

# A *Hubble Space Telescope* survey for novae in M87 – III. Are novae good standard candles 15 d after maximum brightness?

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## ABSTRACT

Ten weeks of daily imaging of the giant elliptical galaxy M87 with the *Hubble Space Telescope* (*HST*) has yielded 41 nova light curves of unprecedented quality for extragalactic cataclysmic variables. We have recently used these light curves to demonstrate that the observational scatter in the so-called maximum-magnitude rate of decline (MMRD) relation for classical novae is so large as to render the nova-MMRD useless as a standard candle. Here, we demonstrate that a modified Buscombe–de Vaucouleurs hypothesis, namely that novae with decline times  $t_2 > 10$  d converge to nearly the same absolute magnitude about two weeks after maximum light in a giant elliptical galaxy, is supported by our M87 nova data. For 13 novae with daily sampled light curves, well determined times of maximum light in both the *F606W* and *F814W* filters, and decline times  $t_2 > 10$  d we find that M87 novae display  $M_{606W,15} = -6.37 \pm 0.46$  and  $M_{814W,15} = -6.11 \pm 0.43$ . If very fast novae with decline times  $t_2 < 10$  d are excluded, the distances to novae in elliptical galaxies with stellar binary populations similar to those of M87 should be determinable with  $1\sigma$  accuracies of  $\pm 20$  per cent with the above calibrations.

