A Survey of Novae in M83

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Abstract

The results of the first synoptic survey of novae in the barred spiral and starburst galaxy, M83 (NGC 5236), are presented. A total of 19 novae and one background supernova were discovered during the course of a nearly 7 year survey comprised of over 200 individual nights of observation between 2012 December 12 and 2019 March 14. After correcting for the limiting magnitude and the spatial and temporal coverage of the survey, the nova rate in M83 was found to be \( R = 19.3 \pm 3 \) yr \(^{-3}\). This rate, when normalized to the \( K \)-band luminosity of the galaxy, yields a luminosity-specific nova rate, \( \nu_K = 3.0^{+0.9}_{-0.6} \times 10^{-10} \) yr \(^{-1} \) L\(_K\). The spatial distribution of the novae is found to be more extended than the overall galaxy light suggesting that the observed novae are likely dominated by a disk population. This result is consistent with the observed nova light curves, which reveals that the M83 novae are on average more luminous at maximum light and fade faster when compared with novae observed in M31. Generally, the more luminous M83 novae were observed to fade more rapidly, with the complete sample being broadly consistent with a linear maximum magnitude versus rate of decline relation.

Unified Astronomy Thesaurus concepts: Classical novae (251); Galaxies (573); Time domain astronomy (210); Cataclysmic variable stars (203); Novae (1127)

Supporting material: machine-readable tables

1 Introduction

Nova eruptions are the result of quasiperiodic thermonuclear runaways (TNRs) on the surfaces of accreting white dwarfs in semidetached binary systems (e.g., see Starrfield et al. 2016 and references therein), with eruptions recurring on timescales as short as a year (Kato et al. 2014).\(^{12}\) Nova are among the most luminous optical transients known, with absolute magnitudes at the peak of the eruption averaging \( M_V \sim -7.5 \), and reaching \( M_V \sim -10 \) for the most luminous systems. As a result, they can be seen to great distances and have been studied in external galaxies for more than a century (e.g., in M31, Ritchey 1917; Hubble 1929).

The observed properties of novae are predicted theoretically to depend strongly on the structure of the progenitor binary system. The mass of the white dwarf and the rate of accretion onto its surface are the most important parameters, ultimately determining the ignition mass required to initiate the TNR (e.g., Nomoto 1982; Townsley & Bildsten 2005; Kato et al. 2014). Systems with high mass white dwarfs accreting at high rates require the lowest ignition masses, and thus have the shortest recurrence times between successive eruptions. The small ignition masses result in eruptions that eject relatively little mass resulting in a rapid photometric evolution (i.e., they produce “fast” novae).

The mass accretion rate is strongly influenced by the evolutionary state of the companion star, with evolved stars typically transferring mass to the white dwarf at a higher rate compared with systems containing main-sequence companions. The amplitudes of the eruptions are also strongly dependent on the nature of the companion star, being as small as \( \sim 5 \) mag as in the case of the M31 recurrent nova M31N 2008--12a (Darnley et al. 2017), or as large as \( \sim 20 \) mag as was observed for the Galactic nova, V1500 Cyg (Duerbeck 1987). Finally, it is also thought that the chemical composition of the accreted material may also play an important role in determining the observed properties of nova eruptions (e.g., Starrfield et al. 2016, and references therein).

Given that the nature of the nova eruptions is predicted to depend sensitively on the properties of the progenitor binary, it is reasonable to expect that the observed properties of a nova in a given galaxy might vary with the underlying stellar population. In particular, the specific rate of nova eruptions can be expected to be much higher in a population of novae containing higher mass white dwarfs, where the average recurrence times are relatively short. An early attempt to explore this question was undertaken by Yungelson et al. (1997) who computed population synthesis models that predicted that young stellar populations, which

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\(^{12}\) Novae where more than one eruption has been recorded (i.e., systems with recurrence times less than of order a century) are collectively referred to a “recurrent nova,” although the terminology is somewhat misleading given that all systems are believed to be recurrent.
contain on average more massive white dwarfs, should produce nova eruptions at a higher rate compared with older populations. Thus, late-type, low-mass galaxies, with a recent history of active star formation were predicted to be more prolific nova producers compared with older, quiescent galaxies.

To date, nova rates have been estimated in well over a dozen galaxies (e.g., see Shafter et al. 2014; Shafter 2019 Della Valle & Izzo 2020 and references therein). Taken together, the results do not suggest a simple relationship between a galaxy’s specific nova rate (usually taken to be its K-band luminosity-specific rate, \( \nu_K \)) and its dominant stellar population (as reflected by its integrated B – K color). Early work by Ciardullo et al. (1990), Shafter et al. (2000), and Williams & Shafter (2004) failed to find any correlation between \( \nu_K \) and Hubble type; however, della Valle et al. (1994) argued that the bluer, late-type systems such as the Magellanic Clouds and M33, had higher specific nova rates compared with earlier type galaxies. More recently, Shara et al. (2016) and Shafter et al. (2017) have analyzed archival HST imaging data of M87 and made a compelling case that the specific nova rate in this giant elliptical galaxy is at least as high, and perhaps higher, than that found in spiral galaxies and the LMC. Given the uncertainties inherent in measuring extragalactic nova rates, particularly in galaxies other than the Magellanic Clouds (where the rates are relatively well constrained by the Optical Gravitational Lensing Experiment (OGLE; Mróz et al. 2016, and Williams & Shafter 1994 Della Valle & Shafter 1994)), it is fair to say that the question of whether the specific rates vary systematically with the underlying stellar population has yet to be answered definitively.

