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A new model for V838 Monocerotis: a born-again object including an episode of accretion

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ABSTRACT

We present new stellar evolution models that show that the born-again phenomenon, also known as a very late thermal pulse, is a viable explanation for the behaviour of V838 Monocerotis if a period of accretion is included. Based on this model, we assert that V838 Mon is a variation of a born-again giant in close orbit with a main-sequence binary companion of mass greater than 0.7 $M_{\odot}$.

Key words: stars: AGB and post-AGB – stars: evolution – stars: individual: V838 Mon – stars: variables: other.

1 INTRODUCTION

1.1 Observations and theories for V838 Mon

The outburst of V838 Mon was first observed by Brown (2002). Little is known of the details of the pre-discovery outburst, and the cause of the outburst remains a mystery. This real-time event provides an important opportunity to test existing models of stellar evolution. V838 Mon was observed in early 2002 February to be 6 magnitudes brighter than its potential progenitor at $V = 15.6$ mag (Munari et al. 2002, 2005). Munari et al. identified the potential progenitor in both the USNO A2.0 and 2MASS catalogues. After a period of decline (∼20 d), it brightened a second time to a maximum of $V = 6.93$ mag. Multiband CCD photometry was obtained by Kimeswenger et al. (2002) and Munari et al. (2002).

V838 Mon's temperature dropped over the course of months to as low as 2300 K, corresponding to a very late M-type giant (Retter & Marom 2003; Kimeswenger et al. 2002). Following the outburst, V838 Mon was reported to have looked like an M10 III star (Desidera & Munari 2002). Based on a spectrum obtained on 2002 October 29, Evans et al. (2003) reported that V838 Mon was probably the coolest supergiant ever seen, referring to it as the first ever L-type supergiant. They estimated a temperature of at most 2300 K and suggested that it might be lower than 1300 K.

According to Wisniewski et al. (2003) its spectrum showed a strong P Cygni profile in early 2002 February, which had weakened considerably by mid-February. Wisniewski et al. also reported that spectral features varied rapidly during the period between 2002 January and March. Munari et al. (2002) described the post-outburst object as having a surface rich in dredged-up barium, lithium, and other s-process elements.

Bond et al. (2003) have presented high-resolution imaging of the light echoes, showing possible evidence of a previous episode of mass loss. Additional observations (van Loon et al. 2004) provided evidence for possible ancient ejecta from this star. Bond et al. (2003) interpreted this to mean that there may have been previous, periodic outbursts. Furthermore, a weak blue continuum suggests the presence of a B3V companion (Munari et al. 2002; Bond et al. 2003). Bond et al. (2003) suggested that it was actually the binary companion that erupted, not the object visually identified in catalogues.

The distance estimates for V838 Mon have ranged from 790 pc to greater than 6 kpc (Munari et al. 2002; Bond et al. 2003; van Loon et al. 2004). More recently, Crause et al. (2005) and Munari et al. (2005) have estimated a distance of 9–10 kpc, although the Crause et al. (2005) estimate could be as low as 5.5 kpc, depending on which model of surrounding dust is used – circumstellar shells or thin (interstellar) sheets.

V838 Mon was initially compared to born-again (BA) objects such as V4334 Sgr (Rauch et al. 2002). Kimeswenger et al. (2002) suggested classifying it as a new class of variable, while Retter & Marom (2004) suggested that the outburst was the result of expansion to a red giant, during which three massive planets in close orbits were swallowed. Munari et al. (2002) and Kimeswenger et al. (2002) both ruled out the possibility that V838 Mon is a nova or cataclysmic variable (CV), based on temperatures being too low during outburst and slow ejection velocities. Finally, Munari et al. (2005) suggested that the progenitor of V838 Mon was a massive supergiant star and that the outburst was the result of a shell thermonuclear event. They estimated the main-sequence (MS) progenitor of this object to be $M = 65\,M_{\odot}$.

1.2 The born-again phenomenon

The BA phenomenon was modelled early on by Schönberner (1979) and Iben (1982). Typical characteristics of BA models include an abrupt and significant increase in luminosity, followed by a significant decrease in temperature, and rapid changes in surface composition. The models also provide a region inside the star for the production of s-process elements. BA models have been invoked to

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explain the behaviour of FG Sge, an object that has been changing composition and becoming cooler since the year 1880 (van Genderen & Gautschy 1995; González et al. 1998). They have also been used to explain the behaviour of V605 Aql. Following an outburst in 1917, V605 Aql's evolution towards cool temperatures took only about two years (Clayton & DeMarco 1997). Clayton & DeMarco (1997) found that this object later developed the characteristics of a Wolf–Rayet central star. A third BA object, known as Sakurai's Object (SO = V4334 Sgr), was first observed by Sakurai in 1994 (Kipper & Klochkova 1997). It brightened and cooled over the course of the following six years (Asplund et al. 1999; Duerbeck et al. 1997), at yet a different time-scale from the previous two objects. Lawlor & MacDonald (2003) offered a complete explanation for the time-scale differences in evolution among these three objects. The explanation they provide is that these objects are in different phases of BA evolution. These phases are, in order, Sakurai-like (evolves quickly to the AGB), V605 Aql-like (return to the blue), and finally FG Sge-like (evolves more slowly back to the AGB a second time).

