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Hubble Space Telescope Observations of the Light Echoes around V838 Monocerotis

Howard E. Bond[1], Arne Henden[2], Zoltan G. Levay[1], Nino Panagia[1], William B. Sparks[1], Sumner Starrfield[3], R. Mark Wagner[4], R. L. M. Corradi[5], and U. Munari[6]

Abstract. The outburst of the unusual variable star V838 Monocerotis is being accompanied by the most spectacular display of light echoes in the history of astronomy. We have imaged the echoes on 5 occasions in 2002 with the *Hubble Space Telescope* and its Advanced Camera for Surveys. Analysis of the angular expansion rates and polarimetry data yields a direct geometric distance (6 kpc), and establishes that the star was extremely luminous at the maximum of its outburst. Unlike a classical nova, V838 Mon has remained a very cool red supergiant, and is now producing copious amounts of dust. The dust illuminated in the echoes was presumably ejected during previous similar outbursts. This event thus bears some similarities to the proto-PN ejection process from more normal AGB and post-AGB stars, and is of relevance to this conference. Light-echo imaging allows construction of fully 3-D maps of the dust distribution, and we present a map based on these early observations. The dust is already seen to be highly non-spherical and non-homogeneous, similar to the structure inferred for many proto-PNe.

1. The Light-Echo Phenomenon

A light echo is produced when a wave of illumination from a stellar outburst sweeps out into space. Due to the extra path length, light scattered off dust near the star arrives at the Earth after the light from the outburst itself. For a light echo to be seen, there are three requirements: (a) the star must vary rapidly in brightness, (b) the outburst must be of high intrinsic luminosity so as to illuminate nearby dust, and (c) there must, of course, be pre-existing dust, either circumstellar or interstellar, in the vicinity of the outbursting star. The

[1]Space Telescope Science Institute

[2]USRA and USNO Flagstaff

[3]Arizona State University

[4]Large Binocular Telescope Observatory

[5]Isaac Newton Group of Telescopes

[6]INAF-Osservatorio Astronomico di Padova

combination of all three is extremely rare, and there have been only a few light echoes observed in the history of astronomy. The most famous to date have been those around Nova Persei 1901 and SN 1987A. *Circumstellar* light echoes, such as the ones described here, are even rarer.

2. V838 Monocerotis

The outburst of V838 Mon, a previously unknown variable star, was detected by an amateur astronomer in January 2002. The light echoes were discovered in February 2002 by A. Henden, and quickly developed into the most spectacular display of light echoes ever seen. Prompted by the ground-based images, our team proposed for Director's Discretionary time on the *Hubble Space Telescope* (*HST*) and its Advanced Camera for Surveys (ACS) to obtain direct images and polarimetry of the echoes, and time was awarded on 5 occasions from April through December 2002.

Results from our observations have already been presented in the literature (Bond et al. 2003), and the color images from *HST* have been circulated widely (see http://hubblesite.org/newscenter/newsdesk/archive/releases/2003/10/), so we will not repeat those details here. Instead, we will concentrate on the issues relevant to the subject of this conference.

3. Geometry of Light Echoes

At a given time t after the stellar outburst, all of the illuminated dust lies on the paraboloid given by $z = x^2/2ct - ct/2$, where x is the projected distance from the star in the plane of the sky, z is the distance from this plane along the line of sight toward the Earth, and c is the speed of light. Hence at any given time, an illuminated dust element appearing to lie at any position in the plane of the sky must lie at an unambiguous distance z from the plane of the sky. Thus continued imaging of a light echo *allows an unambiguous three-dimensional map of the dust distribution around the star to be constructed.* This is the only such method available in astronomy to make such 3-D maps, and it is particularly relevant to the study of asymmetric PNe, where can cannot easily translate the 2-D appearance into the true 3-D structure.

