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PULSATIONAL EVIDENCE FOR MASS LOSS IN NGC 1866 CEPHEIDS

E. Brocato
INAF–Osservatorio Astronomico di Collurania-Teramo, via M. Maggini, I-64100 Teramo, Italy; brocato@te.astro.it

F. Caputo and V. Castellani[1]
INAF–Osservatorio Astronomico di Roma, via Frascati 33, I-00040 Monteporzio Catone, Italy;
caputo@mporzio.astro.it, vittorio@mporzio.astro.it

and

M. Marconi and I. Musella
INAF–Osservatorio Astronomico di Napoli, via Moiariello 16, I-80131 Naples, Italy; marcella@na.astro.it, ilaria@na.astro.it
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ABSTRACT

Available observational data for the 20 known Cepheids in the LMC cluster NGC 1866 have been compared with *Hubble Space Telescope* observations, discovering in the cluster central region five additional variables, one of which appears to be a Cepheid candidate. We also reach the conclusion that only the photometric data for the seven variables in the cluster periphery appear accurate enough to allow a meaningful comparison with the results of pulsational theories. Out of these seven well-observed Cepheids, we find that the six probable cluster members are located in the color-magnitude diagram at the hot tip of the blue nose experienced by He-burning giants. Since evolutionary theory predicts for these giants an original mass on the order of 4 $M_\odot$, we extend down to $\sim$3 $M_\odot$ the theoretical pulsational scenario already presented for $M \geq 5.0\ M_\odot$. On this basis we discuss the four member Cepheids with *VI* magnitudes accurate enough to produce robust constraints on the pulsating structures. Among these variables, one finds evidence for a spread of masses by about 7%, with the structures following a tight mass-luminosity relation. Moreover, we show that periods and colors of the Cepheids give a robust indication of pulsator masses smaller than predicted by stellar evolution theory without mass loss, independently of the occurrence of core overshooting.

Key words: Cepheids — globular clusters: individual (NGC 1866) — Magellanic Clouds — stars: evolution — stars: mass loss

1. INTRODUCTION

For a long time, the pulsational behavior of classical Cepheids has been the target of several investigations, mainly intended to link the observed periods to the star's intrinsic luminosity and, in turn, to use these variables as distance indicators on both Galactic and extragalactic scales. However, empirical calibrations of the period-luminosity (P-L) or period-luminosity-color (P-L-C) relations are still facing uncertainties in the distance, metallicity, and reddening of the variables, leaving, e.g., a parallel uncertainty on the derived distance modulus of the Large Magellanic Cloud (LMC) as large as $\sim\pm0.2$ mag (see, e.g., Carretta et al. 2000; Clementini et al. 2003).

In more recent time, hydrodynamic computations are providing a theoretical pulsational scenario that has already shed light on several observational findings, promising to give robust support to empirical calibrations. However, theoretical predictions need the support of observational constraints as given by suitable samples of well-observed Cepheid pulsators. In this context, classical Cepheid members of young stellar clusters appear to be of particular relevance, since the color-magnitude diagram (CMD) of the companion cluster stars is expected to provide additional constraints on the distance, the reddening, and, last but not least, the mass of stars in the advanced evolutionary phases, as Cepheids are.

According to such a scenario, Cepheids in Galactic open clusters have been the target of several investigations. Unfortunately, the occasional occurrence in these poorly populated stellar systems of only a few variables did not allow firm conclusions, and this field of investigation has been neglected in favor of very large Galactic and extragalactic samples as given, e.g., by the Magellanic Cloud variables or by Cepheids in the Galactic field with *Hipparcos* parallaxes. However, at the present time the increased observational capabilities have already opened for investigation the rich stellar clusters in the Magellanic Clouds, renewing the interest in such an approach.

In this paper we address the case of the LMC cluster NGC 1866, in which a sample of Cepheids as rich as 20 variables has been already detected. This appears as a relevant occurrence, since a sample of 20 well-observed variables at the same distance with a common metallicity and reddening and with rather severe evolutionary constraints on their masses and luminosities should be able to enlighten several characteristics of the pulsation phenomenon.

In § 2, we take advantage of recent *Hubble Space Telescope* (*HST*) observations of the cluster to test the accuracy of photometric data available in the literature for these NGC 1866 Cepheids. Unfortunately, we reach the conclusion for the occurrence of no more than seven "bona fide" well-observed Cepheids, i.e., with photometry accurate enough to allow a tight comparison with theoretical pulsational predictions. To this purpose, § 3 presents the results of new pulsational models covering the range of masses and luminosity expected in the cluster Cepheids. On this basis, § 4 deals with the discussion of an even further

[1] Also at: INFN Sezione di Ferrara, via Paradiso 12, I-44100 Ferrara, Italy.

TABLE 1
PERIOD, MAGNITUDES, AND COLORS FOR THE SAMPLE OF SEVEN PERIPHERAL CEPHEIDS

Identification	log P	$\langle V \rangle$	$\langle B-V \rangle$	$\langle V-I \rangle$	Member?
HV 12197	0.497	16.080	0.645	0.707	Member
HV 12198	0.547	15.945	0.646	0.716	Member
HV 12199	0.421	16.265	0.604	0.680	Member
HV 12202:	0.492	16.058	0.671	0.681	Binary?
HV 12203	0.470	16.133	0.633	0.687	Member
HV 12204::	0.536	15.701	0.466	0.616	?
V7:........................	0.530	15.975	0.640	0.681	Member

restricted sample of four well-observed variables, disclosing evidence for the occurrence of a mass-luminosity relation. Section 5 deals with theoretical constraints on the Cepheid pulsational masses, and a short discussion closes the paper.