We will show here that V838 Mon may have been caught just after a phase of BA evolution that is extremely fast, and that was missed for the three previously discovered BA objects. We present new BA models with the addition of accretion that produce an outburst similar to that observed for V838 Mon. Finally, we calculate and present a model light curve and provide conclusions and discussion in Section 4.

2 THE EVOLUTION CODE

The stellar evolution code is described in detail in Lawlor & MacDonald (2003, 2005 in preparation). We summarize here some of the methods and assumptions used. The Henyey-type code, a modified version of that developed by Eggleton (1971, 1972), evolves the whole star by a relaxation method rather than using separate envelope calculations. Its adaptive-mesh technique is similar to that of Winkler, Norman & Newman (1984). Convective energy transport is modelled via standard mixing-length theory, as described by Mihalas (1970). Composition changes resulting from mixing are modelled by the addition of diffusion terms to the composition equations in a way consistent with mixing-length theory (Iben & MacDonald 1995).

Depending on the temperature, we use OPAL radiative opacities (Iglesias & Rogers 1996) or the opacities of D. R. Alexander, calculated by the method of Alexander & Ferguson (1994). We interpolate between these two for intermediate temperatures. Nuclear reaction rates are taken from Fowler, Caughlan & Zimmerman (1975), Harris et al. (1983), Nomoto, Thielemann & Miyaji (1985), Caughlan & Fowler (1988) and Arnett (1996). The code uses a free-energy formalism (Fontaine, Graboske & van Horn 1977) to calculate the equation of state. Mass loss is included using a scaled ($\eta = 0.35$) Reimers (1975) mass-loss law for cool stars and the theoretical result of Abbott (1982) for hot stars.

3 BORN-AGAIN MODELS INCLUDING ACCRETION

A well-defined time after discovery, V838 Mon experienced a second outburst. This is in stark contrast to the usual BA model, which initially increases by several magnitudes very rapidly, like V838 Mon, but then evolves at a constant luminosity on a time-scale of years (gradually increasing brightness by a few magnitudes). This was the case for SO, for example. We propose as a solution to this problem a period of accretion shortly after the model's first BA rise to brightness. This results in a second outburst as observed for V838 Mon.

3.1 The possible source of accretion

It has been suggested by Retter & Marom (2004) that the 2002 outburst may have been due to the swallowing of planets or a companion brown dwarf during evolution to the red giant branch. In light of the recent, much larger distance determinations for V838 Mon (Crause et al. 2005; Munari et al. 2005), it is very difficult to reconcile the progenitor with a main-sequence star.

We also rule out the possibility that the star expanded into a region of gas. Mass lost during the AGB phase would very probably have drifted too far away to be accreted, and there is no obvious reason to expect the region around the star to contain enough material to explain accretion. Given an expansion from white dwarf size to slightly bigger than solar size (as for the initial BA outburst), we estimate that the density of material surrounding the star would have to be $\sim 3 \times 10^{-5}$ g cm^{-3} to provide an accretion rate comparable to that which our models require to produce an additional outburst. This is not likely given that the average density of an AGB star envelope near the end of the AGB is $\sim 9 \times 10^{-9}$ g cm^{-3}.

An alternative is accretion from a close binary companion, possibly triggered by irradiation (Podsiadlowski 1991; Hameury et al. 1993) of the companion during the hot luminous stage of the BA outburst. There is indeed observational evidence that irradiation effects do exist (Ritter, Zhang & Kolb 2000). Although examples in Ritter et al. (2000) are for irradiating hot white dwarfs, it is reasonable to assume a similar effect for a BA star of similar high temperature and luminosity, but much larger (solar) size. By applying this model, we can place new constraints on the companion star. According to Vaz & Nordlund (1985), irradiation effects are significant for any binary system for which the dimensions of the components are a few per cent of their orbital separation. If we assume that this may be lower than a few per cent ($\sim$1 per cent) for a hot but much larger irradiating star, such as a BA star in its initial outburst, then the orbital separation may still be as small as 0.5 AU. However, because the BA object then proceeds to swell to giant size, and there is no evidence of a merger, we must assume that the separation is at least 1–2 AU initially. Because the separation may be so small, we too conclude that the companion is a main-sequence star, as reported by Munari et al. (2005). Ritter et al. (2000) found that, if an irradiated MS star has $M < 0.7\,M_\odot$, it will be stable against irradiation-induced mass transfer, and the opposite (i.e. unstable) is true for a greater mass. Thus, we also conclude that the companion has a mass that is greater than $0.7\,M_\odot$.

