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HUBBLE SPACE TELESCOPE IMAGING OF THE OUTBURST SITE OF M31 RV[1]

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ABSTRACT

M31 RV is a luminous red variable star that appeared for several months in the bulge of M31 during 1988. Unlike classical novae, M31 RV was cool throughout its outburst. Interest in this object has been revived recently because of its strong resemblance to V838 Mon, a luminous Galactic variable star that appeared in 2002 and is illuminating a spectacular light echo, and has evolved to ever cooler surface temperatures. (V4332 Sgr is a third object that was also a red supergiant throughout its eruption.) We have examined archival *Hubble Space Telescope* (*HST*) images of the site of M31 RV, obtained fortuitously in 1999 with the WFPC2 camera in parallel mode during spectroscopic observations of the nucleus of M31. We located the site of M31 RV in the *HST* frames precisely through astrometric registration with ground-based CCD images, including several taken during the outburst. No light echo is seen at the M31 RV site, implying either that M31 RV is not surrounded by circumstellar (or interstellar) dust similar to that around V838 Mon, or that its extent is less than ~1.7 pc. The stellar population at the outburst site consists purely of old red giants; there is no young population, such as that seen around V838 Mon. There are no stars of unusual color at the site, suggesting either that M31 RV had faded below *HST* detectability in the 11 years since outburst, that it is an unresolved companion of one of the red giants in the field, or that it *is* one of the red giants. We suggest future observations that may help decide among these possibilities.

Key words: novae, cataclysmic variables — stars: evolution — stars: individual (M31 RV, V838 Monocerotis, V4332 Sagittarii) — stars: variables: other

1. INTRODUCTION

In mid-1988, an unusual stellar outburst in the nuclear bulge of the Andromeda galaxy, M31, was discovered independently by Rich et al. (1989), Bryan & Royer (1992), and Tomaney & Shafter (1992). Although similar in luminosity to a classical nova, the object was cool and red throughout its eruption. Its behavior was thus completely different from that of a classical nova, in which an extremely hot and blue remnant is quickly revealed as the ejected envelope expands and becomes optically thin. This remarkable object has been called the "M31 red variable," or "M31 RV."

M31 RV's optical outburst light curve has been assembled from published observations plus analyses of archival plate material by Sharov (1990, 1993) and more recently by Boschi & Munari (2004). Although the rise to maximum was not well observed, M31 RV was brighter than 18.5 B mag ($M_B \lesssim -6$) for at least 80 days, but then rapidly declined to invisibility. Inspection of archival plates shows that the 1988 outburst was the only one in the past half century (Boschi & Munari 2004), the claim of a previous eruption in 1968 (Sharov 1990) having been subsequently withdrawn (Sharov 1993).

Spectroscopic observations of M31 RV near maximum and during the subsequent decline showed a spectrum resembling that of an M0 supergiant (Rich et al. 1989), gradually evolving toward M5 and then late M as the outburst proceeded (Mould et al. 1990). At maximum brightness, M31 RV was one of the most luminous stars in the Local Group, at a bolometric absolute magnitude of $M_{\rm bol} \simeq -10$ (Rich et al. 1989). Unfortunately, M31 RV was not well observed during its outburst, and little else is known about this unusual event.

Interest in M31 RV has been revived recently because of its striking resemblance to V838 Monocerotis. V838 Mon, a previously unknown Galactic variable star, erupted in 2002 January and reached a peak luminosity similar to that of M31 RV (Bond et al. 2003; Munari et al. 2005 and references therein). Its spectrum evolved rapidly from type K to a very cool M and then L type, accompanied by formation of a dense circumstellar dust envelope (Banerjee & Ashok 2002; Evans et al. 2003; Lynch et al. 2004; Rushton et al. 2005). The outburst of V838 Mon was followed by the appearance of a spectacular light echo (Henden et al. 2002; Munari et al. 2002; Bond et al. 2003; Crause et al. 2005), imaged extensively by the *Hubble Space Telescope* (*HST*), as well as from the ground, and continuing to evolve at the present time.

