SPITZER OBSERVATIONS OF V838 MONOCEROTIS: DETECTION OF A RARE INFRARED LIGHT ECHO

D. P. K. Banerjee,1 K. Y. L. Su,2 K. A. Misselt,2 and N. M. Ashok1

Received 2006 March 21; accepted 2006 May 1; published 2006 May 18

ABSTRACT

We present Spitzer observations of the unusual variable V838 Monocerotis. Extended emission is detected around the object at 24, 70, and 160 μm. The extended infrared emission is strongly correlated spatially with the HST optical light echo images taken at a similar epoch. We attribute this diffuse nebulosity to an infrared light echo caused by reprocessed thermal emission from dust heated by the outward-propagating radiation from the 2002 eruption. The detection of an IR light echo provides us with an opportunity to estimate the mass in dust of the echo material and hence constrain its origin. We estimate the dust mass of the light echo to be on the order of a solar mass—thereby implying the total gas plus dust mass to be considerably more—too massive for the echo material to be the ejecta from previous outburst/mass-losing events. This suggests therefore that a significant fraction of the matter seen through the light echo is interstellar in origin. Unresolved emission at 24 and 70 μm is also seen at the position of the central star, possibly indicating the presence of hot dust freshly condensed in the outburst ejecta.

Subject headings: infrared — stars — novae, cataclysmic variables — stars: individual (V838 Monocerotis)

1. INTRODUCTION

The eruption of V838 Monocerotis (V838 Mon) in 2002 January 6 has introduced a seemingly new kind of object in the realm of cataclysmic variables. It was detected in eruption by Brown (2002) with a peak outburst amplitude of \( V_{\text{max}} = 10 \) that was followed by two more outbursts—within the next 2 months—reaching 6.7 and 7 mag, respectively. V838 Mon also showed fast cooling, on a timescale of a few months, to a cool, late M spectral type or beyond (Evans et al. 2003). The multipeaked outbursts in the object and the decrease of its effective temperature with time suggested that the object was different from a classical nova or other known classes of eruptive variables (Munari et al. 2002; Kimeswenger et al. 2002). An expanding light echo was also seen around the star (Henden et al. 2002) whose expansion and accompanying morphological changes are strikingly illustrated by Hubble Space Telescope (HST; Bond et al. 2003) and other images (Crause et al. 2005). Distance estimates to the object, converging to a large value in the range of 7–10 kpc, have been made based on varied approaches, such as the rate of the expanding light echo (e.g., Tylenda 2004; Crause et al. 2005) and the detection of SiO maser emission from the source (Deguchi et al. 2005). Considerable near-infrared studies of the source have been done that have yielded spectra showing an oxygen-rich atmosphere with prominent molecular features of CO, AIO, SiO, TiO, and water (Lynch et al. 2004; Evans et al. 2003; Banerjee & Ashok 2002; Rushton et al. 2005). Although not firmly established, similarities in outburst properties between V838 Mon and two other potential analogs, viz., V4332 Sgr and M31-RV, suggest that they could be unified into a new class of eruptive variables. While the cause for the intriguing outbursts in such objects is yet to be securely established, various mechanisms have been proposed, viz., the merger between main-sequence stars (Soker & Tylenda 2003), or a late flash in a born-again asymptotic giant branch (AGB) star (Lawlor 2005). Aspects relating to the spectral type of the progenitor and whether it is a single or binary star have also been the subject of investigations (Munari et al. 2005; Tylenda et al. 2005).

Here, we present our results on V838 Mon from GO Cycle 1 observations of the Spitzer Space Telescope. The highlight of the Spitzer observations is the striking infrared echo seen around V838 Mon in the mid- and far-IR images. While optical light echoes around novae or supernovae are rare but not unknown, an infrared “echo” is a rare complementary phenomenon—we are only aware of one other instance of a resolved infrared light echo, Cas A (Krause et al. 2005). When photons from the illuminating source interact with the dust grains of the echo material, they can either be absorbed or scattered according to the albedo of the grain. Photons scattered into the line of sight result in an optical light echo, a direct “image” of the impinging radiation. On the other hand, IR “echoes” result from the absorption of the impinging radiation; the thermalized energy of the absorbed photons is reemitted in the IR. Our observations are presented in § 2. Details of the nature of the IR emission are discussed in § 3. In § 4, the important question regarding the origin of the light echo material around V838 Mon is discussed.