2. NGC 1866 CEPHEIDS

Data for NGC 1866 Cepheids have been accumulating for several decades. Arp & Thackeray (1967) and Arp (1967) first presented light curves for seven variables in the cluster periphery. Further variables were discovered by Storm et al. (1988), Welch et al. (1991, hereafter W91), and Welch & Stetson (1993, hereafter WS93) in increasingly crowded cluster regions, the last two papers giving light curves and mean V and $B-V$ values for a final sample of 20 Cepheids. The original plan of the present investigation was to make use of these data in light of the predictions of pulsational theories. However, when comparing the CMDs of these Cepheids, as given in Figure 2 of WS93, with available photometry for cluster nonvariable stars (see, e.g., Brocato et al. 2003), we found unexpected evidence for Cepheids spanning a much larger region of the diagram than nonvariable stars do. This suggested to us that the observational data were possibly not accurate enough to derive meaningful information for the pulsating structures.

To look into this problem, we took advantage of the seven peripheral Cepheids recently observed with great accuracy by Gieren et al. (2000). By integration of the published light curves, we derived intensity-averaged $\langle B \rangle$, $\langle V \rangle$, and $\langle I \rangle$ magnitudes whose values are reported in Table 1. Comparison with data given in W91 discloses that even for these uncrowded stars, one finds color differences up to about $\Delta(B-V) \sim 0.08$ mag, an error that probably increases for stars in the crowded central cluster regions. This suspicion has been confirmed by the analysis of the two available *HST* data sets of WFPC2 observations (F555W and F815W) taken at an interval of about

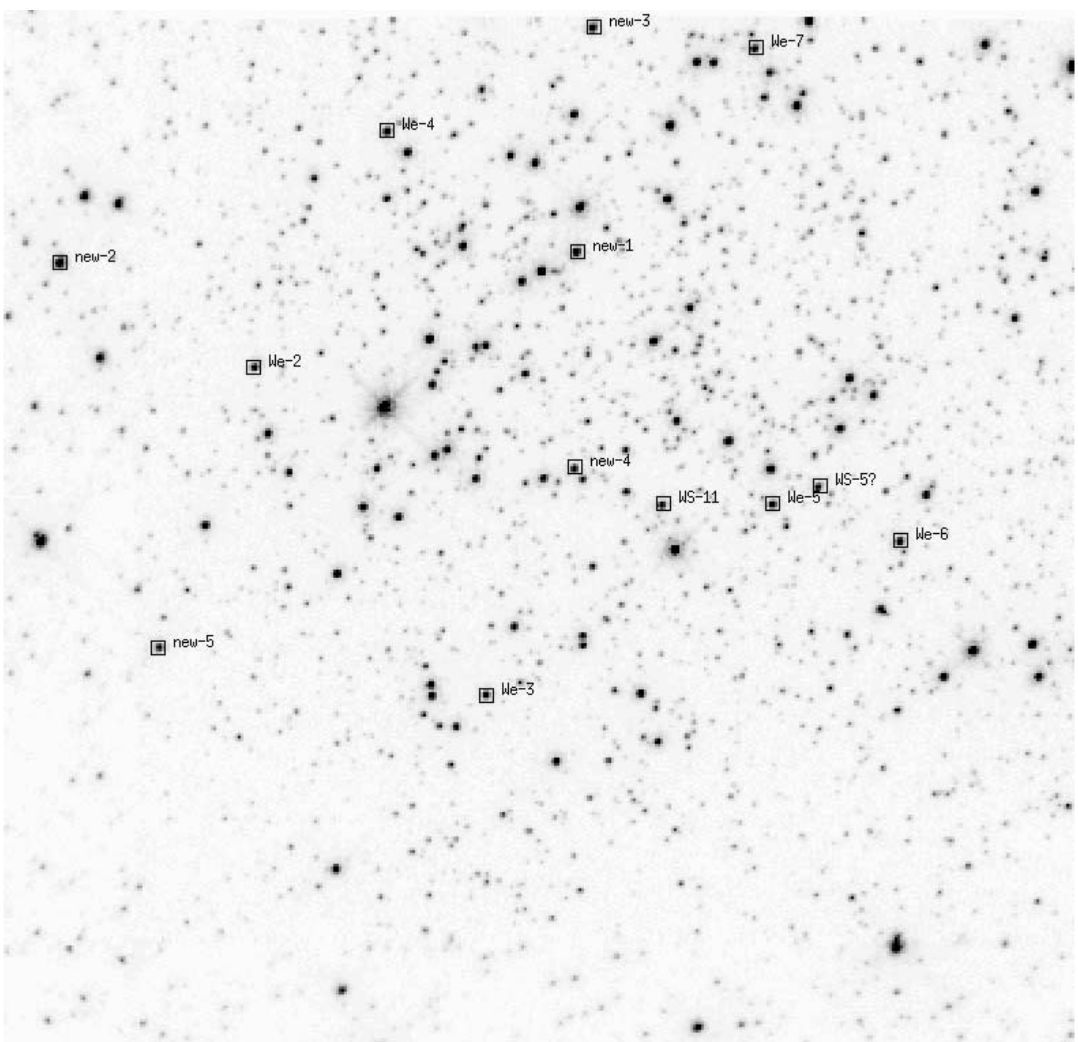

FIG. 1.—Identification map for the newly discovered variables. Already known Cepheids are also identified using the names in WS93.

TABLE 2
V Magnitudes at the Two Epochs for Previous and New Variables in Our *HST* Frame

Identification	V_1	V_2	ΔV	Error (σ)
HV 12200	16.527	16.010	0.517	0.002
V7	16.193	16.060	0.133	0.006
V8	16.024	16.062	−0.380	0.005
WE 2	16.364	16.186	0.178	0.005
WE 3	16.352	16.251	0.101	0.002
WE 4	16.450	15.987	0.463	0.007
WE 6:	16.060	16.194	0.134	0.007
WE 5	16.206	16.069	0.137	0.007
WE 7	16.245	15.999	0.246	0.012
WS 5?	16.395	17.429	−1.034	0.007
WS 11	16.289	16.124	0.165	0.007
New 1	16.167	16.106	0.061	0.007
New 2	15.838	15.920	−0.082	0.010
New 3	16.550	16.456	0.094	0.010
New 4	16.721	16.797	−0.076	0.010
New 5	16.962	17.123	−0.161	0.020

2 months. The log of the first set of observations (HJD = 2,451,470.5923), as obtained to investigate the cluster luminosity function, has been already given in Table 1 of Brocato et al. (2003). The second data set (HJD = 2,451,411.9901) has been retrieved from the *HST* archive.