V4332 Sagittarii is a third object[4] with similarities to M31 RV and V838 Mon. In 1994, V4332 Sgr had a nova-like outburst, during which it remained very cool (Martini et al. 1999; Banerjee & Ashok 2004; Tylenda et al. 2005, and references therein). The absolute luminosity of V4332 Sgr is highly uncertain, but if the star lies in the nuclear bulge of our own Galaxy, it was several magnitudes less luminous than M31 RV and V838 Mon at maximum light.

A number of explanations have been proposed for this new class of peculiar outburst event. These include an outburst from

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[4] Nova V1148 Sgr 1943 was reported to have a late-type spectrum by Mayall (1949) based on three objective-prism plates, making it a possible fourth member of the class, but nothing else is known about this object. More speculatively, Kato (2003) has suggested that Nova CK Vul 1670 could have been a V838 Mon–like event, but of course nothing is known about its outburst spectrum.

a compact object in a red giant envelope (Mould et al. 1990); a hydrogen shell flash on the surface of an accreting cold white dwarf in a short-period binary (Iben & Tutukov 1992); a thermonuclear event in a single star (Martini et al. 1999; Munari et al. 2005); the merger of two main-sequence stars (Soker & Tylenda 2003; Tylenda et al. 2005); the accretion of planets by a giant star (Retter & Marom 2003); and a born-again red giant event in a binary system (Lawlor 2005). Moreover, Yaron et al. (2005) hint that a complete exploration of the parameter space for classical novae might reveal models with properties similar to these objects. The discovery that V838 Mon has an unresolved B-type companion (Munari & Desidera 2002; Wagner & Starrfield 2002), as well as belonging to a small cluster containing several more B-type stars (M. Afsar & H. E. Bond 2006, in preparation), and that it therefore may have arisen from a fairly massive progenitor star, may rule out some of these scenarios, but a fully convincing explanation remains elusive.

The plethora of mutually exclusive scenarios shows that these objects pose a significant challenge to our understanding of stellar physics. In an effort to provide further information on M31 RV, we have examined archival images of the site of the event obtained with *HST* some 11 years after the outburst. The aims of our investigation are to determine whether M31 RV produced a detectable light echo, to characterize the stellar population surrounding the object, and, if possible, to detect a remnant star.

2. ARCHIVAL *HST* AND GROUND-BASED IMAGES

M31 RV has never been targeted specifically by *HST*, but the bulge of M31 has been imaged in several unrelated programs. We searched the archive[5] for images that serendipitously cover the location of M31 RV, obtained with any of the *HST* cameras: the Wide Field and Planetary Camera (WF/PC), Wide Field Planetary Camera 2 (WFPC2), Space Telescope Imaging Spectrograph (STIS), Near Infrared Camera and Multiobject Spectrograph (NICMOS), and Advanced Camera for Surveys (ACS). We found that no images of the site have been obtained with STIS or NICMOS, nor with WF/PC (although one set of frames taken in 1992 July missed M31 RV by only 1.″6!).

With WFPC2, there are two sets of archival observations that do include the site of M31 RV. One set, the "u58 series," was taken on 1999 July 23–24 in program GTO-8018 (principal investigator [PI]: R. F. Green); these WFPC2 images were taken in parallel mode during STIS spectroscopy of the nucleus of M31, and thus the inclusion of M31 RV in the WFPC2 field is purely fortuitous. The u58 series consists of data sets u5850101r through u5850108r, taken through the *V* filter (F555W) (consisting of eight dithered exposures of 600–1000 s), and data sets u5850109m through u585020br, taken through the *I* filter (F814W) (consisting of 13 exposures of 300–1000 s). In these images, M31 RV lies in the high-resolution Planetary Camera (PC) chip.