2. OBSERVATIONS AND DATA REDUCTION

V838 Mon was imaged with the Multiband Imaging Photometer for Spitzer (MIPS; Rieke et al. 2004) at 24, 70, and 160 μm in 2004 and 2005. The log of the observations is given in Table 1.

The MIPS data were reduced using the Data Analysis Tool (DAT; Gordon et al. 2005). Images at 24, 70, and 160 μm are shown in the first column of Figure 1 (Plate 1). While at 24 μm V838 Mon appears as a bright point source (hard saturation in the core), extended nebulosity offset from the central star is readily apparent at 70 and 160 μm. Detailed comparison of the 24 μm radial profiles between the target and an observed standard star indicates that the profiles matched very well between the first bright and dark Airy rings, suggesting that most of the flux in the central region is from an unresolved source, and the extended nebulosity contributes very little flux at the core. To correct the saturation in the 24 μm image, an observed point-spread function (PSF) was scaled to match the brightness of the first bright Airy

---

1 Physical Research Laboratory, Navrangpura, Ahmedabad Gujarat 380009, India: orion@prl.res.in, ashok@prl.res.in.
2 Steward Observatory, University of Arizona, 933 North Cherry Avenue, Tucson, AZ 85721; ksu@as.arizona.edu, kmisselt@as.arizona.edu.
around V838 Mon is shown in Figure 3. Of our 70 μm observations, the total diffuse flux observed toward V838 Mon, obtained by subtracting the unresolved point-source flux from that measured in the 80′ aperture, is given in column (4) of Table 2. In order to compare our infrared images with the optical light echo, we have also obtained archival HST Advanced Camera for Surveys (ACS) images of V838 Mon (Hubble Heritage, GO/DD 10392). The data were obtained with the ACS/Wide Field Camera (WFC) using the F435W, F606W, and F814W filters and were completed on 2004 October 23, within days of our 24 and 160 μm observations and within a few months of our 70 μm observations. The F814W image convolved with the MIPS beams is shown in the third column of Figure 1 for comparison. A three-color composite image was constructed using all three HST filters and is presented in Figure 2 with our 24, 70, and 160 μm contours superposed. The 24–160 μm spectral energy distribution (SED) of the extended nebulosity around V838 Mon is shown in Figure 3.

3. SOURCE OF THE IR EMISSION

The infrared emission associated with V838 Mon consists of an extended component associated with the light echo and a compact, unresolved component spatially coincident with the central star. The unresolved component evident at 24 and 70 μm possibly indicates the condensation of newly formed dust around the central star of V838 Mon. Evidence that such a dust shell had formed after the outburst has already been seen from the mid-IR data of Lynch et al. (2004) in early 2003. These authors show the prominent presence of a 650 K component in their SED in the 8–13 μm region. The detection of water around V838 Mon (Banerjee et al. 2005), from near-IR data in 2002–2003, also supports the existence of a cool envelope at ~800 K. Our MIPS data for the unresolved component (Table 2, col. [3]) are consistent with a temperature T ≥ 100 K. However, a more detailed and accurate characterization of the properties of this unresolved component—such as determining its temperature more accurately, estimating the mass of the newly formed dust around the central star to get a better insight on how much mass is lost in V838 Mon-type of outbursts, and also a detailed study of its spectrum in the 5–40 μm region—will be undertaken in a separate study involving additional Spitzer data.

