THE RED NOVA-LIKE VARIABLE IN M31—A BLUE CANDIDATE IN QUIESCEENCE

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ABSTRACT

M31-RV was an extraordinarily luminous (∼10⁶ L☉) eruptive variable, displaying very cool temperatures (roughly 1000 K) as it faded. While this object’s peak luminosity matched or exceeded those of the brightest known classical novae, its red colors and cool spectra were very different from those of classical novae. The photometric behavior of M31-RV (and several other very red novae, i.e., luminous eruptive red variables) has led to several models of this apparently new class of astrophysical object. We list these models, which predict very red eruptions and very red remnants decades after the eruptions. One of the most detailed models is that of “mergebursts.” Mergebursts are (hypothetical) mergers of close binary stars, predicted to rival or exceed the brightest classical novae in luminosity, but to be much cooler and redder than classical novae, and to become slowly hotter and bluer as they age. This prediction suggests two stringent and definitive tests of the mergeburst hypothesis. First, there should always be a cool red remnant, and NOT a hot blue remnant at the site of such an outburst. Second, the inflated envelope of a mergeburst event should be slowly contracting; hence, it must display a slowly rising effective temperature. We have searched the location of M31-RV in multiple observatory archives. Our search revealed a luminous, UV-bright object within 0″4 (1.5σ of the astrometric position) of M31-RV in archival WFPC2 images taken 10 years after the outburst. Recent Hubble imagery, 20 years after the outburst, determines that this object is still hot and fading; it remains much too hot to be a mergeburst. Furthermore, the effective temperature of this object is declining, contrary to the prediction for mergebursts. If we have correctly identified M31-RV’s remnant, it cannot be a mergeburst—but its behavior is consistent with theoretical nova models which erupt on a low-mass white dwarf. Future Hubble UV and visible images could determine if the M31-RV analogs (in M85 and in M99) are also much more blue than mergeburst theory predicts, and if they, too, are cooling in contradiction to mergeburst theory.

Key words: binaries: close – galaxies: stellar content – novae, cataclysmic variables

1. INTRODUCTION

One of the most puzzling stellar eruptions ever detected is due to the object known as M31-RV. This variable, in the nuclear bulge of M31 (Rich et al. 1989), brightened in mid-1988 to almost 10⁶ L☉. At the peak of its outburst, it rivaled the most luminous stars in the Local Group, and was as bright as the brightest classical nova ever seen. The 2–3 month interval that M31-RV spent brighter than MBol = −6 is consistent with it being a very luminous nova. The old stellar population at the site of M31-RV is also consistent with the classical nova hypothesis (Bond & Siegel 2006). However, as M31-RV faded, its spectrum evolved from that of an M0 supergiant to M5 and then to late M (Rich et al. 1989; Mould et al. 1990). Fading classical novae are not expected to display M supergiant colors or spectra. On the contrary, after ejecting mass of order 10⁻³ M☉ via a thermonuclear runaway on their surface, many models of classical nova white dwarfs remain hotter than 10⁵ K (Yaron et al. 2005; Prialnik et al. 1979) for decades. Thus post-novae are expected to be hot and blue. In Figures 1 (a) and (b), we show the time-dependent luminosities and temperatures of the erupting white dwarf in a nova model.

Some old novae are indeed observed to remain very hot for years, while others eject their envelopes quickly and cool on a timescale of a year or less, as shown by Vanlandingham et al. (2001) and Orio (2006). The values of all of the reddening-corrected, optical, and near-infrared colors of decades-old novae tend to cluster around 0 (Szkody 1994). This is because the optical emission from old novae is usually dominated by the binary system’s accretion disk, displaying an effective temperature of about 10 kK. The spectra of M31-RV are representative of much cooler material (1000–3000 K). If M31-RV was not a nova, then what could it have been?

An even more luminous but similarly red variable in the Virgo cluster galaxy M85 (Kulkarni et al. 2007) was seen in 2006. Like M31-RV, the M85 optical transient (M85-OT) was not associated with any bright star-forming region (Ofek et al. 2008). The g- and z-band absolute magnitudes of the progenitor were fainter than about −4 and −6 mag, respectively, corresponding to an upper limit for a progenitor (main sequence) mass of 7 M☉.

Another remarkably luminous “red nova” has recently been detected in the Virgo spiral galaxy M99 (Kasliwal & Kulkarni 2010).

