A Young Open Cluster Surrounding V838 Monocerotis

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Abstract. During a program of spectroscopic monitoring of V838 Mon, we serendipitously discovered that a neighboring 16th-mag star is of type B. We then carried out a spectroscopic survey of other stars in the vicinity, revealing two more B-type stars, all within 45′′ of V838 Mon. We have determined the distance to this sparse, young cluster, based on spectral classification and photometric main-sequence fitting of the three B stars. The distance is found to be 6.2 ± 1.2 kpc, in excellent agreement with the geometric distance to V838 Mon of 5.9 kpc obtained from Hubble Space Telescope polarimetry of the light echoes. The cluster’s age is less than 25 Myr.

The absolute luminosity of V838 Mon during its outburst, based on our distance measurement, was very similar to that of M31 RV, an object in the bulge of M31 that was also a cool supergiant throughout its eruption in 1988. However, there is no young population at the site of M31 RV.

It does not appear possible to form a nova-like cataclysmic binary system within the young age of the V838 Mon cluster, and the lack of a young population surrounding M31 RV suggests that the outburst mechanism does not require a massive progenitor. These considerations appear to leave stellar-collision or -merger scenarios as one of the remaining viable explanations for the outbursts of V838 Mon and M31 RV.

1. Introduction

A variety of explanations for the outburst of V838 Mon have been proposed, many of them mutually exclusive (see recent summary in Tylenda & Soker 2006, and the proceedings of this conference). These explanations involve either thermonuclear processes (an unusual nova-like outburst on a white dwarf, a thermonuclear event in a massive star, or a helium shell flash in a post-AGB star), or the release of gravitational energy (through stellar or planetary mergers or collisions).

A possible new constraint on the nature of V838 Mon came from the discovery of a B3 V companion to the star (Munari & Desidera 2002; Wagner & Starrfield 2002). The companion is unresolved even at Hubble Space Telescope (HST) resolution.

Another eruptive object has attracted attention as a possible analog of V838 Mon. This is the “M31 red variable,” or “M31 RV,” which underwent an outburst in mid-1988 that was remarkably similar to that of V838 Mon (Bond & Siegel 2006 and references therein), although not as well observed. M31 RV
occurred in the nuclear bulge of the Andromeda Galaxy, and is thus at a known distance.

In this paper, we present our serendipitous discovery that V838 Mon is a member of a small, young open cluster. We will use spectral classification and photometry of the cluster members to determine a distance. We will also derive a limit to the cluster’s age, and will compare the stellar populations surrounding V838 Mon and M31 RV. We will close with a brief discussion of the V838 Mon progenitor object and some new constraints on the outburst mechanism that result from our observations.

2. Observations and Data Reduction

2.1. Spectroscopy

We have been monitoring the spectroscopic development of V838 Mon since early 2003, using the SMARTS 1.5-m telescope at Cerro Tololo Interamerican Observatory (CTIO) and its CCD spectrograph. Most of our observations have been obtained with a setup (grating designation “26/I”) yielding a FWHM resolution of 4.3 Å and a wavelength coverage of 3530–5300 Å.

Our data are long-slit spectra, in which the slit length projected onto the sky is about 6′. It is not unusual for neighboring field stars to fall onto the slit, but we were surprised when a 16th-mag star lying on the slit almost directly east of V838 Mon proved, entirely serendipitously, to have a B-type spectrum. Although V838 Mon lies at a low galactic latitude (ℓ = 21°7.8, b = +1°0), a B-type star as faint as 16th mag would lie at the outskirts of the Galactic disk. This makes its existence very unusual, especially when lying within a few arcseconds of a star that is itself extraordinary. Adding this to the fact that V838 Mon itself has an unresolved B companion made it appear very likely that the serendipitous star is at the same distance. This in turn raised the possibility that there could be further faint early-type objects in the field surrounding V838 Mon.

To investigate this possibility, we used the SMARTS 1.5-m telescope to obtain spectra of several more stars in the immediate vicinity of V838 Mon. For these exploratory observations we used a setup (grating designation “13/I”), giving a resolution of 17.2 Å and coverage 3150–9375 Å. Most of the neighboring stars have proven to be unrelated foreground stars, but our observations to date have disclosed two further 14th-15th mag B-type stars near V838 Mon. All three of these early-type stars lie within 45″ of the variable, or within a projected separation of only 1.3 pc if the distance is ~6 kpc (see below). Thus there is little doubt that V838 Mon is accompanied by a previously unrecognized sparse, young cluster.