An earlier set of six observations, the "u31 series," was taken on 1995 December 5 in program GTO-6255 (PI: I. King), which was also a STIS spectroscopic program on the M31 nucleus, with the WFPC2 images again being taken in parallel. The u31 series contains two 1300 s exposures through the F300W ultraviolet filter (u31k0109t and u31k010bt) and four 2700 s exposures through the F170W ultraviolet filter (u31k010ft through u31k010rt). In the u31 series, the site of M31 RV lies in one of the low-resolution WF chips.

Finally, with the ACS there are two *HST* observations fortuitously showing the M31 RV site, both of them 2200 s exposures in the *B* band (F435W), taken in program GO-10006 (PI: M. Garcia) as part of a project on X-ray novae in M31. Exposures were taken on 2003 December 12 (data set j8vp02010) and 2004 October 2 (j8vp07010), the latter being unavailable to us at this writing due to the proprietary *HST* data policy.

M31 RV lies in an extremely dense stellar field, which is well resolved in *HST* images. It is therefore desirable to locate the site of the outburst event as accurately as possible, as a preliminary to investigation of the *HST* frames. We have done this using two sets of ground-based CCD images that include the site of M31 RV, one of which shows the object during its outburst.

The first ground-based set was obtained by R. Ciardullo on 1988 September 29 with the No. 1 0.9 m reflector at Kitt Peak National Observatory (KPNO), and was kindly made available to us. These images were obtained fortuitously during the eruption of M31 RV, as part of a search for classical novae in the bulge of M31, and contain well-exposed images of M31 RV (which was cataloged as "Nova 36" in Ciardullo et al. 1990). There are two 900 s exposures taken through a narrowband Hα filter and one 420 s frame taken through a wider band continuum filter centered at 6091 Å.

Because of the small field of view of the *HST* images and the relative shallowness of the 0.9 m frames, there are too few detectable stars seen in common in both the *HST* and 0.9 m frames to allow them to be registered astrometrically. We therefore also used a second, deeper set of ground-based frames of the M31 bulge, which had been obtained by H. E. B. for a different purpose with the KPNO 4 m Mayall telescope and its Mosaic camera on 1999 January 17, and which fortuitously cover the location of M31 RV. These frames show the brightest stars seen in the *HST* images, while having a large enough field to also show several stars visible in the 0.9 m frames. We chose for further analysis two 30 s exposures taken in good seeing through a Kron-Cousins *I* filter.

3. ASTROMETRY

3.1. *Absolute Astrometry of M31 RV*

We first used the three KPNO 0.9 m frames that show M31 RV in eruption to derive absolute astrometry of the object. We identified nine nearby field stars contained in the NOMAD astrometric catalog (Zacharias et al. 2004; optical photographic survey plates in the bright M31 bulge are generally saturated, and most of the NOMAD positions at this location are derived from stellar coordinates in the 2MASS infrared catalog). These field stars were used to establish an astrometric grid on each of the three frames, from which we obtained a position for M31 RV accurate to about $\pm0.''04$ in each coordinate, based on the rms scatter in the astrometric solutions and the excellent agreement among our three CCD frames.

The absolute position of M31 RV is given in Table 1 along with, for comparison, the positions derived by Munari et al. (2003) from two photographic plates obtained with the Asiago Schmidt telescope during the outburst. (Munari et al. [2003] also list several earlier, less precise position measurements from the literature.) The agreement is satisfactory, given the smaller plate scale of the Asiago material and the necessity to set up secondary astrometric standards as part of their solutions. This position lies 4.′7 to the southeast of the nucleus of M31, corresponding to a projected linear separation of 1.0 kpc.

3.2. *Astrometric Registration of the Ground-based and HST Images*

We then proceeded to locate the site of M31 RV on the *HST* frames. As noted above, we cannot directly register the

[5] The *HST* data archive is available at http://archive.stsci.edu/hst.