Data reduction has been performed as described in Brocato et al. (2003), and calibrations have been checked to be fully consistent with the previous photometry by comparing the results for the wide sample of common nonvariable stars. By applying the procedure envisaged by WS93, we easily detected all the 11 Cepheids already known in the field, with the addition of five new possible variables. Figure 1 gives the identification map for the new candidates, whereas Table 2 gives the two values of the visual magnitude for all of these stars. However, it turns out that four out of the five candidates have mean $V-I$ colors of $\sim$1.2 mag, suggesting the occurrence of red variables in the cluster. Only the object "New 2" has $V-I = 0.85$ mag, which agrees with the color of a cluster Cepheid near the minimum light (see, e.g., Gieren et al. 2000).

The comparison with WS93 data is not direct because of the lack in their Figure 5 of the scale of magnitudes. However, from their Table 2 and the light curves in the quoted Figure 5 one finds, e.g., for the variable WE 7 a range of magnitudes on the order of $V \sim 15.30 \pm 0.2$ mag, which appears definitely brighter by at least half a magnitude than the *HST* values listed in our Table 2. We conclude that ground-based observations of Cepheids in the crowded cluster region are affected by larger uncertainties, so we remain with the tantalizing evidence for a cluster with at least 20–21 Cepheids but with only the seven objects observed by Gieren et al. (2000) characterized by firm evaluations of magnitudes and colors.

As shown in Table 1, among these seven variables W91 lists a suggested nonmember (HV 12204) and a suspected binary (HV 12202), so one remains with only six bona fide cluster Cepheids, including the suspected binary. Five to six well-studied Cepheids in a given cluster is a small but still a nonnegligible sample of variables, as we discuss in some detail in the following sections.

3. THE PULSATIONAL SCENARIO

Figure 2 shows the recent V, $V-I$ *HST* photometry of nonvariable stars (Brocato et al. 2003) with data added for the seven known Cepheids in Table 1. All of the six probable members are located at the hot tip of the red giant distribution, with the suggested nonmember being a bit hotter and brighter. It appears that in this cluster, evolution is just barely pushing He-burning stars over the red boundary for instability, without reaching the stable region again at larger effective temperatures.

According to the best fit of the theoretical isochrones given by Brocato et al. (2003; but see also Walker et al. 2001) and by adopting for the cluster a metallicity $Z = 0.007$, one derives an apparent distance modulus $\mu_V = V - M_V = 18.5$ mag and a reddening $E(V-I) = 0.075$ mag, predicting that the hot tip of the He-burning blue loop should be populated by stars with original masses 4.2 or 3.9 $M_\odot$, as alternatively predicted within canonical or overshooting evolutionary scenarios. Adopting Padua evolutionary tracks (Girardi et al. 2000) at $Z = 0.008$ (with overshooting), one would derive at the blue loop tip a mass of $\sim$4.0 $M_\odot$. Such predictions are only slightly dependent on uncertainties in the cluster metallicity and/or distance modulus, so that we adopt the mass range 3.5–5 $M_\odot$ as a safe interval covering the *original* mass of cluster He-burning giants.

Accordingly, we have extended to smaller stellar masses the pulsational investigations already presented in Bono et al. (1999, 2000) for $Z = 0.008$ and mass $M \geq 5.0$ $M_\odot$. The pulsational behavior of stellar structures with 3.5 and 4.0 $M_\odot$ has been studied by adopting, for each mass, the luminosity level predicted by canonical evolution for He-burning structures. For selected masses in the range 2.8–5.0 $M_\odot$, these computations have been implemented with models in which the luminosity has been increased in order to allow for overluminous structures as produced by an efficient core overshooting and/or mass loss. In this way, the computations cover a range of magnitudes $M_V = -1.6$ to -3.5 mag, which abundantly covers the luminosity of NGC 1866 Cepheids, even taking into account uncertainties in the cluster distance modulus.

As in previous investigations, we explored the pulsational stability of stellar structures assuming, for each given stellar mass, selected luminosity levels and testing—at each level—the stability in the fundamental mode with an effective temperature step of 100 K. Pulsating models are followed until reaching their limiting cycle, deriving in such a way the bolometric light curve. Adopting model atmospheres by Castelli et al. (1997), we eventually derive the predicted light curves in selected spectral bands and, after a time integration, both the intensity- and magnitude-averaged mean values. Table 3 gives periods and magnitudes for the set of models computed for the present investigation.

As a first result, over the whole explored range of mass and luminosity one finds for fundamental periods the relation

$$\log P_F = (10.854 \pm 0.002) + (0.847 \pm 0.002) \log L - (0.643 \pm 0.004) \log M - (3.300 \pm 0.015) \log T_e,$$

where mass and luminosity are in solar units. Note that this relation is only marginally different from the relation given by Bono et al. (2000) for models in the mass range 5–11 $M_\odot$.

Using the synthetic intensity-weighted mean magnitudes, one can translate this relation into the observational plane, producing the P-L-C relations

$$\log P_F = -(0.457 \pm 0.002) - (0.341 \pm 0.001)\langle M_V \rangle + (0.808 \pm 0.005)(\langle B \rangle - \langle V \rangle) - (0.648 \pm 0.007) \log M$$