Figure 1 presents the Hubble Heritage image of V838 Mon and the light echo, with the three new B stars circled. (In addition, V838 Mon itself is circled.) The picture illustrates that the cluster is not obvious in a direct image, and as we will see below the reddened B-type cluster members and foreground F-G stars have similar colors; hence spectroscopic observations are the only practical means for identifying cluster members in this crowded, low-latitude field.

As this paper was being prepared, we became aware that Wisniewski, Bjorkman, & Magalhães (2003) had already pointed out that our three stars are likely
Figure 1. Hubble Heritage image of V838 Mon and its light echo. The three neighboring B-type stars discovered in our work are circled, along with V838 Mon itself. From top to bottom, the circled stars are V838 Mon and stars 7, 9, and 8. Other bright stars in the image have proven to be foreground stars.

to lie at a similar distance to V838 Mon itself, based on the similar polarimetric properties of all four stars.

2.2. Spectral Classification

Following the serendipitous discovery of the first field B-type star, and our subsequent discoveries of two more B stars with the low-resolution 13/I grating setup, we obtained moderate-resolution of the latter two with the SMARTS 1.5-m spectrograph and the moderate-resolution 26/I grating. In Figure 2 we show these spectra, along with spectra of several classification standards taken with the same setup. Star 7 is the serendipitous star discovered first, and stars 8 and 9 are the other two B stars. Also included in Figure 2 is a spectrum of V838 Mon itself based on observations on five nights between 2003 February and May, a time when the variable had declined considerably from its 2002 outburst, but was still contributing some light even in this blue spectral range (note the TiO bands longward of H½, for example).

We classified the three B stars based both upon a visual comparison with the standard stars shown in Figure 2, and upon equivalent-width measurements of the He I and Balmer lines. The resulting types are B3 V, B4 V, and B6 V, respectively, for stars 9, 8, and 7. We were not able to classify the unresolved B-type companion of V838 Mon itself with these methods because of the contamination from the cool component. However, from a comparison of the equivalent
Figure 2. SMARTS 1.5-m spectra of three B-type stars belonging to the young cluster in the vicinity of V838 Mon, along with spectra of three classification standards and V838 Mon itself (during early 2003). All spectra have been normalized to a continuum level of 1.0, the tick marks on the y axis are separated by 0.5 continuum flux units, and the spectra have been offset by constant successive amounts. Stars 9, 8, and 7 are classified B3 V, B4 V, and B6 V, respectively, by direct comparison with the classification standards, as described in the text. We also classify the unresolved companion of V838 Mon itself as B3 V. Note the strong diffuse interstellar band (DIB) at 4428 Å in the four reddened stars belonging to the V838 Mon cluster.

widths of the bluest Balmer lines (H8, H9, and H10) in V838 Mon (where the contamination is lowest) and in the standard stars, we find a type of B3 V, which agrees well with the other authors cited in the introduction.

2.3. Photometry

We have also been monitoring the field of V838 Mon regularly since early 2003 with the SMARTS 1.3-m telescope and CCD direct camera. Calibrated photometry of the stars surrounding V838 Mon on the Johnson $BV$ system was derived through observations of a standard field from Landolt (1992).

3. Distance and Other Properties of the Cluster

3.1. Spectroscopic Parallax

We now calculate distances to each of the three B stars, and thus determine a distance to the cluster, as shown in Table 1. The first four columns give the star designations, spectral types, and photometry. The fifth column gives the intrinsic color corresponding to each spectral type, $(B - V)_0$, taken from the tabulation of Schmidt-Kaler (1982). The sixth column gives the estimated color excess, $E(B - V) = (B - V) - (B - V)_0$. The color excesses agree well among the
three stars, with a mean of \( E(B - V) = 0.84 \) and a scatter of about \( \pm 0.02 \) mag. This determination agrees well with those of other authors. For example Munari et al. (2005, hereafter M05) found \( E(B - V) = 0.87 \pm 0.01 \) using several different methods. Tylenda (2005) discusses recent reddening determinations by several authors, and adopts \( E(B - V) \approx 0.9 \).