Simple energy arguments also support a thermal origin for the IR emission. During the first 2 months of its multipeaked outburst, when V838 Mon can be thought to have emitted most of its radiation in the form of a prolonged pulse, the star showed an SED well represented by effective temperatures between 5250 and 4250 K (Munari et al. 2002). The V magnitudes ranged from 10 to 6 during the outburst, corresponding to an energy flux output of the V band, corrected for reddening using E(B − V) = 0.5, of between 3.9 × 10^−15 and 1.6 × 10^−14 W cm^−2 μm^−1. Assuming a blackbody temperature of 5000 K and extrapolating to 160 μm, this results in ~10^−14 to 10^−13 W cm^−2 μm^−1 available from the outburst in the 160 μm band. However, our observed flux density at 160 μm of 17.53 Jy corresponds to an energy flux of ~2.0 × 10^−15 W cm^−2 μm^−1. Even if we unrealistically assume 100% scattering efficiency, the outburst provides 3–5 orders of magnitude too little energy to power the 160 μm emission through scattering alone. Thus, scattering is ruled out as the source of the infrared light echo. Instead, the heating of dust grains by optical and UV photons from the outburst pulse and the subsequent reprocessing of the absorbed energy into the thermal infrared remain the likely sources of the infrared light echo in V838 Mon.

4. ORIGIN OF THE IR ECHO MATERIAL: INTERSTELLAR OR CIRCUMSTELLAR?

The origin of the light echo material has been the source of some debate in the literature. Bond et al. (2003) and van Loon et al. (2004) suggest that the echo material has been produced in previous mass-loss episodes while, e.g., Tylenda (2004) has argued that the light echo material is interstellar in origin. This is an important aspect to address since it can help us establish whether the progenitor has undergone previous outbursts (e.g., AGB-like behavior; van Loon et al. 2004) or steady mass loss

### Table 1

| Date        | Instrument Array | λ (μm) | Δλ (μm) | Mode         | Exp. per Frame (s) | Cycles | Integration On-Source (s) | AOR Key |
|-------------|------------------|--------|---------|--------------|-------------------|--------|--------------------------|---------|
| 2004 Oct 14 | MIPS/24          | 23.7   | 4.7     | Fixed photometry | 3                  | 2      | 92.3                     | 10522624|
| 2005 Apr 01 | MIPS/70F         | 71     | 19      | Phot. w/ 8 clus. pointings | 10          | 2      | 612.5                   | 10523648|
| 2004 Oct 15 | MIPS/160         | 156    | 35      | Phot. w/ 4 clus. pointings | 3           | 2      | 50.2                     | 10523904|

### Table 2

| λ_{m} (μm) (1) | Flux Density (Jy) (2) | Core (3) | Extended (4) |
|----------------|----------------------|----------|--------------|
| 23.68          | 15.97                | 15.06    | 0.91         |
| 71.42          | 14.72                | 3.82     | 10.9         |
| 155.89         | 17.53                | ...      | 17.53        |

* Absolute calibration errors are 5%, 10%, and 10%, respectively.
* Total flux density, 80′ aperture.
* Unresolved point source from PSF fitting.
* Residual emission (total − PSF).
While the echo likely arises from material with a range of temperatures, we can use equation (1) and our measured MIPS flux densities. To estimate the mass of the emitting echo material observed by MIPS, we use equation (1) combined with a Monte Carlo technique to explore the range of temperatures and masses that can fit the data. Allowing a range of sizes from 0.1 to 1 μm and compositions (silicate and amorphous carbon; indices from Laor & Draine 1993 and Zubko et al. 1996, respectively), the derived temperatures and masses for the two components are \( -63_{-25}^{+45}/25_{-3}^{+4} \) K and 0.6\( \times 10^{-0.55} \times 10^{-7/1.6} \) \( M_\odot \), respectively, assuming a distance of 8 kpc. Estimates of the uncertainty in the derived mass of the light echo arises from the cold 25 K component that is reasonably well constrained in the fit in Figure 3. Even assuming a lower limit on the distance to V838 Mon of 5 kpc, the mass in the cold component must be \( \gtrsim 0.2 \) \( M_\odot \). As can be seen in Figure 3, the need for a large mass of colder dust is primarily driven by the 160 μm point. The close correspondence of the distribution of emission at 160 μm and the optical light echo (see the bottom row of Fig. 1 and the right panel of Fig. 2) argues that the cold emission is associated with the echo material; indeed, the emission at 160 μm rapidly falls off away from the echo location. Thus, the mass we are estimating from our IR flux measurements is directly associated with the echo material. With a gas-to-dust ratio of 100, we estimate the total mass of the material in the echo to be on the order of a few tens to a few hundred solar masses. At a distance of 8 kpc, the size of the IR echo is \( \sim 3 \) pc; a large diffuse interstellar cloud of this size may have a mass of a few tens of solar masses, while denser clouds could range up to a few hundred solar masses (Whittet 2003). Therefore, the observed mass of the echo material is consistent with an origin in interstellar material.

