V838 Monocerotis Light Echo







Pretty Good Novae: Transients Intermediate between Novae and Supernovae

Howard E. Bond Space Telescope Science Institute

July 15, 2005

STScI Summer Students





Pretty Good Novae: Transients Interm Novae and Super

Howard I Space Telescope S



"It's somewhere between a nova and a supernova -- probably a pretty good nova."

July 15, 2005

STScI Summe

Two case studies

Pretty Good Novae: Transients Interm Novae and Super

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Case Study 1: V838 Monocerotis Before & During 2002 Outburst



Outburst light curve (normalized brightness vs. time)



Normalized flux

Discovery of Light Echo Arne Henden, USNO Flagstaff 1m



Fig. 1. Expansion of the light-echo around V838 Mon, revealing a previously invisible ring of circumstellar material. U band 67 × 67 arcsec images obtained with the USNO 1 m telescope (North to top, East to the left). Dates (seeing in arcsec, U mag of central V838 Mon) from left to right: Jan. 13 (3.2", U = 13.33), Feb. 27 (2.3", U = 12.05), March 10 (2.5", U = 10.62) and March 27 (2.2", U = 12.28).

Hubble Space Telescope **Observations of V838 Mon Echo**

ACS direct images & imaging polarimetry in 2002, 2004, 2005, 2006
WFPC2 imaging 2007, 2008, 2009
Sep 2009 imaging with repaired ACS!

May 20, 2002



September 2, 2002



October 28, 2002



December 17, 2002



Animation (200-day time steps)



V838 Mon Light Echo HST + ACS WFC



November 2005 & September 2006

V838 Monocerotis Light Echo

HST - ACS/WFC



Feb 2007



V838 Mon HST WFPC2 Jan. 2008 F606W V

Jan

2008



V838 Mon HSTWFPC2 Sept. 2007 F606W V Sep 2007 Jan 2009

September 28, 2009 with repaired ACS



Detailed examination of the images shows numerous replicas of the outburst

Remember the light curve? Sharp blue peak, dip, broad red plateau:

















V838 Mon: the Movie (2002-6)



Distance from Polarimetry



Maximum linear polarization occurs for 90° scattering.

This dust lies at x = ct.

The corresponding angular separation from the star gives *d*.

(Sparks 1994)

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Distance from Polarimetry





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(Sparks 1994)

Distance from Polarin



90° scattering.

p

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The corresponding angular separation from the star gives *d*.

(Sparks 1994)

z (pc)

Percentlinearpolarization images

 $(Q^2 + U^2)^{1/2}/I$



Percentlinearpolarization images

 $(Q^2 + U^2)^{1/2}/I$



Percentlinearpolarization images

 $(Q^2 + U^2)^{1/2}/I$

50% linear polarization!



Azimuthally averaged linear polarization



Azimuthally averaged linear polarization



Arrow lengths proportional to time since explosion



Arrow lengths proportional to time since explosion

Setting angular ring radii to *ct* yields *d*



Polarimetric Distance Result (Sparks, Bond, Craycraft et al., 2008 AJ, 135, 605)



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• From September & December 2002 *Hubble* polarimetric observations, we find:

Polarimetric Distance Result (Sparks, Bond, Craycraft et al., 2008 AJ, 135, 605)

- From September & December 2002 *Hubble* polarimetric observations, we find:
- $d = 6.1 \text{ kpc} (\sim 20,000 \text{ light-years})$
Implications

At a distance of 6.1 kpc—
—V838 Mon is located on *outer fringes* of Milky Way
V838 Mon was *orthogoda luminous*

 —V838 Mon was *extremely luminous* during its outburst

Location in Milky Way



Red dot: Sun. Red star: Galactic center Filled circles: distances from trig parallaxes of methanol (blue) & H₂O or SiO masers (green) from Reid et al. ApJ 2009. **Background:** artist's conception of modern Galactic structure, based on Spitzer observations (R. Hurt, SSC)

Location in Milky Way



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The High Luminosity

- For *d* ~ 6.1 kpc, absolute visual magnitude of V838 Mon was *M_V* ~ -9.8
 - 600,000 times brighter than the Sun!
- One of the brightest stars in the entire Milky Way (temporarily)
 - brighter than all but the very brightest classical novae
 - but fainter than SN Ia or normal SN II

Unprecedented Nature of the V838 Mon Outburst

- Spectroscopy shows it was large and cool—a red supergiant—throughout outburst.
- Very unlike classical nova, which ejects outer layers and rapidly becomes blue.
 V838 Mon is *still* very luminous in the IR, and one of the coolest known stars (type L).