| Star | Sp. | \( V \) | \( B - V \) | \( (B - V)_0 \) | \( E(B - V) \) | \( V_0 \) | \( M_V \) | \( (m - M)_0 \) |
|------|-----|--------|----------|--------------|------------|--------|--------|--------------|
| 7    | B6 V | 16.02  | 0.71     | -0.15        | 0.86       | 13.42  | -0.9   | 14.32        |
| 8    | B4 V | 15.90  | 0.63     | -0.19        | 0.82       | 12.40  | -1.4   | 13.80        |
| 9    | B3 V | 14.79  | 0.62     | -0.205       | 0.825      | 12.19  | -1.6   | 13.79        |

Mean: 0.84 14.0

The next column in Table 2 gives the magnitude of each star corrected for extinction, \( V_0 \), calculated assuming \( A_V = 3.1E(B - V) \). Column 8 gives the absolute magnitude corresponding to each spectral type, \( M_V \), again taken from Schmidt-Kaler (1982). The final column gives the distance moduli, \( (m - M)_0 \), whose mean is 14.0, or a distance of 6.3 kpc.

The cluster distance modulus has an internal error of about \( \pm 0.2 \) mag, based on the scatter among the three stars. However, systematic errors are undoubtedly larger. This is indicated by the scatter among different calibrations of the relation between spectral types and absolute magnitudes (e.g., Lesh 1968; Schmidt-Kaler 1982; Cramer 1997), which amounts typically to about \( \pm 0.4 \) mag. At a distance of 6.3 kpc, this corresponds to an error of \( \pm 1.2 \) kpc.

### 3.2. Main-sequence Fitting

We can also estimate the distance to our cluster through photometric main-sequence fitting. In the absence of any spectroscopic information, this method would suffer from the well-known near-degeneracy between extinction and distance for early-type stars; this is due to fact that the main sequence lies along a steep, nearly straight line in the \( V, (B - V) \) diagram. However, with the additional constraints from the spectral types, main-sequence fitting becomes possible.

To define the main sequence, we chose the lightly reddened open cluster NGC 2362, which, at an age of \( \sim 5 \) Myr, has been described as a template for early stellar evolution (Moitinho et al. 2001; hereafter MAHL01). This cluster’s unevolved main sequence extends to type B1 V (Johnson & Morgan 1953). We took \( B, V \) photometry for NGC 2362 from Johnson & Morgan and from Perry (1973), and adopted \( E(B - V) = 0.10 \) and \( d = 1.48 \) kpc from MAHL01. We then corrected the photometry to the spectroscopic reddening and distance for the V838 Mon cluster found above. The match with the three V838 Mon B stars was very good, so we applied just one iteration of adjusting first the reddening of the B stars and then the distance, so as to improve the fit. This resulted in a V838 Mon cluster reddening of \( E(B - V) = 0.85 \) and distance modulus \( (m - M)_0 = 13.97 \) (\( d = 6.2 \) kpc). The external errors here are similar to those for the spectroscopic parallax, since MAHL01 based the distance to NGC 2362 on the Schmidt-Kaler (1982) zero-age main sequence.
In Figure 3 we plot the $V, (B - V)$ values for the three B stars as large filled circles. The small open circles are the Johnson-Morgan and Perry photometry of NGC 2362, adjusted to the V838 Mon reddening and distance found in the previous paragraph. The fit is excellent, and strongly supports the conclusion that our three B stars do form a physical cluster.

A direct geometrical distance determination for V838 Mon has been carried out by Sparks et al. (2006), based on polarimetric imaging of the light echo obtained with HST. Their result, 5.9 kpc, is in excellent agreement with our determination of 6.2 kpc based on the associated B-type stars.

Also plotted in Figure 3, as small filled black circles, is our photometry for all stars within a radius of 90″ of V838 Mon. For most of these stars we do not know whether they are cluster members or not, but we do have SMARTS 1.5-m spectra for six of them that establish them as belonging to the foreground; these non-members are marked with black stars in Figure 3.

