Extragalactic Nova Populations

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Abstract. Nova rates have now been measured for more than a dozen galaxies spanning a wide range of Hubble types. When normalized to the infrared K-band luminosity of the galaxy, the luminosity-specific nova rates typically fall in the range of 1–3 novae per year per 10¹⁰ solar luminosities in K, and do not vary significantly across the Hubble sequence. Preliminary nova rates are presented for three Virgo ellipticals (M49, M84, and M87) with differing globular cluster specific frequencies. No dependence of the luminosity-specific nova rate on globular cluster specific frequency was found. Photometric and spectroscopic observations of novae in the Local Group suggest that galaxies dominated by a younger stellar population (M33 and the LMC) are characterized by novae with a generally faster photometric evolution, and by a higher fraction of He/N novae compared with novae in M31. The recurrent nova population in the LMC appears to be higher than that seen in M31 and the Galaxy.

1. Extragalactic Nova Rates

Classical novae can reach absolute visual magnitudes of V = −10 making them among the brightest transient sources known. Their high luminosities, coupled with their frequency of appearance [35 yr⁻¹ in a galaxy like our own (Shafter 1997)] make novae ideal for probing the properties of close binary stars in different (extragalactic) stellar populations. Theoretical models show that the strength of the nova outburst is most sensitive to the mass of the accreting white dwarf, with outbursts occurring on massive stars expected to be brighter, with shorter recurrence times and faster light curve evolution. Since population synthesis studies predict that the mean white dwarf mass in a nova system will decrease as a function of the time elapsed since the formation of the progenitor binary (e.g., Tutukov & Yungelson 1995; Politano 1996), the proportion of fast and bright novae is expected to be higher in younger stellar populations.

To date, novae have been observed in more than a dozen galaxies, some as distant as the Coma Cluster, with a sufficient sample of novae having been observed to estimate rates in 15 galaxies. Figure 1 shows the nova rates plotted as a function of the integrated K-band luminosity of the host galaxy. The slope of the relation in this log-log plot is consistent with unity, indicating that the nova rate is simply proportional to the K-band luminosity of the galaxy. The dashed line shows the best-fitting linear relation of the...
Figure 1. The dependence of a galaxy’s nova rate on its $K$-band luminosity. A Galactic nova rate of $25\, \text{yr}^{-1}$ is predicted based on the extragalactic scaling.

Figure 2. The dependence of $K$-band LSNR on galaxy color. M87SH is based on Shara & Zurek (2002).
Extragalactic Novae

Figure 3. The spatial distributions of novae in the Virgo ellipticals M49 and M87 are shown along with a comparison of the cumulative nova distributions and the background g-band light. Open circles represent transients that may not be novae associated with the galaxies.

The surprising result that novae in M31 appeared to be primarily associated with the galaxy’s bulge population led Ciardullo et al. (1987) to propose that a significant fraction of novae might be spawned in the galaxy’s globular clusters and subsequently ejected into the bulge through 3-body interactions in the clusters, or through cluster disruption, or both. More recently, the idea that globular clusters may play a role in the formation of nova binaries gained further support by the observation that the nova form $R = v_K L_K$, where $v_K = 2.25 \text{ yr}^{-1} \left[10^{10} L_{\odot, K}\right]^{-1}$. The predicted Galactic rate of $\sim 25 \text{ yr}^{-1}$ is nearly 30% lower than the best direct estimate, raising the possibility that the extragalactic nova rates may be systematically underestimated. Figure 2 shows the luminosity-specific nova rates (LSNRs) plotted as a function of galaxy color. With the possible exception of M87 (Shara & Zurek 2002; Mizusawa 2013), there is no evidence that the LSNR varies significantly with Hubble type.

1.1. Virgo Ellipticals

The surprising result that novae in M31 appeared to be primarily associated with the galaxy’s bulge population led Ciardullo et al. (1987) to propose that a significant fraction of novae might be spawned in the galaxy’s globular clusters and subsequently ejected into the bulge through 3-body interactions in the clusters, or through cluster disruption, or both. More recently, the idea that globular clusters may play a role in the formation of nova binaries gained further support by the observation that the nova
rate in M87 (which has a cluster specific frequency, \( S_N = 14 \)) appeared to be \( \sim 3 \) times higher than that observed for the more luminous Virgo elliptical M49, which is characterized by a cluster specific frequency of only \( S_N = 3.6 \) (Shafter et al. 2000; Ferrarese et al. 2003; Brodie et al. 2006). A weakness of this comparison is that absolute nova rates for different surveys are very difficult to compare because they depend on light curve properties, survey depth, and many other factors. The extrapolations required to convert an observed nova rate to an absolute rate can be large and uncertain.