The next amazing fact... V838 Mon is a binary! Hot (B3 V) star + the cool outbursting star



MMT spectra, Wagner & Starrfield, fall 2002

Outburst Cartoon



Greg Bacon, STScI

Serendipity

We monitor the spectrum of V838 Mon with SMARTS 1.5m, Cerro Tololo/NOAO
By chance, neighboring star happened to lie on the slit, and proved to be B-type!
Subsequent spectra disclosed 2 further B stars in the vicinity (Afsar & Bond 2007)
⇒V838 Mon is in a *young* stellar cluster!



B Stars near V838 Mon

V838 Monocerotis Light Echo



B Stars near V838 Mon

V838 Monocerotis Light Echo



Cluster Distance & Age from Photometry & Spectral Classification (Afsar & Bond 2007)

- Spectral classification of the B stars: B3 V, B4 V, B6 V
- Combined with our photometry & mainsequence fitting, yields distance of 6.2 kpc

Cluster Distance & Age from Photometry & Spectral Classification (Afsar & Bond 2007)

- Spectral classification of the B stars: B3 V, B4 V, B6 V
- Combined with our photometry & mainsequence fitting, yields distance of 6.2 kpc
 - Superb agreement with the *HST*-based polarimetric result of **6.1 kpc**!
 - Cluster age < 25 Myr
 - Confirms that V838 Mon lies in Outer Arm

V838 Monocerotis Light Echo



V838 Monocerotis Light Echo



Pleiades cluster moved to 6100 pc

Pleiades cluster V838 Monocerotis Light Echo moved to 6100 pc

Pleiades cluster V838 Monocerotis Light Echo moved to 6100 pc V838 Mon if in Pleiades: ~-3.5 mag

The Dying of the Light



The Dying of the Light

Dylan

reading his poetry



mag











Stellar Cannibalism



Greg Bacon, STScI

Stellar Cannibalism



Greg Bacon, STScI; defaced by HEB

Stellar Cannibalism



Greg Bacon, STScI; defaced by HEB

Spectroscopic Changes



Spectroscopic Changes



Phase Space of Optical Transients





Kulkarni et al. *Nature* 2007

Outburst Mechanism Constraints and Puzzles

- V838 Mon objects become luminous red supergiants in weeks.
- Progenitors inconspicuous
- Occur in young & old populations
- V838 Mon in cluster too young to contain white dwarfs

Thermonuclear Energy Ruled Out?

Nova explosion of unusual type?

V838 did not behave like any known nova
Can't make a WD in < 25 Myr!

Core collapse?

M31 RV, M85 OT occurred in old populations

Thermonuclear Energy Ruled Out?

• Nova explosion of unusual type? - V838 did not behave like any known nova – Can't make a WD in < 25 Myr.</p> • Core collapse? - M31 RV, M85 OT occurred in old populations • LBV eruption? - No luminous star present before outburst

Gravitational Energy

• Stellar collision or merger (e.g. in an unstable triple) could provide observed energy output

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V838 Mon as a Stellar Merger?

- Antonini, Mendez, Kastner, Bond, Soker, Tylenda & Starrfield (*ApJ*, submitted)
- A merged pair should be rotating more rapidly than a normal red supergiant—
- —and thus might have chromospheric
 activity & emit X-rays
- Experiment: search for X-ray emission from V838 Mon with *XMM-Newton* satellite
 Success ! (?)

XMM-Newton Detection


FIG. 1.— HST image of the field centered on V838 Mon (the bright star at the center of the field) (Sparks et al. 2008) obtained in 2005 November 8 (greyscale) in the V filter (F606W) overlaid with contours from the broad-band (0.5 – 10 keV) XMM-Newton/EPIC image of the same field obtained in 2008 March (contours at 49, 66, and 83% of peak intensity.)



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Source absent in 2003 Chandra observation, and in Jan 2010 Chandra DD observation!



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Source absent in 2003 Chandra observation, and in Jan 2010 Chandra DD observation!

Antonini et al. 201

V838 Mon: Transient X-Ray Source?



