THE ASTROPHYSICAL JOURNAL, 452:704–709, 1995 October 20

THE CALIBRATION OF NOVAE AS DISTANCE INDICATORS

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Received 1994 December 13; accepted 1995 April 28

ABSTRACT

The problem of the correct calibration of the maximum magnitude versus rate of decline relationship for Galactic novae is discussed, on the basis of the properties of the nova populations of M31 and the Large Magellanic Cloud (LMC). We have compared the "observed" maximum magnitude versus rate of decline (hereafter MMRD) distributions of M31 and LMC novae with the most widely used analytic representations of the *Galactic* MMRD relationship, and we find that the *linear* regressions, normally used to interpolate the Galactic data, fit the M31 and LMC distributions only as very rough, first-order approximations. We have used the bright and fast objects belonging to the LMC nova population to improve the fit of the bright end of the Galactic MMRD relationship, previously based only on two fast novae of M31. The new results indicate that at least two O-Ne-Mg novae, Nova Cyg 1992 and Nova Her 1991, do not deviate, within the observational errors, from the main tract of the improved relationship. The new calibration, applied to novae discovered in Virgo, gives a distance to the cluster of 18.6 ± 3.3 Mpc.

Subject headings: novae, cataclysmic variables — stars: distances

1. INTRODUCTION

The study of Galactic novae at maximum light is valuable in many respects. Most notable is the fact that novae in outburst are effective distance indicators (certainly within the Local Group and potentially beyond; see Jacoby et al. 1992 for a review). Their usage as distance indicators is based on the pioneering studies of Zwicky (1936) and McLaughlin (1939), who found that the absolute magnitude of novae at maximum correlates with their rate of decline (v_d).

On the theoretical side, a number of recent studies (e.g., Livio 1992; Prialnik & Kovetz 1995) have shown that the absolute magnitude at maximum and the rate of decline are, to first order, a simple function of the mass of the underlying white dwarf, thus illustrating the potential importance of the knowledge of the exact absolute magnitude at maximum for nova theory.

The absolute calibration of the M_{max}-v_d relationship, often called the maximum magnitude versus rate of decline relationship (hereafter MMRD), has been attempted by several authors in the past 30 years by using a large variety of methods, but never attempting to carry out a systematic and comparative analysis of the results. As a consequence, a number of analytic (phenomenological) expressions for the MMRD (e.g., Schmidt 1957; Pfau 1976; Cohen 1985; Capaccioli et al. 1989) are currently circulating in the literature without any objective judgment of the intrinsic merits of each method. A quite illustrative example of this situation is represented by the recent case of Nova Cyg 1992 (Chochol et al. 1993). In this case, what has been considered as the "best" estimate of the absolute magnitude of the nova at maximum was the "brute force" average of a number of measurements, obtained by applying the above-mentioned relationships without any consideration of the dramatic differences in zero points and different slopes of each fit. As result of this procedure, the estimate of the absolute magnitude at maximum ranges between −7.1 and −8.4.

In the present paper, we carry out a comparative analysis of the most frequently used MMRDs, with the observed MMRDs of the nova populations of M31 and the LMC. Most importantly, we show that O-Ne-Mg novae follow, within the errors, the main track of the MMRD relationship. A strong basis for pursuing this approach is provided by the work of Capaccioli et al. (1989), who have shown that the MMRD for galaxies of different Hubble types can be described, within the observational errors, by the same relationship.

2. THE GALACTIC MMRD

The relationship between the magnitude at maximum of a nova and its rate of decline is normally expressed (see Schmidt 1957) through the general expression:

$$M_{max} = A + B \log(t_2)[\text{or} \log(t_3)] . \qquad (1)$$

The decay time, t_2 (t_3), represents the time that it takes the nova to drop by 2 (3) magnitudes below maximum, and it is normally used to define the speed class of classical novae (e.g., Payne-Gaposchkin 1957). From these quantities, one can define the so-called rates of decline as $v_{d2} = 2/t_2$ and $v_{d3} = 3/t_3$. Because of the fact that t_3 is, on the average, longer than t_2 by about 70%, and as a result of the faintness of extragalactic novae, t_2 is very often the only rate of decline which can be measured during the decay of novae belonging to extragalactic systems. Thus, in order to be able to carry out a sensitive comparison between the nova population in the Milky Way and of those occurring in extragalactic systems, the quantities t_2 and v_{d2} (rather than t_3 and v_{d3}) will be adopted throughout this paper. In Figure 1 we present the MMRD for the nova populations of M31 and the LMC (data from Capaccioli et al. 1989, see their Table VI, and Capaccioli et al. 1990, see their Table 1). The apparent magnitudes have been scaled to the respective distances, namely, distance moduli of 24.30 for M31 (van den Bergh 1992) and 18.50 for the LMC (Panagia et al. 1991) and taking into account the different values of absorption (background and foreground). In Tables 1 and 2 we give

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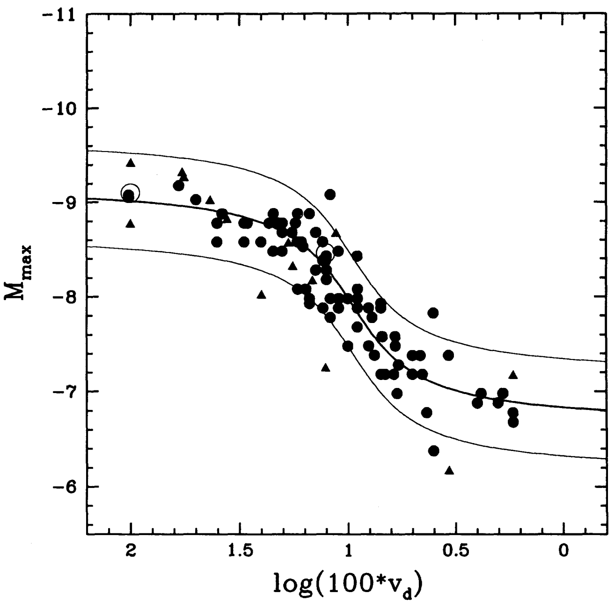