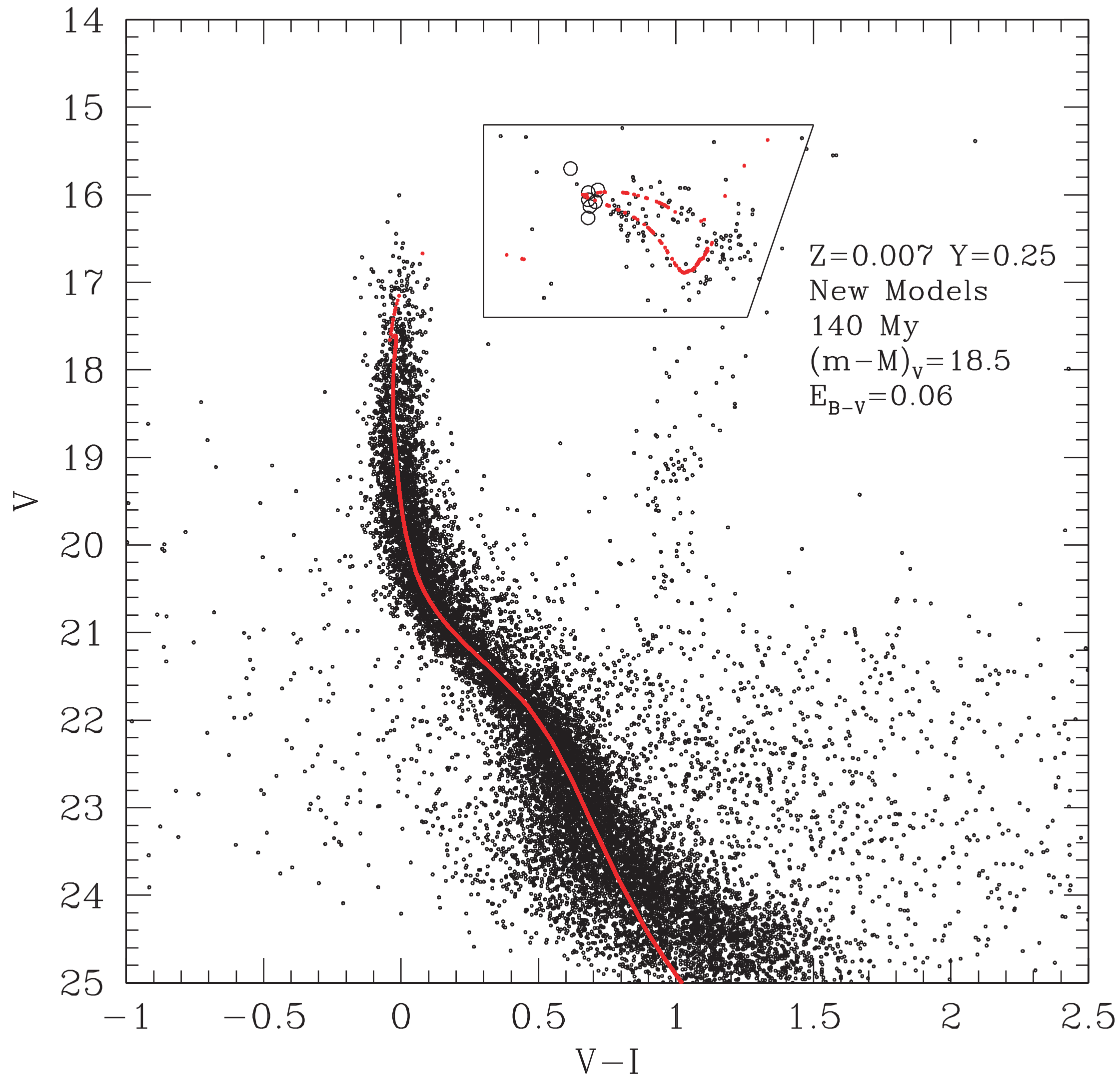

Fig. 2.—Location of the seven Cepheids (*circles*) in the V, $V-I$ color-magnitude diagram by Brocato et al. (2003).

and

$$\log P_F = -(0.657 \pm 0.003) - (0.345 \pm 0.001)\langle M_V \rangle + (0.983 \pm 0.006)(\langle V \rangle - \langle I \rangle) - (0.671 \pm 0.007) \log M.$$

As shown in Figure 3, one finds that fundamental periods strictly correlate not only with the structural parameters L and T_e, as already known, but also, and with similar accuracy, with the intensity-weighted magnitudes and colors of the pulsators. For the sake of the following discussion, it is worth the reminder that theoretical predictions concerning periods, such as the ones given above, appear to be the most reliable results of the theoretical approach, whose dependence on stellar parameters has been supported by several observations (see, e.g., the detailed analysis of RR Lyrae stars in the globular cluster M3 as presented by Marconi et al. 2003).

4. EVIDENCE FOR A MASS SPREAD

We are now in the position of comparing observed to predicted periods with the twofold target of testing theory but also of learning from theory something about the structures of cluster Cepheids. In this section we restrict the investigation to a discussion of period differences, a procedure that allows us to get rid of all assumptions about the cluster distance modulus or reddening.

As a first look at the data, Figure 4 shows the distribution of the six cluster member Cepheids in the $\langle V \rangle$– $\log P$ (period-luminosity) plane, giving a "color-free" picture of the pulsational behavior. One finds that the periods appear well correlated with the pulsator magnitudes. On a theoretical basis, the quite narrow P-L relation of NGC 1866 Cepheids is telling us that the effective temperature and mass of these variables are either constant or more or less tightly correlated with the star luminosity.

This period-luminosity relation can be usefully compared with the same relation for LMC Cepheids, making use of the Wesenheit reddening-free functions (see Madore 1982) to get rid of all reddening differences. Since we are dealing with rather cool objects, such as Cepheids, to this purpose we choose the $V-I$ color index as the most suitable one. Adopting $A_V/E(V-I) = 2.69$ (see Groenewegen & Salaris 2003; Gordon et al. 2003), $\langle W(VI) \rangle = \langle V \rangle - 2.69(\langle V \rangle - \langle I \rangle)$, and the pulsational models yield

$$\log P_F = -(0.633 \pm 0.004) - (0.350 \pm 0.002)\langle W(VI) \rangle - (0.682 \pm 0.011) \log M.$$