In an attempt to shed further light on how the underlying stellar population may affect observed nova properties, we have undertaken a multiyear survey of novae in the grand-design spiral M83 (NGC 5236)—also known as the Southern Pinwheel galaxy—a metal-rich, late-type barred spiral galaxy of morphological type Sab(s)c (de Vaucouleurs et al. 1991).

2. Observations

Our survey for novae in M83 spanned approximately 7 years between 2012 December 12 and 2019 March 14. During this time we acquired a total of 205 nightly images of the galaxy. All observations were acquired with the 1.54 m Danish reflector at the La Silla Observatory using the DFOSC 2048 × 2048 CCD imager. The telescope-detector combination resulted in final images covering a square area of approximately 13.5′ on a side, with a spatial resolution of 0.396 arcsec pixel\(^{-1}\). In visual light, M83 has an apparent size of 12.9′ × 11.5′, assuring that our observations cover essentially all of the galaxy. However, as described later in Section 5.3, the outer halo of M83 may extend slightly beyond our survey’s spatial coverage.

The vast majority of our images were taken through a broadband R filter, with occasional exposure taken through an I filter. We chose to conduct our primary survey in the R band both because novae develop strong Hα emission shortly after eruption, which adds to the flux in the R band, and because the quantum efficiency of the CCD detector reaches a peak near the R band. A complete log of our observations is given in Table 1.

2.1. Image Processing

All images were pipeline processed in the usual manner by first subtracting the bias and dark current, and then flat-fielding the individual images to remove the high-frequency, pixel-to-pixel variations using APHOT (a synthetic aperture photometry

\[ \text{Table 1} \]

| UT Date | Julian Date | Limiting mag |
|---------|-------------|--------------|
| (yr month day) | (2,450,000+) | (R) |
| 2012 12 12.361 | 6273.861 | 22.3 | 1 |
| 2012 12 18.368 | 6279.868 | 22.7 | 1 |
| 2012 12 22.352 | 6283.852 | 22.5 | 1 |
| 2012 12 23.345 | 6284.845 | 22.9 | 1 |
| 2012 12 28.314 | 6289.814 | 21.8 | 1 |

Notes: All observations were made with the 1.54 m Danish Telescope at La Silla.

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\( ^a \) Observer(s): (1) K. Hornoch.

This table is available in its entirety in machine-readable form.

and astrometry software developed by M. Velen and P. Pravec at the Ondřejov observatory; Pravec et al. 1994). To eliminate cosmic-ray artifacts in our nightly images, we obtained a series of 120 s images that were later spatially registered and median stacked using SIPS\(^13\) to produce a final image for a given night of observation intended for nova searching. Photometric and astrometric measurements of the novae were done using APHOT on spatially registered and stacked nightly images.

3. Nova Detection

Novae are transient sources that can be effectively identified through careful comparisons between images from synoptic imaging surveys having a variable cadence such as the one we have conducted. Coarse temporal coverage is sufficient to identify transient sources, but sufficiently dense coverage is required to measure the light curves. The light curves provide assurance that the detected transients are indeed novae and not some other variable objects, such as luminous blue variables (LBVs), or the more common luminous red variables (i.e., Mira variables) that can mimic novae in poorly sampled surveys. Novae can also be distinguished from other variable stars through their V – I color, which is the reason we augmented our data with occasional I-band images. The strong Hα emission contributing to the R-band flux results in a V – I color that is significantly bluer than that of the extremely red Mira variables, which are characterized by V – I \( \gtrsim 2 \) (e.g., see Bhardwaj et al. 2019).

Nova candidates were identified using two different procedures: first, through a direct comparison (blinking) of images from different epochs, and second, through a comparison of images from differing epochs using the image subtraction software, ISIS (Alard & Lupton 1998). Direct comparison of the images proved to be a very effective technique for identifying novae in the outer regions of the galaxy; however, in regions of the galaxy with high surface brightness (i.e., within \( \sim 3′ \) of the nucleus and in some very dense regions of the spiral arms) we had to modify our approach. To detect novae in regions of high background, we first created smoothed (median-filtered) images by sliding an 11 × 11 pixel box across the image, pixel-by-pixel, replacing the central pixel by the median of all 121 pixels in the box. This median-smoothed image was then subtracted from the original image to produce a median-subtracted image with greatly reduced background variations. These median-subtracted images were once again blinked by eye.

\( ^{13} \) https://www.gxccd.com/cat?id=146&lang=409
In addition to blinking median-subtracted images, we also employed image subtraction routines from the ISIS image processing package, which increased our sensitivity to novae in regions of high background. Figure 1 shows an example of our ISIS nova detection procedure. The top panel shows a $75'' \times 57''$ portion of a median-combined image from 2014 February 11 UT. The middle panel shows an image of the same region of the galaxy 1 month later on 2014 March 11 UT. The nova, M83N 2014-03a, is visible in the March image, and clearly visible in the ISIS subtracted image at the bottom.

We discovered a total of 19 novae over the course of our 7-year survey of M83. Their positions and offsets from the center of M83 ($\text{R.A.} = 13^h 37^m 00^s 919$, decl. $= -29^\circ 51' 56''/4$, J2000) are given in Table 2. These detections represent the first novae to be reported in M83. It is worth noting that during our inspection of the images we found one transient source located extremely close ($\sim 2''$ E and $\sim 1.6''$ S) to the center of an anonymous background spiral galaxy (see Figure 2). The background galaxy, which is located at R.A. $= 13^h 37^m 19^s 59$, decl. $= -29^\circ 53' 47''/1$, lies 242.3'' E and 110.3'' S from the center of M83. While it is possible that this transient could be a nova in M83, given its proximity to the nucleus of the spiral, we consider it far more likely to have been a supernova in the galaxy discovered serendipitously during the course of our survey (Hornoch et al. 2013). This assessment is backed up by the light curve of the transient (see Figure 3), which shows the relatively slow rise to peak brightness characteristic of supernovae, but not novae. A comparison with the supernova light-curve templates given in Doggett & Branch (1985) suggests that the transient is likely a supernova of Type Ia. In view of these considerations, we have excluded this source from our final tally of M83 novae.

