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DISCOVERY OF A NOVA IN THE VIRGO GALAXY M100

LAURA FERRARESE AND MARIO LIVIO
Space Telescope Science Institute, Baltimore, MD 21218

WENDY FREEDMAN
Carnegie Observatories, Pasadena, CA 91101

ABHIJIT SAHA
Space Telescope Science Institute, Baltimore, MD 21218

PETER B. STETSON
Dominion Astrophysical Observatory, Herzberg Institute of Astrophysics, National Research Council of Canada, Victoria, BC V8X 4M6, Canada

HOLLAND C. FORD
Johns Hopkins University, Baltimore, MD 21218

ROBERT J. HILL
Goddard Space Flight Center, Greenbelt, MD 20771

AND

BARRY F. MADORE
NASA/IPAC Extragalactic Database and California Institute of Technology, Pasadena, CA 91125
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ABSTRACT

We present the V and I light curves of a nova discovered in the disk of the spiral galaxy M100, located in the Virgo Cluster. In spite of the fact that the light curve is not well sampled around maximum light and the reddening to the nova is not accurately known, by adopting the maximum magnitude versus rate of decline relation by Della Valle & Livio we derive a distance modulus to M100 of μ_0 ~31.0 ± 0.3 mag, fully consistent with the Cepheid distance modulus of 31.04 ± 0.17 mag found by Ferrarese et al. from the same set of *HST*/WFPC2 data.

Subject headings: galaxies: individual (M100, NGC 4321) — novae, cataclysmic variables — stars: distances

1. INTRODUCTION

The aim of the *Hubble Space Telescope* (*HST*) Key Project on the Extragalactic Distance Scale (e.g., Freedman et al. 1994a, 1994b, 1994c; Mould et al. 1995; Kennicutt et al. 1995) is to refine the zero points of secondary distance indicators by measuring Cepheid distances to a sample of 18 galaxies, out to distances of about 20 Mpc. These galaxies are located in the field, small groups (e.g., Leo I) and larger clusters (Virgo and Fornax). In addition to Cepheids, several other variable stars are bound to be discovered, even if the observing strategy is not designed to provide the best sampled light curve and/or period determination. Possible detections are eclipsing binaries, short-period variables such as RR Lyrae stars, luminous blue variables—and novae. Even if a systematic search for any of these variables has *not* been carried out in the project's galaxies (after all, Cepheids are the primary objective), occasionally some of them are in fact observed (Freedman et al. 1994a; Kelson et al. 1996; Silbermann et al. 1996; Ferrarese et al. 1996). In particular, we report in the present work the detection of a nova in the spiral galaxy M100, located in the Virgo Cluster. This is a truly exciting discovery: only a handful of novae have been observed as far as Virgo (two are reported by Hubble [Bowen 1952] in M87; nine more were observed in an immense effort by Pritchet & van den Bergh 1987 in NGC 4472 and NGC 4365).

The M100 nova surpasses all of the previous discoveries in terms of the sampling of the light curve and the quality of the photometry. In spite of the fact that the usefulness of one nova in M100 as a distance indicator is limited (at best), especially when a more solid distance to the same galaxy is available through a sample of a few dozen Cepheids, this nova is a precious addition to the sample of novae already known, in the Galaxy, the LMC, M31, M33, NGC 5128, M81, and Virgo. Its excellently determined light curve testifies to the ease with which *HST* can find such objects and to their potential use as distance indicators in remote galaxies. Furthermore, a comparison with the Cepheid distance allows an assessment of the quality of the maximum magnitude versus rate of decline (MMRD) relation for novae. After the discovery of the M100 nova, the photometry for all of the Key Project galaxies is currently being reexamined in a search for novae.

In this short Letter, we therefore report the discovery of the M100 nova, present its V and I light curves, and apply to it the MMRD relation. We also discuss briefly the nova rate in M100.