**Key words:** techniques: imaging spectroscopy – novae, cataclysmic variables.

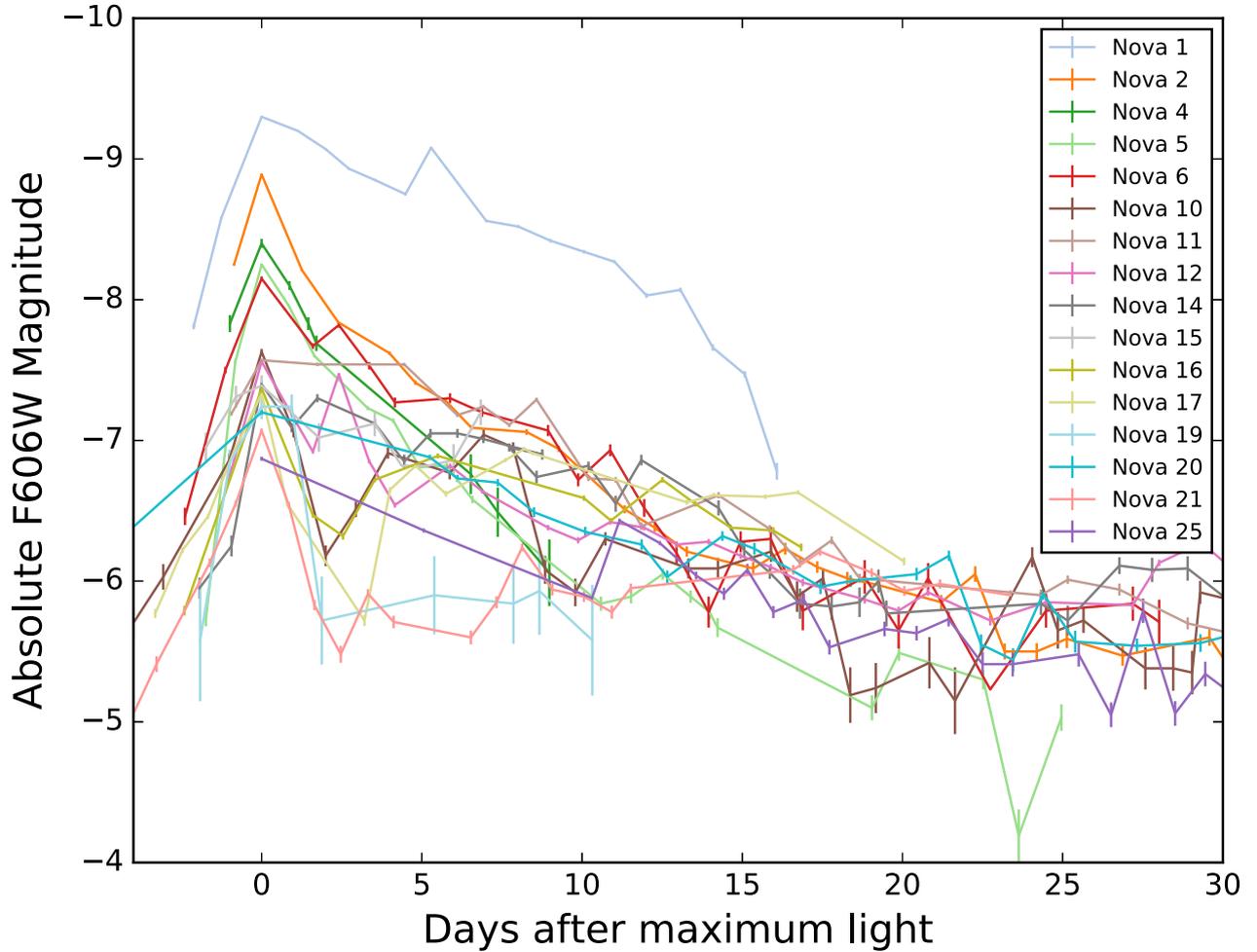
## 1 INTRODUCTION

Novae near maximum light are so luminous – ranging from  $M_V \sim -5$  to  $-10.7$  (Shafter et al. 2009) – that they can be detected with the *Hubble Space Telescope* (*HST*) out to cosmologically interesting distances, well beyond the useful ranges of RR Lyrae stars, Cepheids and planetary nebulae. After the announcement of their

discovery in the Andromeda galaxy (Hubble 1929), Zwicky (1936) claimed that novae behave as standard candles, with light curves that can be interpreted to yield the distances to their host galaxies. Zwicky's initial correlation between the maximum magnitude of a nova and its rate of decline [now known as the maximum-magnitude rate of decline (MMRD) relation], was improved upon by McLaughlin (1945) and Arp (1956).

If the MMRD relation did indeed calibrate novae as standard candles, then they could be used to independently measure distances to galaxies with Cepheids. More importantly, they could determine

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**Figure 1.** The *HST* *F606W* light curves of 16 novae in M87 with well-observed maxima, from Paper I. Each of these nova eruptions was observed within 12 h of maximum light. Magnitude error bars are  $1\sigma$ .

distances to, for example, elliptical galaxies with no Cepheids, to low-luminosity dwarf galaxies (Conroy & Bullock 2015), and even to intergalactic ‘tramp novae’ (Shara 2006; Teyssier, Johnston & Shara 2009), which act as tracers of stars unbound to any galaxy.

Because it is *not* just WD mass, but also total accreted envelope mass that control nova thermonuclear runaways, and because different accretion rates can produce a significant range of accreted envelope masses (Yaron et al. 2005; Shara et al. 2017), the scatter in the MMRD was predicted to be significant (Priyalnik & Kovetz 1995; Yaron et al. 2005; Hachisu & Kato 2010). The many observed MMRD relations in the literature are summarized in Downes & Duerbeck (2000). It is clear from their fig. 17 that the observational scatter in an MMRD plot is far from negligible. With the discovery of ‘faint, fast novae’ in M31 (Kasliwal et al. 2011; Darnley et al. 2016) and in M87 (Shara et al. 2016), increasing the observed scatter in the MMRD to 3 mag, it is now evident from observations that the above-noted predictions from theory were correct: The MMRD has no value as a distance indicator (Shara et al. 2017). Ferrarese, Côté & Jordán (2003) reached the same conclusion, based on a smaller and less densely sampled group of nine novae in the Virgo cluster elliptical galaxy M49.

