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DISTANCE OF THE LARGE MAGELLANIC CLOUD THROUGH THE MAXIMUM MAGNITUDE VERSUS RATE OF DECLINE RELATION FOR NOVAE

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ABSTRACT

The distance modulus of the Large Magellanic Cloud (LMC) is derived by application of the newly calibrated maximum magnitude versus rate of decline relationship (=MMRD; Capaccioli *et al.*) to the whole sample of novae so far discovered in this satellite galaxy. The result, $(m - M)_0 = 18.70^{+0.20}_{-0.25}$, is in close agreement with the determinations based on Cepheids. We also compare and discuss the properties of the MMRD of the Galactic, M31, and LMC nova populations.

Subject headings: galaxies: distances — galaxies: Magellanic Clouds — stars: novae

I. INTRODUCTION

Though considerably more luminous than Cepheids at maximum, novae have seldom been considered among the more reliable and convenient extragalactic distance indicators because of (*a*) their tendency to provide a systematically "shorter" distance modulus for the "test target" M31 (see Table 7 in Capaccioli *et al.* 1989*a*; hereafter Paper I), and (*b*) the transient nature of the nova event which imposes time-consuming and tedious survey campaigns. Recently, however, the discovery of an handful of novae in some elliptical galaxies belonging to the Virgo Cluster (Pritchet and van den Bergh 1987*b*), and the revised calibration of the maximum magnitude versus rate of decline (MMRD) relationship between the magnitude at maximum and the rate of decline (Paper I) has once more raised the possibility of use of these stars. In fact, the distance modulus of M31 based on the newly calibrated MMRD, $(m - M)_0 = 24.3 \pm 0.2$ mag (Paper I), agrees closely with the determinations based upon Cepheids and other classical indicators (Welch, Smarr, and Bruno 1985; Mould and Kristian 1986; Pritchet and van den Bergh 1987*a*). Similarly, the distance modulus of the Virgo Cluster based on novae is consistent with the other state-of-the-art distance determinations (Capaccioli *et al.* 1989*b*).

In view of the above results, we have decided to review the magnitudes at maximum and rates of decline of the Large Magellanic Cloud novae, aiming to measure the distance of the LMC and also to compare the MMRD properties in galaxies of different morphological types.

II. THE LMC NOVAE

The frequency and the characteristics of novae in the LMC are not well established. The reason is mainly the paucity of the data: though the first LMC nova was discovered in 1926, systematic search campaigns have been carried out only sporadically. So far, no indication has been reported of differences between LMC novae and those of the Galaxy and of M31. On the basis of the results of the most extensive survey (Graham 1979) and by applying the zero-order statistics outlined in Paper I, we estimate that the frequency of nova events in the LMC is $\sim 2 \pm 1$ per year.

Studying the light curves of six LMC novae and of four novae discovered in the Small Magellanic Cloud, Buscombe and de Vaucouleurs (1955; hereafter BdV) reached the conclusion that the shape of the MMRD relation is likely the same for the Clouds and the Galaxy. We have not reviewed the light curves of BdV's sample. We have instead transformed their parameter t_3 into the rate of decline $v_d = 2/t_2$, through the transformation formulae

$$t_3 = 1.68(\pm 0.08) \times t_2 + 1.9(\pm 1.5) \quad \text{with} \quad t_3 < 80^{\rm d} , \quad (1)$$

and

$$t_3 = 1.68(\pm 0.04) \times t_2 + 2.3(\pm 1.6) \quad \text{with} \quad t_3 > 80^{\rm d} , \quad (2)$$

which hold for the Galactic novae (Della Valle 1989): here t_2 and t_3 indicate the time intervals required by the nova to decline by 2 and 3 magnitudes from maximum, respectively.

For the remaining 15 novae discovered in the LMC up to the present, we have collected all the published observations (see the notes to Table 1 for details on individual objects) and, whenever possible, we have extracted the photometric parameters in a homogeneous fashion.

Basic data for the entire sample of 21 LMC novae are listed in Table 1. The successive columns give the nova identification, the 1950.0 equatorial coordinates (kindly provided by B. G. Marsden), the photometric band, the values of the estimated maximum magnitude $m_{\rm max}$, the magnitude 15 days past maximum m_{15} and the rate of decline, v_d. Our judgment of the reliability and completeness of the photometric data is coded in the last column. Note that the photographic magnitudes can be reduced to the V band through the two color equations (see the Appendix in Paper I):

$$(m_{\rm pg} - V)_{\rm max} = 0.15 , \quad (3)$$

and

$$(m_{\rm pg} - V)_{15} = -0.08 , \quad (4)$$

taking care that the absorption corrections subsequently applied are those pertinent to the original color.