V838 Mon is the best-studied Galactic eruptive variable which rivals M31-RV and M85-OT in outburst peak luminosity; it was also very cool and red as it faded; many details are reported in Corradi & Munari (2007). This object resembled M31-RV both in luminosity and spectral evolution, cooling to an L-type supergiant (Lynch et al. 2004) and displaying both a dust shell and an extended, evolving light echo (Munari et al. 2002). However, the stellar environments of M31-RV and M85-OT stand in sharp contrast to that of V838 Mon (Bond et al. 2003). V838 Mon has been associated with a group of B stars, and is unresolved by the Hubble Space Telescope (HST) at the 0″2 level from a B3 dwarf, though the progenitor of the eruptive variable was not luminous (Afsar & Bond 2007). Since V838 Mon seems to be coeval with the B stars, it must be far too young to have evolved into a nova binary system. The deep eclipses of the B3V star noted by Munari et al. (2007b), Goranskij et al.
(2008), and Kolka et al. (2009) are suggestive of accretion and interaction in a wide binary. Do V838 Mon and other very red, luminous eruptive variables represent a new and rare class of astrophysical object? The photometric and spectroscopic behaviors of the red nova outbursts are very similar, as noted by Munari et al. (2007a) and Boschi & Munari (2004). The frequently claimed inability of classical novae to produce cool, red spectra and the young environment of V838 Mon have led to a plethora of alternative models. These include the planet-capture model (Retter & Marom 2003; Retter et al. 2006), born-again objects (Lawlor 2005), a thermonuclear shell flash in the outer layers of a highly evolved, young massive star (Munari & Hendon 2005), a low-mass asymptotic giant branch (AGB) star experiencing thermal pulses going into the post-AGB phase (van Loon et al. 2004), a mass-transfer episode from an extreme AGB star to a main-sequence companion (Kasliwal & Kulkarni 2010), and the electron-capture supernova model (Botticella et al. 2009). Most of these models have been extensively reviewed and critiqued by Soker & Tylenda (2006), who maintain that all but one fail to explain the extensive observations of V838 Mon and M31-RV. That one notable exception is the mergeburst model (Soker & Tylenda 2006), which describes the merger of two stars. A significant fraction of the energy released during such a merger must inevitably swell the merger product envelope, cooling it to 2000 K or less. To quote Soker & Tylenda (2006): “Violent and luminous mergers, which we term mergebursts, can be observed as V838 Monocerotis-type events, where a star undergoes a fast brightening lasting days to months, with a peak luminosity of up to $10^6 L_\odot$ followed by a slow decline at very low effective temperatures.” These clean, simple predictions are testable, and they sharply differentiate the mergeburst model from models of classical novae.

A white dwarf which powers a classical nova is inevitably left with a thin, very hot shell of hydrogen after mass ejection ends. Thus, the central stars of classical novae initially display high effective temperatures and appear very blue after their eruptions subside and their ejecta become optically thin. As the remnant hydrogen-rich shell on its white dwarf cools, the effective temperature displayed by an old nova must decrease, and the system must become much redder on a timescale of decades. The two key mergeburst observables behave in opposite fashion: a mergeburst’s bloated envelope must initially produce a cool, red remnant, and that remnant must get hotter (on a timescale of millennia) as the swollen envelope contracts (Soker & Tylenda 2006). This sharp contrast in behavior suggests that recovery of M31-RV, M85-OT, and similar objects years and decades after their eruptions can be a crucial test of the mergeburst models.

In the next section, we note the satellite and ground-based images that we have examined in a search for the remnant of M31-RV, and show evidence for a very luminous, variable blue star at its position. We then present a new series of HST images of this star, showing both its current blue color and continued fading. Just as important, the longer baseline we now have shows that our M31-RV candidate is unquestionably cooling. Both of these observations suggest that M31-RV and V838 Mon may be very different phenomena. Both of these observations are in disagreement with the predictions of the mergeburst scenario. We compare the observations of M31-RV to the theoretical predictions of new classical nova models, and find remarkably good agreement. We conclude by outlining future observations to further test these models’ predictions. An accompanying paper (Shara et al. 2010) details new nova models (with very massive WD envelopes) which mimic, with considerable fidelity, the “red nova” M31-RV.

2. M31-RV’S POSITION

We have searched ground-based telescopes’ archives for images of M31-RV in quiescence. The very best available are those from the Canada–France–Hawaii Telescope (CFHT), with seeing in the 0.5" range. Even these images are hopelessly confused by the severe crowding in M31. We have also searched the Galaxy Evolution Explorer (GALEX) far-ultraviolet (FUV)
Figure 2. (a) This image is taken with the F435W filter and HST/ACS/WFC in 2003. The circled objects are sources which are easily identified in the images (a) and (b). The square region is the area in the close-up images in Figure 3. (b) This image is taken with the F435W filter and HST/ACS/WFC in 2004. These sources allow us to pinpoint the position of our candidate Red Variable in the F300W which is the circled object in the center of the square. The scale bar at the top left is 5′′. (c) This image is taken with the F300W filter and HST/WFPC2 in 1994. The circled objects are sources which are easily identified in both images (a) and (b). The scale bar at the top left is 5′′. (d) This image is taken with the F170W filter and HST/WFPC2 in 1994.