TABLE 1
Absolute Astrometry of M31 RV

α (J2000.0)	δ (J2000.0)	Source
00 43 02.433	+41 12 56.17	This paper
00 43 02.42	+41 12 56.7	Munari et al. (2003), plate 14197
00 43 02.41	+41 12 57.1	Munari et al. (2003), plate 14222

KPNO 0.9 m frames showing M31 RV with the *HST* frames, since there are insufficient visible stars in common.

We therefore used the KPNO 4 m frames in an intermediate step, as follows. First, we selected the 0.9 m frame with the best seeing and identified nine stars visible both on this frame and in an image created by registering and combining the two excellent 4 m frames. We then used the IRAF[6] routine *geomap* to compute the geometric transformation to be applied to the 0.9 m image so as to register it with the 4 m frame, and then the *geotran* routine to actually apply this transformation. This allowed us to mark the location of M31 RV precisely in the 4 m frame.

Next, we applied the IRAF routine *wmosaic* to *HST* images in the u58 series so as to combine the four WFPC2 chips into single-image mosaics, and used a similar geometric transformation from the 4 m image to locate the site of M31 RV in the WFPC2 mosaic. Finally, we did a transformation from the WFPC2 mosaic to the PC chip to locate M31 RV in the latter.[7] A formal error-propagation calculation indicates that the location in the PC chip is accurate to $\pm0\farcs18 = \pm3.9$ PC pixels in the x-coordinate and $\pm0\farcs27 = \pm5.9$ PC pixels in y.

[6] IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

[7] The WFPC2 reference image chosen was u5850103r, in which the derived location of M31 RV lies in the PC chip at pixel coordinates $(x,\ y) = (549.6,\ 675.4)$.

4. THE SITE OF M31 RV

4.1. *Visual Examination*

We prepared high-signal-to-noise, cosmic-ray-rejected WFPC2 images of the M31 RV site by registering and combining all the u58 series V and I images. Figure 1 illustrates the location of M31 RV in the combined *HST* images. These are $3'' \times 3''$ images centered on the derived location of the outburst.

The sheet of stars belonging to the bulge of M31 is well resolved in these deep V and I frames. There are no obvious stars with unusual colors or brightnesses at the M31 RV location. Detailed stellar photometry of the field is presented below.

We also examined the ultraviolet (F300W and F170W) WFPC2 frames from the u31 series visually. These frames show very few stars, and there is nothing obvious at the M31 RV site. The single ACS B-band image currently available in the *HST* archive likewise shows no stars of unusual colors at the outburst site.

4.2. *Absence of Light Echo*

Although the WFPC2 frames in Figure 1 are considerably deeper than *HST* frames that show the light echo around V838 Mon, no such feature is visible at the location of M31 RV at the 1999.6 epoch. The geometry of a light echo is simple (e.g., Bond et al. 2003 and references therein): at a time t after the outburst, 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.

Figure 2 illustrates the geometry for M31 RV. It shows the light-echo paraboloids at $t = 2$ through 10 yr after the outburst, with a spacing of 2 yr, and, as a darker line, the parabola at the time of the u58 series of *HST* images, 11.0 yr after the outburst. Also shown at the top is the conversion to angular units, at the nominal 725 kpc distance of M31. The dashed circle shows a radius of 2 pc around the star, which is the approximate outer