III. MMRD RELATION AND DISTANCE MODULUS

Figure 1 shows the MMRD for the 14 LMC novae which possess sufficient photometric information. These are objects with either "good" (G) or "poor" (P) light curves, shown by filled or open symbols, respectively. Circles indicate data from

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TABLE 1

NOVAE IN THE LARGE MAGELLANIC CLOUD

Nova	R.A. (1950.0)	Decl. (1950.0)	Phot.	m_{max} [mag]	m_{15}	v_d [mag d^{-1}]	Quality
LMC 1926	05^h14^m9	−66°55′	pg	12.0	12.6	0.017	G
1935	03 59 4	−67 55	pg	11.0	13.7	0.145	G
1936	05 07 4	−66 47	pg	10.5	13.0	0.113	G
1937	05 57 7	−68 55	pg	10.6	13.2	0.187	G
1948	05 39 4	−70 24	pg	13.0	13.7	0.034	G
1951	05 13 7	−70 05	pg	11.9	15.7	0.771	G:
1968	05 10 4	−71 42	pg	$10.4^{+0.2}_{-0.4}$	13.7	$1.00^{+0.33}_{-0.33}$	P
1970A	05 33 5	−70 36	*V*	12.0	...	...	VP
1970B	05 36 0	−70 48	*V*	$11.0^{+0.5}_{-0.5}$	14.7	$0.25^{+0.01}_{-0.05}$	P
1971A	04 58 4	−68 08	*V*	$11.77^{+0.11}_{-0.11}$	13.4	$0.127^{+0.040}_{-0.040}$	G
1971B	05 40 6	−66 41	*V*	13.0	...	...	VP
1972	05 28 6	−68 50	...	...	...	...	VP
1973	05 15 5	−69 41	...	...	...	...	VP
1977A	06 05 9	−68 38	...	...	...	...	VP
1977B	05 05 4	−70 11	*V*	$10.70^{+0.05}_{-0.05}$	13.2	$0.179^{+0.002}_{-0.002}$	G
1978A	05 05 8	−65 55	*V*	$9.75^{+0.20}_{-0.60}$	15.1	$0.57^{+0.08}_{-0.11}$	P
1978B	05 01 0	−67 15	...	...	...	...	VP
1981	05 32 7	−70 24	...	...	...	...	VP
1987	05 24 3	−70 03	*V*	$9.6^{+0.2}_{-0.2}$	14.6	$1.00^{+0.17}_{-0.20}$	G
1988A	05 36 0	−70 23	*V*	$11.0^{+0.2}_{-0.1}$	12.3	$0.09^{+0.03}_{-0.03}$	G
1988B	05 08 2	−68 41	*V*	$10.0^{+0.2}_{-0.2}$	13.4	$0.43^{+0.22}_{-0.04}$	G

NOTES.—*Nova LMC 1926 to LMC 1951.*—Studied by Buscombe and de Vaucouleurs (1955). Nova LMC 1951 is heavily absorbed.

Nova LMC 1968.—The only available data are reported by J. Sievers in *Inf. Bull. Var. Stars.* No. 448. This is a case in which the light curve is qualified as "poor." We estimate a maximum of $10.4m_{pg}$ on Dec 16, but brighter values are possible.

Nova LMC 1970A.—Only two observations are available (*IAU Circ.* No. 2238), on Feb 8, when the nova was still invisible, and on Mar 8, when $m_{pg} \sim 12$. The quality is obviously "very poor."

Nova LMC 1970B.—The *B* and *V* photometry of this nova is given by Graham and Araya (1971) and Ardeberg and de Groot (1973); data also in *IAU Circ.* Nos. 2288, 2290. The object was discovered during decline ($B \simeq 12.5$), and no previous observations are available. A reasonable extrapolation yields $B_{max} \sim 11.0$.

Nova LMC 1971A.—Data from the same reference as for nova LMC 1970B. The star was not present in the plate of Jan 24. The maximum likely occurred within a few days from the time of discovery with $B \sim 11.5$. Data from *IAU Circ.* Nos. 2305 and 2307.

Nova LMC 1971B.—Only one observation reported in the *IAU Circ.* No. 2353. The nova was probably far from maximum at the epoch of discovery.