Table 1

| Instrument | Filter | Exposure Time (sec) | Date (mm/dd/yyyy) | MJD       | Magnitude       |
|------------|--------|---------------------|--------------------|-----------|-----------------|
| WFPC2      | F814W  | 10400.0             | 07/24/1999         | 51382.81612849 | 23.28 ± 0.03   |
| WFPC2      | F814W  | 2400.0              | 07/26/2008         | 54673.70436972 | 22.95 ± 0.05   |
| WFPC2      | F555W  | 7200.0              | 07/23/1999         | 51382.55293404 | 23.34 ± 0.03   |
| WFPC2      | F555W  | 800.0               | 07/26/2008         | 54673.71409194 | 23.39 ± 0.06   |
| ACS/WFC    | F435W  | 2200.0              | 12/25/2003         | 52998.89373337 | 24.47 ± 0.02   |
| ACS/WFC    | F435W  | 2200.0              | 10/02/2004         | 53280.17994121 | 24.25 ± 0.02   |
| WFPC2      | F439W  | 1600.0              | 07/26/2008         | 54673.72034194 | 23.86 ± 0.1    |
| WFPC2      | F300W  | 2600.0              | 12/05/1995         | 50056.18491969 | 21.40 ± 0.1    |
| WFPC2      | F300W  | 2400.0              | 07/26/2008         | 54673.7278639  | <24.2           |
| WFPC2      | F170W  | 10800.0             | 12/05/1995         | 50056.25366969 | Not detected    |
| ACS/SBC    | F140LP | 2552.0              | 07/26/2008         | 54674.43248819 | Not detected    |
and near-ultraviolet (NUV) images of M31. While there are a few FUV pixels significantly above background at the position of M31-RV, the 6′ pixels of this satellite are far too coarse to yield a reliable detection. There are no X-ray sources close to the position of M31-RV. We conclude that only with the HST is there any realistic chance of resolving and recovering the remnant of M31-RV.

A position for M31-RV (with a 1σ error of 0.′27) has been determined by Bond & Siegel (2006) from archival CCD frames of that star in eruption. This was done with three Kitt Peak National Observatory (KPNO) CCD frames, showing M31-RV in eruption. These frames were used to determine a position for the variable, accurate to 0.′04 in each coordinate, relative to nine bright astrometric stars in the NOMAD catalog (Zacharias et al. 2004). The same nine stars were located on deeper KPNO 4 m telescope frames, which were then matched to several epochs of HST images of the same field in M31.

Because the results of this investigation depend critically on the accuracy of the astrometric position that we can determine for M31-RV, D.Z. has independently re-measured the position of M31-RV. The same CCD frames of M31-RV in eruption (taken by R. Ciardullo; see Bond & Siegel 2006 for details) were analyzed in a similar fashion as above, except that different astrometric standard stars were located on deep CFHT archival images, which were in turn matched to HST images of the same field in M31. The position determined by D.Z. is 00:43:02.438 and +41:12:56.24 (J2000). The M31-RV position determined by Bond & Siegel (2006) is 00:43:02.433 and +41:12:56.17 (J2000). This excellent agreement (to within 0.′09), using independently selected astrometric standard stars and different archival 4 m telescope images, strongly supports both the 0.′27 error and the position of M31-RV claimed by Bond & Siegel (2006), both of which we adopt.

3. THE ARCHIVAL HST DATA AND BLUE CANDIDATE

Table 1 details all available HST images covering the field of M31-RV. Figures 2(a)–(d) are HST archival images of the neighborhood of M31-RV. Figures 2(a) and (b) were taken in 2003 and 2004 through the blue filter F435W with the
Advanced Camera for Surveys (ACS), while Figures 2(c) and (d) were taken in 1995 through the two UV filters F300W and F170W (with the Wide Field and Planetary Camera (WFPC2)), respectively. The extraordinary crowding in M31 is apparent, especially in Figures 2(a) and (b). The archival F300W and F170W images are much shallower, but enough objects are seen in common (and circled in both images) that there is no doubt that we are looking at the identical field in each filter, and that this field corresponds to the position of M31-RV determined in the previous section.