To better test the dependence of nova rate on cluster specific frequency, and thereby the idea that a significant fraction of novae are formed in a galaxy’s globular cluster system, we initiated a survey with the MegaCam on the CFHT 3.6 m reflector to determine the relative nova rates in M49 and M87 using the same telescope, instrument, and filter, and on the same nights with the same temporal sampling (Shafter et al. 2013). In a total of 4 epochs spanning 2 years of observation we discovered a total of 29 nova candidates in each galaxy.

The spatial distributions of the nova candidates from our preliminary analyses of M49 and M87 are shown in Figure 3. The distribution for M87 shows an excess of nova candidates at a distance beyond 10’ from the nucleus. It is possible that these transients are either intracluster novae, or some other type of variable. If we exclude these objects, the number of nova candidates in M87 falls to 22. Clearly, there is no evidence from our data that the nova rate in M87 is enhanced relative to the rate in M49, particularly if we restrict our analysis to nova candidates that are clearly associated with the galaxies.

2. Populations of Novae in the Local Group

2.1. M31

The number of novae in M31 with known spectroscopic class has been increasing dramatically in recent years\(^1\). At the beginning of 2010 a total of 91 spectroscopic classifications were available for M31 novae, with 75 of these (82.4%) belonging to the Fe II class (Shafter et al. 2011). Since then, spectroscopic classes have been determined for an additional 50 novae bringing the total to 141. The overall percentage of Fe II novae has not changed significantly, with 115 novae (81.6%) now among members of the Fe II spectroscopic class. Figure 4 shows the cumulative distributions of Fe II and He/N (+Fe IIb) novae in M31 plotted as a function of isophotal radius. Although the Fe II novae appear to be slightly more spatially extended compared with the He/N (+Fe IIb) novae, a KS statistic of 0.8 indicates that this difference is not significant. A caveat to this analysis is that the high inclination of M31’s disk relative to our line of sight makes it impossible to separate unambiguously true bulge novae from disk novae that may be projected onto M31’s bulge (or vice versa). A better approach to studying whether the spectroscopic class may vary with stellar population is to compare the spectroscopic properties of novae from galaxies with differing Hubble types.

2.2. M33

M33 is a relatively low mass, nearby, nearly bulgeless Local Group galaxy of morphological type SA(s)cd (de Vaucouleurs et al. 1991). With an estimated nova rate of only

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\(^1\)See Williams (1992) for an introduction to the spectroscopic classification of novae.
2.5 ± 1.0 yr⁻¹ [Williams & Shafter 2004], little is known about the typical spectroscopic and photometric properties of novae in this galaxy. Through the end of 2011, a total of 36 novae had been observed in M31, including 8 with spectroscopic classifications [Shafter et al. 2012]. Since then, 2 additional classifications have become available from the discovery of 3 new novae. Of the 10 spectroscopic classifications, 5 are members of the Fe II class, with 5 members of the He/N or Fe IIb class. The fraction of Fe II novae in M33 appears to be lower than that observed in M31, but is this result significant? If we assume the fraction of Fe II novae in M31 is 0.82, the probability of observing 5 or fewer Fe II novae out of 10 with known spectroscopic class is given by:

\[
P_{\leq 5.10} = \sum_{n=0}^{5} \frac{10!}{n!(10-n)!} 0.82^n 0.18^{(10-n)} = 0.021. \tag{1}
\]

In other words, the mix of spectroscopic nova types in M33 differs from that of M31 at the 98% confidence level.