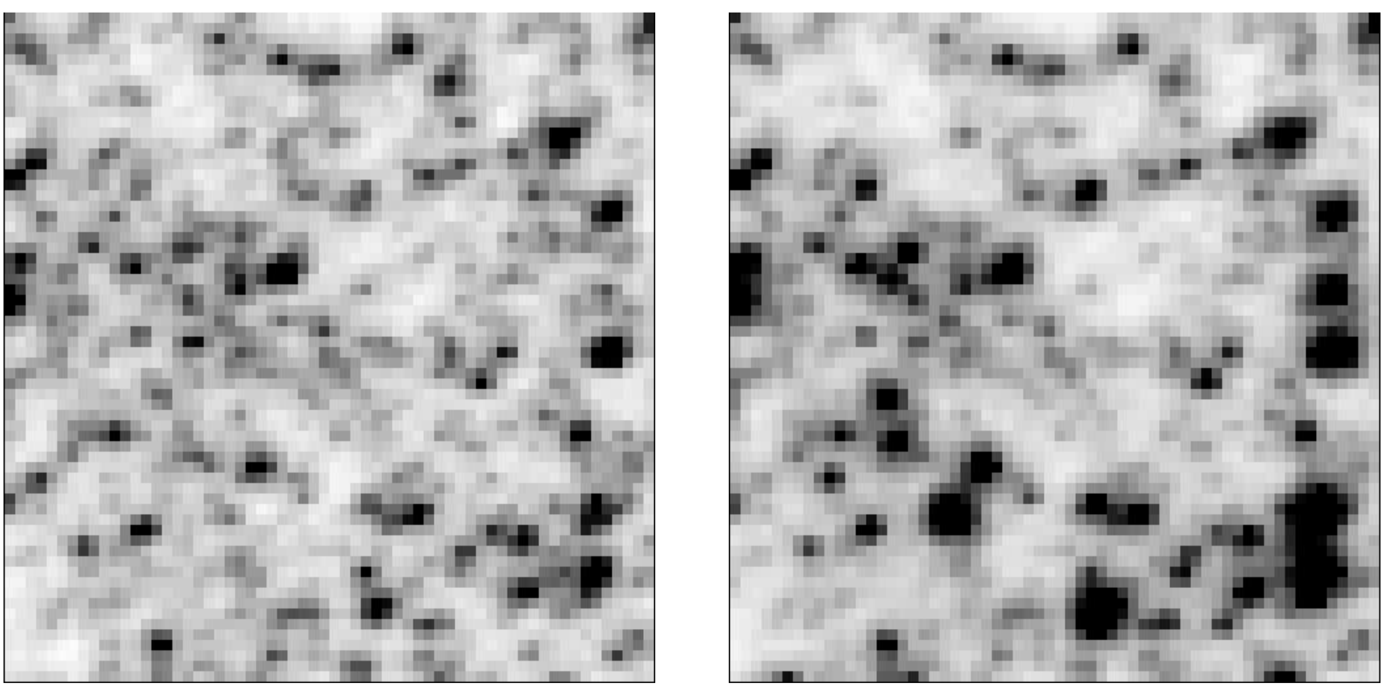

Fig. 1.—WFPC2 images of the site of M31 RV, prepared from *HST* frames obtained in 1999 July (11 yr after the outburst) as described in the text. Both images are $3''\times3''$; north lies 51° counterclockwise from up, and east is 141° counterclockwise from up. *Left*: V-band (F555W) image prepared by combining eight images totaling 7200 s exposure time. *Right*: I-band (F814W) image prepared by combining 13 images totaling 10,400 s. There is no evidence for stars of unusual color at the site of M31 RV, and no light echo is seen.

