time-scales for the duration of each event and the time intervals between events are naturally similar. Note that in this case, the observed rise time of the peaks, which were discussed in Section 3, represents the slowing down process of a single planet in three different orbits rather than the final stopping times of three planets.

6.2 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). Five of them can be easily rejected. This is because they are restricted to a single type of stars, while the members in the V838 Mon class are of different kinds. It was concluded that the progenitor of V838 Mon is a B supergiant while that of V4332 Sgr, and most likely M31RV, are red giants (Tylenda et al. 2005a; Bond & Siegel 2006). Therefore, only scenarios that use different types of stars could be invoked to explain their eruptions. This includes the binary merger and the planet(s)-swallowing models.

Recently, Tylenda & Soker (2006) presented an analysis of the observational properties of the V838 Mon-like objects and compared in detail the various explanations of their eruptions. They argued that thermonuclear models (novae and Helium shell flashes including born again AGB) cannot be applied to the outbursts of these objects. The major arguments against these scenarios were that the observed spectral evolution of these stars, the proposed B-type progenitor of V838-Mon and the presence of circumstellar non-ionized matter are inconsistent with these models. In addition, Tylenda & Soker (2006) pointed out that there is no indication of matter processed by nuclear burning in these objects. That work can thus be used as a further argument against these five models.

Tylenda & Soker (2006) argued that only a merger model fits all observed features of the V838-Mon-like stars. They discussed the energies obtained in the outbursts of the three objects in this group. For M31RV, only an upper limit on the brightness of the progenitor is available, so no conclusion can be made. For V4332 Sgr, Tylenda et al. (2005a) and Tylenda & Soker (2006) calculated that its outburst can be explained by a merger of a solar-like star and a planet. For V838 Mon, however, Tylenda & Soker claimed that the energy released by a planet that falls on to a massive star is not sufficient to explain the observed eruption, and thus they invoked instead a merger with a low-mass ($M \sim 0.10$–$0.33\,M_{\odot}$) star. They also suggested that the outburst may occur as a result of a binary merger with a single companion or with two stars. This implies that V838 Mon is a member in a multiple system, because it was found that it also has a massive B companion (Section 1). Tylenda & Soker (2006) stated that a merger with several physical bodies can better explain the huge inflation of the stellar radius.

Tylenda & Soker (2006) listed three arguments against the planets-swallowing scenario of V838 Mon. Two of them are that the progenitor is not a red giant and that the two outbursts in February–March might have occurred at the base of the inflated envelope within 1–2 d. Our model is certainly consistent with a B-type star (Section 1.1). Tylenda (2005) found three different slopes in the radius expansion of V838 Mon. Extrapolating these lines to earlier times, he suggested that they occur within about 2.5 d. Therefore, he argued that the eruption phase in 2002 February–March originated from a single outburst event during the last days of 2002 January. This would be consistent with our suggestion to explain the outburst by a single planet. Tylenda added that this would mean that the expansion velocity during the first event (the second peak in the light curve) should be about 800 km s^{-1}, and twice larger than that in the second event (the third peak). However, this seems inconsistent with the observations, which indicate that the expansion velocities in the two events are similar (Rushton et al. 2005b; Tylenda et al. 2005b). An alternative simple interpretation to the different rates in the radius derivative is that the expansion of the stellar envelope was slower with larger radii.

The major difficulty to the planets-capture model of V838 Mon raised by Tylenda & Soker (2006) is probably the question whether the energy produced by this process is sufficient to explain the observed outburst. Tylenda & Soker argued that the total energy involved in the event is about $3 - 10 \times 10^{47}$ erg. Thus, they concluded that the $\sim 8\,M_{\odot}$ star could have merged with a companion star with a mass of ~ 0.10–$0.33\,M_{\odot}$. This is about 3–10 times larger than the total mass of three massive Jupiter-like planets. Tylenda & Soker (2006) assumed that the falling planet reaches a final distance of about $5\,R_{\odot}$ from the centre of its $\sim 8\,M_{\odot}$ host star. However, we estimate that the consumption occurs much deeper, say at a radius of ~1 $R_\odot$. 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. Therefore, it seems that the energy release by the swallowed planets can account for the observed outburst of V838 Mon.

The conclusions of Tylenda & Soker (2006) are based on very rough estimates for the mass of the ejecta and the inflated envelope. Tylenda & Soker, respectively, used 0.01–0.1 and ~0.2 $M_\odot$ for these two quantities. However, these values have large uncertainties. The measurements of the ejecta mass span a large range of values (Section 1), so the mass of the ejected material and the energy release could be much smaller than the estimates of Tylenda & Soker (2006). Tylenda (2005) argued that the decline of V838 Mon can be described by a collapsing envelope of ~0.2 $M_\odot$. Such a mass is larger than the total mass of three massive planets, and thus challenges our model. However, Tylenda did not give any error for this value. From his equation (A20), we conclude that the envelope mass is correlated with the third power of the stellar radius (R^3). Therefore, a possible error of a factor of 2 in the radius could lead to an envelope mass of approximately eight times smaller. Taking into account the uncertainties in the other parameters, and possible asymmetry, which is very likely to occur in the planets-devouring model, and could further complicate the picture, the shell mass could easily be about 20 times lower than 0.2 $M_\odot$, which is consistent with our model even for a single planet.

The scenarios proposed to explain the outbursts in V838 Mon-like stars seem to converge to an explanation by accretion of a second mass. The difference between the merger model (Soker & Tylenda 2003; Tylenda & Soker 2006) and our model (Retter & Marom 2003; this work) stems from the mass of the companion. In the binary merger model, a low-mass star merged with the primary star, while in our model one to three massive planets were consumed. It is interesting to note that the two models seem to merge. In Section 6.1, we proposed that instead of three planets, three steps in the falling process of a single planet may be invoked to explain the multistage optical light curve of V838 Mon. Tylenda & Soker (2006) suggested that maybe two low-mass stars were merged with the primary B star in V838 Mon. In this case, it may have been a rare quadrapole system. They also stated that the outburst of V4332 Sgr could be explained by a merger of a solar-like star and a planet. Therefore, the differences between the two models are relatively small.

7 SUMMARY AND CONCLUSIONS

Within the planets-capture model for the eruption of V838 Mon, this work yields a 'semi-empirical' answer to a very interesting question: 'how deep into giant stars do planets reach before consumption?'. The estimates obtained from the luminosities of the peaks in the optical light curve of V838 Mon, from the rising time-scale of a few days of these peaks and from the Roche lobe geometry, are in agreement with each other and suggest a final typical stopping distance of about one solar radius from the centre of the host star. This consistency adds further support to the planets-devouring model of V838 Mon.

The planets-capture scenario for the eruption of V838 Mon supplies a consistent description to the differences in the luminosities and rising times of the three peaks in its optical light curve. In addition, the engulfment of the nearby planets in the stellar envelope and their swallowing is a natural result of the secular evolution of solar-like stars and their huge expansion after they leave the main-sequence stage. We thus believe that this is a plausible model for the spectacular multistage outburst of this peculiar object and the other stars in its class. 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.

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