Nova LMC 1972, LMC 1973, LMC 1977A.—Same as for the previous nova LMC 1971B. Data from *IAU Circ.* Nos. 2441, 2605, 3045.

Nova LMC 1977B.—This is the best observed nova of the sample. The photometry is reported by Canterna and Schwartz (1977), who give a magnitude at maximum $V = 10.67 \pm 0.04$, a color index $(B - V) = 0.10 \pm 0.04$, and mean color excess $E(B - V) = 0.11$. Data also in *IAU Circ.* Nos. 3049, 3056.

Nova LMC 1978A.—Data in *IAU Circ.* Nos. 3204, 3206. Graham (1979) argued that the maximum was reached between Mar 18 and 20. In spite of the lack of direct observations, a value between 9.5 and 10.0 mag for the maximum magnitude seems quite reasonable.

Nova LMC 1978B, LMC 1981.—These belong to the class of "very poor" novae. Data in *IAU Circ.* Nos. 3308 and 3641, 3648 respectively.

Nova LMC 1987.—Discovery reported in *IAU Circ.* No. 4453. Data are also present in *IAU Circ.* Nos. 4456, 4459, 4468. Maximum very likely attained on Sep 17.

Nova LMC 1988A.—Data in *IAU Circ.* Nos. 4568, 4569, 4574, 4577, 4580, 4588, 4589, 4601, 4610. This is a slow nova, with a value of $t_2 = 22$ days. The visual magnitude at maximum of 11.0 was on Mar 23.

Nova LMC 1988B.—Data in *IAU Circ.* Nos. 4663, 4664, 4666, 4669, 4673. Maximum reached between Oct 12 and 13. The decline is smooth and moderately fast.

BdV; squares are for the novae which appeared later. Magnitudes have been all reduced to the *V* band using equation (3), and corrected for the total (foreground and internal) absorption *A* by means of the classical relations: $A_{pg} \simeq A_B = 4.3 \times E(B-V)$, and $A_V = 3.3 \times E(B-V)$ (Feast 1988*a*). Adopting for the color excess the value $E(B-V) = 0.09 \pm 0.03$, which is the mean of 11 measurements of reddening for Cepheids and young associations in the LMC (Table 2), we obtain $A_{pg} \simeq 0.4 \pm 0.1$ and $A_V \simeq 0.3 \pm 0.1$. These figures are probably lower limits; we note in fact that (1) just the foreground (galactic) absorption alone amounts to $A_V \simeq 0.2$ mag in the direction of the LMC (Burstein and Heiles 1984), and that (2) the internal extinction correction for the novae of the earlier type spiral M31 has been estimated to be as large as $A^i_{pg} \simeq 0.2$ in Paper I.

The MMRD of the galactic novae (Paper I, § VII) is well represented by the equation[4]

$$M_V(\max) = -7.89 - 0.81 \times \arctan\{[1.32 - \log(t_2)]/0.19\} \quad (5)$$

[4] The value of arctan is in radians.

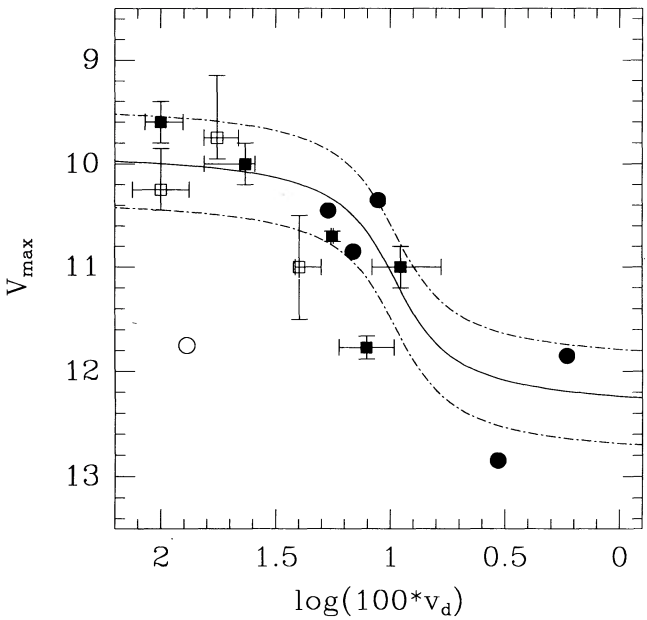

FIG. 1.—Maximum magnitude vs. rate of decline relationship (MMRD) for the novae of the Large Magellanic Cloud; magnitudes are reduced to the V band. Circles represent the six novae in the sample studied by Buscombe and de Vaucouleurs (1955), squares are novae appeared afterward (Table 1); filled symbols correspond to "good" (G) quality light curves, open symbols to "poor" (P). The solid line shows the best fit of the galactic MMRD model (Capaccioli *et al.* 1989*a*; formula [5]) to the "good" data, with reduced weight for the two novae—possibly absorbed—which lie outside the 3 σ strip (*dashed lines*).