### 3.1. Photometry

Instrumental magnitudes for all nova candidates were determined by summing the fluxes in $2''$ diameter circular apertures in all epochs in which they were visible. Calibrated $R$-band magnitudes were then determined by differential photometry with respect to a set of six secondary standard stars in the M83 field. Both the $R$-band and $I$-band magnitudes of the secondary standard stars were photometrically calibrated by us using the same instrumentation as we used for the survey. As primary standards we used the stars and their magnitudes published in Landolt (1992). We observed both the primary standards and the M83 field during one night under excellent photometric conditions to properly calibrate the secondary standards in the field of M83, which allow us to obtain photometry of the novae also in nonphotometric nights.

The calibrated magnitudes of all 19 novae discovered as part of our survey, on all nights where they were visible, are presented in Table 3. The temporal sampling of our survey was sufficient to produce useful $R$-band light curves for all but one of the 19 novae. The light curves for these 18 novae having multiple epochs of observation are shown in Figure 4. The properties of the light curves (i.e., their peak magnitudes and fade rates) will be explored further in Section 6.
effectively blind to novae within surface brightness near the nucleus of the galaxy renders us R three cumulative light distributions starting with inner radii at

5 M83N 2013

6 M83N 2013

7 M83N 2013

8 M83N 2013

9 M83N 2013

10 M83N 2013

11 M83N 2015

12 M83N 2015

13 M83N 2016

14 M83N 2016

15 M83N 2016

16 M83N 2016

17 M83N 2018

18 M83N 2019

19 M83N 2019

4. The Spatial Distribution of M83 Novae

Figure 5 shows the spatial distribution of the 19 novae discovered in M83 superimposed on a (negative) image of the galaxy. It is immediately apparent that the novae seem to be more spatially extended than the galaxy light. We can explore this impression more quantitatively by comparing the cumulative distribution of the novae with that of the background R-band light, as shown in Figure 6. The cumulative background light has been determined by integrating the surface photometry from Table 4, which we have derived from digitizing the radial surface brightness profiles given in Figure 4 of Kuchinski et al. (2000). Since the high surface brightness near the nucleus of the galaxy renders us effectively blind to novae within ∼ 30′ of the center of the galaxy, and likely significantly incomplete within 60′, we have considered three cumulative light distributions starting with inner radii at R_m = 30′, R_m = 60′, and R_m = 90′. Regardless of the adopted inner radius, the cumulative background light clearly falls off faster than the observed nova distribution. This result is formally confirmed by Kolmogorov–Smirnov (K-S) tests (ρ = 1.6 × 10^{-3}, ρ = 3.7 × 10^{-3}, and ρ = 1.1 × 10^{-2} for cases where we considered inner radii of R_m = 30′, R_m = 60′, and R_m = 90′, respectively), suggesting we can reject the null hypothesis (i.e., the nova and light distributions were drawn from the same parent distribution) with ≥ 99% confidence. Thus, it appears that the novae detected in M83 are primarily associated with a more extended disk population of the galaxy.

Before considering possible explanations for why the novae do not appear to follow the overall background light in M83, it is important to rule out the possibility that we may be missing a significant fraction of novae in the inner regions of the galaxy due to the difficulty in detecting them against the high central surface brightness. We explore this possibility below in our determination of the nova rate in M83, which also depends critically on the overall completeness of our survey.

5. The Nova Rate in M83

As transient objects, novae are visible for a limited time that depends both on the intrinsic properties of the novae themselves (e.g., their peak luminosities, fade rates, and spatial location within the galaxy) and on parameters inherent to the survey itself; specifically, the temporal sampling and survey depth (the effective limiting magnitude). Whether or not a given nova in M83 can potentially be detected depends on a combination of its peak apparent magnitude, its position within the galaxy, and on the limiting magnitude of our survey images at that location in the galaxy. Then, whether it will actually be detected depends on the time it erupted relative to the dates of our observations and the rate of decline in the nova’s brightness. Given a population of novae with a variety of light-curve properties (peak luminosities and fade rates), distributed at different positions within the galaxy, and observed at different times, the only practical way of determining the number of novae we can expect to see in our survey given an intrinsic rate, R, is to conduct numerical (Monte Carlo) simulations. Before the simulations can be performed, the first step is to determine the effective completeness of the survey at a given magnitude, C(m).

5.1. The Effective Limiting Magnitude of the Survey

A determination of the limiting magnitude of our survey images is complicated by the fact that the galaxy background surface brightness is highly variable and that the spatial distribution of the novae cannot be assumed to be uniform across the survey images. Thus, no one limiting magnitude can represent the coverage of a given image. We have approached this problem following the procedure described in our earlier work on NGC 2403 (Franck et al. 2012). Specifically, we have conducted artificial nova tests on a representative image (hereafter the fiducial image) under the assumption that the spatial distribution of the artificial novae follows the background light of the galaxy.