3.2 Starting model

The starting evolution model for this numerical experiment is taken from Lawlor & MacDonald (2003). The progenitor model for this work has $1\,M_\odot$, $Z = 0.01$ and was evolved from the pre-main-sequence Hayashi phase to the white dwarf cooling track, and through a BA thermal pulse. By the time the model reaches the white dwarf cooling track, its mass is $0.57\,M_\odot$ because of mass loss on the RGB and AGB. We alter the evolution of this model by accreting matter onto its surface following the BA thermal pulse. The accreted matter for our model is placed at the stellar surface under the same conditions that existed there just following the BA thermal pulse, and is distributed uniformly throughout the top surface layer of the model. While this is artificial in that matter would

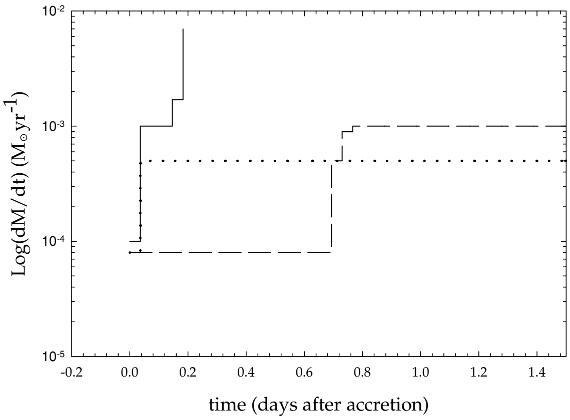

Figure 1. Variation of accretion rate for three models. Models with higher accretion rates (solid and dashed lines) result in an additional outburst on a time-scale of days, while the lower-accretion-rate model (dotted line) results in no additional outburst and evolves on a time-scale of years.

not accrete in spherically concentric shells, it allows us to test the plausibility of an accretion model to explain the additional outbursts of V838 Mon. We do not, moreover, include gravitational energy released by the material as it travels from its source to the model stellar surface. However, such accretion energy would probably be radiated at too short a wavelength to be observed directly.

Because we adopt the most likely scenario for accretion to be irradiation of a companion, we begin accretion after the initial BA outburst at a time when $\log T_{\rm eff} = 4.6$, and the luminosity is $\log(L/\mathrm{L}_\odot) = 3.6$. It is also a time at which the envelope is radiative, so we expect that there will be an increase in luminosity owing to compressional heating by accretion. Because a binary system would have formed from material of the same composition, we choose the composition of the accreted matter to be X = 0.70, Y = 0.28, and Z = 0.01. Our model does not include any effects arising from the dust that formed due to rapid mass loss during the initial or second outburst.

We calculate models for four accretion rates (including a rate of zero). For each case, we turn on accretion and gradually increase it (because of computational considerations) to a maximum rate until there is a second outburst or, for our model with no outburst, until the temperature becomes cool. Based on the observed temperatures of other irradiating stars (Ritter et al. 2000), we assume that high temperatures are a condition for irradiation. The average accretion rates for each model are 5.0×10^{-4}, 5.5×10^{-4}, and 9.0×10^{-4} $\mathrm{M}_\odot$ yr^{-1}. The maximum accretion rate for each is 5.0×10^{-4}, 1.0×10^{-3}, and 7.0×10^{-3} $\mathrm{M}_\odot$ yr^{-1}, respectively. The variations of accretion rate are shown in Fig. 1 and summarized in Table 1. The table also shows the duration of accretion and the total mass accreted during that time.

3.3 Results

The effects of accretion on evolution are shown on the HR diagrams in Fig. 2. Higher accretion rates result in an additional and

Table 1. Accretion rates, duration, and total mass accreted.