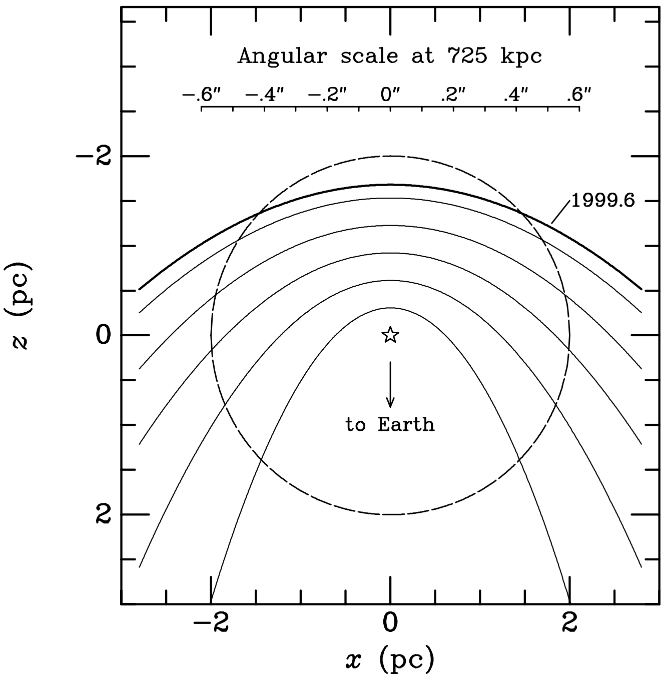

FIG. 2.—Light-echo geometry for M31 RV. As explained in the text, at a time t after the outburst, illuminated dust lies on a paraboloid with the open end pointing toward the observer. Plotted here are the paraboloids for $t = 2$ through 10 yr after the outburst at a spacing of 2 yr (*thin lines*), and for the date of the WFPC2 images shown in Fig. 1 ($t = 11.0$ yr; *thick line labeled 1999.6*). Shown at the top is the angular scale at the distance of M31. The dashed circle shows a radius of 2 pc around the star, the approximate size of the circumstellar dust around V838 Mon. If there were similar dust around M31 RV, a light echo would have been readily visible in Fig. 1.

boundary of illuminated dust currently being seen around V838 Mon (e.g., Bond et al. 2003; Crause et al. 2005).

This figure demonstrates that if M31 RV were surrounded by circumstellar dust with an extent and density similar to that around V838 Mon, we should have seen a light echo in the WFPC2 images taken in 1999. The approximate diameter would have been $\sim$0″.8, which would be readily resolved in Figure 1.

The absence of a light echo has two possible explanations: (1) there is very little circumstellar (or interstellar)[8] dust around M31 RV, or (2) if there is circumstellar dust around M31 RV similar in density to that around V838 Mon, Figure 2 shows that it extends less than $\sim$1.7 pc from the star. Figure 2 suggests that it might be worthwhile to examine any existing high-resolution ground-based images of the M31 bulge obtained around the early to mid-1990s, at which time any light echo from circumstellar dust would have had maximum apparent radius.

4.3. *Stellar Photometry*

We performed stellar photometry on the u58 series images, using HSTphot (Dolphin 2000), a program that performs automated PSF-fitting photometry, accounts for aperture corrections and charge-transfer effects, and transforms the instrumental magnitudes to the Johnson-Kron-Cousins standard system. HSTphot detected over 70,000 stellar objects in the WFPC2 field, 12,000 of which lie on the PC chip that contains the location of M31 RV.

The quality of the photometry is excellent, with errors of less than 0.1 mag down to $V \simeq 25.5$ and $I \simeq 24.7$ for isolated stars in the PC field. However, because of the extreme crowding in this field, the total star counts roll over at $V \simeq 24$ and $I \simeq 22$, with a steady decline over the next 2 mag.