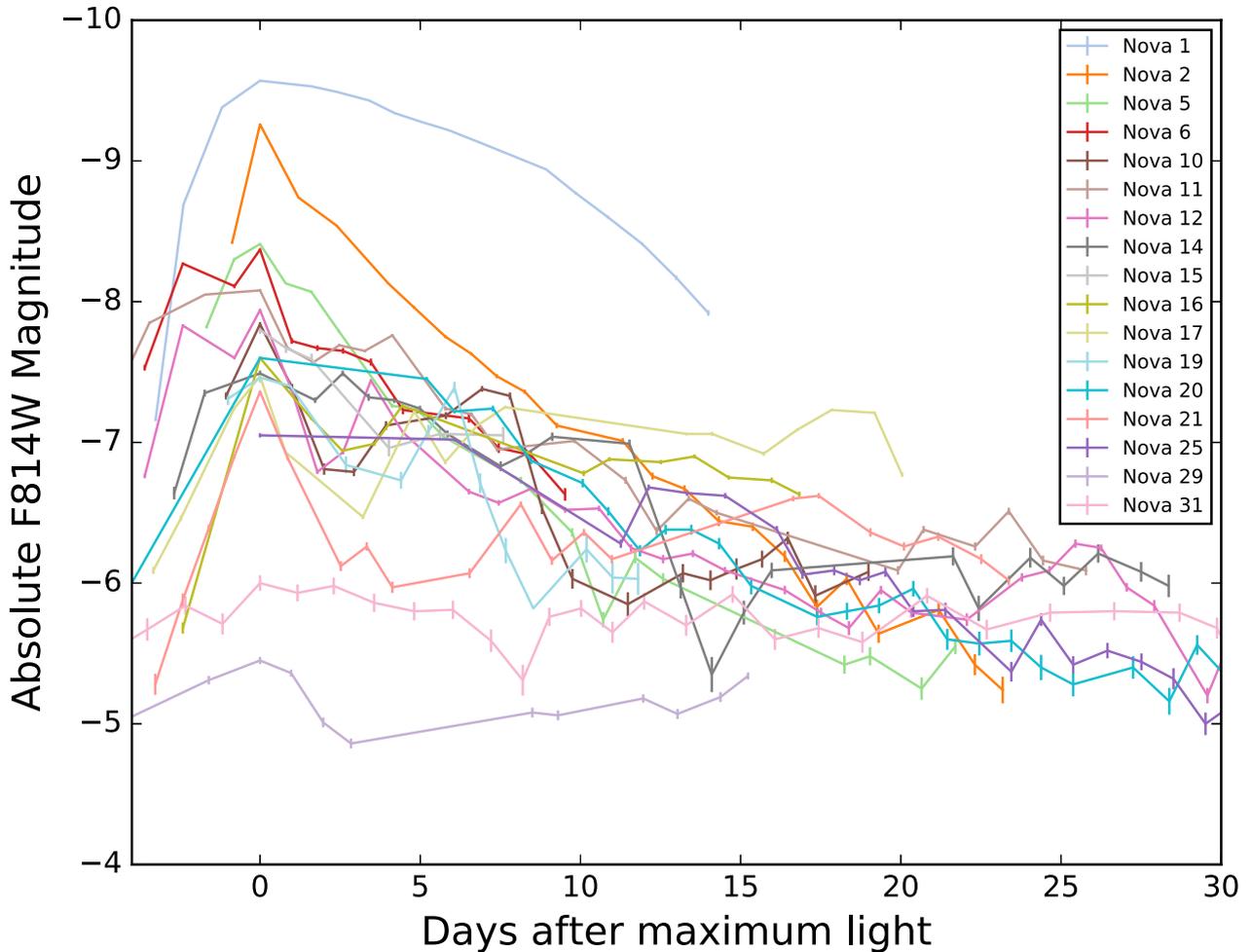
There is another methodology that has been proposed to use novae as distance indicators. Buscombe & de Vaucouleurs (1955) suggested that all novae reach roughly the same absolute photographic magnitude,  $M_{pg,15} \sim -5.2 \pm 0.1$ , 14–16 d after maximum

light. Ferrarese, Côté & Jordán (2003) and Darnley et al. (2006) presented evidence that the scatter in absolute magnitude at 15 d after maximum light for novae in M49 and in M31, respectively, is much larger than claimed by Buscombe & de Vaucouleurs (1955).