| Nova # | Nova Name     | R.A. (2000.0) (h m s) | Decl. (2000.0) (° ′ ″) | R.A. Offset Δα cos(δ) (°) | Decl. Offset Δδ (°) | Notes |
|--------|---------------|------------------------|--------------------------|---------------------------|---------------------|-------|
| 1      | M83N 2013–01a | 13 36 44.30            | −29 50 33.9              | −216.2                    | 82.8                | 1     |
| 2      | M83N 2013–01b | 13 37 03.42            | −29 53 39.8              | 32.5                      | −103.1              | 2     |
| 3      | M83N 2013–01c | 13 37 06.75            | −29 56 15.5              | 75.8                      | −258.8              |       |
| 4      | M83N 2013–01d | 13 37 10.51            | −29 45 19.6              | 124.8                     | 397.1               |       |
| 5      | M83N 2013–03a | 13 36 58.76            | −29 53 22.6              | −28.1                     | −85.9               |       |
| 6      | M83N 2013–04a | 13 37 05.80            | −29 48 11.4              | 63.5                      | 225.3               |       |
| 7      | M83N 2014–01a | 13 37 17.86            | −29 53 47.7              | 220.3                     | −111.0              |       |
| 8      | M83N 2014–01b | 13 37 05.81            | −29 56 02.0              | 63.6                      | −245.3              |       |
| 9      | M83N 2014–01c | 13 37 15.48            | −29 56 10.9              | 189.3                     | −254.2              |       |
| 10     | M83N 2014–03a | 13 37 08.88            | −29 50 16.6              | 103.6                     | 100.1               |       |
| 11     | M83N 2015–01a | 13 36 35.15            | −29 56 41.0              | −335.1                    | −284.3              |       |
| 12     | M83N 2015–04a | 13 37 08.42            | −29 51 13.5              | 97.6                      | 43.2                |       |
| 13     | M83N 2016–02a | 13 36 53.01            | −29 56 19.9              | −102.8                    | −263.2              |       |
| 14     | M83N 2016–02b | 13 36 45.52            | −29 55 57.2              | −200.2                    | −240.5              |       |
| 15     | M83N 2016–03a | 13 36 36.15            | −29 51 44.9              | −322.2                    | 11.8                | 3     |
| 16     | M83N 2018–01a | 13 37 09.78            | −29 56 57.6              | 115.2                     | −300.9              | 4     |
| 17     | M83N 2018–02a | 13 37 01.26            | −29 55 48.2              | 4.4                       | −231.5              | 4     |
| 18     | M83N 2019–02a | 13 37 03.82            | −29 48 21.7              | 37.7                      | 215.0               | 5     |
| 19     | M83N 2019–03a | 13 37 18.18            | −29 48 29.0              | 224.6                     | 207.7               | 6     |

Notes.

(1) Hornoch (2013a), (2) Hornoch (2013b; see also Prieto & Morrell 2013, for spectroscopic classification), (3) Hornoch & Paunzen (2018), (4) Hornoch & Kucakova (2018), (5) Hornoch & Kucakova (2019), (6) Hornoch et al. (2019).

(This table is available in machine-readable form.)
The artificial novae were generated using tasks in the IRAF DAOPHOT package, which enabled us to match the point-spread functions of the real stars in the image. Using the routine addstar, the fiducial image was then seeded with 100 artificial novae having apparent magnitudes randomly distributed within each of a total of eight, 0.5 mag wide, bins. For each of the magnitude bins, the artificial novae were distributed randomly, but with a spatial density that was constrained to follow the integrated background galaxy light of M83. We then searched for the artificial novae using the same procedures that we employed in identifying the real novae. The completeness at the fainter magnitudes was somewhat higher using the ISIS image subtraction analysis, but was generally consistent with the results from a direct comparison of median-subtracted images.

The fraction of novae recovered from the two search techniques in each magnitude bin yielded the completeness functions shown in Figure 7. Given that we discovered the same number of novae in M83 employing both techniques, we have chosen to take the average completeness in a given magnitude bin (the heavy line in Figure 7) to form the basis of the completeness function, \( C(m) \). To allow for uncertainty in magnitude bins where the completeness functions differ (the shaded regions), we randomly sample allowed values of \( C(m) \) in the analysis to follow. This completeness function can be generalized to any epoch, \( i \), of observation by applying a shift, \( \Delta m_i = (m_{\text{lim},0} - m_{\text{lim},i}) \), which represents the difference in the limiting magnitudes (as measured by the faintest star that could be reliably detected near the perimeter of the image away from the galaxy) of our fiducial image and that of the \( i \)th epoch image. Thus, for any epoch, \( i \), we have \( C_i(m) = C(m + \Delta m_i) \).

5.2. The Monte Carlo Simulation

As in our earlier extragalactic nova studies (e.g., Franck et al. 2012; Güth et al. 2010; Coelho et al. 2008; Williams & Shafter 2004), we have employed a Monte Carlo simulation to...
Figure 4. Light curves for 18 of the 19 novae discovered in our survey plotted with consistent axes scales in order to better reveal the relative photometric properties of the novae. The one nova not shown is M83N 2015-04a, where the nova was only seen in one epoch ($R = 21.4 \pm 0.25$ on JD 2,457,120.915). The red triangles represent upper limits on the flux at times when the novae were not detected.
compute the number of M83 novae that we would expect to observe during the course of our survey.

For a given assumed annual nova rate, \( R \), we begin by producing trial novae erupting at random times throughout the time span covered by our survey, each having a peak luminosity and fade rate that has been selected at random from a large sample of known \( R \)-band light-curve parameters. Ideally, we would like to use light-curve parameters specific to the full population of M83 novae, but such an unbiased sample does not exist. Instead, we have used the M83 light-curve parameters from our observations given in Table 5, augmented with additional \( R \)-band light-curve parameters from the M31 light curves observed by Shafter et al. (2011).