FIG. 1*a*

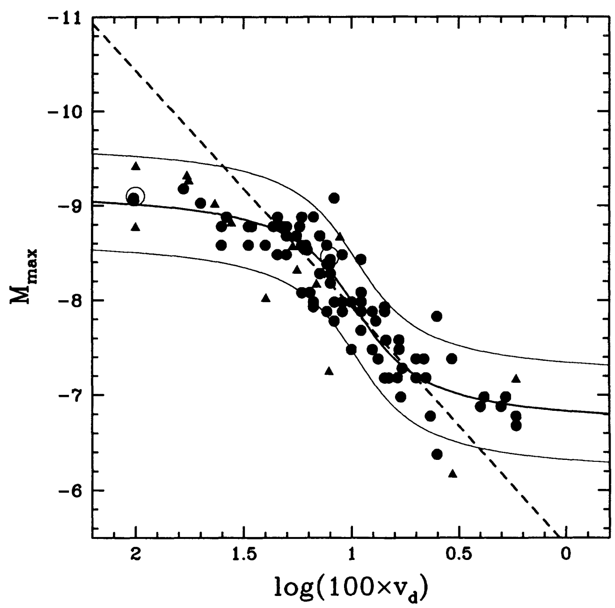

FIG. 1*b*

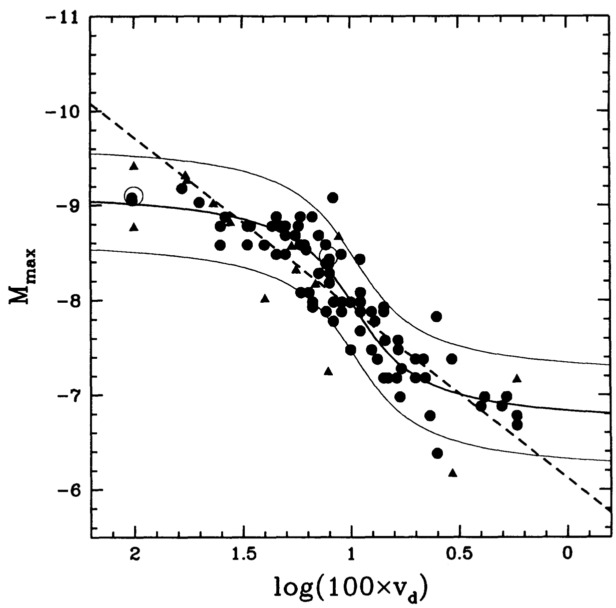

FIG. 1*c*

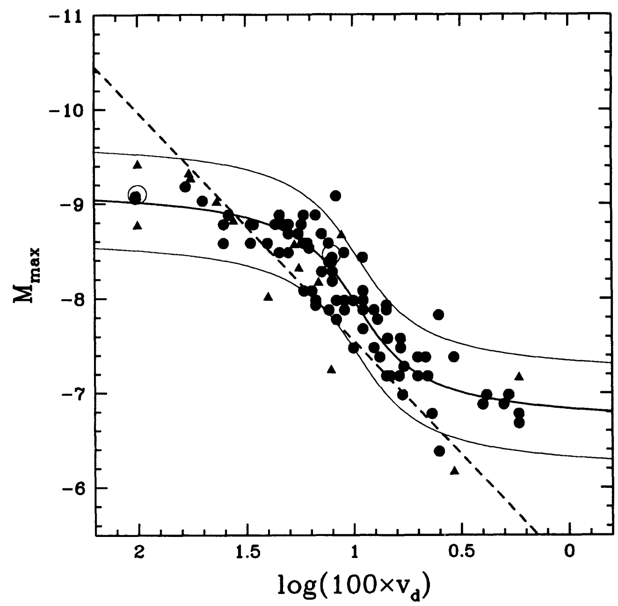

FIG. 1*d*

FIG. 1.—(*a*) Maximum magnitude vs. rate of decline relationship for novae in M31 (*filled circles*) and the LMC (*triangles*). Each apparent magnitude has been transformed to an absolute *V* magnitude by using the different distance moduli and absorptions for M31 and the LMC. The "best" fit is indicated by the solid curve. Open circles represent the positions of Nova Cyg 1992 and Nova Her 1991. Upper and lower curves are located $\pm 3\ \sigma$ above and below the relation of eq. (2). (*b*) Same data as in (*a*), but with the phenomenological relation of Schmidt (1957). (*c*) Same data as in (*a*), but with the phenomenological relation of Pfau (1976). (*d*) Same data as in (*a*), but with the phenomenological relation of Cohen (1985). (*e*) Same data as in (*a*), but with the theoretical relation of Livio (1992).

the magnitudes and rates of decline that have been used. The fit has been performed for over 84 novae of M31 and 15 novae of the LMC, without using the overluminous objects which deviate from the main relation by at least $5\ \sigma \gtrsim 1$ mag (Della Valle 1991) and the two subluminous ones (patchy absorbed or recurrent novae). The minor differences with the fit performed by Capaccioli et al. (1990) are caused by the fact that the latter fit was based only on novae of M31. The main advantage of adding the LMC novae to the original sample is that the LMC nova population is rich in bright and fast objects (e.g., Della Valle et al. 1994). Consequently, we have substantially increased (by a full factor of 2) the number of bright and fast novae which are suitable to calibrate the bright shoulder of the relationship.

The best fit (indicated in Fig. 1*a* by the continuous curve) yields (the value of arctan is in radians)