2. OBSERVATIONS

The set of observations that led to the detection of the M100 nova are presented in detail and extensively discussed in Ferrarese et al. (1996) and Hill et al. (1996). In those papers the reader can also find details of the reduction procedure and the photometric analysis. Here it suffices to say that the nova was observed in 12 V (F555W) and four I (F814W) epochs using the Wide Field and Planetary Camera 2 (WFPC2) on board *HST*. The observations span a period of 58 days. Unfortunately, the nova outburst occurred between the first

TABLE 1

V AND *I* PHOTOMETRY OF THE M100 NOVA

Observation Date[a] (JD)	$V \pm \Delta V$[b]	$I \pm \Delta I$[b]
2,449,465.78	26.78 ± 0.28	···
2,449,465.91	···	25.06 ± 0.16
2,449,476.71	23.99 ± 0.04	···
2,449,478.99	24.43 ± 0.04	···
2,449,482.40	25.00 ± 0.07	···
2,449,485.22	25.29 ± 0.08	···
2,449,485.35	···	24.15 ± 0.07
2,449,489.04	25.67 ± 0.10	···
2,449,493.53	25.93 ± 0.13	···
2,449,498.82	26.01 ± 0.15	···
2,449,503.85	26.28 ± 0.18	···
2,449,510.82	26.28 ± 0.19	25.10 ± 0.14
2,449,520.95	26.57 ± 0.19	···
2,449,522.96	26.60 ± 0.24	···
2,449,523.09	···	25.18 ± 0.17

[a] The column lists the middle time, in Julian Days, for each epoch.

[b] The *V* and *I* magnitudes reported are *not* corrected for extinction (see text).

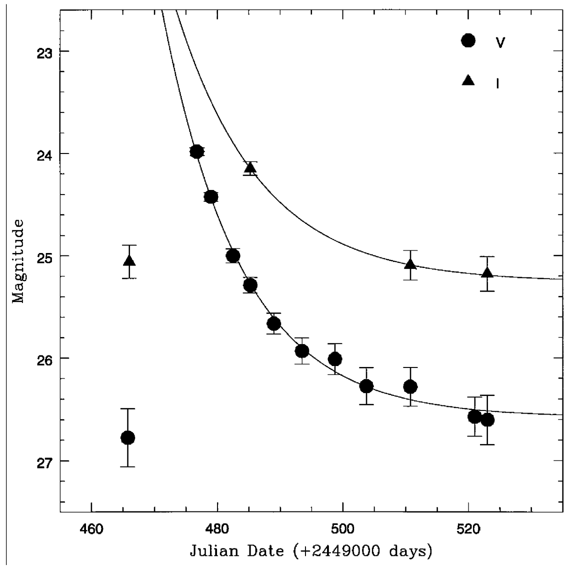

FIG. 3.—*V* and *I* light curves of the M100 nova. The magnitudes are *not* corrected for extinction. The solid lines are the best exponential fits to the light curves after outburst (see text for further explanation).

and the second epoch, which are set about 11 days apart, and we therefore lack good sampling of the light curve near maximum light.

3. RESULTS AND DISCUSSION

Figure 1 (Plate L15) shows a gray-scale ground-based image of M100, obtained by R. Peletier with the Isaac Newton Telescope (INT) at La Palma. We have superimposed a deep *HST*/WFPC2 exposure obtained by combining all 12 *V* epochs. The nova, shown by the white circle, was found in an uncrowded region in the outer part of the galactic disk. The low stellar density in the region around the nova is better seen in Figure 2 (Plate L16), which shows a 22″ × 22″ region centered on the nova itself, as it appears in the first (before outburst), second, sixth, and last epochs. The dramatic change in the brightness of the nova between subsequent epochs is readily apparent. The absence of nearby companions and bright stars makes it very easy to obtain extremely accurate photometry in this region, as testified by the very low errors associated with the nova magnitudes (Table 1).

The *V* and *I* light curves of the M100 nova are shown in Figure 3 and tabulated in Table 1. Although we are missing data around maximum light, the declining part of the light curve is beautifully sampled. We believe this to be an important result on its own account: since well-sampled (high-accuracy) nova light curves are sparse in the literature, the M100 nova provides a useful template for novae with similar decline rates. The nova light curve, linear in the earliest part of the decline and then sloping more gently at later times, is typical of very well sampled novae found in the literature (e.g., Nova Cygni 1975 and Nova Cygni 1978 [van den Bergh & Younger 1987]; we note that the almost linear decline shown by some novae [e.g., Rosino 1973; Arp 1956; van den Bergh & Younger 1987] is at least in some cases due to poor temporal sampling rather than being intrinsic).

An accurate distance to M100 was determined as a part of the *HST* Key Project on the Extragalactic Distance Scale, by fitting period-luminosity relations to a sample of 52 Cepheids found from the same set of *HST*/WFPC2 data in which the nova was discovered (Ferrarese et al. 1996). The M100 Cepheid distance modulus is $\mu_0 = 31.04 \pm 0.17$ mag, and the total (Galactic plus internal) mean color excess $E(B-V) = 0.10 \pm 0.06$ mag.