TABLE 3

MAGNITUDES AND COLORS FOR FUNDAMENTAL PULSATING MODELS

T_e	log P	M_V	$B-V$	$V-I$	$V-J$	$V-R$	$V-K$
			Canonical				
M = 3.50, log L = 2.570:							
6000	First overtone						
5950	0.1752	−1.640	0.529	0.642	1.032	0.314	1.392
5900	0.1875	−1.633	0.546	0.657	1.055	0.322	1.424
5800	0.2111	−1.621	0.578	0.684	1.097	0.336	1.480
5700	Stable						
M = 4.00, log L = 2.777:							
6000	First overtone						
5900	0.3221	−2.153	0.542	0.654	1.055	0.320	1.426
5800	0.3472	−2.139	0.577	0.684	1.102	0.335	1.489
5700	0.3716	−2.125	0.612	0.713	1.148	0.351	1.552
5600	Stable						
M = 5.00, log L = 3.070:							
6000	First overtone						
5900	0.5108	−2.900	0.530	0.645	1.046	0.314	1.418
5800	0.5356	−2.886	0.568	0.678	1.097	0.331	1.486
5700	0.5597	−2.870	0.607	0.709	1.146	0.348	1.553
5600	0.5853	−2.854	0.646	0.740	1.195	0.365	1.619
5500	0.6114	−2.837	0.688	0.771	1.245	0.382	1.685
5400	Stable						
			Overluminous				
M = 2.80, log L = 2.570:							
6300	First overtone						
6200	0.1786	−1.6430	0.4665	0.5848	0.9452	0.2835	1.2762
6100	0.2018	−1.6607	0.4774	0.5942	0.9597	0.2886	1.2953
6000	0.2257	−1.6478	0.5111	0.6256	1.0087	0.3051	1.3620
5900	0.2498	−1.6345	0.5444	0.6556	1.0556	0.3208	1.4255
5800	0.2741	−1.6213	0.5774	0.6839	1.1003	0.3357	1.4865
5700	0.2987	−1.6085	0.6112	0.7109	1.1428	0.3503	1.5436
5600	Stable						
M = 2.80, log L = 2.777:							
6300	First overtone						
6200	0.3526	−2.1963	0.4315	0.5537	0.9017	0.2664	1.2192
6100	0.3756	−2.1854	0.4676	0.5860	0.9508	0.2836	1.2851
6000	0.3993	−2.1730	0.5023	0.6177	0.9990	0.3004	1.3497
5900	0.4236	−2.1587	0.5386	0.6500	1.0490	0.3174	1.4170
5800	0.4489	−2.1431	0.5762	0.6823	1.1002	0.3344	1.4867
5700	0.4745	−2.1278	0.6123	0.7119	1.1473	0.3501	1.5509
5600	0.4995	−2.1114	0.6492	0.7416	1.1953	0.3658	1.6170
5500	0.5258	−2.0945	0.6867	0.7706	1.2425	0.3811	1.6820
5400	Stable						
M = 3.50, log L = 2.777:							
6000	First overtone						
5900	0.3593	−2.154	0.540	0.652	1.053	0.319	1.424
5800	0.3847	−2.140	0.576	0.683	1.102	0.335	1.490
5700	0.4096	−2.125	0.612	0.713	1.149	0.351	1.555
5600	0.4351	−2.110	0.648	0.741	1.194	0.366	1.615
5500	Stable						
M = 4.00, log L = 3.070:							
6000	First overtone						
5900	0.5696	−2.894	0.531	0.644	1.044	0.314	1.044
5800	0.5939	−2.878	0.570	0.677	1.096	0.331	1.482
5700	0.6194	−2.862	0.610	0.710	1.148	0.349	1.553
5600	0.6446	−2.844	0.650	0.742	1.199	0.366	1.622
5500	0.6711	−2.826	0.690	0.773	1.249	0.383	1.691
5400	0.6977	−2.807	0.730	0.804	1.299	0.399	1.759
5300	0.7239	−2.786	0.771	0.834	1.350	0.415	1.829
5200	Stable						

TABLE 3—*Continued*

T_e	log P	M_V	$B-V$	$V-I$	$V-J$	$V-R$	$V-K$
M = 5.00, log L = 3.300:							
6100	First overtone						
6000	0.6814	−3.452	0.539	0.637	1.026	0.312	1.378
5800	0.7300	−3.427	0.607	0.697	1.123	0.343	1.512
5600	0.7822	−3.410	0.672	0.753	1.214	0.372	1.638
5400	0.8341	−3.383	0.744	0.810	1.309	0.403	1.770
5300	0.8619	−3.367	0.781	0.839	1.357	0.418	1.837
5200	Stable						

Notes.—Effective temperatures, periods (days), visual absolute magnitudes, and color indexes for fundamental pulsating models with the given values of masses and luminosities, both in solar units. All magnitudes are intensity-averaged over the pulsation cycle.

However, using observed $\langle V\rangle-\langle I\rangle$ colors, we should reject as at least "suspected" two further objects, namely, HV 12202, whose color could be affected by the binarity, and V7, because of the evidence for a much-scattered light curve with respect to the other five selected Cepheids. One thus is left with only four objects with firm and reliable data: HV 12197, 12198, 121999, and 12203. The result of such a prudent selection can be appreciated in Figure 5, in which we report the Wesenheit P-L relation of the NGC 1866 variables as compared with the distribution of LMC fundamental Cepheids in the OGLE sample (Udalski et al. 1999). One finds that the four selected stars are arranged along a tight sequence, in full agreement with the general behavior of LMC Cepheids, whereas this is not the case for the two suspected objects, reinforcing their exclusion. The comparison in Figure 5 allows two main conclusions: the first one is that NGC 1866 Cepheids are undoubtedly pulsating in their fundamental mode, with the four bona fide pulsators in excellent agreement with the general behavior of LMC Cepheids, and the second one is that the distance of NGC 1866 appears quite close to the distance of other LMC Cepheids.