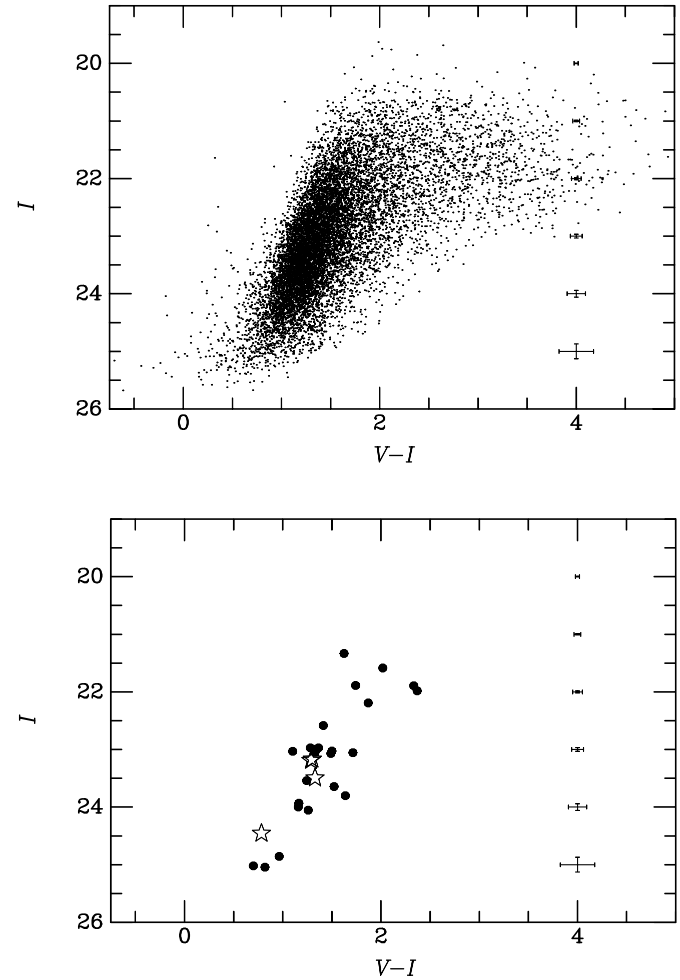

FIG. 3.—*Top*: CMD for the field surrounding the site of M31 RV. All the $\sim$12,000 stars contained in the PC chip of the WFPC2 camera are plotted. *Bottom*: CMD for stars lying within a radius of 6 pixels (*stars*) and within 6–18 pixels (*circles*) of the site. These radii correspond approximately to locations within 1 and 3 σ of M31 RV (see text), and the corresponding angular radii are 0″.27 and 0″.82. All the stars appear to be normal M31 red giants, including all four that are within $\sim$1 σ of the M31 RV site. Error bars at the right sides of both diagrams show the mean photometric errors as functions of I magnitude.

The color-magnitude diagram (CMD) for the entire PC chip is shown in Figure 3 (*top*). The CMD is that of an old population of red giants, in agreement with other studies of the M31 bulge (e.g., Jablonka et al. 1999; Stephens et al. 2003; and references therein). Apart from less than a dozen blue objects (some of which could be background unresolved galaxies or blue stragglers in M31), there is no evidence for any significant young population at this location in the M31 bulge.

Figure 3 (*bottom*) shows the CMD of stars within radii of 6 pixels (*stars*) and radii of 6–18 pixels (*circles*); these radii correspond to approximately 1 and 3 σ position errors, based on the values given in § 3.2. None of these stars have unusual colors; all of them lie on the M31 bulge red giant branch.

5. DISCUSSION

5.1. *The Stellar Population of M31 RV*

We have shown that M31 RV belongs to an old stellar population in the bulge of M31. This is in striking contrast to

[8] Note that some authors (Tylenda 2004; Crause et al. 2005) have suggested that the light echo around V838 Mon arises from ambient interstellar dust rather than from material ejected from the star.

V838 Mon, which has an unresolved B-type companion, as well as belonging to a small cluster containing several additional B-type stars.

The similarities of the light curves, spectral evolution, and peak luminosities of M31 RV and V838 Mon strongly suggest a common outburst mechanism. If this is the case, this mechanism must be one that can occur in stars belonging to both young and old populations. Whether this constrains any of the scenarios mentioned in § 1 is unclear. The lack of any young stars near M31 RV does suggest, however, that the B-type companion of V838 Mon is a bystander that did not play an essential role in the outburst.

5.2. *Searching for a Stellar Remnant*

All 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: (1) the object had faded below *HST* detectability in the 11 yr since outburst, either intrinsically or because of heavy dust obscuration; (2) the remnant is an unseen companion of (or its image is blended with) one of the red giants in the field; or (3) the remnant *is* one of the red giants.