Adopting a distance modulus to M83 of \( \mu_0 = 28.34 \pm 0.14 \), which represents the mean of the Cepheid and the tip of the red giant branch distances from the recent study by Tully et al. (2016), enables us to compute the expected apparent magnitude distribution at any given epoch, \( i \), during our survey, \( n_i(m, R) \). To account for uncertainty in the distance, our numerical simulations also randomly select values of the distance modulus normally distributed about the mean value. The number of novae expected to be detectable during the course of our survey, \( N_{\text{obs}}(R) \), can then be computed by convolving the simulated apparent magnitude distribution with the completeness function, \( C_i(m) \), and then summing over all epochs of observation:
Table 4
M83 Surface Photometry

| Semimajor Axis (arcsec) | $\Sigma_R$ (mag arcsec$^{-2}$) | Semimajor Axis (arcsec) | $\Sigma_R$ (mag arcsec$^{-2}$) |
|------------------------|--------------------------------|------------------------|--------------------------------|
| 0.4                    | 15.90                          | 2.7                    | 16.01                          |
| 2.7                    | 16.01                          | 4.4                    | 16.42                          |
| 4.4                    | 16.42                          | 7.1                    | 16.98                          |
| 7.1                    | 16.98                          | 9.3                    | 17.59                          |
| 9.3                    | 17.59                          | 11.5                   | 17.91                          |
| 11.5                   | 17.91                          | 13.7                   | 18.17                          |
| 13.7                   | 18.17                          | 16.3                   | 18.45                          |
| 16.3                   | 18.45                          | 18.1                  | 18.65                          |
| 18.1                  | 18.65                          | 20.7                  | 18.80                          |
| 20.7                  | 18.80                          | 22.1                  | 18.91                          |
| 22.1                  | 18.91                          | 24.7                  | 18.99                          |
| 24.7                  | 18.99                          | 25.6                  | 19.06                          |
| 25.6                  | 19.06                          | 27.4                  | 19.19                          |
| 27.4                  | 19.19                          | 29.6                  | 19.25                          |
| 29.6                  | 19.25                          | 31.8                  | 19.30                          |
| 31.8                  | 19.30                          | 33.5                  | 19.38                          |
| 33.5                  | 19.38                          | 36.2                  | 19.45                          |
| 36.2                  | 19.45                          | 38.4                  | 19.51                          |
| 38.4                  | 19.51                          | 41.0                  | 19.60                          |
| 41.0                  | 19.60                          | 43.2                  | 19.64                          |
| 43.2                  | 19.64                          | 46.8                  | 19.68                          |
| 46.8                  | 19.68                          | 49.9                  | 19.73                          |
| 49.9                  | 19.73                          | 52.9                 | 19.81                          |
| 52.9                 | 19.81                          | 55.9                 | 19.86                          |
| 55.9                 | 19.86                          | 58.9                 | 19.92                          |
| 58.9                 | 19.92                          | 61.3                 | 19.99                          |
| 61.3                 | 19.99                          | 64.7                 | 20.03                          |
| 64.7                 | 20.03                          | 67.1                 | 20.10                          |
| 67.1                 | 20.10                          | 69.5                 | 20.14                          |
| 69.5                 | 20.14                          | 72.0                 | 20.20                          |
| 72.0                 | 20.20                          | 74.5                 | 20.25                          |
| 74.5                 | 20.25                          | 77.0                 | 20.30                          |
| 77.0                 | 20.30                          | 79.5                 | 20.37                          |
| 79.5                 | 20.37                          | 82.0                 | 20.43                          |
| 82.0                 | 20.43                          | 84.5                 | 20.50                          |
| 84.5                 | 20.50                          | 87.0                 | 20.58                          |
| 87.0                 | 20.58                          | 89.5                 | 20.66                          |
| 89.5                 | 20.66                          | 92.0                 | 20.75                          |

Notes.

a Digitized from Kuchinski et al. (2000). P.A. = 80°; ellipticity, b/a = 0.9, assumed for all values.

b Extrapolated value.

Figure 6. The cumulative distribution of the isophotal radii of the 19 novae (black histogram) compared with the cumulative galaxy R-band light for three representative values of the inner radius, $R_{in}$ (shown in red).

Figure 7. The survey completeness as a function of the R-band apparent magnitude, $C(m)$, as determined from our artificial nova tests. The red dashed line shows the completeness from the ISIS image subtraction procedure, the blue dotted-dashed line shows the completeness using the median-subtraction technique, and the heavy black line shows the average completeness in each magnitude bin. The shaded region shows the range of completeness in each magnitude bin bounded by the two search techniques and used in our Monte Carlo nova rate simulations.

The intrinsic nova rate in M83, R, and its uncertainty can now be determined through a comparison of the number of novae found in our survey, $n_{obs} = 19$, with the number of novae predicted by Equation (1). We explored trial nova rates ranging from $R = 1$ to $R = 50$ novae per year, repeating the numerical simulation $10^5$ times for each trial value of $R$. The number of matches, $M(R)$, between the predicted number of observable novae, $N_{obs}(R)$, and the actual number of novae discovered in our survey, $n_{obs} = 19$, was recorded for each trial value of $R$. The number of matches was then normalized by the total number of matches for all $R$ to give the probability distribution function, $P(R) = M(R)/\Sigma M(R)$ shown in Figure 8. The most probable nova rate in the portion of the galaxy covered by our survey images is $18_{-5}^{+5}$ yr$^{-1}$, where the error range (1σ) for the asymmetrical probability distribution has been computed assuming it can be approximated by a bi-Gaussian function.

The $K$-band photometry of M83 from the Two-Micron All Sky Survey (2MASS) suggests that the extended halo may extend out to a distance of $R_{halo} \sim 8.5$ from the center of M83. Thus, it is possible that our survey images may be missing a small fraction ($\leq 5\%$) of the light from the extended halo of M83. Under the assumption that we are sampling 0.95 ± 0.05 of the total M83 light, we estimate the global nova rate for M83 to be $R_{M83} = 19_{-3}^{+5}$ yr$^{-1}$.

