HUBBLE SPACE TELESCOPE IMAGING OF THE OUTBURST SITE OF M31 RV. II.
NO BLUE REMNANT IN QUIESCENCE*

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ABSTRACT
M31 RV is a red transient that erupted in 1988 in the Andromeda bulge, reaching a luminosity intermediate between novae and supernovae. It was cool throughout its outburst, unlike a normal classical nova. In 2006, Bond & Siegel examined archival Hubble Space Telescope (HST) optical images of the M31 RV site, obtained in 1999. We found only old red giants at the site and no stars of unusual color. However, Shara et al. recently claimed to have detected (1) a bright UV source within the error box in HST UV images taken in 1995, (2) a hot \( (T_{\text{eff}} > 40,000 \text{ K}) \) optical source in the same 1999 images that we examined, and (3) cooling of this source from 1999 to 2008. Shara et al. argue that this source’s behavior is consistent with a classical-nova outburst occurring on a low-mass white dwarf. I have re-examined all of the HST frames, including new ones obtained in 2009–2010. I find that (1) the bright 1995 UV source reported by Shara et al. was actually due to cosmic rays striking the same pixel in two successive exposures; (2) the claim that an optically bright star in the error box is very hot is actually due to misinterpretation of red-giant colors in the STmagnitude system; (3) there is no evidence for variability of any source within the error box from 1999 to 2010; and (4) there are no stars of unusually blue or red color in the error box. Our 2006 conclusions remain valid: either M31 RV had faded below HST detectability by 1999, or its remnant is an unresolved companion of a red giant in the field, or the remnant is one of the red giants.

Key words: stars: individual (M31 RV, V838 Mon, V1309 Sco, V4332 Sgr, NGC 300-OT-2008) – stars: variables: general

1. INTRODUCTION: INTERMEDIATE-LUMINOSITY RED TRANSIENTS
Over the past several years, several new classes of outbursting objects have been recognized, having maximum luminosities intermediate between those of classical novae and supernovae, and eruptions lasting several weeks to a few months. These transients typically become very red as their outbursts progress. I will call them “intermediate-luminosity red transients” (ILRTs). They have alternatively been designated “luminous red novae” (e.g., Kasliwal et al. 2011 and references therein). This terminology might suggest that the events belong to a subclass of ordinary novae.

The Galactic variable star V838 Monocerotis is a prototypical ILRT. Its 2002 eruption illuminated a spectacular light echo (Bond et al. 2003; Bond 2007) from which a geometric distance was obtained (Sparks et al. 2008), implying an absolute magnitude at maximum of \( M_V = -9.8 \). V838 Mon became very red during its outburst, eventually enshrouding itself in circumstellar dust. The mechanism producing its eruption remains controversial, but it has been argued that it was due to a stellar merger (e.g., Soker & Tylenda 2006; Corradi & Munari 2007, and references therein).

New support for the stellar-merger hypothesis for at least some ILRTs comes from the recent discovery (Tylenda et al. 2011) that the progenitor of the 2008 Galactic ILRT V1309 Scorpii was a short-period contact binary. Similarities between the outbursts of V1309 Sco and V838 Mon had been pointed out earlier by Mason et al. (2010).

However, in the past three years, several ILRTs have occurred in external galaxies, and clearly had an origin in heavily dust-enshrouded massive stars. Two of the best-studied members of this class are the 2008 optical transient (OT) in the nearby galaxy NGC 300, designated NGC 300-OT-2008 (Bond et al. 2009; Berger et al. 2009), and SN 2008S in NGC 6946 (Thompson et al. 2009; Smith et al. 2009). Both NGC 300-OT-2008 and SN 2008S were identified with luminous mid-IR sources in pre-outburst Spitzer Space Telescope images (Prieto 2008; Prieto et al. 2008); however, NGC 300-OT-2008 and SN 2008S were both extremely faint in the optical band before their eruptions (Bond et al. 2009; Prieto et al. 2008). The outbursts of these dust-obscured objects may thus be related to the eruptions of luminous blue variables, and it is unclear whether they are connected to lower-luminosity ILRTs such as V838 Mon and V1309 Sco. Experiments like the Palomar Transient Factory are now finding ILRTs in nearby galaxies in large numbers (e.g., Kasliwal et al. 2011 and references therein). Amateur astronomers are also continuing to contribute discoveries; the discoverer of NGC 300-OT-2008 recently found a second ILRT in the same galaxy, designated SN 2010da (Monard 2010), which was also a luminous mid-IR source before its eruption (Khan et al. 2010). These objects are sometimes called “supernova impostors,” having luminosities at maximum several magnitudes fainter than true supernovae (e.g., Van Dyk 2005).