Figures 3(a)–(d) are archival HST images taken at different epochs and with different filters, of the part of Figure 2 that is indicated with a square. The astrometric position of M31-RV (Bond & Siegel 2006) is indicated with an “x,” with 1σ and 3σ error circles surrounding that position. It is clear in Figure 3(a) that a very bright star was present within 1.5σ (0′′.41) of that astrometric position for M31-RV in 1994, about seven years after the eruption. The star appeared in the HST F300W (U band) images at m(F300W) = 21.4. This corresponds to an unreddened absolute magnitude M(F300W) = −2.6 or 1000 L⊙ (in excellent agreement with the luminosity predicted in Figure 1(a) for a nova seven years after outburst). The observed reddening of globular clusters near the nucleus of M31 (next paragraph) suggest a dereddened M0(F300W) that is at least a magnitude more luminous. Unfortunately, these F300W images have never been repeated, and the same field was not imaged in other filters in 1999. The rarity of such luminous and hot, UV-bright objects in M31 is immediately apparent from Figure 3(a). A main-sequence dwarf star would have to be of early-type B (with a mass of at least 8 M⊙) to be this luminous, and display U − B (∼−0.3), B (∼21.7), and an effective temperature of at least 20 kK.

Five years later, in 1999, the same object appeared at m(F555W) = 23.33 and m(F814W) = 23.28, corresponding to V − I = 0.05. Most globular clusters close to the nucleus of M31 display 0.3 < E(V − I) < 0.5 (Barmby et al. 2000), so that (V − I)⊙ for the blue star we are considering is in the range −0.25 < (V − I)⊙ < −0.45. This immediately implies a photospheric temperature T > 40 kK, far too blue and hot for any mergeburst model (with expected apparent temperatures of 1000–3000 K). Even ignoring reddening, the observed color in 1999 (about 10 kK) of our candidate for M31-RV rules it out as a mergeburst. The apparent luminosity (∼250 L⊙) of the object in 1999 is again in good agreement with that expected from a nova 11 years after eruption, as shown in Figure 1(a).

Finally, the object was seen at m(F435W) = 24.1 in both 2003 and 2004, so (at least during that one year long interval) it was nearly constant in brightness at about 100 L⊙. This is again in reasonable agreement with Figure 1(a), which also shows that an old nova is expected to fade only very slowly once it is 15–16 years past eruption.

The object must be variable. If not, we could then derive its color from the 1994 (F300W) and 2004 (F435W) magnitudes. The resulting F300W–F435W color is −2.7, which is unphysical. It is possible that the unphysical color noted above is due to strong emission lines in the ejecta spectrum. Clearly, it is important to image this object simultaneously in multiple passbands to determine its present colors, effective temperature, and luminosity. If our candidate is M31-RV and it was a mergeburst, then it must slowly get hotter as its bloated envelope contracts. Conversely, if our candidate for M31-RV was a classical nova, then it must continue to fade and to cool on a timescale of decades in accordance with Figures 1(a) and (b).

Figure 4 is our F555W versus F555W–F814W color–magnitude diagram of the field of M31-RV, taken in 1999. This is the only HST archival epoch where images in two colors are simultaneously available. Our candidate stands out as the brightest (and by far the UV-brightest) object in its vicinity.

Of course it is always possible that our blue candidate might have nothing to do with M31-RV. We can rule out a background supernova as it would have faded away completely between 1994 and 1999. We can rule out an M31 RR Lyrae star as the object seen in 1994 is much too luminous to be one. We can also rule out the planet-capture model, born-again objects, a thermonuclear shell flash in the outer layers of a highly evolved, young massive star, a low-mass AGB star experiencing thermal pulses going into the post-AGB phase, and a mass-transfer episode from an extreme AGB star to a main-sequence companion; all of these models leave very cool remnants that are far redder than the blue object we have described at the site of M31-RV.

We cannot rule out an erupting intergalactic dwarf nova that lies between the Milky Way and M31, within 0′′.41 of M31-RV. Barring this unlikely coincidence we conclude, on the basis of color and brightness, that M31-RV could well be an old nova, and that it cannot be a mergeburst, or any of the other models listed above. The hypothesis that M31-RV is the prototype of a new class of astrophysical phenomenon—mergebursts—is refuted by the 1999 color of the observed remnant if our candidate is, in fact, M31-RV.
4. NEW HST OBSERVATIONS

To further constrain the nature of M31-RV we requested, and were granted, five orbits of HST time to re-observe M31-RV on 2008 July 26. A log of our new observations is given in Table 1. The aging WFPC2 camera of HST did not enable us to image quite as deeply as at previous epochs, but the new data are still extremely useful in characterizing M31-RV two decades after it erupted. A mosaic of the F300W, F435W, F555W, and F814W images is shown in Figure 5.