5.3. The Luminosity-specific Nova Rate

In order to compare the nova rates between different galaxies or different stellar populations, the rates must first be suitably normalized. Ideally, it would be appropriate to normalize the rates by the mass of stars in the region surveyed, but the mass cannot be measured directly. As a proxy for the mass in stars, it has become standard practice to normalize the nova rate by the infrared $K$-band luminosity of the galaxy. In the case of M83, the integrated apparent $K$-band magnitude as measured by
2MASS is $K = 4.62 \pm 0.03$. Given the distance modulus, $\mu_0 = 28.34 \pm 0.14$, and taking the absolute $K$-band magnitude of the Sun to be $M_K = 3.27 \pm 0.02$ (Willmer 2018), we find that M83 has an absolute magnitude in the $K$ band of $M_K = -23.72$, and a corresponding $K$-band luminosity of $(6.32 \pm 0.84) \times 10^{10} L_{\odot,K}$. Since we estimate that our survey covers $0.95 \pm 0.05$ of the entire galaxy where we have found an overall nova rate of $18^{+3}_{-5}$ yr$^{-1}$, we arrive at a $K$-band luminosity-specific nova rate for M83 of $\nu_K = (3.0^{+0.9}_{-0.6}) \times 10^{-10}$ yr$^{-1} L_{\odot,K}^{-1}$.

As recently reviewed by Shafter (2019) and Della Valle & Izzo (2020) prior to the present study, luminosity-specific nova rates had been measured for a total of 15 external galaxies. Figure 9 shows our value of $\nu_K$ for M83, along with the values for the other 15 galaxies taken from Table 7.3 in Shafter (2019), plotted as a function of the $B-K$ color of the host galaxy. The specific nova rate for M83 is consistent with those of other spiral galaxies with measured nova rates. As we have noted in previous studies, despite the relatively high $\nu_K$ values reported for the Magellanic Clouds and M87—galaxies with very different Hubble types—there is no compelling evidence that $\nu_K$ varies systematically with the underlying stellar population.

### 6. Light-curve Properties

As described in Section 3.1, the temporal coverage during the course of our survey was sufficiently dense to enable us to measure $R$-band light curves for 18 of the 19 M83 novae that were detected. These light curves, drawn from an equidistant sample of novae, offer a rare opportunity to explore the relationship between a nova’s peak luminosity and its rate of decline from maximum light, and thus test whether or not the novae obey the canonical (but recently questioned) maximum magnitude versus rate of decline (MMRD) relation.
6.1. The MMRD Relation

The MMRD relation for novae was first introduced by Mclaughlin (1945), who discovered that the most luminous members of a sample of 30 (mostly Galactic) novae faded more quickly than did their fainter counterparts. He was able to quantify a linear MMRD relation of the form, $M = a + b \log(t_f)$, where $a$ and $b$ are fitting parameters and $t_f$ is the time it takes a nova to fade 3 mag from maximum light (in recent years, $t_f$, which is more easily measured, is often used as an alternative). Over the years the MMRD relation has been calibrated many times, both in the Galaxy (e.g., Cohen 1985; Downes & Duerbeck 2000), and in nearby galaxies such as M31 (e.g., Capaccioli et al. 1989; Shafter et al. 2011), and has often been used as a means for determining the distances to novae where the apparent magnitude at maximum light and the fade rate have been measured.

Over the years it has become increasingly apparent that there is significant scatter in the MMRD, with the existence of the relation itself being called into question, initially by (e.g., Kasliwal et al. 2011) who found that a number of M31 novae observed with the Palomar Transient Factory (PTF) appeared to fall below the canonical MMRD relation (but, see Della Valle & Izzo 2020 for a different interpretation). Recently, it has become clear that a small subset of novae, typically those with massive white dwarfs that are accreting at high rates (e.g., recurrent novae) fade rapidly despite having relatively low peak luminosities, and thus deviate sharply from the MMRD relation.

A good example is the M31 recurrent nova M31N 2008-12a (Darnley et al. 2014; Tang et al. 2014). Given that such systems do in fact exist, it is clear that not all novae will follow a universal MMRD relation. On this basis it has been recently suggested that the notion of an MMRD relation should be abandoned altogether (Schaefer 2018). However, the question of whether it is useful to continue to refer to an MMRD relation would seem to depend on the relative frequency of outliers. If the so-called “faint and fast” (FFN) novae, such as M31N 2008-12a, are intrinsically rare, then continuing to refer to an MMRD might make sense when considering the behavior of the majority of (nonrecurrent) novae. On the other hand, if such systems are relatively common, but just missed in most surveys that lack the depth and cadence to discover them, then perhaps the existence of a MMRD relation would be best considered as resulting from an observational selection effect. In either case, it appears that broadly speaking, luminous novae do fade more quickly than do their low luminosity counterparts.

Figure 10 shows the MMRD relation for the 17 novae in M83 where the light curves were sufficiently complete to allow a measurement of the peak magnitude and the rate of decline (here measured as $t_f$, the time for the nova to fade 2 mag from peak). Although there is significant scatter as expected, there is no question that a general trend, where the more luminous novae fade more quickly, is apparent. The best-fitting linear MMRD relation is given by: $M_R = (-10.79 \pm 0.42) + (1.96 \pm 0.29) \log t_f$. The M31 $R$-band MMRD relation from the study of Shafter et al. (2011) is shown for comparison, and is remarkably similar.

14 In his 1945 paper Mclaughlin referred to the MMRD relation as the “life-luminosity” relation for novae.

15 MMRD relations are sometimes fit using a more complicated arctan function, which has been shown to provide a somewhat better fit to data for M31 and the LMC (e.g., see Della Valle & Livio 1995). Given the limited data in the present study, we have chosen to employ the traditional linear fit.