2. M31 RV, THE M31 RED VARIABLE
One of the earliest ILRTs to be recognized had its eruption in 1988. This event occurred in the nuclear bulge of the Andromeda Galaxy, M31; it was discovered independently by Rich et al. (1989), Bryan & Royer (1992), and Tomaney & Shafter (1992). Its maximum luminosity \( M_{\text{bol}} \simeq -10 \) (Rich et al. 1989) was somewhat brighter than that of the most luminous classical nova, but the transient remained cool and red throughout its ~3-month eruption. Thus, its behavior was completely different from that of a nova, in which an extremely hot and blue
remnant is quickly revealed as the ejected envelope expands and becomes optically thin. This transient was, however, rather similar in luminosity, outburst duration, and color evolution to V838 Mon. This remarkable object has been called the “M31 red variable,” or “M31 RV.” Unfortunately, M31 RV was not observed extensively during its outburst; the available information is summarized in Bond & Siegel (2006; hereafter Paper I) and Shara et al. (2010b; hereafter SZPYK10), and in references therein.

M31 RV appears to belong to a subclass of ILRTs that arise from old populations. Another possible member of this subclass is M85-OT-2006 (Rau et al. 2007; Kulkarni et al. 2007), which occurred in an S0 galaxy lacking obvious signs of massive stars. V1309 Sco, along with another Milky Way ILRT, V4332 Sgr (Martini et al. 1999), also do not appear to be associated with V1309 Sco, along with another Milky Way ILRT, V4332 Sgr occurred in an S0 galaxy lacking obvious signs of massive stars.  

Table 1

| Date (UT)         | Camera   | Filter  | Total Exp. Time (s) | Program ID/PI |
|-------------------|----------|---------|---------------------|---------------|
| 1995 December 5   | WFPC2/WF | F170W   | 10800               | 6255/King     |
|                   |          | F300W   | 2600                |               |
| 1999 July 23–24   | WFPC2/PC | F555W   | 7200                | 8018/Green    |
|                   |          | F814W   | 10400               |               |
| 2003 December 25  | ACS/WFC  | F435W   | 2200                | 10006/Garcia  |
| 2004 October 2    | ACS/WFC  | F435W   | 2200                | 10006/Garcia  |
| 2008 July 26      | WFPC2/PC | F300W   | 2400                | 11546/Shara   |
|                   |          | F439W   | 1600                |               |
|                   |          | F555W   | 800                 |               |
|                   |          | F814W   | 2400                |               |
| 2008 July 27      | ACS/SBC  | F140LP  | 2552                | 11546/Shara   |
| 2009 December 7   | WFC3/UVIS| F555W   | 1707                | 11716/Bond    |
|                   |          | F814W   | 987                 |               |
| 2010 July 23      | ACS/WFC  | F475W   | 1720                | 12058/Dalcanton |
|                   |          | F814W   | 1520                | 12058/Dalcanton |
| 2010 July 25      | ACS/WFC  | F475W   | 1720                | 12058/Dalcanton |
|                   |          | F814W   | 1520                | 12058/Dalcanton |
| 2010 December 24  | WFC3/UVIS| F275W   | 1010                | 12058/Dalcanton |
|                   |          | F336W   | 1350                | 12058/Dalcanton |
| 2010 December 25–26| WFC3/IR | F110W   | 799                 | 12058/Dalcanton |
|                   |          | F160W   | 1697                | 12058/Dalcanton |
| 2010 December 26  | WFC3/UVIS| F275W   | 1010                | 12058/Dalcanton |
|                   |          | F336W   | 1350                |               |

Note. Camera abbreviations are—WFPC2: Wide Field Planetary Camera 2 (WF: wide-field chip, PC: planetary chip); ACS: Advanced Camera for Surveys (WFC: wide-field optical channel; SBC: solar-blind UV channel); WFC3: Wide Field Camera 3 (UVIS: UV/optical channel; IR: near-infrared channel).

I have searched the HST data archive for all imaging observations that have covered the site of M31 RV. My search is complete through 2011 January 1. The available data are summarized in Table 1. Most of these observations were made for other purposes and contain the location of M31 RV only fortuitously, except that the two programs of Shara and myself were specifically targeted at M31 RV.

As described in Paper I, we located the site of M31 RV in the HST frames of 1999, by registering them with ground-based CCD images taken during the 1988 outburst by R. Ciardullo and kindly made available to us. The resulting error box in the HST frames has a 1σ size of ±0.18 × ±0.27. SZPYK10 independently determined the location of M31 RV in the HST frames and verified the Paper I result to within 0′′.09.