Conversely, it is extremely unlikely that a single previous outburst could have ejected a total mass of the order of 10 \( M_\odot \) or above. In nova eruptions, typically \( 10^{-7} \) \( M_\odot \) matter is ejected; an amount in the range \( 10^{-2} \) to \( 10^{-5} \) \( M_\odot \) is suggested from limits/estimates of the ejecta mass in V838 Mon (Banerjee & Ashok 2002; Rushton et al. 2003). Steady mass loss from the progenitor in the past also does not appear to be favored as the sole contributor to the echo matter. The radius of the emitting zone (\( R \)),

Fig. 2.—Morphological comparison between the optical and infrared light echo. The background is the three-color composite HST image from 2004 October 23 of the optical light echo around V838 Mon using F435W as blue, F606W as green, and F814W as red. Overlaid from left to right are the 24 (PSF-subtracted; see text), 70 (PSF-subtracted; see text) and 160 μm contours. Contours are 0.074 (1 σ), 0.11, 0.17, 0.26, 0.40, and 0.61 mJy arcsec\(^{-2} \) at 24 μm; 0.17 (3 σ), 0.28, 0.56, 1.23, 1.69, 2.26, 2.82, and 3.38 mJy arcsec\(^{-2} \) at 70 μm; and 0.52 (3 σ), 0.67, 0.87, 1.13, 1.46, 1.89 mJy arcsec\(^{-2} \) at 160 μm. The yellow line in the left image indicates a scale of 50″. All images are oriented with north up and east to the left.

Fig. 3.—The 24–160 μm SED of the extended component (light echo) of V838 Mon in late 2004 and early 2005. The filled circles are the observed flux densities of the light echo data (Table 2, col. [4]) that were fit by two modified blackbodies with temperatures of \( \sim 25 \) and \( \sim 63 \) K (dashed and dotted lines, respectively). The resultant sum of these fits is shown by the solid line. See the text for further details.
either derived from the light-travel distance since the outburst ∼2.75 yr ago or from the angular radius of the echo in 2004 December (70"
H11033
), is on the order of parsecs. The amount of matter that could have been lost in such a zone of radius R from a star with a wind velocity v, ejecting mass at a rate of 10−4 M⊙ yr−1, can then be easily computed. Even a massive AGB star with a high mass-loss rate of 10−3 M⊙ yr−1 (van Loon et al. 2005) in a slow wind with v = 10 km s−1 can only generate a total echo mass (gas plus dust) of ∼1 M⊙. Even this is just at the margin of the lower limits of our estimate for the echo material mass, and we are thus led to believe that a considerable part of the echo material is likely to lie in an intervening dust sheet. This is consistent with some of the models explaining the light echo expansion rate and observed morphological changes in the light echo (Tylenda 2004). However, our calculations do not completely preclude a component of circumstellar origin for the echo material; indeed, the presence of an unresolved core of emission at 24 and 70 μm argues that some of the material may well be “circumstellar” in origin.

5. CONCLUSION

We report the detection of a rare infrared “light echo” around the unusual variable V838 Mon. Our Spitzer data reveal both an unresolved hot component and an extended cooler component. The unresolved component is attributed to the formation of dust in the ejecta of the 2002 outburst. The extended component is spatially coincident with the optical light echo and is likely caused by thermal emission from dust heated by the energy of the outburst pulse. The large derived mass of the infrared light echo makes it unlikely that the echo material is the remnant of previous mass-loss episodes in V838 Mon but rather is interstellar material along the line of sight to V838 Mon.