and has been fitted to the data points of Figure 1 (*solid line*), through the equation

$$m_V(\text{max}) = 11.12 - 0.81 \times \arctan\{[1.32 - \log(t_2)]/0.19\}, \quad (6)$$

yielding an absolute distance modulus for the Large Magellanic Cloud of $(m - M)_0 = 18.71^{+0.27}_{-0.32}$ mag. The errors have been computed by combining three sources. One is the formal standard deviation of the mean for the residuals of the "good" data of Figure 1 (*solid symbols*) with respect to the interpolation formula: σ (O − C) = 0.15 mag. Note that, both in fitting the interpolation formula and in computing the errors, one half weight has been attributed to the two "good" data points falling outside the 3 σ strip (dashed lines in Fig. 1); they likely correspond to novae affected by a larger-than-average (patchy) internal absorption (this is certainly the case of LMC 1951). A second contribution to the total error comes from the uncertainty of 0.20 mag on the zero point of the galactic MMRD used to fit the data. Finally, there is the uncertainty in the absorption term, $\Delta A = ^{+0.2}_{-0.1}$; it is double-valued to take into account the possibility that the adopted corrections are lower limits.

The distance modulus can be also estimated through the magnitude 15 days past maximum; according to BdV, this has a constant value, independent of the rate of decline. Figure 2 plots $V(15)$ versus v_d for the same 14 LMC novae of Figure 1; all magnitudes are transformed to the V band through equation (4), and corrected for the total absorption as above. Even if we reject the reddened nova LMC 1951 and three other objects with poor photometry (*open circles*), the distribution of the remaining 10 data points is definitely not independent of the rate of decline. Nonetheless with the mean value $\langle V_0(15)\rangle = 13.05^{+0.22}_{-0.28}$ and adopting $\langle M_V(15)\rangle = -5.69 \pm 0.14$ as in Paper I, we obtain once more $(m - M)_0 = 18.74^{+0.26}_{-0.32}$.

TABLE 2

REDDENING IN THE LARGE MAGELLANIC CLOUD

$E(B-V)$	Object	Reference
0.08	Cepheids	Gascoigne 1969
0.14	Cepheids	Payne-Gaposchkin 1971
0.08	Cepheids	Payne-Gaposchkin 1971
0.04	Cepheids	Martin, Warren, and Feast 1979
0.074......	Cepheids	Caldwell and Coulson 1985
0.06	RR Lyrae	Walker 1985
0.10	OB stars	Lucke 1972
0.10	OB stars	Crampton 1979
0.12	Supergiants	Brunet 1975
0.11	Supergiants	Humphreys 1979
0.12	Stars of known spectral type	Ardeberg *et al.* 1973

IV. DISCUSSION

The mean of the previous two partly independent and very consistent determinations based on novae gives a distance modulus of $(m - M)_0 = 18.70^{+0.20}_{-0.25}$ for the LMC. The agreement with the distance determinations based on Cepheids (Table 3) confirms the reliability of our calibration of the galactic MMRD, and adds weight to the distances based on the MMRD of novae. The partial disagreement with the distances provided by the RR Lyrae (Table 3) may be the consequence of the current uncertainty (~0.3 mag) in the photometric calibration of these indicators (Hesser 1988; Strugnell, Reid, and Murray 1986; Jones *et al.* 1987).

The present result, combined with the previous studies of the Galaxy, M31, and the Virgo ellipticals, shows that at the level of accuracy of ~0.25 mag, the MMRD may be a universal relation. This gives support to the idea that there are no obvious differences in the nova populations of galaxies with different morphological types and bulge-to-disk ratios, with the possible exception of the frequency distribution along the