3.1. The 1995 UV Observation: Cosmic Rays Do Strike Twice

The first HST images of the M31 RV site were obtained in 1995 (see Table 1). A pair of 1300 s frames was taken in...
the Wide Field Planetary Camera 2 (WFPC2) F300W filter, a bandpass located in the optical UV around the atmospheric cutoff. SZPYK10 reported finding a bright UV source in these frames within the M31 RV error box. Moreover, they suggested that this source coincides with a relatively bright star seen in frames taken at longer wavelengths (see below). I will call this star “Star S.” Its J2000 coordinates are 00:43:02.43 and +41:12:57.0.

To investigate this claim, which is at variance with what we had reported in Paper I, I re-examined the pair of archival images from 1995. The two F300W exposures were taken in immediate succession (during the same telescope orbit) without dithering the telescope pointing, so I simply combined the images using a standard cosmic-ray (CR) rejection algorithm. Because there are very few stars detected in the F300W frames, I then registered the combined frame with a frame taken in 2003 at a longer wavelength in which the location of the error box could be identified unambiguously. The combined F300W image indeed shows an apparent object within the M31 RV error box, but it has a very unusual appearance: it looks abnormally sharp compared to images of nearby real stars. I measure the FWHM of the object to be only 0.7 pixels, in contrast with a typical 1.4–1.5 pixels for real stars in the frame. The FWHM of stellar images is set by diffraction in the telescope optics, and it is physically impossible for a real point source to have an FWHM of 0.7 pixels.

Figure 1 illustrates the unusual visual appearance of the SZPYK10 object in the two individual F300W images. I created this mosaic by extracting 9 × 9 pixel postage stamps around the object (the two left-hand frames in the mosaic) and four real stars from the same two images. (The real stars were selected to be free of CR hits within the 9 × 9 boxes.) It is immediately clear that the SZPYK10 object lacks the broad point-spread function (PSF) wings associated with real stars in these images. The same image stretch was used throughout Figure 1, and the real stars cover a range of magnitudes that bracket the “magnitude” of the M31 RV candidate. Thus, the obvious difference in appearance between the candidate and the real stars is not an artifact of the image presentation.

To quantify this disparity, I measured two parameters in the two individual F300W frames for the SZPYK10 object and several real stars: the signal in data numbers (DN) for the brightest pixel in the image and the total background-subtracted flux (also in DN) within a 2 pixel radius aperture centered on the object. Figure 2 plots the results. Note that I made these measurements on raw frames, which have a bias level of about 355 DN. Only stars without CR hits in their vicinity were measured; there are actually very few uncontaminated real stars in these frames, and essentially all of them are plotted in Figure 2. There is, as expected, a linear relation between the DN value of the brightest pixel and the total stellar flux (with some scatter due to different centerings of the stars within the central pixel as well as Poissonian noise); a least-squares linear fit to these values is plotted in Figure 2. However, the SZPYK10 object stands out strikingly from this relation in both individual images: it has an unusually bright central pixel relative to the total stellar flux in the image. In other words, most of the flux of its image is contributed by the central pixel, and this is true for both individual images. The images lack the appreciable extended PSF wings of real stars. When a CR deposits energy in a single WFPC2 CCD pixel, about 25% of the charge diffuses to the immediately adjacent pixels (see Riess et al. 1999). The dashed line in Figure 2 plots the predicted behavior of single pixels impacted by CRs, with 75% of the charge remaining in the central pixel. It provides a good fit to the two measurements of the SZPYK10 object.

In summary, the candidate object has a visual appearance very different from that of real stars, and quantitatively its image parameters not only depart significantly from those of...
Figure 3. Color–magnitude diagram for stars lying within a radius of 6 WFPC2 pixels (stars) and within 6 to 18 pixels (filled circles) of the M31 RV site, taken from Paper I. These radii correspond to locations within 1σ and 3σ of the outburst site (see text); the corresponding angular radii are 0′′.27 and 0′′.82. The bright candidate Star S is labelled. Also plotted are BaSTI isochrones for an age of 10 Gyr and metallicities of [M/H] = −0.66, −0.25, and +0.25, adjusted to the reddening and distance of M31. All of the stars within the error box are normal M31 old red giants, including Star S. Error bars at the right-hand side show the mean photometric errors as functions of I magnitude.

real stars, but have parameters that are predictable from the charge-diffusion properties of the detector. The conclusion seems inescapable that the apparent object in these frames is in fact a case of CRs striking the same pixel in both images (in the second frame, the CR actually spread its charge over two pixels), and thus not being removed from a combined image made with a standard CR-rejection algorithm.