However, such an agreement raises a relevant question: does the agreement imply that NGC 1866 variables follow a mass-luminosity relation as expected at the basis of the LMC period-luminosity relation? The dashed lines plotted in Figure 5 show the predicted slope at constant mass, giving a first support to the existence of a mass-luminosity relation not only within the LMC sample, but also among NGC 1866 variables. Further light on such an issue can be obtained by making use of the additional constraint that cluster Cepheids are all at a common

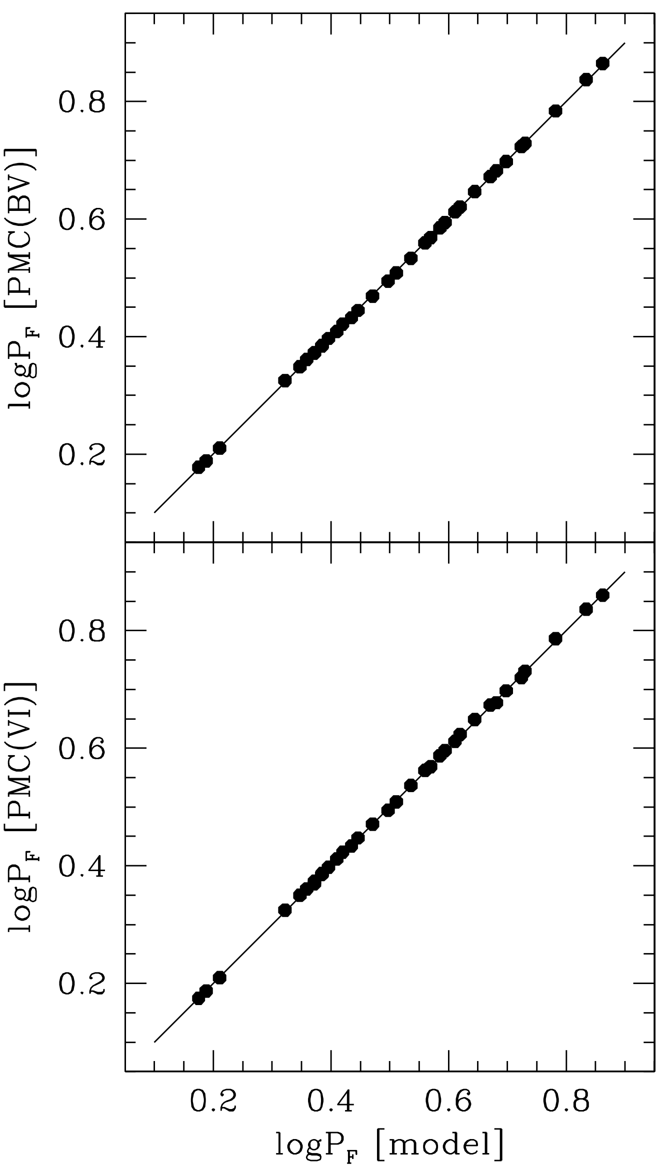

Fig. 3.—Fundamental periods of pulsational models compared with periods predicted by the P-L-C relations given in the text for intensity-averaged magnitudes in the *BV* (*top*) or *VI* bands (*bottom*).

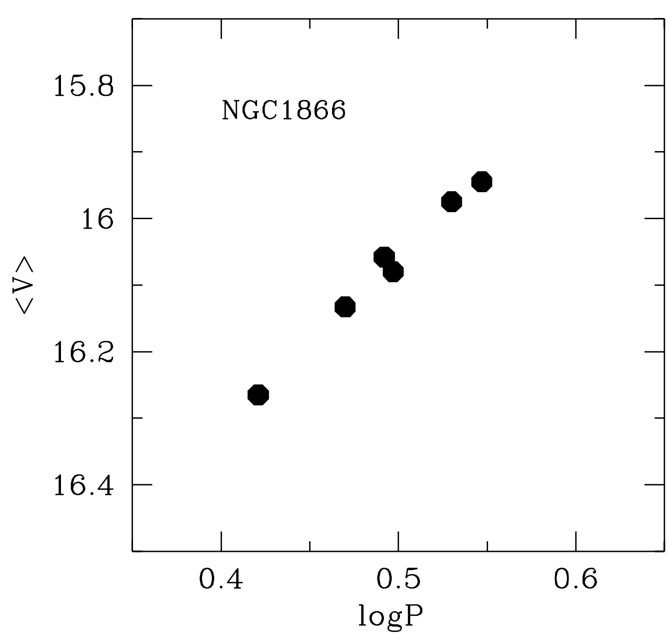

Fig. 4.—The $\langle V\rangle$– log P distribution for the six cluster Cepheids.

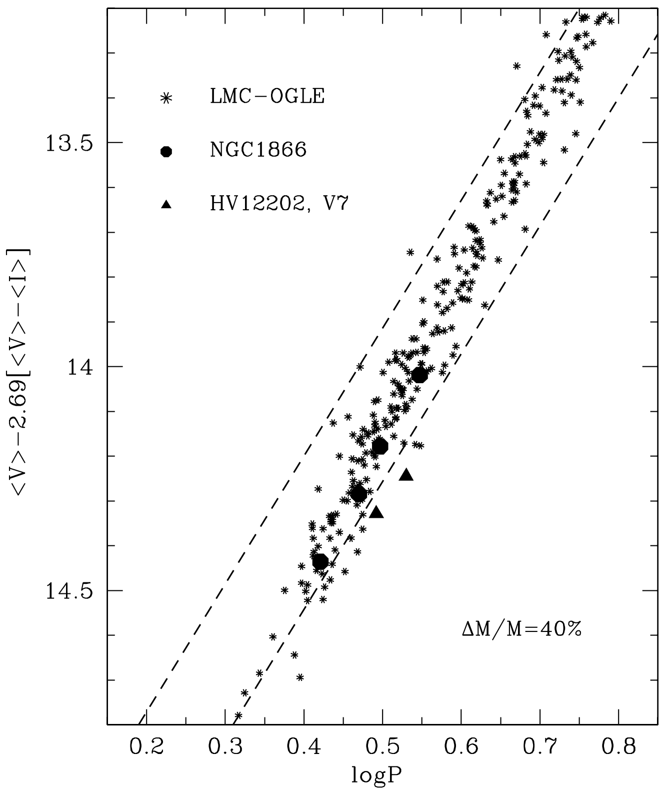

FIG. 5.—Reddening-free Wesenheit function vs. $\log P$ for the cluster Cepheids as compared with the OGLE LMC distribution. The large dots represent the selected sample of four well-observed cluster objects, whereas the triangles depict the two "suspected" ones. Dashed lines show the predicted slope at constant mass and are shifted according to a mass difference of 40%.