$$M_V = -7.92 - 0.81 \arctan \frac{1.32 - \log(t_2)}{0.23} . \quad (2)$$

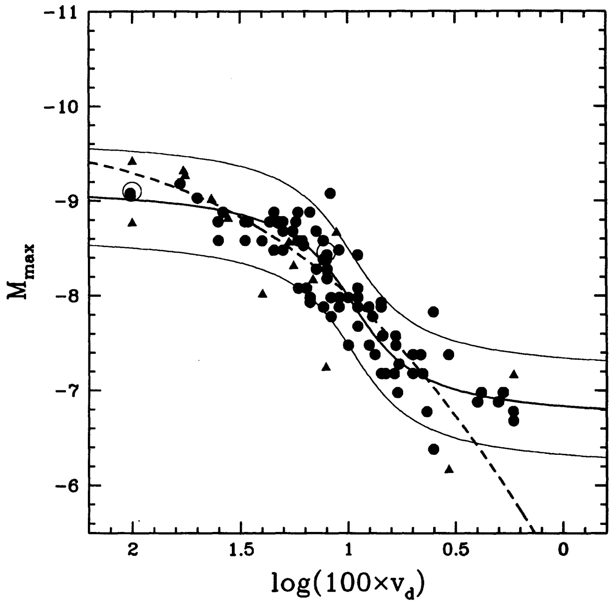

FIG. 1*e*

In Figures 1*b*–1*e*, we show (with the same data) three of the most popular empirical MMRD relationships, namely, Schmidt (1957), Pfau (1976), Cohen (1985), and the theoretical relation obtained by Livio (1992). In order to make a quantitative comparison of the quality of these fits, we ran a χ^2 test for each fit and summarized the results in Table 3. A close inspection of Figure 1 and Table 3 reveals the following.

1. Schmidt's fit is a simple linear regression for novae falling into the range of the MMRD relationship, $10^d \lesssim t_2 \lesssim 50^d$. Schmidt suggested linear fits with different slopes for the ranges $\log t_2 \lesssim 1.0$ and $\log t_2 \gtrsim 1.6$. In Figure 1*b* we show only the linear fit to the range $1.0 \lesssim \log t_2 \lesssim 1.6$, which is most commonly used (e.g., Chochol et al. 1993). Consequently, the χ^2 value in Table 3 represents deviations from this linear fit and not from the complete relation of Schmidt (1957).

2. Pfau attempts to fit a linear regression along the whole range of rates of decline by imposing a less steep slope than Schmidt's. Although it fails to fit properly the data distribution even where the MMRD is actually linear, Pfau's fit provides a better estimate of the absolute magnitudes for very fast and very slow novae.

3. Cohen's relationship exhibits a slope which is very similar to Schmidt's, but with a zero point which is fainter by ≈0.5 mag. This accounts for the 0.3–0.4 mag lower distance modulus to M31 determined by the same author.

4. The theoretical fit by Livio, though calibrated by only one object (Nova Cyg 1975), is the only one able to reproduce simultaneously the observed flattening of the relationship on its bright side and the linear decay at intermediate rates of decline. The discrepancy between the theoretical fit and the trend of faint novae is responsible for the relatively large value of χ^2 of Table 3. However, the flattening of the relationship at faint luminosity levels could definitely be the result of an observational bias, rather than being real. In particular, the representation of novae with $t_2 \gtrsim 50$ days is rather sparse (see also Warner 1995). On the other hand, the nature of the outbursts for very low mass white dwarfs ($M_{WD} < 0.6\ M_\odot$) has not been sufficiently explored, and it is therefore possible (in principle) that the flattening is indeed a consequence of the