All of the nova magnitudes used in Buscombe & de Vaucouleurs (1955) were, of course, photographic, rather than CCD-based. Visual and (blue) photographic magnitudes were used interchangeably in that study, using the rationale that nova colour-indices are close to zero near maximum light. Absolute magnitudes for novae were based on nebular expansion parallaxes and interstellar absorption line widths. An interstellar absorption coefficient of  $A_{pg} = 0.8 \text{ mag kpc}^{-1}$  was assumed to correct the measured magnitudes at maximum light. All of these assumptions were reasonable, and the best that could be done in 1955, but no quantification of the multiple sources of error was made. As noted above, the claimed error in  $M_{pg,15}$ ,  $\pm 0.1 \text{ mag}$ , is overly optimistic (Ferrarese, Côté & Jordán 2003; Darnley et al. 2006).

The goals of this paper are to use our recently reported by *HST* survey of novae in M87, and the M87 nova light curves, to determine whether the absolute magnitudes of novae in M87 converge about 15 d after maximum light; if so, to measure those absolute magnitudes in two of the most frequently used *HST* filters; and to provide realistic estimates of the errors of those absolute magnitudes.

In Section 2, we summarize our observations of well-observed novae in M87, and plot the light curves and daily standard deviations



**Figure 2.** The *HST* *F814W* light curves of 17 novae in M87 with well-observed maxima, from Paper I. Each of these eruptions was observed within 12 h of maximum light. Magnitude error bars are  $1\sigma$ .

of all M87 novae with well-observed maxima. We compare those results with previous determinations in Section 3, and summarize our results and conclusions in Section 4.