As Figure 3 shows, the foreground F- and G-type stars have similar colors to the reddened B-type cluster members. This demonstrates that spectroscopic observations are essential to the identification of cluster members. It would be very interesting to have spectra of the other stars in the vicinity of V838 Mon, especially below $V \simeq 17.5$, where the slope of the main sequence changes; any
of these candidates that proved to be cluster members would provide tighter constraints on the cluster reddening and distance.

We can compare the luminosity of V838 Mon with that of the apparently similar object M31 RV (see §1). At maximum light (2002 February 6) V838 Mon had $B = 7.9$ (M05, their Figure 1). For the reddening and distance derived here, this corresponds to an absolute blue magnitude at maximum of $M_B = -9.6$. The brightest $B$ magnitude measured for M31 RV during its 1988 outburst was 17.3 (Bryan & Royer 1992; Boschi & Munari 2004). The latter authors, adopting $E(B-V) = 0.12$ and $(m-M)_0 = 24.48$ for M31, found an absolute magnitude of $M_B = -7.7$. However, the light curve of M31 RV was very poorly sampled around its maximum. It is more meaningful to compare the luminosities of the two objects at the same well-covered portions of both light curves. Referring to Figure 2 of Boschi & Munari (2004), and using their light curves in Kron-Cousins $R$, we can compare the luminosities at a point just before the rapid fading in the $R$ band. For M31 RV, this brightness is $R \approx 15$, and for V838 Mon it is $R \approx 6.2$. Correcting for reddening and distance, the corresponding absolute magnitudes are $M_R \approx -9.8$ and $-9.7$, respectively. Thus, at least at this stage in their outbursts, the absolute luminosities were nearly identical.

### 3.3. Cluster Age and Stellar Masses

Since the three B stars all appear to lie on the zero-age main sequence, we can only set an upper limit to the age of the V838 Mon cluster. By reference to the isochrones and evolutionary tracks of Pietrinferni et al. (2006), we find that this upper limit is about 25 Myr.

### 4. The Stellar Populations of V838 Mon and M31 RV

V838 Mon is accompanied by a previously reported, unresolved B3 V companion. In this paper we have shown that V838 Mon also belongs to a sparse cluster, containing at least three other B-type members.

We could thus be tempted to speculate that the outburst of V838 Mon in 2002 represents an explosive event that occurs in stars of masses $\sim 7–8 M_\odot$. Unfortunately, such a speculation appears to be dashed by the recent study of M31 RV by Bond & Siegel (2006). They used archival HST images that serendipitously included the outburst site of M31 RV, and showed that the population surrounding the object contains exclusively old, low-mass stars belonging to the nuclear bulge of M31. There is no young population at all at this site, let alone bright B stars younger than 25 Myr.

Thus, if the outbursts of both V838 Mon and M31 RV arose from a common mechanism, the mechanism occurs among both very young and very old stars.

### 5. The Outburst Mechanism

Our observations have revealed that V838 Mon belongs to a young cluster. This discovery has, however, only deepened the enigma of V838 Mon and the similar object M31 RV, because we now know that the former arose from a very young population, whereas the latter belongs to a very old population.
What, then, was the nature of the progenitor objects that produced the outbursts of V838 Mon and M31 RV? They apparently can exist at both ends of the range of stellar ages. The luminosity of the progenitor before outburst, at least in the case of V838 Mon, was small compared to that of a B3 dwarf (see Afsar & Bond 2006). That would be consistent with the low luminosity of a typical nova-like cataclysmic variable. However, the young age of the V838 Mon cluster would appear to rule out the evolutionary timescale required to produce an accreting white dwarf in a compact binary, a requirement of a nova-like outburst mechanism.

It may be that the stellar-merger scenario advocated by several participants at this conference, as well as in a recent series of papers (e.g., Tylenda & Soker 2006 and references therein; see also Retter et al. 2006, who advocate a planet-star merger) can satisfy these new constraints, provided that collisions between low-mass stars (which exist in all populations) could produce the required high luminosities, and can be shown to occur often enough. At the moment, however, the nature of these extraordinary outbursts remains one of the leading unsolved problems in stellar astrophysics.

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