TABLE 1

DATA FOR M31

Nova	M_v	v_d	Reference	Nova	M_v	v_d	Reference	Nova	M_v	v_d	Reference
A01	−9.1	1.02	1	R04	−8.4	0.13	2	R46	−8.2	0.125	2
A02	−9.1	1.02	1	R05	−9.2	0.60	2	R49	−8.4	0.09	2
A03	−8.9	0.38	1	R06	−8.3	0.14	2	R52	−8.4	0.125	2
A05	−8.9	0.17	1	R07	−8.6	0.40	2	R53	−7.8	0.04	2
A06	−8.8	0.23	1	R09	−8.0	0.15	2	R58	−8.3	0.125	2
A07	−8.9	0.15	1	R12	−7.2	0.05	2	R59	−7.5	0.10	2
A08	−8.8	0.23	1	R13	−8.0	0.12	2	R60	−8.4	0.13	2
A09	−8.8	0.174	1	R14	−7.5	0.08	2	R67	−8.6	0.13	2
A10	−8.8	0.29	1	R15	−8.5	0.11	2	R76	−8.7	0.14	2
A12	−8.7	0.18	1	R16	−8.5	0.16	2	R77	−8.9	0.20	2
A13	−7.8	0.077	1	R17	−8.1	0.17	2	R78	−7.9	0.08	2
A14	−8.6	0.163	1	R18	−7.7	0.09	2	R80	−7.4	0.034	2
A15	−8.4	0.126	1	R19	−6.9	0.025	2	R85	−9.1	0.12	2
A16	−8.1	0.156	1	R20	−7.9	0.09	2	R86	−7.5	0.06	2
A17	−7.6	0.069	1	R21	−8.1	0.09	2	R89	−8.0	0.10	2
A18	−7.3	0.058	1	R23	−7.9	0.15	2	R95	−8.6	0.30	2
A19	−7.2	0.070	1	R24	−8.7	0.20	2	R98	−8.8	0.21	2
A20	−7.6	0.060	1	R27	−7.9	0.07	2	R100......	−8.8	0.20	2
A21	−7.4	0.075	1	R29	−8.8	0.30	2	R104......	−6.4	0.04	2
A22	−7.2	0.067	1	R30	−8.6	0.17	2	R105......	−7.9	0.13	2
A23	−7.4	0.046	1	R32	−9.0	0.50	2	R106......	−7.2	0.045	2
A24	−7.0	0.059	1	R33	−8.6	0.25	2	R109......	−8.5	0.20	2
A25	−7.2	0.061	1	R34	−7.8	0.12	2	R112......	−7.5	0.10	2
A26	−6.8	0.043	1	R37	−8.0	0.11	2	R113......	−8.8	0.40	2
A27	−7.0	0.024	1	R38	−7.9	0.11	2	R117......	−6.9	0.02	2
A28	−7.0	0.019	1	R41	−6.9	0.02	2	R118......	−7.9	0.07	2
A29	−6.8	0.017	1	R42	−7.9	0.07	2	R120......	−7.4	0.05	2
A30	−6.7	0.017	1	R43	−8.5	0.22	2	R129......	−8.0	0.09	2

REFERENCES.—(1) Arp 1956; (2) Capaccioli et al. 1989.

TABLE 2

DATA FOR LMC

Nova	M_v	v_d	Reference	Nova	M_v	v_d	Reference	Nova	M_v	v_d	Reference
N1926........	−7.2	0.017	1	N1968........	−8.8	1.00	2	N1987........	−9.4	1.00	6
N1935........	−8.2	0.145	1	N1970B......	−8.0	0.25	3	N1988A......	−8.0	0.09	7
N1936........	−8.7	0.113	1	N1971A......	−7.3	0.127	3	N1988B......	−9.0	0.43	8
N1937........	−8.6	0.187	1	N1977B......	−8.3	0:179	4	N1990A......	−9.3	0.58	9
N1948........	−6.2	0.034	1	N1978A......	−9.3	0.57	5	N1992........	−8.8	0.36	10

REFERENCES.—(1) Buscombe & de Vaucouleurs 1955. (2) Sievers 1970. (3) Graham & Araya 1971; Ardeberg & de Groot 1973. (4) Canterna & Schwarz 1977. (5) Graham 1979. (6) McNaught & Garradd 1987; McNaught, Hartley, & Savage 1987; McNaught 1987a, b. (7) Garradd & Tregaskis 1988; McNaught & Tregaskis 1988a, b; Williams 1988a, b; Seargent 1988a, b; Pearce 1988; Kilmartin 1988; McNaught 1988a, b, c; Kilmartin & Gilmore 1988. (8) Hamuy, Gonzales, & Martin 1988; Martin, Hamuy, & Suntzeff 1988; McNaught 1988a, b, c; Seargent 1988a, b; Williams 1988a, b. (9) McNaught 1990; Pearce 1990; Seargent 1990; Gilmore & Kilmartin 1990; Gilmore 1990a, b; Liller 1990. (10) Liller 1992a, b; Camilleri 1992; Hers 1992; Gilmore 1992a, b. c. d.

physics of the outburst (Livio's relation was based only on models with $M_{\rm WD} \gtrsim 0.6\ M_\odot$). This point will require clarification by future nova calculations.