How probable is it that CRs would hit the same pixel in two successive exposures? The brightest pixel in the first frame showing the SZPYK10 object has a value of 514 DN, and in the second frame the two brightest pixels have values of 502 and 398 DN. The fraction of pixels having CR hits of 398 DN or brighter in the two entire images is measured to be 1.1%. The total number of pixels within the 3σ M31 RV error box is 44, so the probability of a CR hit somewhere in the error box in a single image is ~48%. The probability of this same pixel then being hit again in the second image is 1.1%, a small value but not vanishingly so.

The site of M31 RV was imaged again in the same WFPC2 F300W filter in 2008 (see Table 1). This time, as reported by SZPYK10, and verified independently by myself, no UV source was detected anywhere within the M31 RV error box. There were four individual dithered frames taken for this observation, in contrast to only two in 1995, resulting in a negligible number of CR hits surviving into the combined frame. Also, the long (10,800 s) WFPC2 exposure of the site taken in 1995 with the F170W near-UV filter shows nothing at the M31 RV site, as reported by SZPYK10 and confirmed by myself.

This is not the first time that CRs striking the same pixel in WFPC2 images have resulted in an astrophysical misinterpretation; see Sahu et al. (2002).

3.2. Star S: Not so Hot

As noted above, SZPYK10 reported that the purported UV object in the 1995 frames coincides with a bright star, Star S, seen in images taken at longer wavelengths. Figure 3 in SZPYK10 gives a finding chart for this star, and it is also visible (but not marked) in Figure 1 of Paper I. Although I have just presented evidence that the 1995 object is a spurious case of CRs striking twice, I carried out a careful registration of the 1995 frames with an Advanced Camera for Survey (ACS) image obtained in an F435W filter in 2003, using stars detected in both images. The result shows that the spurious UV object is offset from the real optical Star S by 0′′.17, approximately 11 times the 1σ error of the registration. Thus, even if the UV source had been real, it did not coincide with the star seen at optical wavelengths.

However, SZPYK10 have further reported that the optical star is blue and extremely hot, and that it is therefore a strong candidate for the remnant of M31 RV as well as providing support for the classical-nova hypothesis. This is again in striking contradiction to the findings we reported in Paper I. In Figure 3 of the present paper, I have reproduced our color–magnitude diagram (CMD) from Paper I, which plots stars that lie within the 3σ positional error box for M31 RV. This CMD was derived by M. Siegel from PSF photometry of an excellent set of dithered WFPC2/PC frames obtained in 1999, as described in detail in Paper I. The magnitudes in the WFPC2 F555W and F814W filters were transformed to the traditional ground-based Johnson–Kron–Cousins V and I system. Star S is the brightest object in the error box, and is now labeled in Figure 3. We had measured its magnitudes and color as $V = 22.95$, $I = 21.33$, and $V - I = 1.62$, with errors of about ±0.01–0.02 mag. As we already remarked in Paper I, this CMD shows only a population of cool red giants belonging to the M31 bulge.

To verify that there are only old red giants in the error box, I have also added three isochrones to Figure 3, taken from the BaSTI database\(^2\) (Pietrinferni et al. 2004, 2006). I chose parameters typically found in recent studies of the M31 bulge population (e.g., Saglia et al. 2010 and references therein): an age of 10 Gyr and metallicities of [M/H] = +0.25, −0.25, and −0.66, with scaled solar element ratios. I then adjusted the isochrones for a reddening of $E(B-V) = 0.062$ (Schlegel et al. 1998), corresponding to $E(V-I) = 0.08$, and for an M31 distance modulus of $(m-M)_0 = 24.4$ (van den Bergh 2000). The three adjusted isochrones nicely bracket the positions of all of these normal red giants in the CMD.

Star S, with a Johnson–Kron–Cousins color index of $(V-I)_0 = 1.54$, has an implied effective temperature near $T_{\text{eff}} = 4000$ K (e.g., Bessell 1979). How then did SZPYK10 find $(V-I)_0 \approx -0.35$ for the same star from the same 1999 data, and then derive a temperature of $T_{\text{eff}} > 40,000$ K? The discrepancy is partly due to the considerably higher reddening of $E(V-I) \approx 0.4$ adopted by SZPYK10, compared to the $E(V-I) \approx 0.08$ used in most studies of the M31 bulge (and verified by the good isochrone fit in Figure 3). However, most of the difference appears to arise from a misunderstanding of the “STmagnitude” system that is sometimes used in analyses of HST data. It is clear, e.g., from the axis labels in their figures, that SZPYK10 used STmagnitudes.