The usefulness of novae as distance indicators relies on the existence of a relation between the absolute magnitude at maximum light and the rate of decline, also known as the MMRD relation. In this paper we adopt the formulation of the MMRD relation obtained by Della Valle & Livio (1995). While it is not possible to obtain a reliable distance to M100 based on one nova, it is useful to estimate a distance on the basis of the MMRD relation, as a consistency check.

There are two main sources of uncertainties in deriving a distance to M100 from the nova light curve: the *V* magnitude at maximum light, and the reddening. The reddening for the nova is likely lower than for the M100 Cepheids [$E(B-V) = 0.10 \pm 0.06$ mag; Ferrarese et al. 1996], since Cepheids are found in regions of more recent star-forming activity and more dust. On the other hand, the reddening of the nova cannot be lower than provided by the Galactic foreground extinction: $E(B-V) = 0.01 \pm 0.015$ mag (Burstein & Heiles 1984). In all cases, following Ferrarese et al. (1996), we will assume $A_V/E(B-V) = 3.3$, the standard value for the interstellar medium, and adopt the reddening law by Cardelli, Clayton, & Mathis (1989).

An *upper* limit to the distance can be easily determined: adopting the lower limit for the reddening (since we are deriving an *upper* limit to the distance, $E(B-V) = 0.01 \pm 0.015$ mag), we can confidently say that $m_{\max} \leq 23.96 \pm 0.04$ mag (equal to the magnitude, corrected for extinction, at the second epoch). Counting from this magnitude, the time taken by the nova to decline by 2 mag is $t_2 \sim 19$ days, which, when substituted in the Della Valle & Livio (1995) MMRD relation, gives $M_V \sim -8.1$ mag. The corresponding distance modulus then must be $\mu_0 \leq 32.1$ mag.

On the other hand, a *lower* limit to the distance can be obtained assuming that the light curve has zero rise time (i.e., the maximum is reached at the first epoch) and a "sawtooth" shape (i.e., the decline is linear): Livio (1992) shows that nova