$\dot{M}_{\rm ave}$ ($\mathrm{M}_\odot$ yr^{-1})	$\dot{M}_{\rm peak}$($\mathrm{M}_\odot$ yr^{-1})	$\Delta t_{\rm accr}$(days)	$\Delta M_{\rm total}$ ($M/\mathrm{M}_\odot$)
5.0×10^{-4}	5.0×10^{-4}	39.9	5.5×10^{-5}
5.5×10^{-4}	1.0×10^{-3}	5.86	9.0×10^{-6}
9.0×10^{-4}	7.0×10^{-3}	0.26	6.6×10^{-7}

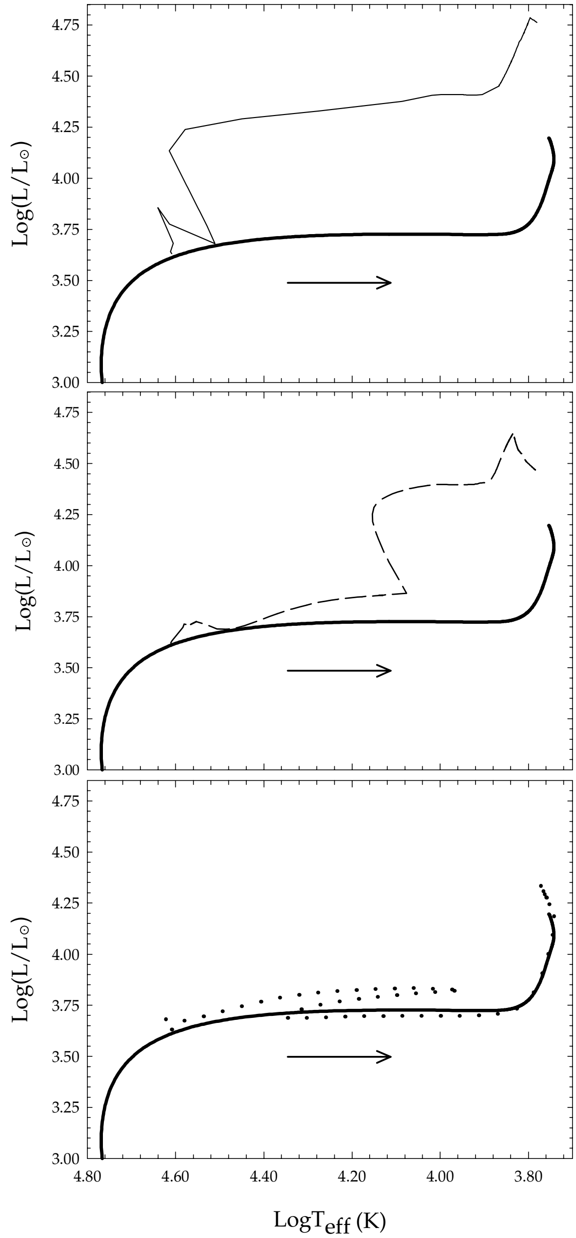

Figure 2. HR diagrams showing three models with accretion (as in Fig. 1). Each case is contrasted with a model with no accretion (thick line). The outburst models (top two panels) evolve for a few days, which compares with about 5 yr for the model with no accretion.

sudden outburst. The magnitude of the luminosity increase and the time-scale over which the models evolve depend sensitively on the accretion rate. For an accretion rate of 9.0×10^{-4} $\mathrm{M}_\odot$ yr^{-1}, there is an additional pulse 19 h after accretion is turned on. The time from accretion onset to maximum luminosity is 1.24 d. For an average rate of 5.5×10^{-4} $\mathrm{M}_\odot$ yr^{-1}, there is a second outburst 2.3 d later, and the total time for the additional outburst in this case is 2.6 d. For a rate of 5.0×10^{-4} $\mathrm{M}_\odot$ yr^{-1}, there is no comparable additional outburst. The time between the onset of accretion and minimum temperature for a model with this rate is 11.1 yr. The corresponding time for the BA model with no accretion shown in the same figure (thick line) is 4.8 yr, typical for a BA model. The shapes of the evolutionary tracks for models that include accretion are similar to those presented by

