A Hubble Space Telescope Survey for Novae in the Globular Clusters of M87

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Abstract

The giant elliptical galaxy M87 has been imaged over 30 consecutive days in 2001, 60 consecutive days in 2006, and every 5 days over a 265-day span in 2016–2017 with the Hubble Space Telescope, leading to the detection of 137 classical novae throughout M87. We have identified 2134 globular clusters (GC) in M87 in these images and carried out searches of the clusters for classical novae erupting in or near them. One GC CN was detected in the 2001 data, while zero novae were found during the 2005–2006 observations. Four candidate GC novae were (barely) detected in visible light during the 2016–2017 observations, but none of the four were seen in near-ultraviolet light, leading us to reject them. Combining these results with our detection of one M87 GC nova out of a total of 137 detected CN, we conclude that such novae may be overabundant relative to the field, but small number statistics dominate this and all other searches. A definitive determination of GC CN abundance (or not) will require much larger samples, which LSST should provide in the coming decade.

Key words: galaxies: star clusters: general – novae, cataclysmic variables

1. Introduction

Classical novae (CN) are powered by thermonuclear runaways on the surfaces of white dwarf stars, which have accreted hydrogen-rich envelopes from red dwarf or red giant companions (Warner 1995). The luminosities of CN are near maximum range from $M_V = -5.5$ to $-10.5$ (Aydi et al. 2018; Schaefer 2018), so they are detectable in galaxies all the way out to the Fornax and Virgo clusters. Surveys with large ground-based telescopes have searched for differences between the CN populations of spiral and elliptical galaxies, located intracluster tramp novae, and determined the nova rates in different kinds of galaxies (Pritchet & van der Bergh 1987; Neill et al. 2005; Curtin et al. 2015).

CN should exist in all stellar populations, including those found in globular clusters (GC). The remarkable discovery that X-ray binaries are enhanced 100-fold in GC relative to the field (Katz 1975) inspired theory and models (Fabian et al. 1975; Krolik 1984) of 100× enhanced cataclysmic variable (Di Stefano & Rappaport 1994) and CN rates in GC. The fraction of stars, f, in GCs is $\sim 2 \times 10^{-3}$ that of the stars in their host giant elliptical galaxies (Curtin et al. 2015). The overall Galactic CN rate is $\sim 50$ yr$^{-1}$, with an uncertainty of about 50% (Shafter 2017). Assuming the same value of f in the Milky Way as in giant elliptical galaxies, one might expect 1600 CN/160 yr in our Galaxy’s GC if the predicted 100× enhancement occurs.

In fact, only one certain CN (nova T Sco 1860 in M80; Auwers 1862; Shara & Drissen 1995) and one possible CN (Nova Oph 1938 in M14; Sawyer 1938; Wehau et al. 1990) have been detected in the 150 GC of the Galaxy in the past 160 yr, for an apparent Galactic rate of $(4-8) \times 10^{-5}$ CN/GC/yr. This corresponds to a factor of eight rarity of Galactic GC CN relative to field CN. This “rarity” is at least partly due to incompleteness. Most Galactic GC have not been monitored at least weekly for CN by amateur or professional astronomers since 1860, and the appearances of a bright star inside a GC could easily have been ignored. This realization has prompted searches for GC CN in external galaxies with much larger numbers of GC than the Milky Way, both with ground-based telescopes, the Hubble Space Telescope (HST; Ferrarese et al. 1996, 2003; Madrid et al. 2007; Shara et al. 2016), and XMM-Newton and Chandra (Henze et al. 2013).

Over an effective survey time of 1 yr, Ciardullo et al. (1990) and Tomaney et al. (1992) monitored the entire M31 GC population in H$\alpha$, detecting zero CN. Three certain and one more possible CN have since been found in M31 (Shafter & Quimby 2007; Henze et al. 2009, 2013; Peacock et al. 2010; Cao et al. 2012). Henze et al. (2013) suggested that the M31 nova rate might be as high as 0.05 CN/GC/yr. Shara et al. (2004) found one GC CN during a 30-day survey of the GC of M87 with HST. Two additional GC CN were reported in GC of M84 and M87 by Curtin et al. (2015), who estimated a GC nova rate of $4 \times 10^{-4}$ CN/GC/yr.

Because only nine GC CN are known, small number statistics dominate these searches. In addition, all ground-based searches to date are subject to significant incompleteness due to weather and lunar phases. Our ongoing survey of M87 with HST for CN (Shara et al. 2016) partially overcomes these problems because HST observations rule out gaps due to weather, and there are no variations in limiting magnitude due to variable seeing or lunar phase. Our 2005–2006 daily imaging over a 9-week span, and 2016–2017 imaging every 5 days over a 265 day span, were deep enough to be almost impervious to M87’s background light, revealing CN to within 10° of the galaxy’s nucleus. In addition, field CN were detected over a nearly 6 mag range of brightness, so that even the faintest and fastest of M87 field novae were detected. Our data sets are sensitive to GC CN (see Section 4.1), and we report the results of our latest searches here. In Section 2, we summarize our HST observations of M87, and in Section 3, we describe our search methodology for CN associated with its GCs. In Section 4, we present our results, and we compare them with...
2. Observations