3. THE ABSOLUTE MAGNITUDE AT MAXIMUM OF NOVA CYGNI 92 AND NOVA HERCULIS 91

By adopting the MMRD as discussed above and taking $t_2(V) = 16$ days (Chochol et al. 1993), we find the absolute magnitude at maximum of Nova Cyg 1992 (V1974 Cyg) to be $M_V \approx -8.3$. The correction for absorption is rather uncertain; however, we can assume $A_v = 0$ (Shara 1994) and $A_v = 0.95$ (Chochol et al. 1993) as conservative lower and upper limits, respectively. After applying this correction to the apparent magnitude at maximum, one obtains $V_0 = 4.4$. We find the distance to the nova to be in the range of $\approx$2.2–3.4 kpc. These values are in agreement with the range of possible distances (Chochol et al. 1993; Paresce et al. 1995; Chochol et al. 1994). This agreement is particularly interesting in view of the possibility raised by Starrfield et al. (1992) that the MMRD distance method fails for neon novae such as V1974 Cyg (e.g., Paresce et al. 1995; Austin et al. 1994). This claim was based on Woodward et al.'s (1992) finding that the distance of Nova Her 1991, obtained via the MMRD relationship, overestimates the distance to this object by a full factor of 2. Taken at face value, this observation could cast a serious doubt on the applicability of the MMRD relationship to the class of "neon" novae. A closer examination of this issue, however, reveals the following: when we apply the MMRD relationship, calibrated on the M31 and LMC nova populations (eq. [2]), to Nova Her 1991, we find an absolute magnitude at maximum of $M_v = -9$ ($t_2 = 2$) days. After combining this value with the estimated reddening of $E(B-V) \approx 0.6$ mag (Starrfield et al. 1992) and the apparent magnitude at maximum of Nova Her 1991 ($V = 5.3$, Woodward et al. 1992), a distance of 3.2 kpc is found. This is in remarkably good agreement with both the distance of 3.4 kpc determined by Starrfield et al. (1992) from the ratio of the UV fluxes above and below 2000 Å and the 2.8 kpc distance derived by Woodward et al. (1992) using a blackbody law. In view of this agreement, we conclude that the 6.5 kpc distance obtained by Woodward et al. (1992) for Nova Her 1991 was simply the result of the use of a linear fit in the *bright* and *fast* region of the MMRD plane (typically $t_2 \leq 6$ days), where the trend of the relationship is, in fact, not linear (see also Shara 1994). That the two novae, Nova Cyg 1992 and Nova Her 1991, obey the MMRD relation can be clearly seen in Figure 1*a*, which shows that these two novae (*large open circles*) fall well inside the $\pm 3\ \sigma$ strip. The rates of decline of the novae were taken from Chochol et al. (1993) and Woodward et al. (1992), and their absolute magnitudes were taken from Paresce (1994), Woodward et al. (1992), and Starrfield et al. (1992).

As an interesting by-product of this work, one can use the new MMRD to redetermine the distance to the *core* of the Virgo Cluster by using the data obtained by Pritchet & van den Bergh (1987). These authors discovered a handful of novae in the giant ellipticals NGC 4365, NGC 4472, and NGC 4649 and were able to measure, for seven of them, both the magnitude at maximum and the rate of decline. To properly compare the Pritchet & van den Bergh data with our relationship, we have first reduced the $B_{\rm max}$ magnitudes of the Virgo novae to the V band through the color correction $(B-V)_0^{\rm max} = +0.23$ (van den Bergh & Younger 1987) and secondly, we disregarded the peculiar object discovered in NGC 4472, which belongs perhaps to the superbright class of classical novae studied by Della Valle (1991). A χ^2 test of the data gives the best fit with the relationship (Fig. 2) by assuming a distance modulus to the Virgo Cluster of $(m - M) = 31.35 \pm 0.35$, which corresponds to a distance of 18.6 ± 3.3 Mpc. This value is consistent with the recent determination by Freedman et al. (1994), and it reconfirms the potential usefulness of novae as distance indicators.