distance and have the same reddening. In this case, according to the procedure envisaged by Sandage (1981), one can get rid of the effects of star luminosity on periods by defining the so-called reduced period as the value corresponding to a common reference magnitude V_r. Indeed, looking at the above P-L-C relation and assuming $M_V = M_{V,r} + \Delta V$, one derives

$$\log P_F^* = \log P_F + 0.345\Delta V$$
$$= -0.657 - 0.345 M_{V,r} + 0.984(\langle V\rangle - \langle I\rangle) - 0.671 \log M.$$

Figure 6 shows the relation between reduced periods and $\langle V\rangle - \langle I\rangle$ colors, adopting the reference magnitude $V_r = 16$ mag. One finds that the four "high-quality" Cepheids are arranged along a rather well-defined $\log P_F^*$–$(\langle V\rangle - \langle I\rangle)$ relation but with a slope of 0.42 (*solid line*) instead of the value 0.98 predicted at constant mass (*dashed line*). On the basis of such evidence, one can only conclude that the increased $\langle V\rangle - \langle I\rangle$ color is progressively counteracted by a corresponding increase in the pulsator masses.

From the data in Figure 6, one easily derives that the observed distribution implies a difference in mass over the whole interval of $V-I$ colors as given by

$$\Delta \log M = 0.03,$$

which is thus on the order of 7%. However unexpected, such a conclusion can be hardly escaped, unless one invokes the occurrence of unbelievable macroscopic errors either in observed colors or in the theoretical periods. By relating this mass variation with the observed luminosity, one eventually

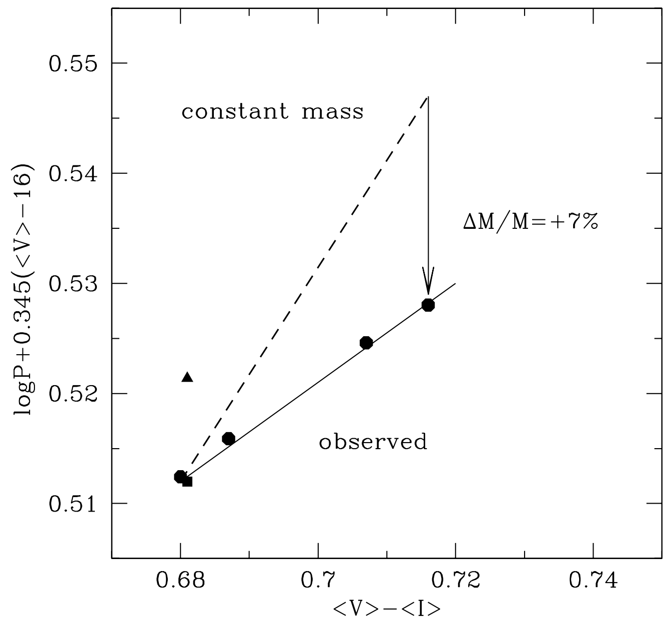

FIG. 6.—Run of the reduced periods $\log P^*$ against the observed $\langle V\rangle - \langle I\rangle$ colors. The solid line is the observed slope, while the dashed line shows the predicted slope for constant pulsator masses.

obtains that NGC 1866 Cepheids appear to follow a mass-luminosity relation as given by

$$\Delta \log M = -0.10 \Delta V.$$

The problem then arises as to where such a mass dispersion is coming from. According to a general approach, one can foresee two different mechanisms, namely, either a spread of the stellar ages (i.e., a spread of time in the star formation episode) or a stochastic mass loss in the Cepheid progenitors. In Table 4, we compare the empirical result with theoretical predictions concerning the evolutionary mass-luminosity relation for stars at the He-burning tip, as derived from data in the Pisa Evolutionary Library (Castellani et al. 2003), both for canonical stellar models and models with moderate overshooting ($\beta = 0.25$). The same table shows also the predicted mass-luminosity relation for stars at the hot tip of the He-burning loop in the case of different mass losses, as derived for a 4 $M_\odot$ stellar structure from the numerical experiments reported in Figure 2 in Castellani et al. (2003).

Inspection of data in Table 4 discloses that differential mass loss appears to be the preferred option for the origin of the "observed" mass dispersion, with only minor room for a dispersion of ages with core overshooting evolution.

5. PULSATIONAL AND EVOLUTIONARY MASSES

Let us address the question of the actual masses of cluster Cepheids, as derived from the observed periods and magnitudes.

TABLE 4

EMPIRICAL CORRELATION BETWEEN MASS AND VISUAL MAGNITUDE COMPARED WITH THEORETICAL PREDICTIONS

	$\Delta \log M/\Delta V$
Empirical	−0.101
Star formation time spread (canonical)	−0.058
Star formation time spread (overshooting)	−0.072
Mass loss	−0.107

TABLE 5

Pulsational M_{pul} and Evolutionary M_{ev} Masses of the Four Selected Cepheids

Star	M_{pul}	M_{ev}(Canonical)	M_{ev}(Overshooting)
$Z = 0.008$:			
HV 12197	2.83	4.11	4.01
HV 12198	2.88	4.19	4.10
HV 12199	2.69	4.01	3.89
HV 12203	2.72	4.08	3.98
$Z = 0.004$:			
HV 12197	2.86	4.06	3.81
HV 12198	2.91	4.17	3.94
HV 12199	2.72	3.91	3.64
HV 12203	2.75	4.01	3.76

Notes.—The two labeled values of metallicity adopt Brocato et al. (2003) cluster reddening and distance moduli. All masses are in solar units.