2.3. LMC

Like M33, the LMC (Irr/SB(s)m) is another late-type, low-mass Local Group galaxy with a recent history of active star formation [Harris & Zaritsky 2009]. As described in [Shafter 2013], a total of 35 nova candidates have been discovered in the LMC, 18 of which have spectroscopic data sufficient to establish their spectroscopic classes. Of these, like in M33, 50% belong to the Fe II class with the remaining 50% belonging to either the He/N or the Fe IIb classes.
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Of the 35 LMC novae, 29 have photometric data sufficient to estimate fade rates. Figure 5 shows a maximum-magnitude versus rate-of-decline (MMRD) relation for the LMC from Shafter (2013). Although the scatter is significant (the magnitudes at maximum light are often poorly determined), the most luminous novae generally fade the fastest. Figure 6 shows the cumulative distribution of LMC nova fade rates compared with those of M31 and the Galaxy. In addition, as has been noted previously (Della Valle & Duerbeck 1993), novae in the LMC are generally “faster” than novae in M31 and the Galaxy.

The fraction of recurrent novae (RNe) in the LMC appears to be somewhat higher than that observed in M31 and the Galaxy (see §3). Of the 38 reliable nova eruptions observed in the LMC, 6 of them (~ 16%) belong to 3 RN systems (Shafter 2013).

3. Recurrent Novae in M31

One approach to searching for RN candidates in M31 involves the detection of the secondary star in quiescence for those RNe that contain evolved secondaries (Bode et al. 2009; Williams et al. 2013). This approach will identify systems that are likely to be RNe, but will miss any short orbital period systems. A more direct approach for identifying potential RNe involves a search for positional coincidences among the more than 900 M31 nova candidates discovered to date. Given that the coordinates for novae

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2See http://www.mpe.mpg.de/~m31novae/opt/m31/index.php
discovered on photographic plates are not as accurate as those for more modern discoveries, we were forced to allow for a relatively large uncertainty in our analysis. Our cross-correlation yielded a total of 50 nova candidates that were spatially coincident to within 0.1'. Clearly, most of these “matches” represent chance positional coincidences. To estimate what fraction, we performed a Monte Carlo simulation where we randomly distributed artificial novae with a surface density proportional to the background $R$-band light of the galaxy, and then searched for spatial coincidences of less than 0.1' in the model distribution. The simulation suggests that approximately 35 of the 50 spatial near coincidences observed in the real data are expected by chance.

It is also possible to narrow down the list of 50 possible RNe by computing the probability that a specific spatial coincidence is expected by chance. For example, a nova pair of a given separation observed near the nucleus (where the nova density is high) will be much more likely to be a chance positional coincidence than would a pair with the same separation observed in the outskirts of the galaxy. For a given observed separation $s$, we can compute the probability of a specific chance coincidence, $P_C$, by considering the nova density in an isophotal annulus of area, $A$, centered at the position of each nova. Specifically,

$$P_C = 1 - \exp\left[\sum_{i=1}^{n-1} \ln(1 - ix)\right],$$  \hspace{1cm} (2)$$

where $n$ is the number of novae in the annulus, and $x = \pi s^2/A$.  

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**Figure 6.** The cumulative distribution of decline rates for LMC (solid line), M31 (dashed line), and Galactic novae (dotted line). The LMC novae are clearly faster on average than those seen in M31 and the Galaxy. (Figure from Shafter (2013), reproduced by permission of the AAS.)
If we restrict our list of potential RNe to spatial coincidences with separations $s \leq 0.1'$ and $P_C \leq 0.1$ we find a total of 15 RN “strong” candidates, which agrees with the number expected from our Monte Carlo experiments. These 15 RNe candidates represent a total of 35 eruptions (4 of the candidates have multiple eruptions). Of course, the only way to be sure that any specific candidate is in fact a RN and not a chance positional coincidence is to perform precise astrometry on images taken during each eruption. So far, Shafter et al. (in preparation) have been able to establish conclusively that at least 6 of the 15 strong candidates are in fact RN. Assuming that all 15 candidates (representing 35 eruptions) are eventually confirmed as RNe, we estimate that ~4% of the ~ 900 nova eruptions observed in M31 are due to RN, compared with ~10% in the Galaxy and ~16% in the LMC (Shafter 2013). Further work, including an analysis of the observational biases in nova surveys, will be required before any definitive conclusions regarding the relative RN rates in these 3 galaxies can be reached.

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