TABLE 3

FITS

Fit	χ^2
Schmidt 1957...............	2.94
Pfau 1976....................	1.50
Cohen 1985................	3.78
Capaccioli et al. 1990......	1.29
Livio 1992	1.74
This paper	1.19

4. SUMMARY AND CONCLUSIONS

Reliable values for the magnitude at maximum of novae are important for a number of reasons (i) they enable one to determine the distance to novae and thus, to use novae as distance indicators; (ii) Since the *main* physical parameter determining the luminosity at maximum is the mass of the white dwarf, the magnitude at maximum can be used to determine (at least in a statistical sense) white dwarf masses (see discussions by Livio 1992; Prialnik & Kovetz 1995).

In the present work, we have first shown that, unless the Galactic nova population follows a very different MMRD relation from those of M31 and the LMC, *linear* fits to the Galactic

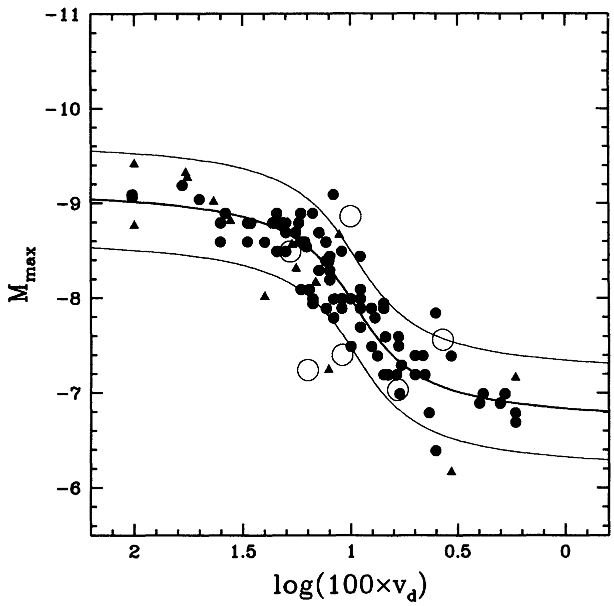

FIG. 2.—Virgo novae (*large open circles*) have been superimposed on the maximum magnitude vs. rate of decline relationship for novae in M31 and the LMC. Their apparent magnitude at maximum has been scaled to a distance modulus of $(m - M) = 31.35$.

MMRD are inadequate to describe the data distribution. Since a nonlinear relation (at least for bright novae) is also expected on theoretical grounds (e.g., Livio 1992; Prialnik & Kovetz 1995), we believe that the relation presented here should also be used for Galactic novae. The metallicity of the *accreted* material has a negligible effect on the outburst properties, since the enrichments by heavy elements almost certainly represent dredged-up material from the underlying white dwarf (e.g., Livio & Truran 1994).

Secondly, by applying the new calibration to the recent Nova Cyg 1992 and Nova Her 1991, we have shown that the rates of decline of these two neon novae are consistent with the absolute magnitudes derived by independent ways (Fig. 1). This shows that there is presently no reason to assume that the MMRD relation does not apply also to neon novae.

A direct application of the *average* relation between the white dwarf mass and the magnitude at maximum (Livio 1992), for the case of Nova Cyg 1992 (with M_V^{max} obtained here), gives $M_{WD} = 0.9$–$1.1\ M_\odot$. This is in complete agreement with the range of values obtained by Paresce et al. (1995), using several methods.

The following points should be noted:

(1) The relatively large scatter around the MMRD relation *is expected* from theoretical considerations (Livio 1992). It is a direct consequence of the fact that the strength of a nova outburst also depends on physical parameters other than the white dwarf mass (e.g., the accretion rate, the white dwarf temperature, and the magnetic field: Livio 1994; Prialnik & Kovetz 1995).

(2) The luminosity of novae in the plateau phase (of constant bolometric luminosity) can be used (especially for moderately fast to slow novae) effectively as a standard candle (Livio 1992). The luminosity in this phase is given by Iben & Tutukov (1989), who find

$$L/L_\odot \simeq 4.6 \times 10^4 (M_{WD}/M_\odot - 0.26)\ . \quad (3)$$

If only moderately fast to slow novae are used, then the total expected range in magnitude is less than $\Delta m \sim 1$ (Livio 1992).

We thank an anonymous referee for helpful comments. M. L. acknowledges support from NASA grant GO 5255. M. D. V. thanks the Space Telescope Science Institute, where a part of this work was completed, for its hospitality.

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