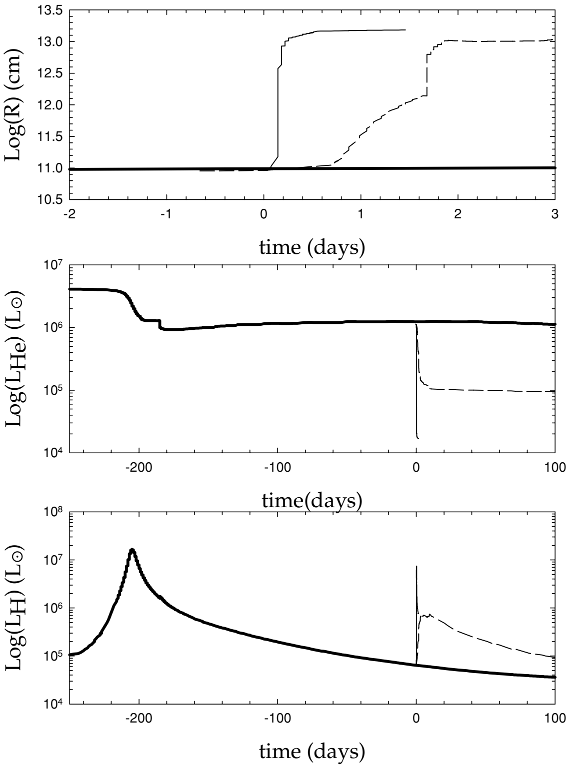

Figure 3. Radii and hydrogen- and helium-burning luminosities as a function of time for the models in Fig. 1. $t = 0$ corresponds to the second outburst.

Munari et al. (2002) and Crause et al. (2003) for V838 Mon. Both of these papers show in their observations that there is a brief increase in temperature and luminosity at the time of the second outburst. This feature is also present in both of our outburst models, although it occurs at a higher temperature (10 000 K as compared with 4000 K). Furthermore, our coolest model reaches a minimum at about 5500 K, while V838 Mon cools to 2300 K (and possibly as low as 1300 K). A future, larger grid of models may solve this problem. Both observations and our accretion models show significant and rapid cooling following the second outburst.

In Fig. 3 we show radius, helium-burning luminosity, and hydrogen-burning luminosity as a function of time. At the time of the second outburst ($t = 0$ in this figure), there is a rapid increase in radius. In both outburst cases, the radius swells from just bigger than solar size to giant size ($R > 10^{13}$ cm). Although this size is typical for a BA model, it occurs on a greatly accelerated time-scale: almost immediately rather than over years. Mass loss is typically associated with the initial BA outburst over the period of that outburst ($\sim$3 weeks). It is possible for some of that lost mass to be overtaken by the expanding stellar surface, which expands after accretion very rapidly, in as little as one day. This may explain the evidence for the presence of a shock wave and for the observation that molecular material falls back onto the surface (Rushton et al. 2005).

For our plots of hydrogen- and helium-burning luminosities, the initial BA helium flash is shown at day -200. At $t = 0$, there is a very sudden, conspicuous hydrogen pulse arising from compressional heating by accretion. It is this accretion-induced hydrogen pulse that is responsible for the model's fast increase in radius (the second outburst). The induced hydrogen pulse extinguishes helium burning as a result of expansion and is evident in the middle panel of the same figure. For reference, a BA model without accretion is shown (thick line). For the lower-accretion-rate model, there is a continued period of helium burning (not shown in Fig. 3) because it is not driven out by the accretion-induced hydrogen pulse. The result of this is a brief increase in temperature before the model re-traces the usual BA model evolution track (Fig. 2, bottom panel).

The surface composition for the two outburst models remains essentially constant during the time between the onset of accretion and maximum luminosity. In contrast, the model with no accretion experiences a significant change in surface composition, and its evolution across the HR diagram takes much longer. These changes in surface abundance are due to the dredging up of heavier material before an entropy barrier develops between the helium- and hydrogen-burning shells. Because the addition of accretion induces an intense hydrogen pulse, helium burning is driven out and dredge-up is hampered. It is also thwarted by the very quick swelling of the stellar envelope from solar to giant size. BA models without accretion swell to giant size more slowly, on the order of years. For a BA model with no accretion, the hydrogen, helium, and carbon abundances (X,Y,C) in mass fractions change from (0.70, 0.286, 0.002) to (0.41, 0.46, 0.09). There are similar changes for nitrogen, oxygen, and magnesium (N,O,Mg) from (0.001, 0.005, 0.003) to (0.004, 0.029, 0.0085). For the model with low accretion, the changes are even more significant: to (0.15, 0.56, 0.20) for (X,Y,C) and to (0.0073, 0.06, 0.017) for (N,O,Mg). The increased helium burning mixes down more hydrogen and mixes up more helium and carbon (as well as heavier elements).