## 2 OBSERVATIONS AND LIGHT CURVES

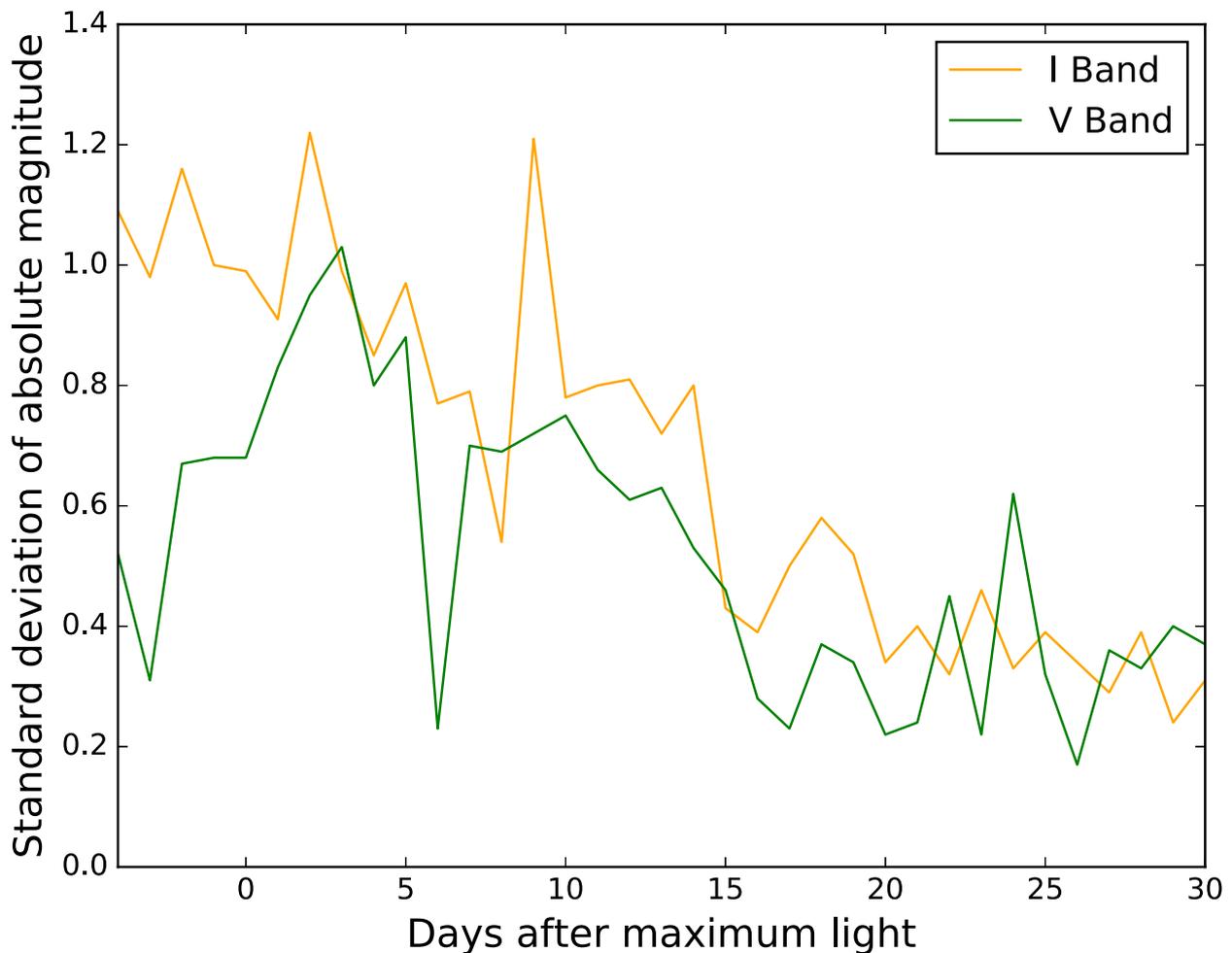
We carried out *Hubble Space Telescope* Advanced Camera for Surveys (*HST*/ACS) imaging of the giant elliptical galaxy M87 in the *F606W* and *F814W* filters taken for *HST* Cycle-14 programme 10543 (PI - E. Baltz) over the 72 d interval 24 December 2005 through 5 March 2006. Full details of the observations, data reductions, detections and characterisations of 41 variables – 32 certain and 9 likely novae – and their images, and light and colour curves, are given in Shara et al. (2016) (hereafter Paper I). Table 2 of that paper lists all photometric measurements (in Vega magnitudes) and errors for the 41 novae. A brief summary of the time coverage, its regularity, and the photometric errors is as follows.

Each one-orbit epoch of observations consisted of four 360-s exposures in the *F814W* filter followed by one exposure of 500 s in the *F606W* filter. We note that the original motivation of this proposal was to search for microlensing events in M87, while the detection of novae was foreseen as a potential ‘bonus’. That is why the bulk of exposures were taken in *F814W* (to detect the faintest red giants possible), and why, despite admitting  $H\alpha$ , the broader filter

*F606W* was chosen rather than *F555W* (obviously,  $H\alpha$  emission is not expected in microlensing events). Some M87 nova  $H\alpha$  photons have inevitably leaked into the *F606W* filter so it measures both nova continuum and emission. This is a likely contributor to some of the scatter in the brightness in the *F606W* filter, which will vary from nova to nova, and with time for each nova.

This survey for extragalactic novae is unique. *HST* enables observations with nearly perfect daily cadence and constant limiting magnitude extending over a six magnitude range throughout most of M87. Photometric errors for most novae range from 0.01 to 0.04 mag near maximum to 0.3–0.4 mag by the time they have faded by 2–3 mag from maximum. The first four epochs were spaced  $5.00 \pm 0.02$  d apart, followed by  $1.00 \pm 0.11$  d spacing for the remaining 60 epochs. Thus, while all novae visible on any given day were observed at precisely the same times, the maxima of individual novae were not, so the spacing between subsequent days for the novae in our sample are not all identical. As noted above, observations were taken at a cadence of  $1.00 \pm 0.11$  d. We have calculated the mean magnitudes and standard deviations of those mean nova magnitudes on day  $N$  after maximum light by using the magnitudes of each nova at the time closest to  $N$  days after its maximum.