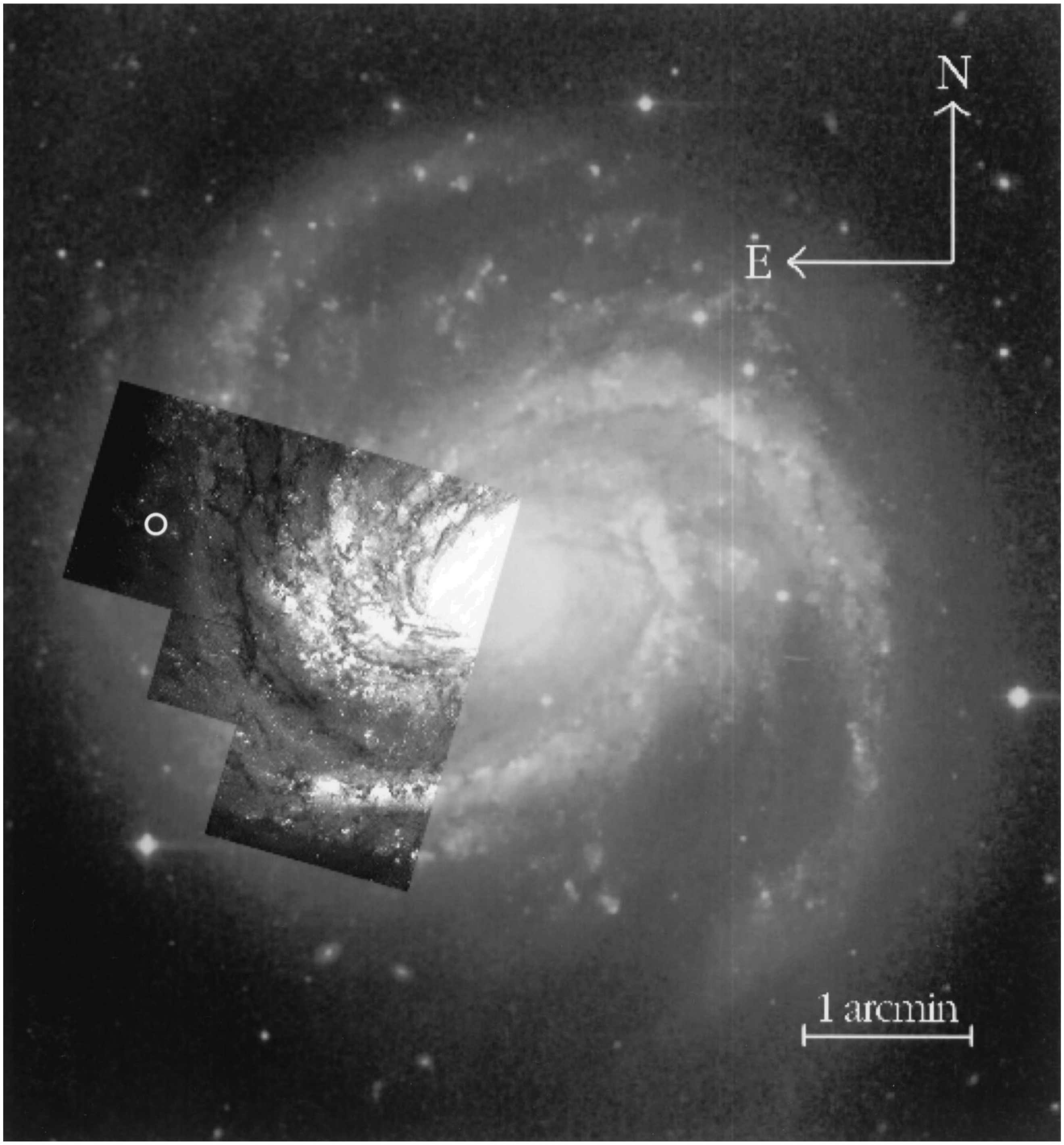

FIG. 1.—Deep *HST*/WFPC2 exposure of M100 superimposed on a ground-based image obtained by R. Peletier with the INT at La Palma. The position of the nova is shown by the white circle.

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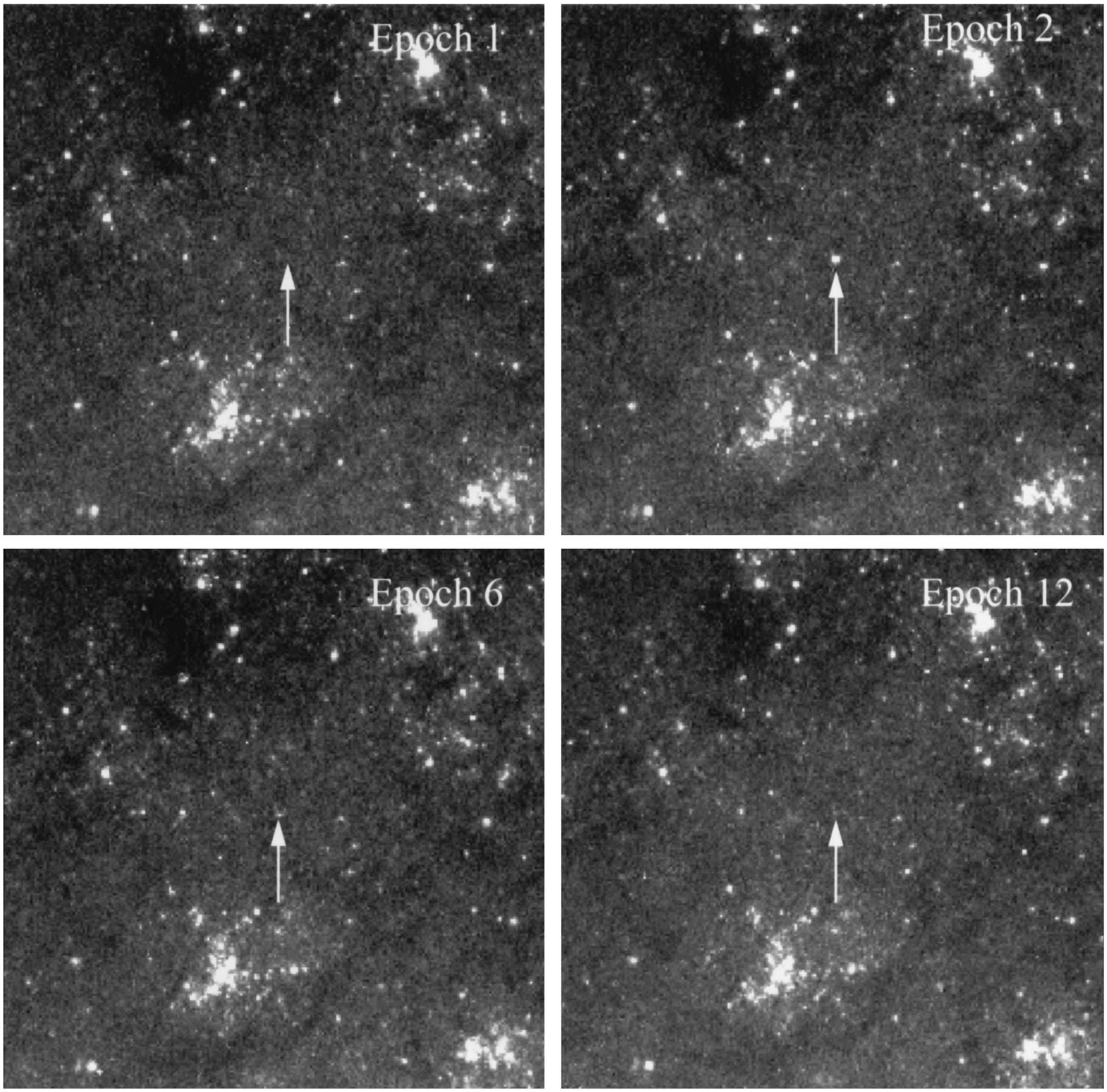