Finally, we present a model light curve (Fig. 4) for an accretion model with a rate of $5.5 \times 10^{-4}\ M_\odot\ yr^{-1}$. For comparison, we also plot a light curve for V838 Mon, as published by Kimeswenger et al. (2002). We approximate a bolometric light curve assuming an absolute bolometric magnitude for the Sun of $M_\odot = 4.77$ mag. The uniqueness of BA models and V838 Mon makes it difficult to apply a bolometric correction to our model light curve. As an approximation, we apply bolometric corrections for supergiants (Allen

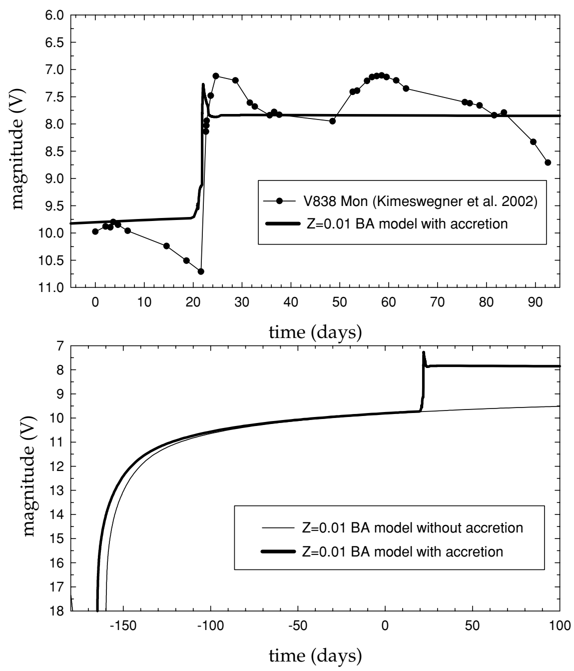

Figure 4. Top: BA accretion model (thick line) and a light curve for V838 Mon from Kimeswenger et al. (2002). Bottom: BA models with (thick line) and without (thin line) accretion.

1963). Because BA models increase to only solar size while evolving through high temperatures ($\log(T) > 3.9$), our estimates for bolometric correction during that time are not likely to be appropriate. None the less, accretion models quickly evolve to giant size and cooler temperatures within days after that blue phase.

For determination of our model V, we use a distance consistent with the distance determination of Crause et al. (2005) and Munari et al. (2005). We find that V for our model matches observations well when using a distance of 6300 pc. Varying the distance in our estimates between 5500 and 6500 pc changes V by less than ± 0.25 mag. This difference increases to about 1.0 mag if the distance is increased to 10 kpc, as Munari et al. (2005) suggest. This can still be accounted for by small errors in bolometric correction, progenitor mass, or accretion rate.

The observed light curve declines slightly before the second outburst, but, being in the V band, this is probably an effect of dust formation (Crause et al. 2003). We do not include dimming due to dust formation in our model light curve. There is a conspicuous second outburst shortly following the switching on of accretion. We also present in the bottom panel of Fig. 4 the initial BA outburst for which the brightness increases by more than 5 mag from $V > 15$ to $V \sim 10$ mag. We overlie our accretion model showing a second outburst, which occurs a few days after accretion is turned on. While our model light curve spikes and plateaus, the observations evolve more smoothly and show a modest third brightening. This discrepancy may be because we accrete matter onto the surface in a uniform and spherical way. Moreover, we do not consider the impact of material onto the surface of the star or the contribution of the irradiated companion to the light curve. It may further be possible that the third outburst is because the outbursting object overflows onto the irradiated companion. Given that this model requires a small orbital separation, overflow may be expected to occur.

4 CONCLUSIONS AND DISCUSSION

We have presented BA evolution models that include an episode of accretion shortly following the initial BA outburst. This scenario can solve many of the problems occurring when the BA phenomenon is given as an explanation for the behaviour of V838 Mon. We conclude that V838 Mon began as a white dwarf (WD) in a close binary system and underwent a BA thermal pulse. A hot, bright WD as a progenitor is consistent with models presented by Munari et al. (2005) in that they suggest that V838 Mon was a star with $T \sim 50\,000$ K before outburst. Our picture is in stark contrast, however, to their estimate for progenitor mass and its nature. They suggest a massive supergiant star that evolved from a MS star of mass $65\,\mathrm{M}_{\odot}$. However, they do not consider that, even at their larger distance of 10 kpc, a supergiant of that size could not have had $V \sim 15$ mag before the initial outburst. For that size star, luminosity would be (at a time near carbon ignition) $\sim 700\,000\,\mathrm{L}_{\odot}$, corresponding to $V \sim 6$ mag. Even as a MS star, its luminosity would have been $\sim 500\,000\,\mathrm{L}_{\odot}$. Thus, their mass determination is inconsistent with their distance determination. If the binary companion is indeed a B3V MS star, then our model here may need to be revised for a more massive MS (thus WD) progenitor. If our BA picture here proves to be correct, the spectral type for the companion may be in question since it was determined without including the possible effects of irradiation, which may lead to significant heating and expansion of the companion (Beer & Podsiadlowski 2002).