16 Since the $t_f(R)$ distributions are highly asymmetric, the values of $(t_f(R))$ are computed from the average of the log $t_f(R)$ values for each galaxy.

Figure 10. The peak absolute $R$-band magnitudes for the 17 M83 novae with complete light curves are plotted as a function of the log of the fade rate, as measured by the time in days a nova takes to fade by 2 mag in the $R$ band from its peak luminosity, $t_f(R)$. The M83 nova sample clearly displays a correlation between peak nova luminosity and $\log(t_f)$, as shown by the black dashed line. The $R$-band MMRD relation for M31 from Shafter et al. (2011; red dotted line) is shown for comparison. The two relations are remarkably similar.

6.2. Comparison with the M31 Nova Population

As part of a comprehensive spectroscopic and photometric survey of novae in M31, Shafter et al. (2011) determined $R$-band light-curve parameters for a total of 42 novae and found that, as in the case of M83, the M31 nova sample also generally followed an MMRD relation, albeit with significant scatter (see Table 6 and Figure 19 in Shafter et al. 2011). The M31 novae are characterized by a mean absolute magnitude, $(M_R) = -7.55 \pm 0.14$ and $(t_f(R)) = 38^{+6}_{-5}$ day, while their M83 counterparts from Table 5 yield $(M_R) = -8.06 \pm 0.21$ and $(t_f(R)) = 25^{+5}_{-6}$ day.

It is interesting to compare the cumulative distributions of the peak luminosities and fade rates from each galaxy, as shown in Figures 11 and 12. The results of K-S tests show that the peak luminosity and fade rate distributions differ between each galaxy with 94% and 74% confidence, respectively. Thus, there is some evidence that the novae in the M83 sample are, on average, more luminous at maximum light and perhaps fade somewhat more rapidly compared with the M31 sample. A possible explanation for this difference is that M31 is an earlier Hubble type galaxy, SA(s)b, and the nova population observed by Shafter et al. (2011) was predominately a bulge population. On the other hand, as discussed earlier, our M31 sample appears to be primarily associated with the galaxy’s disk. Taken together, Figures 11 and 12 provide additional support for the existence of two populations of novae, as originally suggested for Galactic systems three decades ago by Duerbeck (1990) and Della Valle & Livio (1998) based on photometric and spectroscopic observations, respectively.
The determination of extragalactic nova rates is challenging, with many sources of uncertainty that must be properly considered in the analysis. Among these, uncertainty in the determination of the survey completeness is perhaps the most important. As described earlier, the completeness—the fraction of novae erupting in the galaxy that can be detected in a given survey—depends quite sensitively on the intrinsic properties of the novae and their actual distribution within the galaxy under investigation. Since neither of these factors are known a priori, assumptions concerning both must always be made.

To guard against potential bias in our M83 nova sample, we chose to include light-curve parameters from previous observations of novae in M31 in our Monte Carlo nova rate simulations. As a check on the sensitivity of the final nova rate to the inclusion of the M31 light-curve parameters, we have also performed the analysis using only the light-curve parameters from the M83 novae discovered in our survey. Despite the differences in the light-curve properties between the two samples discussed in the previous section, the final nova rate determination is essentially unchanged (the rate ranges from 17 yr⁻¹ to 20 yr⁻¹ when the analysis is restricted to the M83 and M31 light-curve parameters, respectively). In this case, the insensitivity of the nova rate to the choice of light-curve parameters results from the fact that the M83 novae generally follow an MMRD relation. The M83 novae are on average brighter compared with their M31 counterparts, and thus easier to detect in our simulations, but they fade generally more quickly, so they are observable on average for less time. Thus, the two effects tend to cancel, leaving the final nova rate insensitive to the choice of light-curve parameters.

To guard against potential bias in our M83 nova sample, we adopted in the artificial nova completeness experiments can also affect the final nova rate computation. In the absence of strong evidence to the contrary, the default approach—and the one we have followed here—is to assume that the spatial density of novae follows the surface brightness of the galaxy (i.e., more light, more novae). However, in the case of M83, it appears that this assumption may be violated. As shown in Figure 5 the observed M83 nova spatial distribution is significantly more extended than the galaxy’s R-band light. If this result accurately reflects the intrinsic nova spatial distribution (i.e., we are not missing novae in the inner regions of the galaxy), our artificial nova simulations may underestimate the overall completeness of our survey by placing a greater fraction of the artificial novae in the bright central regions of the galaxy where they are generally more difficult to detect. This bias, although we consider it to be small, would have the effect of slightly overestimating the nova rate determined earlier in our Monte Carlo simulations.

On the other hand, it is worth noting that M83 is an active star-forming galaxy (e.g., see Calzetti et al. 1999), which likely interacted ~1–2 Gyr ago with the nearby metal-poor dwarf galaxy, NGC 5253, triggering starbursts in both galaxies (van den Bergh 1980; Calzetti et al. 1999). The starburst activity in M83 is concentrated in the spiral arms and near the nucleus of the galaxy, which is heavily shrouded in dust (Gallais et al. 1991; Lundgren et al. 2008). These are the same regions of the galaxy where the high surface brightness and complex structure render the detection of novae difficult. Thus, despite our careful nova searches, the possibility that we may be missing some novae in these regions of the galaxy cannot be definitively ruled out. If such a putative population of heavily extincted novae exists, it would not be properly accounted for by our artificial nova tests, the completeness would be overestimated, and our simulations would then underestimate the true nova rate.