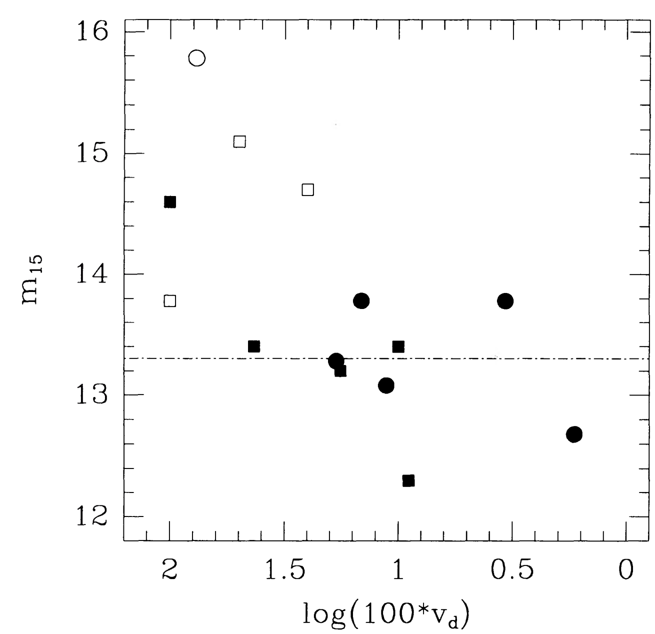

FIG. 2.—Same as Fig. 1 for the magnitude 15 days past maximum. The dashed line marks the adopted average value $\langle m_{15}\rangle$.

TABLE 3

A Catalogue of Distance Moduli for the Large Magellanic Cloud

$(m - M)_0$	Object	Mean	Source
18.86.........	Cepheids	...	Sandage and Tammann 1971
19.01.........	Cepheids	...	Gascoigne 1974
18.73.........	Cepheids	...	Iben and Tuggles 1975
19.29.........	Cepheids	...	van den Bergh 1977
19.05.........	Cepheids	...	Butler 1978
18.77.........	Cepheids	...	Martin, Warren, and Feast 1979
18.65.........	Cepheids	...	Madore 1983
18.55.........	Cepheids	...	Farnley, Jameson, and Sherrington 1985
18.82.........	Cepheids	...	Visvanathan 1985
18.57.........	Cepheids	...	Welch, Smarr, and Bruno 1987
18.47.........	Cepheids	18.80 ± 0.25	Feast and Walker 1987
18.61.........	RR Lyrae	...	Graham 1975
18.28.........	RR Lyrae	...	van den Bergh 1977
18.36.........	RR Lyrae	...	de Vaucouleurs 1978
18.42.........	RR Lyrae	18.42 ± 0.14	Walker and Mack 1988
18.36.........	Eclipsing binaries	...	Dworak 1974
18.7..........	Equivalent width Hγ	...	Crampton 1979
18.3..........	Spectral parallax	...	Conti, Garmany, and Massey 1986
18.15.........	H II regions	...	Issa 1986
18.30.........	B stars	...	Shobbrook and Visvanathan 1987
18.48.........	Miras	...	Feast 1988*b*
18.28.........	Mira variables	...	Feast 1988*b*
19.08.........	Novae	...	van den Bergh 1977
18.65.........	Novae	...	de Vaucouleurs 1978
18.70.........	Novae	...	This paper

MMRD sequence and the relative percentage of the bright and fast novae.

A second result of this study concerns the shape of and the frequency distribution along the MMRD. The question of the MMRD shape has recently acquired some interest after the suggestion (Paper I) of the possible existence of a less populated sequence of super-bright novae deviating from the classical S-shaped relation at $\simeq 5\ \sigma$ level; they appear ~ 1 mag brighter than suggested by their rate of decline (see Fig. 8, Paper I).

We also note that (*a*) the flattening of the M31 MMRD at the very high rates of decline depends only on two objects, Arp's (1956) novae no. 1 and no. 2, which, in addition, have an uncertain photometry near maximum, and (*b*) the existence of the bright shoulder is weakly supported by the MMRD of the galactic novae.

The reality of this feature, which is fundamental for a confirmation of the existence of a second sequence of novae, is now proved by the data of Figure 1.

Finally, we also note the high percentage of LMC novae in the bright and fast part of the MMRD, $\sim 30\%$ compared to $\sim 10\%$ in M31. Assuming that the expected frequency for the very fast and bright novae is $\omega_i \sim 0.1$, the rms difference between the observed LMC–nova distribution and that predicted from M31 data (Paper I) is $\simeq 2.3\ \sigma$. This indication, that the LMC novae are in some way different from those of M31, at least in the density ratio of the fast population to that of the slow population, could be meaningless. In addition to the small size of the LMC sample, we must also consider selection effects which act against the discovery of very fast and bright novae in M31, very fast novae may not be seen in M31 but are unlikely to be missed in the closer LMC.

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