We propose that, during our accretion model's first BA rise to brightness [$\log(L/\mathrm{L}_{\odot}) \sim 3.6$], it begins to irradiate its main-sequence companion, increasing mass transfer onto the outbursting, now solar-size, object. This addition of accreting material results in an additional and significant outburst, increasing the model luminosity to as high as $\log(L/\mathrm{L}_{\odot}) \sim 4.7$. This value is similar to the value of $\log(L/\mathrm{L}_{\odot}) \sim 5$ predicted by van Loon et al. (2004). The second outburst only requires a total accretion mass of as little as $6.6 \times 10^{-7}\,\mathrm{M}_{\odot}$.

We also presented a light curve for our new models. The initial BA helium pulse increases the model's V from >15 to ~ 10 mag on the order of weeks, while the second accretion-induced outburst further increases the model star's magnitude from $V \sim 10$ to $V \sim 7$ mag in less than one day. This is very similar to what has been observed for V838 Mon.

Other observations can also be explained by the BA scenario. Recently, van Loon et al. (2004) reported evidence for a multiple shell structure, which one would expect to be surrounding an evolved white dwarf, becoming visible during a BA outburst. Multiple dust-shell structures have also been observed around other BA objects (Clayton & DeMarco 1997; Parker, Gull & Kirshner 1979; Barnard 1913). Van Loon et al. suggest that this latest outburst is a fourth thermal pulse while the star is still on the AGB. However, it may be difficult for this scenario to explain the magnitude of the likely progenitor: one with $V > 15$ mag (Munari et al. 2005).

V838 Mon had a blue excess when it faded, and this is likened to the 'blue decline' behaviour associated with RCrB stars (Crause et al. 2003; Clayton 1996). Moreover, Sakurai's Object and FG Sge have both been described as RCrB-like stars (Asplund et al. 1998; González et al. 1998; Iben, Tutukov & Yungelson 1996).

Furthermore, many of the differences between V838 Mon and BA objects that have been previously cited can be resolved by our accretion models. For example, Munari et al. (2002) suggest that V838 Mon's rise to maximum brightness is too fast compared with other BA objects. However, BA models rise to maximum brightness in as little as three weeks for a solar-mass progenitor. This time-scale is sufficient. Rauch et al. (2002) were the first to suggest that V838 Mon was an initial BA outburst. Kimeswenger et al. (2002) report that V838 Mon differs from SO and V605 Aql in that these two objects remained at constant bolometric luminosity for 7 and 85 yr, respectively. In the same work, they point out that V838 Mon should have a much slower evolution after outburst in order to be BA. A lack of strong carbon overabundance in the spectra is also noted. These differences can best be explained and predicted by the addition of accretion for V838 Mon, which we have shown can considerably speed up the model star's evolution after outburst, and would change its post-BA evolution significantly. We also find that accretion models that undergo a second outburst remain at constant surface abundance. This may explain the lack of carbon overabundance.

Our scenario, however, is inconsistent with the temperature determination of Evans et al. (2003). In that work, they adopt a temperature for V838 Mon of at most 2300 K. They further suggest that it may be as low as 1300 K, although they also state that determination of V838 Mon's effective temperature must await detailed analysis. Their suggestion of the latter temperature is based on comparison with the transition between CO and CH_4 in brown dwarfs, which may not be relevant since the chemistry in giant and dwarf atmospheres can be quite different as a result of pressure differences. This may change the strength or even presence of molecular bands (Alexander 2005, private communication). In any case, we will certainly need to address further the discrepancy between observed temperatures and those predicted by our models. We do find that a higher accretion rate produces a slightly cooler outburst, and we expect that a larger progenitor mass may provide a more extended and cooler model.

Finally, we do conclude that V838 Mon is essentially a new breed of variable star, as proposed by Kimeswenger et al. (2002). It is a variation of a BA object – one occurring in a binary system with the first outburst causing a period of mass transfer as a result of irradiation, leading to an additional outburst that occurs on an accelerated time-scale.