Adopting cluster reddening and a distance modulus from Brocato et al. (2003), as given by $\mu_V = 18.5$ mag and $E(V-I) = 0.075$ mag, the predicted P-L-C relation presented in the previous section allows us to derive for each Cepheid the mass values M_{pul} listed in Table 5 together with the corresponding values M_{ev} as predicted by the evolutionary mass-luminosity relations. As a result, one finds that the predicted pulsational masses are close to 2.8 $M_{\odot}$, smaller by about 30% with respect to evolutionary predictions ($\sim$4 $M_{\odot}$), irrespective of the occurrence of core overshooting.

Following the suggestion of our referee, we have explored the sensitivity of this result to the adopted cluster metallicity. One finds that the discrepancy between pulsational and evolutionary masses decreases when the metallicity is decreased, even though the pulsational scenario is little affected by reasonable variations in this parameter. The data reported in Table 5 show indeed that by decreasing the metallicity from $Z = 0.008$ down to $Z = 0.004$, the discrepancy is only marginally decreased. Thus we conclude that the cluster metallicity plays a minor role in such an issue.

One can approach the problem on much more general grounds by noting that for each given assumption about the cluster reddening and distance modulus, the P-L-C relation provides the "pulsational" mass of each observed Cepheid, whereas the "evolutionary" mass can be easily evaluated from the evolutionary mass-luminosity relation. On this basis, Figure 7 discloses the scenario of the predicted amount of mass loss (ΔM = evolutionary minus pulsational mass) as a function of both the cluster distance modulus and the interstellar extinction A_V, with this last parameter covering a range from 0 to 0.4 mag. i.e., $E(B-V) = 0.0$–0.12 mag. One finds that the occurrence of overshooting plays a minor role, slightly decreasing the mass-loss predictions, whereas the agreement between evolutionary and pulsational masses (i.e., no mass loss) would require rather improbable assumptions, as given by no reddening with a distance modulus $\mu_V \sim 18.6$ mag or adopting the usual reddening value $E(B-V) = 0.06$ ($A_V = 0.2$ mag) with a distance modulus $\mu_V \sim 18.85$.

In Figure 7, we report the predicted mean mass loss, adopting cluster reddening and a distance modulus from Brocato et al. (2003; *filled circle*) or following the recent suggestion by Groenewegen & Salaris (2003), for which $V - M_V = \mu_V \sim 19$ mag and $A_V \sim 0.39$ mag. As a whole, if one relies on the pulsational scenario, it appears difficult to escape the evidence for the occurrence of a substantial mass loss in NGC 1866 Cepheids, i.e., in stars with original mass around 4 $M_{\odot}$. However, the actual amount of mass loss sensitively depends on the adopted cluster reddening and distance modulus. According to our preferred choice, i.e., following Brocato et al. (2003), one would derive a mass loss larger by a factor of 2 with respect to the results by Beaulieu et al. (2001) concerning LMC Cepheids. As shown by the dotted lines in Figure 7, by increasing the reddening and distance modulus according to Groenewegen & Salaris (2003), the mass loss would decrease down to about 10%, matching in this way the amount of mass loss found by Bono et al. (2001) in their sample of Galactic Cepheids.

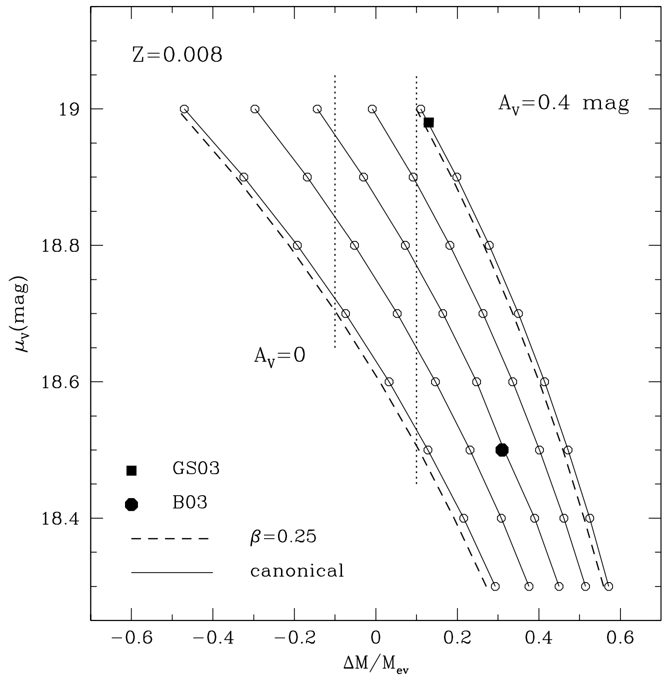

Fig. 7.—Amount of mass lost as a function of the distance modulus $\mu_V = V - M_V$ for selected assumptions about the cluster extinction. The two symbols show the predictions according to distance modulus and reddening values by Brocato et al. (2003) or by Groenewegen & Salaris (2003). The two dotted lines encompass the region in which $\Delta M/M \leq 10\%$.

6. FINAL REMARKS

In this paper we investigated the pulsational properties of Cepheids in the LMC globular cluster NGC 1866. Making use of the selected sample of four well-observed variables, we have derived pulsational evidence for Cepheids with difference in mass on the order of 7%, with a mass-luminosity relation that appears to be in reasonable agreement with the predictions inferred from the evolution of mass-losing structures. As for the amount of mass loss, it depends on the assumptions about the cluster reddening and distance modulus. However, under reasonable assumptions about these two parameters, it appears difficult to escape the evidence for a substantial amount of mass loss. Even with the extreme values $\mu_V = 19$ mag and $A_V = 0.4$ from Groenewegen & Salaris (2003), the original mass is decreased from $\sim$4.4 $M_{\odot}$ down to $\sim$3.9 $M_{\odot}$.

These conclusions are based only on the theoretical P-L-C relation, which is generally regarded as a quite robust result of pulsation theory, disregarding other pulsational predictions, such as the ones concerning the boundaries of the instability strip, which are affected by theoretical uncertainties connected, e.g., with the efficiency of superadiabatic surface convection (see, e.g., Marconi et al. 2003). As a result, we feel that we are facing rather robust observational evidence, worth reexamining and discussing in the light of new and reliable observational data for the much larger sample of Cepheids populating NGC 1866.

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