### 7. Discussion

#### 7.1. Uncertainty in the Derived Nova Rate

As discussed earlier, it was surprising to find that the observed spatial distribution of novae in M83 did not follow the background light of the galaxy. To put this result into context, it is instructive to compare the observed spatial distribution of novae in M83 with similar galaxies for which nova populations have been studied. Such galaxies include the massive, late-type, and nearly face-on spirals M51 and M101 (morphological types SA(s)bc and SAB(rs)cd, respectively), the relatively low-mass, late-type systems NGC 2403 and M33 (SAB(s)cd and SA(s)cd, respectively), and M81, a relatively early-type SA(s)ab spiral with a prominent bulge component. Unfortunately, as we explore below, a review of these studies does not suggest a simple association between the morphological type of the galaxy and the degree to which the nova distribution follows the light of the host galaxy.
In the case of the face-on, grand-design spiral M101 (Shafer et al. 2000; Coelho et al. 2008), the nova density appears to track the background light remarkably well (K-S, $p = 0.94$), while for M33 (Williams & Shafer 2004; Shafer et al. 2012), the cumulative distributions of the novae and the background light were only marginally consistent (K-S, $p = 0.4$). Similar to our result for M83, the spatial distributions of novae in both M51 (Shafer et al. 2000) and NGC 2403 (Franck et al. 2012), were also found to be more spatially extended than the background light (with 97% and 75% confidence, respectively). In these cases, however, observational incompleteness in the central region of M51 and the spiral arms of NGC 2403 could possibly explain the discrepancy.

The situation with regard to M81 is more complex. The spatial distribution of novae in this galaxy has been studied extensively by a number of groups, all of whom have come to somewhat different conclusions about how the nova distribution compares with the galaxy light. Based on a total of 15 and 12 detected novae, respectively, Moses & Shafer (1993) and Neill & Shara (2004) argued that the M81 novae most closely follow the galaxy’s bulge light, as was found in several studies of the nova population in M31 (Ciardullo et al. 1987; Shafer et al. 2000; Darnley et al. 2006). More recently, however, Hornoch et al. (2008) analyzed a much larger sample of novae (49) than either of the previous studies, finding that the nova density distribution best matches the overall (bulge + disk) background galaxy light. Given that M81 has a prominent bulge component that dominates the overall light in regions where most novae are found, the apparent discrepancy between these studies may be a distinction without much of a difference. In reviewing the earlier studies in more detail, it appears that neither the Moses & Shafer nor the Neill & Shara data are inconsistent with the hypothesis that the novae follow the overall light.

The only M81 nova study that reached a very different conclusion is that of Shara et al. (1999), who analyzed a sample of 23 novae discovered nearly a half century earlier on Palomar photographic plates taken between 1950 and 1955. They found a significant (disk) population of novae in the outer regions of the galaxy that resulted in a poor fit of the full nova distribution to the overall galaxy light (and clearly a worse fit to the bulge light). The poor fit to the overall light persisted even after the authors attempted to correct their data for missing novae in the inner bulge region of the galaxy. It is not obvious how to reconcile these early photographic data with subsequent CCD studies other than to posit that perhaps an even larger number of bulge novae than expected were missed due to the difficulty in detecting them on photographic plates when projected against the bright background of the galaxy’s bulge.

Taken together, the best evidence currently available suggests that the nova distribution in M81 likely follows the overall background light of the galaxy, with novae belonging to both the bulge and disk populations. In the case of most other galaxies, the situation remains less clear. A combination of small number statistics, spatial variations in extinction (especially in late-type spiral galaxies), and limited spatial coverage (e.g., in M31) have all conspired to make it difficult to differentiate a real spatial (stellar population) variation from biases caused by observational incompleteness. As is often the case, more data will be required before we have a full and complete understanding of how the nova properties, including their specific rates, vary with the underlying stellar population.

8. Summary

The principal results of our M83 nova survey are as follows:

1. We have conducted an imaging survey of the SAB(s)c starburst galaxy M83 and discovered a total of 19 novae over the course of our 7 year survey.

2. After correcting for the survey’s limiting magnitude and spatial and temporal coverage, we find an overall nova rate of $R_{M83} = 19.5 \pm 3$ novae yr$^{-1}$ for the galaxy.

3. Adopting an integrated $K$-band magnitude of $K_{M83} = 4.62 \pm 0.03$ from the 2MASS survey, and a distance modulus for M83 of $(m - M)_0 = 28.34 \pm 0.14$, we find the absolute magnitude of M83 in the $K$ band is $M_K = -23.72$, which corresponds to a luminosity of $6.32 \times 10^{10} L_{\odot}$. The luminosity-specific nova rate of M83 is then found to be $\nu_{K} = 3.0_{-0.6}^{+0.6} \times 10^{-10}$ yr$^{-1} L_{\odot}^{-1}$.

4. The value of $\nu_{K}$ for M83 is typical of those found for other galaxies with measured nova rates, and, in agreement with our earlier studies, no compelling evidence is found for a variation of $\nu_{K}$ with galaxy color, or Hubble type.

5. Our survey has enabled us to measure light curves for a total of 18 of the 19 novae discovered in M83. Of these, the peak brightnesses and fade rates ($t_2$ times) could be measured for 17 of the novae. These data show that the most luminous nova we observed in M83 generally faded the fastest from maximum light in accordance with the canonical MMRD relation.

6. We have found the spatial distribution of novae in M83 to be more extended than the background galaxy light suggesting that they are predominately associated with the disk population of the galaxy. In addition, the M83 novae appear, on average, to reach higher luminosities and to evolve more quickly compared with novae in M31, which are predominately associated with that galaxy’s bulge. These findings are consistent with the claim made by Duerbeck (1990), Della Valle & Livio (1998), and others that there are two populations of novae, a “disk” population characterized by generally brighter and faster novae, and a “bulge” population, characterized by novae that are typically slower and less luminous.

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