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REFERENCES

Abbott D., 1982, ApJ, 259, 282
Alexander D. R., Ferguson J. W., 1994, ApJ, 437, 879
Allen C. W., 1963, Astrophysical Quantities. Oxford Univ. Press, New York
Arnett D., 1996, Supernovae and Nucleosynthesis. Princeton Univ. Press Princeton
Asplund M., Gustafsson B., Rao N. K., Lambert D. L., 1998, A&A, 332, 651
Asplund M., Lambert D. L., Kipper T., Pollacco D., Shetrone M. D., 1999, A&A, 343, 507
Barnard E. E., 1913, Pub. Lick. Obs., Plate 67
Beer M., Podsiadlowski P., 2002, in Tout C.A., Van Hamme W., eds, ASP Conf. Ser. Vol. 279, Exotic Stars as Challenges to Evolution. Astron. Soc. Pac., San Francisco, p. 253
Bond H. E., Panagia N., Sparks W. B., Starrfield S. G., Wagner R. M., Henden A., 2002, IAU Circ. 7943, 2
Bond H. E. et al., 2003, Nat, 422, 405
Brown N. J., 2002, IAU Circ., 7785, 1
Caughlan G. R., Fowler W. A., 1988, At. Data Nucl. Data Tables, 40, 283
Clayton G. C., 1996, PASP, 108, 225
Clayton G. C., DeMarco O., 1997, AJ, 114, 2679
Crause L. A., Lawson W. A., Kilkenny D., van Wyk F., Marang F., Jones A. F., 2003, MNRAS, 341, 755
Crause L. A., Lawson W. A., Menzies J. W., Marang F., 2005, MNRAS, 358, 1352
Desidera S., Munari U., 2002, IAU Circ. 7982, 1
Duerbeck H., Benetti S., Gautschy A., van Genderen A. M., Kemper C., Liller W., Thomas T., 1997, AJ, 114, 1657
Eggleton P. P., 1971, MNRAS, 151, 351
Eggleton P. P., 1972, MNRAS, 156, 361
Evans A., Geballe T. R., Rushton M. T., Smalley B., van Loon J. Th., Eyres S. P. S., Tyne V. H., 2003, MNRAS, 343, 1054
Fontaine G., Graboske H. C., Jr, van Horn H. M., 1977, ApJS, 35, 293
Fowler W. A., Caughlan G. R., Zimmerman B. A., 1975, ARA&A, 13, 69
González G., Lambert D. L., Wallerstein G., Rao N. K., Smith V. V., McCarthy J. K., 1998, ApJS, 114, 133
Hameury J.-M., King A. R., Lasota J.-P., Raison F., 1993, A&A, 277, 81
Harris M. J., Fowler W. A., Caughlan G. R., Zimmerman B. A., 1983, ARA&A, 21, 165
Iben I., Jr, 1982, ApJ, 260, 821
Iben I., Jr, MacDonald J., 1995, in Koester D., Werner K., eds, Proc. 9th European Workshop on White Dwarfs. Lecture Notes in Physics, Vol. 443, Springer, Berlin, p. 48
Iben I., Jr, Tutukov A. V., Yungelson L. R., 1996, ApJ, 456, 750
Iglesias C. A., Rogers F. J., 1996, ApJ, 464, 943
Kimeswenger S., Lederle C., Schmeja S., Armdorfer B., 2002, MNRAS, 336, L43
Kipper T., Klochkova G., 1997, A&A, 324, L65
Lawlor T. M., MacDonald J., 2003, ApJ, 583, 913
Mihalas D., 1970, Stellar Atmospheres. Freeman, San Francisco
Munari U. et al., 2002, A&A, 389, L51
Munari U. et al., 2005, A&A, 434, 1107
Nomoto K., Thielemann F.-K., Miyaji S., 1985, A&A, 149, 239
Parker R. A. R., Gull T. R., Kirshner R. P., 1979, NASA SP-434, NASA, Washington, DC
Podsiadlowski P., 1991, Nat, 350, 136
Rauch T. et al., 2002, in Tout C.A., Van Hamme W., eds, ASP Conf. Ser. Vol. 279, Exotic Stars as Challenges to Evolution. Astron. Soc. Pac., San Francisco, p. 345
Reimers D., 1975, Mem. Soc. R. Sci. Liège, 8, 369
Retter A., Marom A., 2003, MNRAS, 345, L25
Ritter H., Zhang Z.-Y., Kolb U., 2000, A&A, 360, 969
Rushton M. T., Geballe T. R., Evans A., Smalley B., van Loon J. Th., Eyres S. P. S., 2005, MNRAS, 359, 624
Schönberner D., 1979, A&A, 79, 108
van Genderen A. M., Gautschy A., 1995, A&A, 294, 453
van Loon J. Th., Evans A., Rushton M. T., Smalley B., 2004, A&A, 427, 193
Vaz L. P. R., Nordlund A., 1985, A&A, 147, 281
Winkler K.-H. A., Norman M. L., Newman M. J., 1984, J. Phys., 12, 408
Wisniewski J. P., Morrison N. D., Bjorkman D. S., Miroshnichenko A. C. G., Hoffman J. L., Meade M. R., Nett J. M., 2003, ApJ, 588, 486

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