Fig. 7.— Left panel: 6.8ks Chandra/ACIS-S image obtained in February 2003. Middle panel: full energy range for the XMM/EPIC (pn) image of the region surrounding V838 Mon obtained in 2008 March 17. Right panel: 25ks Chandra/ACIS-S image obtained in 2010 January 17. Red arrows indicate the position of V838 Mon. Blue and red circles indicate, respectively, field X-ray sources located $\approx 55''$ southwest and $\approx 35''$ southeast of V838 Mon that were detected in all three observations.

Antonini et al. 2010

Case Study 2: The 2008 Optical Transient in NGC 300



NGC 300 ©ESO

NGC 300 ©ESO

0

- Nearby (~1.9 Mpc) spiral
- Amateur B. Monard discovered new transient in May 2008, reaching 14.2 mag on May 15 (M_V ~ -12.5)
 - Spectrum obtained by HEB & F. Walter (SMARTS 1.5m) on 2008 May 15 similar to V838 Mon during its outburst (and also to a SN IIn, although much fainter)

NGC 300 Optical Transient First Spectrum



2008 May 15: SMARTS 1.5m, Bond & Walter

NGC 300 Optical Transient Spectral Evolution



SMARTS 1.5m, Bond et al. 2009, ApJ, 695, L154

NGC 300 Optical Transient Spectral Evolution



SMARTS 1.5m, Bond et al. 2009, ApJ, 695, L154

NGC 300 Optical Transient Spectral Evolution



SMARTS 1.5m, Bond et al. 2009, ApJ, 695, L154

Searching for the Progenitor:

Searching for the Progenitor: Archival *HST*/ACS images, 2002 & 2006



ACS image renditions: Rolly Bedin green circle radius 3"









 Pre-outburst *HST* images (Bedin & HEB) show no star at site brighter than ~28.5.
 – confirmed by our DD *HST* imaging on 6/9/08, showing precise location of transient

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 Pre-outburst HST images (Bedin & HEB) show no star at site brighter than ~28.5. - confirmed by our DD HST imaging on 6/9/08, showing precise location of transient • Is the NGC 300 event a V838 Mon-type outburst? We initially thought so, but... • ... its light curve proved to be very different...

NGC 300 OT Light Curve



Pre-outburst Spitzer Observation

Prieto et al. (ATel 1550, 5/29/08) reported that *Spitzer* observations showed a luminous mid-IR source *before* the outburst
Dust temperature of ~300 K, radius 300 AU
Luminosity suggests star of 10-15 M_☉

Pre-outburst Spitzer Image



Berger et al. 2009; IRAC RGB=8.0,5.8,4.5 µm

Spitzer Pre-outburst SED 2007 Dec 28



Prieto et al. 2008

The NGC 300 Progenitor

- Pre-outburst progenitor undetected in deep *HST* optical images...
 - ...but conspicuous in pre-outburst *Spitzer* images at 3.6 µm and longward
 - Conclusion: an outburst of a new kind on a heavily dust-enshrouded massive star
 - Strong Ca II & [Ca II] emission: vaporized dust (Prieto et al. 08; Smith et al. 09-10)

NGC 300 OT's Environment

Surrounding population contains stars formed in burst ~8–13 Myr ago, with MSTO at ~12–25 M_{\odot} (Gogarten et al. 2009).

HST/ACS CMD courtesy L. Bedin

black dots: entire ACS field red circles: within 2.5" of transient green stars: within 0.25"

2.5'' = 23 pc



HST/ACS CMD courtesy L. Bedin

black dots: entire ACS field red circles: within 2.5" of transient green stars: within 0.25"

2.5'' = 23 pc



NGC300 - WFC/ACS

HST/ACS CMD courtesy L. Bedin

black dots: entire ACS field red circles: within 2.5" of transient green stars: within 0.25"

2.5'' = 23 pc



NGC300 - WFC/ACS

Outburst Mechanism **Explosion or Eruption?** Proposals include-- Electron-capture SN from super-AGB star – LBV giant eruption - Extreme mass-transfer episode in a massive binary

Electron-capture SN?

- EC SNe may arise from stellar masses between those ending as SN II-P or WDs
 - $-M_{\rm init} \sim 6 10 M_{\odot}$
 - star burns C to make ONeMg core, which then collapses thru e-capture, producing weak SN
 - but..
 - No definite case of an e-capture SN known
 - Several identified SN II-P SNe progenitors were in this mass range
 - NGC 300 progenitor was likely >10 M_{\odot}

LBV Eruption?

- The recognized LBVs occur >20 M_{\odot}
- Eruptions occur on optically conspicuous stars that are able to exceed Eddington limit
 Outburst mechanism not well understood
 Do similar phenomena extend to lower masses and dust-enshrouded stars?