We considered only the 32 ‘certain’ novae in what follows. (1) As the survey ended, 5 of 32 novae were still visible, but all had been visible for  $<15$  d. (2) 8 of 32 novae were already in eruption and



**Figure 3.** The daily standard deviations of 13 *HST F606W* and *F814W* light curves of novae in M87 which had well-observed maxima and which were seen for at least 15 d after maximum light.

past maximum when the survey began. (3) 6 of 32 novae evolved so quickly, or were so close to the centre of M87, that they were too faint, 15 d after maximum light, to be detected by *HST*.

This left  $32 - (5 + 8 + 6) = 13$  novae whose maxima were seen, and which remained visible in both filters for at least 15 d. The numbering of these novae in the figures below follows the nomenclature of Paper I.

Novae were detected with two-magnitude decline times  $t_2$  ranging from 2 d to 36 d (table 3 of Shara et al. 2016). Simulations demonstrate that we detected all novae with  $t_2 > 2$  d and which are located  $> 20$  arcsec from the nucleus. A nova with  $t_2 \sim 1$  d might have been seen only once ( $\sim 1$  mag past maximum) or twice (at  $\sim 1$  and  $\sim 3$  magnitudes past maximum); no such object was detected. Even faster novae ( $t_2 \sim 6$  h) are predicted to exist (Shara et al. 2017) but at most one detection of each such object could have occurred. None was detected.