FIG. 2.—The nova (*arrow*) at four different epochs. The first epoch was obtained before the nova outburst. Each panel shows a 22″ × 22″ region of the sky.

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light curves in the early phase of the decline are indeed approximately linear, with a slope equal to $2/t_2$. Since we are calculating a *lower* limit to the distance, we adopt the *upper* limit on the reddening [$E(B-V) = 0.10 \pm 0.06$ mag]. By fitting a straight line to the first three points (after maximum) in our light curve, we obtain $t_2 = 11$ days ($t_2 = 13$ days if the first four points are used). From the Della Valle & Livio (1995) MMRD relation, $M_V = -8.6$. According to our assumptions, the apparent magnitude at maximum must be fainter than the M_V intercept of the straight line at the time corresponding to the first epoch (JD = 2,449,465.78), $m_V > 22.1$ mag. From this we obtain $\mu_0 \geq 30.7$ mag.

A more precise estimate of the distance modulus can be attempted by knowing that at maximum light $(B-V)_0^{\max} = +0.23 \pm 0.06$ (van den Bergh & Younger 1987). This implies that the nova progenitor is of spectral type between A7 and F0, therefore the $B-V$ color translates to $(V-I)_0^{\max} \sim 0.37 \pm 0.10$ (e.g., Zombeck 1990). According to the arguments presented earlier in this section, we constrain the reddening to be $E(B-V) = 0.06 \pm 0.03$ mag [where the error represents the standard deviation assuming a uniform probability distribution over the range $0.01 \leq E(B-V) \leq 0.10$]. If the V and I light curves are fitted with an exponential profile (the best fits are shown in Fig. 3), the condition on $(V-I)_0^{\max}$ is satisfied for $V \sim 22.27 \pm 0.11$ mag, implying $t_2 \sim 8.4 \pm 0.7$ days, $M_V \sim -8.77 \pm 0.04$, and $\mu_0 \sim 31.0 \pm 0.2$. To this formal error, we need to add (in quadrature) the uncertainty due to the intrinsic scatter observed around the MMRD relation, corresponding to $\sigma \sim 0.2$ mag (e.g., Della Valle & Livio 1995). This brings the uncertainty on the distance modulus to 0.3 mag. However, the reader should not be misled by the still apparently small error bar: it does not take into account deviations, undoubtedly present, of the real light curve from our adopted exponential fit. The derived distance falls just in the middle of the acceptable distance range derived in the previous paragraph, and it agrees remarkably well with the Cepheid distance derived by Ferrarese et al. (1996). Good agreement is also present between the M100 distance derived in this paper and the distance to Virgo Cluster elliptical galaxies derived by Pritchet & van den Bergh (1987) from observations of six novae ($\mu_0 \sim 31.45 \pm 0.43$).

We conclude this Letter with a short note on the nova rate. Della Valle & Livio (1994) found an approximately linear relationship between the rate of production of novae and the H luminosity of the parent galaxy. This relationship, applied to M100 ($m_{\rm H} = 8.97$ mag; Aaronson 1977) predicts that about 15 novae $\rm yr^{-1}$ are expected in the galaxy. An empirical estimate of the nova rate in M100 is easily derived. The WFPC2 field of view, which is $\sim$5.7 $\rm arcsec^2$, covers about one-fourth of the stellar flux of the entire galaxy. Having observed one nova in a 58 day window, the nova rate per year is about 25, in agreement with the Della Valle & Livio (1994) prediction.

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