Which Was it?

Continued deep imaging may show whether NGC 300 survived outburst (LBV)...
...or did not (SN)
It's Becoming Trendy: Related Transients 2008-10

• NGC 300 OT-like events are not rare: - "SN" 2008S in NGC 6946: near-twin outburst of enshrouded luminous star - "SN" 2009ip & UGC 2773 OT-2009 also somewhat similar, but arose from optically luminous & variable LBV progenitors (Smith et al. 2010; Foley et al. 2010) "SN" 2010U in NGC 4214: $M_V \sim -12$

Summary

- V838 Mon & NGC 300 OT: prototypes of new classes of stars that rapidly expand to cool supergiants
- V838's multi-peaked light curve & X-ray flaring may support merger scenario
 - But stars can only merge once!
 - Where did the surrounding dust come from??
 - Is its association with a cluster having stars near the WD/SN boundary just a coincidence?

Summary cont'd

- NGC 300 OT & SN 2008S outbursts occurred in dust-obscured massive stars
 - Origin of the outbursts uncertain
- These classes of intermediate-luminosity events are not rare!
- They are examples of the **zoo of unanticipated new transients** that synoptic surveys will find in enormous numbers!

V mag at max at various distances

Located in	V838 Mon	NGC 300 OT
M31	15.0	11.7
M81	18.0	14.7
Virgo cluster	21.9	18.6
Coma cluster	25.4	22.1
z = 0.05	27.0	23.7

July 15, 2005

STScI Summer Students

HST V838 Mon Team

- Sumner Starrfield (Arizona State U)
- Zolt Levay, Nino Panagia, Bill Sparks, Misty Cracraft, Ben Sugerman, Rick White (STScI)
- Arne Henden (AAVSO)
- Mark Wagner (U Arizona)
- Romano Corradi (ING, La Palma, Canarias)
- Ulisse Munari (Padova)
- Lisa Crause (SAAO)
- Mike Dopita (ANU)
- H. E. Bond (STScI), PI

NGC 300 Team

- Rolly Bedin (STScI)
- Alceste Bonanos (STScI, now Nat'l Obs Greece)
- Roberta Humphreys (Minnesota)
- Berto Monard (Bronberg Obs, South Africa)
- José Prieto (Ohio State; now Hubble Fellow @ Carnegie Obs)
- Fred Walter (Stony Brook)
- H. E. Bond (STScI), PI

Nomenclature for outbursts lying between novae & supernovae? Nomenclature for outbursts lying between novae & supernovae?



"It's somewhere between a nova and a supernova -- probably a pretty good nova."

© S. Harris

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Read all about it...





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echoes of a strange star

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Reflected glory

Light echoes around V838 Monocerotis

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Tango Der Tanz der Gefühle lebt wieder auf

Borneo

Den Orang-Utans droht die Ausrottung

DIE SUCHE NACH DER SCHÖPFUNG

FOTOS VOM ANFANG DER ZEIT

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OCTOBER 14, 2006 PAGES 247-254 VOL. 170. NO. 16

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The Outburst of V838 Mon

- Previously unknown Milky Way variable
- Discovered by amateur
- Rose from ~16th to 10th mag in Jan 2002
- Rose another 4 mag in early Feb—unlike any previously known nova, supernova, or other variable star

Related Extragalactic Objects • M31 Red Variable ("M31 RV") -1988 outburst, reached $M_V \sim -9.5$ for several months, cool throughout - HST imaged site in 1999: only old bulge population is present (Bond & Siegel 2006) • M85 OT 2006-1 -2006 outburst, reached $M_V \sim -11.5$ (Kulkarni et al. 2007), cool throughout - M85 is an S0 galaxy in Virgo; old population

Energy-Filtered XMM Contours



Electron-capture SN?



mag

Electron-capture SN?



mag

Electron-capture SN?



mag

Hubble Space Telescope **Observations of V838 Mon Echo**

- *HST* direct images & imaging polarimetry obtained in April, May, Sep, Oct, & Dec 2002 —
- —using *HST*'s brand-new ACS
- Imaged again with ACS in Feb & Oct 2004 by Hubble Heritage team, Oct-Jan 2005-6, Sep 2006 by our team
- With WFPC2 in Feb & Sep 2007, Jan 2008, Jan 2009
 - Sep 2009 with repaired ACS!