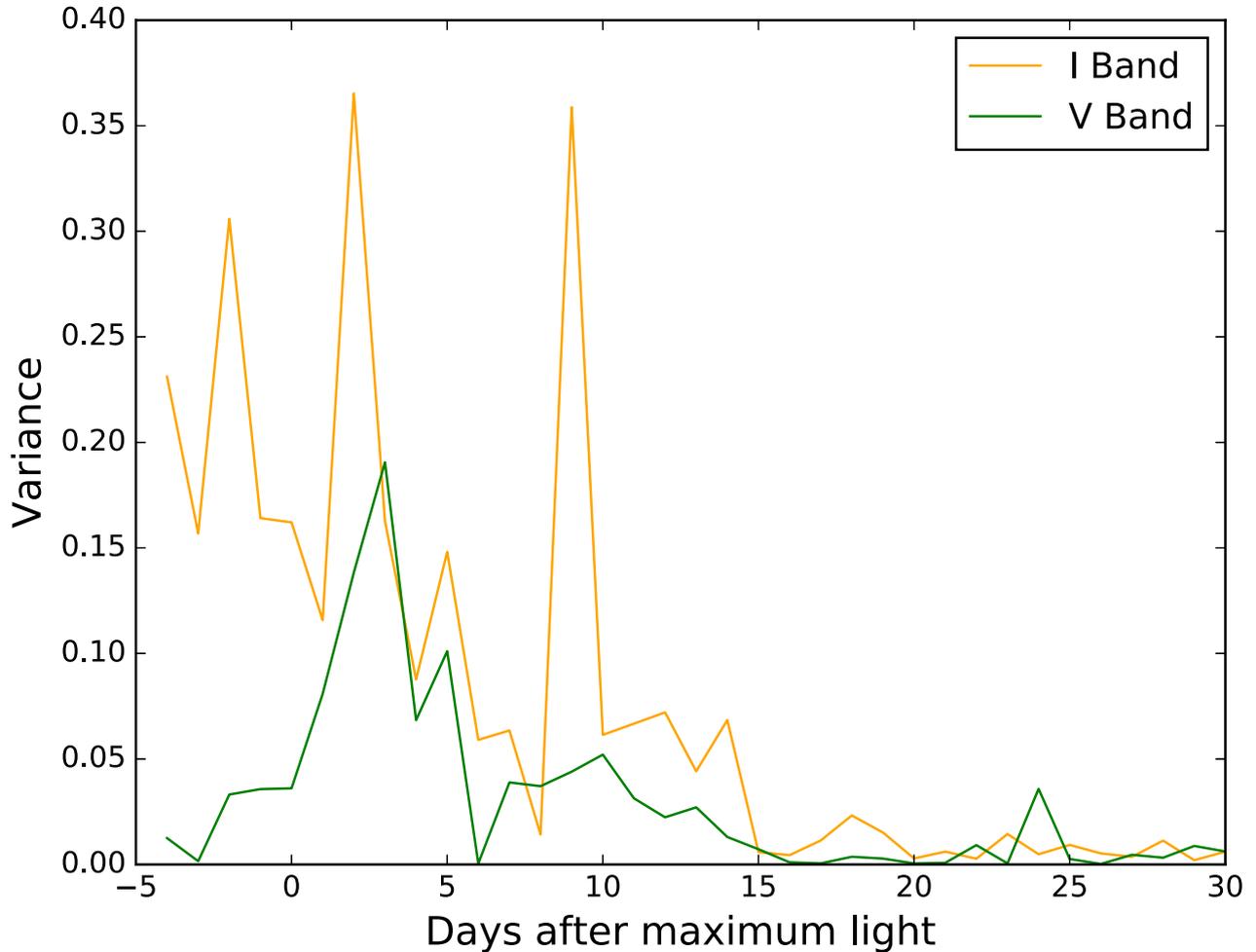
The apparent *HST F606W* and *F814W* magnitudes of the novae presented in Paper I were converted into absolute magnitudes using the distance modulus to M87 derived by Bird et al. (2010), i.e.  $(m-M)_0 = 31.08 \pm 0.06$ . The 16 *HST F606W* and 17 *F814W* light curves of novae in M87 with well-defined maxima are shown in Figs 1 and 2, respectively. Only those 13 novae that were visible for at least 15 d after maximum light in both filters' images were used to calculate the daily means and standard deviations of M87 nova brightnesses. The daily mean on (for example) day 7 is taken to be

the mean of the magnitudes of all of the novae on the seventh day after their individual maximum. As noted above, the spacing between subsequent days for the individual novae is actually  $1.00 \pm 0.11$  d.

Except for nova 1, the novae in Figs 1 and 2 display remarkably similar light curves, and a convergence in brightness that is obvious from simple inspection. The shapes of the light curves in Figs 1 and 2 may be contrasted with those of novae in M31 (Darnley et al. 2004), the Magellanic Clouds (Mróz et al. 2016) and in the Galaxy (Strope, Schaefer & Henden 2010), which display a wide range of morphologies.

### 3 USING NOVAE AS DISTANCE INDICATORS

Several authors after Buscombe & de Vaucouleurs (1955) investigated whether novae are useful standard candles when measured 15 d after maximum brightness. The largest such sample of novae is from Pfau (1976). For 46 well-observed novae in M31, the Galaxy, and the Magellanic Clouds he determined that  $M_{B,15} = -5.74 \pm 0.60$ . Cohen (1985) and van den Bergh & Younger (1987) used their ground-based samples of 11 and 6 Galactic novae, respectively, to determine values of  $M_{V,15} = -5.60 \pm 0.45$  and  $-5.23 \pm 0.39$ . Downes & Duerbeck (2000) used 15 Galactic novae to determine  $M_{V,15} = -6.05 \pm 0.44$ . *HST* observations of five novae in M49 allowed Ferrarese, Côté & Jordán (2003) to measure  $M_{V,15} = -6.36 \pm 0.43$ . They stated that their value is strongly at odds



**Figure 4.** The daily variance of the variance of 13 *HST* *F606W* and *F814W* light curves of novae in M87 which had well-observed maxima and which were seen for at least 15 d after maximum light.

with that of van den Bergh & Younger (1987), barely consistent with that of Cohen (1985) and in reasonable agreement with Downes & Duerbeck (2000).