Comparing Figure 3(a) with Figure 5(a) we see, in the F300W images, that the UV-bright object seen 0.41′′ from the nominal position of M31-RV in 1995 has faded almost to the WFPC2 detection limit in 2008. The fading object is at least 2.8 mag (a factor of 13.2) fainter in 2008 compared with 1995. This rules out a luminous field star that is not highly variable. It supports the suggestion that this variable is really M31-RV. The object became considerably redder, too; it displayed $V - I = 0.05$ in 1999 and $V - I = 0.44$ in 2008. The importance of this color change cannot be overstated. A mergeburst must slowly become hotter as its bloated envelope contracts. M31-RV is observed to have become much cooler.

The corresponding dereddened values for M31-RV are $-0.45 < (V - I)_0 < -0.25$ and $-0.06 < (V - I)_0 < 0.08 < 0.14$. The 2008 $(B - V)$ color is 0.47, corresponding to $0.07 < (B - V)_0 < 0.35$. The latter dereddened (2008) values of $(V - I)_0$ and $(B - V)_0$ correspond to an early A star, with an effective temperature ~8000 K, still far too hot for a mergeburst. The largest published compilation of old nova colors is that of Szkody (1994). She showed that the dereddened values of $(B - V), (V - R),$ and $(V - J)$ all cluster around zero, corresponding to an effective temperature of ~10 kK, in agreement with what we observe for our candidate. A very red mergeburst would display colors with values $>2$.

While our candidate has faded dramatically in the F300W filter, it has remained essentially constant in the F435W, F555W, and F814W filters (compare Figures 3(b), (c), and (d) with Figures 5(b), (c), and (d), respectively, and see Table 1 and Figure 6).

5. A SECOND LOOK AT CLASSICAL NOVAE

The observations reported here of M31-RV’s observed colors are very problematic for all of the models except the nova
model listed in the introduction. The observation that M31-RV’s Galactic counterpart V838 Mon appears to be a member of a young group of B stars is very problematic for a classical nova model for V838 Mon. It is not inconceivable that there are two different phenomena at work—a mergerburst in the case of V838 Mon and an extreme classical nova in the case of M31-RV.

Thus, carrying out a reexamination of the nova model is in order to see if the extremely red colors and high luminosity of M31-RV can be produced by a classical nova.

The outburst characteristics of a nova (peak brightness, ejected mass and velocity, color, and temperature) are determined by the underlying white dwarf mass, temperature, and accretion rate. The most extensive set of nova simulations covering these three parameter values is due to Yaron et al. (2005).

Both they and Iben & Tutukov (1994) noted that a little-studied parameter in these models is the rate at which material is ejected from the nova, the mass accretion rate. The most extensive set of nova simulations covered by the underlying white dwarf mass, temperature, and accretion rate, cold white dwarf) leads to unusually massive hydrogen envelopes ($\sim 10^{-3} M_\odot$) before an eruption occurs. As they slowly expand, these massive shells remain optically thick to radii of order 10 times larger than those of most other novae (with shells of order 100 times more massive). This can account qualitatively for the very cool, red spectra of objects like M31-RV without invoking new astrophysical phenomena.

These new nova models do not yet include opacities appropriate for the very low temperatures (1–5 kK) observed in M31-RV, and thus produce peak luminosities that are still a factor of two less than those observed in M31-RV. At the low temperatures observed in M31 RV’s ejecta, recombinations decrease the number of free electrons dramatically, with a consequent decrease in the ejecta opacity. This decrease in opacity would permit the rapid “leakage” of photons out of the expanding, cool envelope that would give rise to luminosity spikes of up to $10^4 L_\odot$ (Shara et al. 2010).

5.1. Summary and Conclusions

We have shown that, in 1994, a very luminous ($\sim 1000 L_\odot$), UV-bright candidate existed very close to the site of the 1988 eruption of M31-RV. We have also been able to follow up with sufficient sensitivity with $HST$ to show that the same blue object was at least 13 times fainter in F300W in 2008 than it was in 1994. Over the past 20 years the object has not only faded, but it has also become much redder as predicted and observed for old novae. The extremely blue colors of M31-RV (at least 40 kK in 1999 and about 8 kK in 2008) are incompatible with all the models proposed for V838 Mon (including models of mergerbursts), but in agreement with models and observations of post-novae.