In addition, light echoes provide two independent methods for a direct geometrical determination of the distance to the star. One method relies on apparent angular expansion rates of the echoes, and the other on polarimetry; see Bond et al. (2003) for details and references. The angular expansion rates at present give a lower limit to the distance to V838 Mon of 2 kpc, while the polarimetry indicates that the distance is in fact about 6 kpc. At such a distance, V838 Mon was extremely luminous at the peak of its outburst ($M_V \simeq -9.6$). The star was also nearly unique in that it was a very cool red supergiant throughout its outburst, making it completely different from a classical nova (which quickly exposes a very hot central source), and indeed different from all other known types of variable stars.

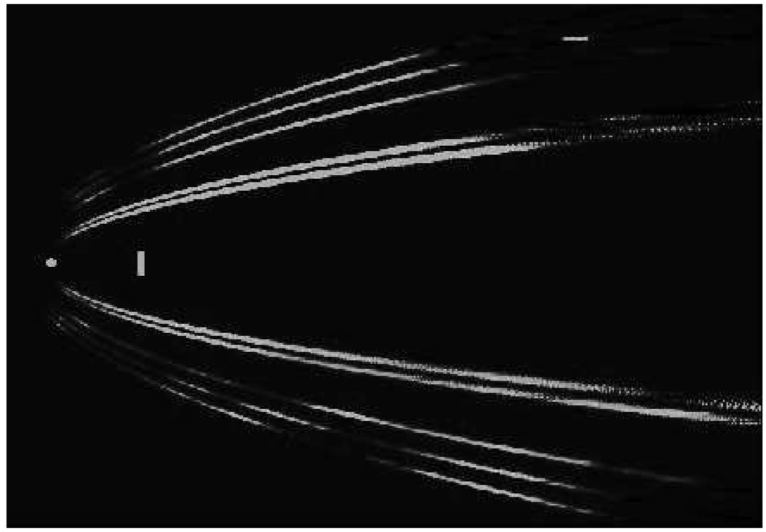

Figure 1. Map of the 2-D dust distribution around V838 Mon in an east-west plane containing the star, derived from 5 *HST* images. The star is the dot at the left, and the small scale bar to the right of the star is 0.1 pc high. The direction to the Earth is to the right. Intensity in the image is proportional to dust density.

4. Three-Dimensional Structure of the Circumstellar Dust

The illuminated dust around V838 Mon was, presumably, ejected during one or more previous episodes of expansion to a cool, somewhat AGB-like red supergiant. Thus, its 3-D structure may tell us something about the morphology of dust shells around AGB and post-AGB stars.

We are still early in the development of the echoes. A rough estimate is that they will be visible for the rest of this decade—indeed, the echoes are still in the phase of rapid apparent expansion. About halfway through the event, the expansion will convert to an apparent contraction, with the echoes eventually disappearing as the echo paraboloid grows to a size larger than the outer radius of the dust shell.

The mapping that is possible to date is thus confined to a relatively narrow region on the front side of the dust envelope. Fig. 1 shows an example of such a map; here we have taken an east-west cut through the 5 *HST* images and transformed these cuts into the corresponding 2-D map. Several interesting features are present in the map: (a) the star lies within a cavity, which is elongated in the E-W direction; (b) the dust distribution is highly non-spherical, e.g., it extends further toward the Earth on the bottom (E) side that on the W side; (c) there are density enhancements, especially along the two smallest paraboloids on the W side, that point roughly in the direction of the Earth, suggestive of a bipolar outflow or jet; (d) the outer edges of the dust shell are fairly sharp, indicating a sharp drop in dust density possibly corresponding to the onset of dust production in a previous outburst; and (e) there are numerous voids in the dust, suggestive of a "Swiss-cheese" structure.

Note that it will be several more years before the overall structural morphology of the dust becomes apparent. We are continuing to monitor the echoes from the ground (for example, Bond is observing it every two weeks with the CTIO 1.3-m telescope through an arrangement with the SMARTS telescope consortium), and of course we plan to propose additional monitoring with *HST* and ACS.

References

Bond, H. E. et al. 2003, Nature, 422, 405