Over the 30-day interval from 2001 May 28 through 2001 June 25, the HST Wide Field and Planetary Camera 2 (WFPC2) provided imaging of the giant elliptical galaxy M87 in the F606W (V band) and F814W (I band) filters, taken for HST Cycle-9 program 8592 (PI—J. Silk). Four 260 s exposures in the F814W filter were followed by one exposure of 400 s in the F606W filter during each one-orbit epoch of observations. The 30 epochs were spaced 1.0 ± 0.1 days apart. The observations, data reductions, detections, and characterizations of M87 variables (mostly novae) are given in Baltz et al. (2004). We refer to these data as the “2001 data set”.

Over the 72-day interval from 2005 December 24 through 2006 March 5, we carried out HST Advanced Camera for Surveys (ACS) imaging of the giant elliptical galaxy M87 in the F606W (V band) and F814W (I band) filters, taken for HST Cycle-14 program 10543 (PI—E. Baltz). The observations, data reductions, detections, and characterizations of the M87 novae we detected are given in Shara et al. (2016, hereafter Paper I). Four 360 s exposures in the F814W filter were followed by one exposure of 500 s in the F606W filter during each one-orbit epoch of observations. The first four epochs were spaced 5.00 ± 0.02 days apart, followed by 1.00 ± 0.11 day spacing for the remaining 60 epochs. Photometric errors in F814W range from 0.01 to 0.04 mag for M87 novae near maximum at 22nd magnitude to 0.3–0.4 mag by the time they have faded by 2–3 mag from maximum. We refer to these data as the “2005–2006 data set”.

Over the 265-day interval from 2016 November 13 through 2017 July 31, we carried out HST Wide Field Camera 3 (WFC3) imaging of M87 in the F606W (V band) and F275W (NUV band) filters, taken for HST Cycle-24 program 14618 (PI—M. Shara). The observations, data reductions, detections, and characterizations of the M87 novae we detected will be published elsewhere. Two 360 s exposures in the F606W filter were followed by three exposure of 500 s each in the F275W filter during each one-orbit epoch of observations. The 53 epochs were spaced 5.00 ± 0.3 days apart. Photometric errors in F606W range from 0.01 to 0.04 mag for M87 novae near maximum at 22nd magnitude to 0.3–0.4 mag at 25th magnitude. We refer to these data as the “2016–2017 data set”.

3. Data Analysis

3.1. Globular Clusters

We used the 2005–2006 data set to create two median images, one of the F814W images, and one of the F606W data. DAOFIND (Stetson 1987) within pyRAF was applied to each image to generate a list of candidate GCs. The sky image output of DAOFIND was blurred to create a background galaxy image, which we subtracted from the median images. These sky subtracted images were used to eliminate candidate GC with significantly elongated or irregular radial profiles. Our refined list of 2134 GCs display V magnitudes between 21 and 26 and V—I colors between 0.5 and 1.5 (we conservatively excluded sources outside these limits). The overlap with the 2250 objects in the M87 GC list of Peng et al. (2009) is excellent, with their extra GCs almost all displaying V magnitudes fainter than 26.0.

3.2. Nova Searches

We used the package ASTRODRIZZLE to combine the four F814W images at each epoch of the 2005–2006 data set. We used PHOT from pyRAF to obtain photometry of every GC at each epoch. For each GC, we identified epochs of interest as those in which a GC brightened by at least 3σ relative to the mean brightness it exhibited in the other epochs. Each such candidate’s four F814W images were examined individually to eliminate obvious cosmic rays or other sources of noise. No nova candidates were found in the 2005–2006 data set.

We used ASTRODRIZZLE to combine the 2016–2017 data set images for each epoch in each of the F275W and F606W images. Because cosmic rays are common and we had only two F606W images per epoch, we used the software’s mimmed parameter to create a median image, conservatively setting the sigma parameters such that the software would always choose the minimum image. Next, we used PHOT to obtain photometry for these minimum F606W images at each epoch. For each GC, we identified epochs of interest as those in which a GC brightened by at least 3σ relative to the mean brightness it exhibited in the other 52 epochs. Each such candidate’s five images (two in F606W and three in F275W) were examined individually to eliminate obvious cosmic rays or other sources of noise. Four nova candidates, each a few tenths of a magnitude brighter than its host GC, were detected in the minimum image F606W frames. Their brightnesses (after subtracting off their GC hosts), ranged from m(F606W) = 23.5 to 24.8. Using the distance modulus to M87 derived by Bird et al. (2010), i.e., (m−M)0 = 31.08 ± 0.06, these candidate nova brightnesses correspond to absolute I-band magnitudes of −7.6 to −5.3, typical of M87 CN near maximum light (Shara et al. 2016). None of the four candidates showed a significant detection in any of the F275W frames for the entire duration of the 9 months of the 2016–2017 observations.