STmagnitudes are easily obtained from HST images through calibration information included in the image headers, but it is essential to understand their meaning. They are defined (e.g., Siriani et al. 2005) in terms of stellar flux density, $F_\nu$, through the formula $STmag = -2.5 \log F_\nu + \text{const.}$, where the constant is set such that the $V_{\text{STmag}}$ of Vega is zero. By contrast, a hypothetical object with a flat $F_\nu$ energy distribution would have colors of zero in the STmagnitude system.

\(^2\) Available at http://albione.oa-teramo.inaf.it/.
The Johnson–Kron–Cousins $V - I$ color index of Vega in the STmagnitude system is $(V - I)_{\text{STmag}} = -1.27$, not zero. If STmagnitude-based $V - I$ colors are interpreted using calibrations, such as that of Bessell, based on a Vega-magnitude system, stellar temperatures will be grossly overestimated. This appears to explain why Star S was misinterpreted as a very blue and hot star, when in fact it is an ordinary red giant.

### 3.3. Is Star S Variable?

Lastly, SZPYK10 report that the candidate M31 RV remnant, Star S in my terminology, has varied at longer wavelengths, becoming redder between 1999 and 2008. I will report detailed PSF photometry of all objects in the error box in a separate paper, but I have made an exploratory investigation of the star’s variability using simple quick-look aperture photometry. I measured the brightness of Star S within a 2 pixel radius aperture in all of the available frames taken in F435W, F475W, F555W, and F814W. Unfortunately, a wide variety of cameras has been used in these observations, making direct comparisons difficult. Nevertheless, the results are presented in Table 2. Star S was, at best, only marginally detected in all filters shortward of F435W, so those data are omitted. The magnitudes listed in Table 2 are differential with respect to a nearby, well-isolated comparison star (J2000 coordinates: 00:43:02.56, +41:12:58.3).

Table 2 shows little evidence for variability of Star S exceeding about $\pm 0.1$ mag, which is the approximate precision of these quick-look measurements, over the interval from 1999 to 2010. Note also the similarity of the differential magnitudes across all of the filters; this shows that the comparison star has very similar colors to Star S, and is another normal red giant of the M31 bulge.

### 4. ARE THERE OTHER CANDIDATE REMNANTS?

#### 4.1. Preliminary Search for Variable Sources

I have made a preliminary search for other possible candidate remnants of M31 RV by registering frames taken in the same bandpasses, and then visually blinking them as well as calculating difference images. This was done using the five F814W frames (1999 to 2010), and separately using the three F555W frames (1999 to 2009), as listed in Table 1. Although there are many variable stars in these frames, none of them lie within the M31 RV error box. For well-exposed stars, variability in excess of $\sim 0.2$ mag would have been seen. A separate search for variable objects at fainter levels will be reported later, but there are no objects among the numerous fainter sources that appear to have faded dramatically or disappeared.

#### 4.2. Near-infrared Images

The M31 RV site has been imaged once by $HST$ in the near-IR, using the IR channel of Wide Field Camera 3 (WFC3) and the broadband F110W and F160W filters. I have compared these frames visually with the optical (F555W and F814W) images, and found no unusually red objects. Thus, if the remnant of M31 RV is now embedded in dust, the obsuration is such that the source is not detectable out to the $H$ band.

### 5. SUMMARY

I have investigated all available $HST$ images of the site of M31 RV, an ILRT event that occurred in M31 in 1988. These frames were taken between 1995 and 2010. I have been unable to verify the reports by SZPYK10 of (1) a UV-bright object at the outburst site in 1995 (the apparent source is due to an unfortunate case of CRs striking the same pixel in two different images), (2) a hot optical source in 1999 and 2008 (due to a misinterpretation of the $HST$ STmagnitude system), and (3) variability of this candidate source.

Thus, the conclusions we reached in Paper I all remain valid. I quote them verbatim: “All of the stars at the outburst site have the magnitudes and colors of ordinary red giants in the M31 bulge. The absence of any conspicuous remnant star has three possible explanations: (a) the object had faded below $HST$ detectability in the 11 years since outburst, either intrinsically or because of heavy dust obscuration; (b) the remnant is an unseen companion of (or its image is blended with) one of the red giants in the field; or (c) the remnant is one of the red giants (P. 988).”

In addition, none of the red giants within the error box have faded significantly over the 1995–2010 time interval covered by the available $HST$ images. The nature of M31 RV remains as puzzling as ever.

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**Facilities:** $HST$ (WFC2, ACS, WFC3)

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