We would like to thank the referee, J. T. van Loon, for comments that substantially improved the Letter. This work is based on observations made with the Spitzer Space Telescope, which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under NASA contract 1407. Support for this work was provided by NASA through contract 397230 issued by JPL at Caltech. Research at the Physical Research Laboratory is funded by the Department of Space, Government of India.

REFERENCES

Banerjee, D. P. K., & Ashok, N. M. 2002, A&A, 395, 161
Banerjee, D. P. K., Barber, R. J., Ashok, N. M., & Tennyson, J. 2005, ApJ, 627, L141
Bond, H. E., et al. 2003, Nature, 422, 405
Brown, N. J. 2002, IAU Circ. 7785
Crause, L. A., Lawson, W. A., Menzies, J. W., & Marang, F. 2005, MNRAS, 358, 1352
Deguchi, S., Matsumaga, N., & Fukushi, H. 2005, PASJ, 57, L25
Evans, A., Geballe, T. R., Rushton, M. T., Smales, B., van Loon, J. T., Eyres, S. P. S., & Tyne, V. H. 2003, MNRAS, 343, 1054
Gordon, K. D., et al. 2005, PASP, 117, 503
Henden, A., Munari, U., & Schwartz, M. 2002, IAU Circ. 7859
Kimeswenger, S., Lederle, C., Schmeja, S., & Armstron, B. 2002, MNRAS, 336, L43
Krause, O., et al. 2005, Science, 308, 1604
Laor, A., & Draine, B. T. 1993, ApJ, 402, 441
Lawlor, T. M. 2005, MNRAS, 361, 695
Lynch, D. K., et al. 2004, ApJ, 607, 460
Munari, U., et al. 2002, A&A, 389, L1
———. 2005, A&A, 434, 1107
Rettler, A., & Maron, A. 2003, MNRAS, 345, L25
Ricke, G. H., et al. 2004, ApJS, 154, 25
Rushton, M. T., Geballe, T. R., Evans, A., Smales, B., van Loon, J. T., & Eyres, S. P. S. 2005, MNRAS, 359, 624
Rushton, M. T., et al. 2003, A&A, 412, 767
Soker, N., & Tylenda, R. 2003, ApJ, 582, L105
Tylenda, R. 2004, A&A, 414, 223
Tylenda, R., Soker, N., & Szczepanek, R. 2005, A&A, 441, 1099
van Loon, J. T., Cioni, M.-R. L., Zijlstra, A. A., & Loup, C. 2005, A&A, 438, 273
van Loon, J. T., Evans, A., Rushton, M. T., & Smales, B. 2004, A&A, 427, 193
Whittet, D. C. B. 2003, Dust in the Galactic Environment (Bristol: IoP)
Zubko, V. G., Mennella, V., Colangeli, L., & Bussoletti, E. 1996, MNRAS, 282, 1321
First column of panels: MIPS 24, 70, and 160 μm images (top to bottom); second column: PSF-subtracted images (no point source detected at 160 μm; see text); third column: HST F814W image convolved to the MIPS resolution at 24, 70, and 160 μm images (top to bottom) after removal of field stars in the HST image. MIPS beam sizes are indicated by the white circles with an FWHM of 6′, 18′, and 40′, respectively. All images are displayed in a field of view of 160′ × 160′, with north up and east toward the left, and in false-color logarithmic scale with brightness and contrast adjusted for best presentation of each image. The displayed surface brightness (top to bottom) ranges from $10^{-3}$ to $10^{-1}$ mJy arcsec$^{-2}$ at 24 μm, $5 \times 10^{-3}$ to 8 mJy arcsec$^{-2}$ at 70 μm, $6 \times 10^{-3}$ to 2 mJy arcsec$^{-2}$ at 160 μm for the first column; and from $3 \times 10^{-3}$ to $5 \times 10^{-1}$ mJy arcsec$^{-2}$ at 24 μm and $3 \times 10^{-3}$ to 4 mJy arcsec$^{-2}$ at 70 μm for the second column.