CN usually peak in ultraviolet brightness a few days before (Cao et al. 2012), or days to weeks after visual maximum (e.g., (Gallagher & Code 1974; Cao et al. 2012), with UV minus Visual colors close to zero. Three of the four candidates were bright enough to have been detected in our F275W frames. That none were detected leads us to discard them as likely CCD or low level cosmic ray artifacts. A fourth candidate, seen in the minimum brightness image of the F606W image of 2017 March 18 at R.A. (2000) = 12:30:47.519, decl. (2000) = +12:23:18.11 was too faint to have been detected in F275W. Its uncontaminated detection in just one F606W CCD frame is insufficient for us to consider it to be real. In summary, we detected zero novae in 2134 GC of M87 in either of our (72 days long) 2005–2006 or (265 days long) 2016–2017 databases, in contrast with 1 GC CN detected during our earlier 30-day survey (Shara et al. 2004).

4. Results

4.1. Completeness

Because the peak brightness of a nova is comparable to that of a typical GC, Kato et al. (2013) have suggested that we will miss faint GC novae, and we should expect a lower nova discovery rate in GC than in the field (assuming that the
distributions of WD masses in GC and field binaries are similar). Could we be missing most M87 GC novae because they are masked by the brightness of their host GC? To test our completeness, we determined what fraction of synthetic novae added to the 2005–2006 F814W images and the 2016–2017 F606W images we could recover. We used IRAF’s point-spread function (PSF) function to generate a PSF model from the brighter stars in the field of the galaxy in each filter. For each GC, we randomly selected one or more epochs in which to add novae. For these epochs, we randomly selected a nova magnitude between 21 and 27 and a distance from each GC center between 0 and 5 pixels. We then used ADDSTAR to add simulated novae to the original images. Running the same nova candidate detection software on these images (with \( \sim 5000 \) simulated novae in each filter), we created completeness curves for recovery of these simulated novae, shown in Figures 1(a) and (b). Both figures demonstrate that we can recover \( \sim 50\% \) of erupting GC CN that are within \( \sim 2 \) mag of their cluster hosts.

Half of all M87 GC are fainter than \( m(F814W) = 22.5 \) and \( m(F606W) = 23.5 \) (Peng et al. 2009), so we can detect CN in these GC that become brighter than \( m(F814W) \sim 24.5 \) and \( m(F606W) \sim 25.5 \). Thirty of 31 CN identified by Shara et al. (2016) in M87 became brighter than \( m(F606W) = 25.5 \), while 25 of the same 31 CN became brighter than \( m(814W) = 24.5 \). Approximately 20% of M87 CN become as bright as \( m(606W) = 23 \), making them detectable in even the most luminous M87 GC. This demonstrates that our searches have detected at least 50% of all GC CN but significantly less than 100%.

### 4.2. The M87 GC CN Rate

The moderately different areal coverages of the three HST instruments used for these surveys (the Wide Field Camera 2 (WFPC2), the ACS, and WFC3) mean that the number of GC checked for CN is slightly smaller in the WFPC2 survey. Ignoring this modest difference, our detection rate is \( \sim 1 \) CN/2000 GC/367 days \( \sim 5 \times 10^{-4} \) CN/GC/yr, in good agreement with the rate measured by Curtin et al. (2015), \( 4 \times 10^{-4} \) CN/GC/yr. Those authors argued, on the basis of their discovery of two GC novae (one in M84, one in M87, and zero in M49) out of a total of 83 CN, that novae are likely enhanced relative to the field by at least an order of magnitude. While our rates are in apparently good agreement with those of Curtin et al. (2015), the significantly lower detection rate in our M87 survey suggests that the novae in M87 are not as bright as those in M84 and M87.

![Figure 1](image-url)
agreement, we believe it premature to claim an enhanced nova rate in GC.

We detected ∼100 CN in M87 in the 2016–2017 data set, 31 in the 2005–2006 data set (Shafter et al. 2000), and at least six in the 2001 data set, for a total of 137 CN, compared to just one GC CN. Our detections of 1/137 GC CN, and those of Curtin et al. (2015) (2/83) are dominated by small number statistics. Our small number statistics, and those of all other surveys, suggest to us that the Large Synoptic Survey Telescope’s planned imaging of the Virgo and Fornax clusters of galaxies every few nights for several years, in the coming decade, will be essential to finally providing 100 or more GC CN, and thousands of galaxy CN. Only then will a definitive determination of the rate of GC CN in different galaxies, and a direct measurement (if real) of the overabundance of GC CN relative to those in the field, be possible.

5. Summary

We have searched HST images of ∼2000 GC of the Virgo giant elliptical galaxy M87, taken over a total timeframe of one year. One GC CN was observed to erupt during that time. Our search was sufficiently sensitive to have detected at least half of all erupting CN in GC. The rate we deduce is ∼5 × 10⁻⁴ CN/GC/yr. Only much larger samples, expected in the coming decade from LSST, can definitively determine if this rate is correct and if GCs produce CN at a higher rate than the field.

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