The post-outburst histories of V838 Mon and V4332 Sgr give us only modest guidance. At the present time, V838 Mon remains enshrouded in dust, but it continues to be luminous at long wavelengths. For example, in 2004 December it had an apparent magnitude of $I \simeq 10.5$ and an extremely red color of $V - I \simeq 4.7$ (Crause et al. 2005). Assuming $E(B - V) = 0.9$ and a nominal minimum distance of 6 kpc for V838 Mon (Munari et al. 2002, 2005; Bond et al. 2003) and neglecting the small foreground reddening for M31, the corresponding values if the V838 Mon of 2004 December were located in M31 would be $I \lesssim 19.4$ and $V - I \simeq 3.4$. Figures 1 and 3 show that there was *no such bright, very red star* at the location of M31 RV in 1999.[9]

Of course, V838 Mon in 2004 December—less than 3 years after its outburst maximum—is not the most suitable comparison object for M31 RV observed 11 years after its eruption. V4332 Sgr may provide a more apt comparison, since more than 11 years have now elapsed since its eruption in early 1994.

CCD photometry of V4332 Sgr is collected in Table 2; in addition to previously published photometry at maximum light and in 2003, we include observations made by us in 2004–2005 at the 1.3 m SMARTS Consortium telescope at Cerro Tololo, which have errors of about ±0.05 mag. In recent years, V4332 Sgr has been essentially constant near an apparent magnitude of $I \simeq 15.1$ and a color of $V - I \simeq 2.5$. At maximum light (Martini et al. 1999, their Fig. 2), the I magnitude was about 7. The star has therefore declined from its maximum by about 8 mag at the present time. Note, however, that pre-outburst sky survey images show a star at the location of V4332 Sgr of approximately the same brightness as the object seen at present. This fact, along with the constancy of the past few years, may suggest that the 15 mag object is a field star that is blended with the variable (or is possibly a physical companion). In this case the variable has now declined by *more* than 8 mag. We note, though, that V4332 Sgr was imaged with *HST* on 1997 November 3 (program SNAP-7386, PI: F. Ringwald), using WFPC2 with a narrowband Hα filter. The image, which lies in the PC chip, shows no strong evidence for a resolved companion star, but the FWHM of the stellar profile does appear marginally larger than for nearby field stars.

TABLE 2
Photometry of V4332 Sgr

Date	V	I	$V - I$	Source
1994 Feb (maximum).....	8.5	7.0	1.5	Martini et al. (1999)
2003 May 21.................	17.63	15.09	2.54	Tylenda et al. (2005)
2003 Sep 29..................	17.52	15.01	2.51	Banerjee & Ashok (2004)
2004 Jul 16....................	. . .	15.09	. . .	This paper
2005 Sep 16..................	17.67	15.10	2.57	This paper

The I magnitude of M31 RV at maximum was approximately 14 (see Boschi & Munari 2004). If it had faded by only 8 mag by 1999.6, it would have been at $I \simeq 22$. The reddening of V4332 Sgr is $E(B - V) \simeq 0.32$ (Martini et al. 1999), so its recent intrinsic color (see Table 2) is $(V - I)_0 \simeq 2.1$. Figure 3 (*bottom*) shows that there *are* several stars with these characteristics in the vicinity of M31 RV, although none of them are within 1 σ of the site.

5.3. *Future Work*

We are left with the unsatisfying situation that there are several stars near the site of M31 RV that could be the remnant but that could also merely be normal field red giants. There are several types of observations that could shed additional light on the situation. These include: (1) a new *HST* observation, to see whether any of the stars near the outburst site have faded since 1999; (2) a grism observation with *HST* to determine whether any of the stars near the site share the remarkable very low excitation emission-line spectrum now exhibited by V4332 Sgr (Banerjee & Ashok 2004; Tylenda et al. 2005); and (3) near-infrared imaging with NICMOS to see whether any of the stars show an IR excess similar to that currently shown by the dust-obscured V838 Mon.

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[9] We also examined images from the 2MASS survey taken in 1997 October, which likewise show no red star at the M31 RV location; however, V838 Mon as of 2004 December moved to the distance of M31 would have been fainter than the 2MASS survey completeness limits.

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