Darnley et al. (2006) found the largest scatter of all observers for their sample of M31 novae:  $M_{r',15} = -6.3 \pm 0.9$  and  $M_{i',15} = -6.3 \pm 1.0$ . Their filters and effective cadence were similar to the ones used in the current work. Their result led them to write: ‘We can conclude that the POINT-AGAPE CN catalogue shows no evidence of a t15 relationship, nor strong evidence of convergence at another time-scale’. This is the strongest evidence and statement in the literature against using novae in spiral galaxies as standard candles when observed 15 d after maximum light.

Fig. 3 yields the epochs of minimum standard deviation of 13 M87 nova light curves observed with *HST*. The number of still-visible novae begins to decrease after day 16; there are, for example, 10 novae left at day 21 and 7 novae left at day 29. The standard deviation is then affected by the decreasing number of novae, and a comparison with the earlier epochs is no longer meaningful. In Fig. 4, we plot the variance of the variance of the M87 nova magnitudes, which supports the Buscombe & de Vaucouleurs (1955) empirical, photographic (pg) determination of minimum deviation at 14–16 d after maximum light, though our sample is larger, of higher cadence and based on *HST* CCD magnitudes. We adopt the mean magnitudes and their standard deviations of the 13 still-visible M87 novae at

day 15 after maximum light as the most useful nova standard candle in an elliptical galaxy to date.

We use the M87 distance modulus noted in Section 2, and absorptions to M87 of  $A(F606W) = 0.07$  and  $A(F814W) = 0.04$ . The absolute *F606W* and *F814W* magnitudes 15 d after maximum light are  $M_{606W,15} = -6.37 \pm 0.46$  and  $M_{814W,15} = -6.11 \pm 0.43$ . The *F606W* value is in excellent agreement with the only other *HST*-determined value (Ferrarese, Côté & Jordán 2003), also for an elliptical galaxy. Our M87 novae are all at the same distance and are densely time-sampled with no gaps, and are observed with invariant seeing and background that is immune to lunar phase. We thus suggest that our derived values of  $M_{F606W,15}$  and  $M_{F814W,15}$  are the most reliable values currently available for using novae as standard candles in *elliptical galaxies*. These values of  $M_{15}$ , the key results of this paper, enable the determination of nova distances in elliptical galaxies with  $1\sigma$  accuracies of  $\pm 20$  per cent.

Finally, we note that there are theoretical studies that predict nova luminosities, and times of minimum spread of those luminosities, in good agreement with the results noted above. If one excludes the class of faint, fast novae (Kasliwal et al. 2011; Shara et al. 2017) then the absolute magnitude – rate of decline (MMRD) relation for novae (i.e. that luminous novae decline faster than faint novae) follows from the fact that nova eruptions are largely controlled by the WD mass (Shara 1981). The scatter in MMRD is controlled by

the variable envelope mass (Hachisu & Kato 2010). The derivative of the MMRD relation Shara (1981), and the universal decline law of novae (Hachisu & Kato 2010) demonstrate that about 15 d after maximum light one expects all nova absolute magnitudes to decline to roughly  $-6$ .

#### 4 SUMMARY AND CONCLUSIONS

We have determined that the absolute  $F606W$  and  $F814W$  magnitudes of 13 novae in M87 observed with *HST* 15 d after maximum light are  $M_{V,15} = -6.37 \pm 0.46$  and  $M_{I,15} = -6.11 \pm 0.43$ . These values are useful for determining  $1\sigma$  nova distances in elliptical galaxies to accuracies of  $\pm 20$  per cent. The scatter in the magnitudes of novae in spiral galaxies, observed 15 d after maximum, is too large for them, or tramp novae, to be used as distance indicators.

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