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LEAVITT VARIABLES: BRIGHT VARIABLE SUPERGIANTS AND THEIR IMPLICATIONS FOR THE DISTANCE SCALE

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ABSTRACT

We report observations of low-amplitude ($\Delta V \approx 0.2$ mag) light variations in two Large Magellanic Cloud supergiants. The stars S65-08 and S65-48 are both found to have periods of approximately 250 days. The optical data suggest that these stars are high-luminosity variables falling more than one magnitude brighter than any of the previously known Cepheids in the LMC. Confirmation of the Cepheid-like nature of these stars comes from their H-band magnitudes which place them accurately on a simple linear extrapolation of the narrower infrared Period-Luminosity (P-L) relation. It now appears, then, that the Cepheid P-L relation might extend up to $M_v \approx -8.5$ mag. As soon as these long-period (but presumably low-amplitude) variables are discovered in other external galaxies, reliable distances should be possible out to $(m - M) \approx 30$ mag.
Subject headings: galaxies: Magellanic Clouds — stars: Cepheids — stars: pulsation

I. INTRODUCTION

Out to what distance can we calibrate the extragalactic distance scale using classical Cepheids? The answer certainly depends on a technical limit set by modern detectors, but it also depends on the maximum intrinsic brightness imposed on the Cepheid phenomenon by nature. The technical limit depends, among other things, on the wavelength of the radiation considered, the aperture of the telescope, seeing, endurance of the observer, etc., and a conservative limit for precise observations might now be $B \approx 22$ mag. The limit imposed at the source of the phenomenon has been largely unexplored.

It is the commonly held belief that Cepheids span a period range extending from 1 to 50 or 60 days (cf. Cox 1980 or Strohmeier 1972), but this is a somewhat constrained view imposed by our galactic perspective. It has in fact been known since the discovery of the P-L relation for Cepheids by Leavitt (1907) that the relation extends to periods beyond 200 days. The calibration of the longest period—and hence brightest—Cepheids is critical to the determination of Cepheid-based distances at the limit.

Comprehensive reviews of the status of the extragalactic sample with the inevitable emphasis on the Magellanic Cloud Cepheids have been published by Feast (1984) and Madore (1983, 1985). It is emphasized by these reviewers and has been noted before (Sandage and Tammann 1968) that in the optical, the longest period Cepheids (log $P > 2.0$) are somewhat deviant from a simple linear P-L relation as extrapolated from shorter periods. Sandage and Tammann (1968) considered this nonlinearity (an apparent flattening in the P-L relation beyond 100 days) to be intrinsic to the calibration. On the other hand, Madore (1982) has argued that based on a reddening-free formulation of the P-L relation, the same data indicate no curvature, and that excess differential reddening of the four LMC Cepheids might offer a natural explanation. And finally, from a different perspective, van Genderen (1983) has suggested that a mix of Cepheids in their first and second crossings could produce the increased scatter. Obviously, small number statistics play an important role in such an evaluation, and from all points of view, a larger sample or complementary observations would be desirable. That is the purpose of this note.

II. THE NEW VARIABLES S65-08 AND S65-48

Recently, Grieve (1983) has completed a photoelectric program monitoring all the brightest Magellanic Cloud intermediate-type supergiants using the Las Campanas 61 cm reflector of the University of Toronto. The purpose was to discover the frequency and type of light variations to be found in these stars. Low-amplitude variations (<0.5 mag) could easily have been missed in the early photographic surveys, and extrapolation of the period-amplitude diagram (e.g., Schaltenbrand and Tammann 1970) would suggest that very long period Cepheids might be expected to have small amplitudes. The recent observations of Eggen (1983) confirm this suspicion.

The results of the Las Campanas survey have yet to be published, but one star, S65-08 (Sanduleak 1968, 1969) is of sufficient interest to warrant an independent discussion. The *BVRI* data on S65-08 are given in Table 1 and it is apparent that the star is variable with an amplitude of approximately 0.3 mag at V and 0.1 mag in $(B-V)$. The spectral type of S65-08 is G2 Ia according to Ardeberg *et al.* (1972). The radial velocity of $+311$ km s^{-1} found by Brunet *et al.* (1973) confirms the membership of S65-08 in the LMC. A periodogram analysis of the V data in Table 1 yields a best-fitting period of 250 days. Phased to this period, the data are presented in Figure 1.

A second low-amplitude supergiant variable reported here was first pointed out by Eggen (1983). This star, S65-48, was found to have a V amplitude of $\sim$0.3 mag. Grieve (1983) also observed this star and, in combining these data, a period of

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TABLE 1

OBSERVATIONS OF S65-08 (mag)

JD (−2,440,000)	V	$U-B$	$B-V$	$V-R$	$V-I$
3100.761	10.07	0.74	1.03	0.47	0.86
3463.719	9.96	0.65	0.92	0.40	0.80
3510.775	9.89	0.80	0.87	0.46	0.78
3832.767	10.05	0.85	0.98	0.45	0.84
3833.746	10.04	0.94	1.02	0.44	0.82
3844.648	10.02	0.92	1.00	0.43	0.82
3848.618	10.01	0.86	1.01	0.43	0.81
3893.557	9.94	0.89	0.97	0.42	0.77
3898.636	9.93	0.76	0.94	0.39	0.77
3901.715	9.92	0.74	0.91	0.40	0.77
3902.580	9.91	0.77	0.96	0.40	0.77
3906.581	9.92	0.72	0.91	0.40	0.80
4197.789	9.92	0.75	0.90	0.43	0.76
4218.790	9.94	0.80	0.91	0.38	0.78
4220.786	9.94	0.81	0.89	0.40	0.76
4226.576	9.97	0.74	0.92	0.41	0.78
4228.560	9.95	0.76	0.92	0.41	0.81
4254.610	10.04	0.54	0.93	0.43	0.84
4573.741	10.09	0.84	1.03	0.47	0.87
4574.690	10.08	0.93	1.01	0.44	0.88
4577.735	10.10	0.93	1.05	0.45	0.85
4579.724	10.04	0.88	1.06	0.44	0.82
4580.744	10.08	0.95	1.01	0.44	0.81
4581.622	10.06	0.90	1.02	0.46	0.85
4582.675	10.06	0.88	1.03	0.48	0.84
4583.678	10.04	...	1.07	0.44	0.84
4584.630	10.05	0.81	1.03	0.46	0.83
4585.668	10.05	0.89	1.03	0.44	0.85

TABLE 2

OBSERVATIONS OF S65-48 (mag)

JD (−2,440,000)	V	$U-B$	$B-V$	$V-R$	$V-I$
3104.794	9.64	0.35	0.64	0.31	0.58
3463.756	9.68	0.37	0.72	0.32	0.66
3464.647	9.68	0.30	0.70	0.34	0.63
3508.823	9.62	0.58	0.65	0.38	0.65
3510.781	9.67	0.59	0.68	0.38	0.65
3815.659	9.66	0.50	0.65	0.33	...
3815.837	9.67	0.50	0.67	0.32	...
3816.667	9.65	0.52	0.67	0.32	...
3816.822	9.67	0.49	0.67	0.30	...
3817.679	9.67	0.49	0.67	0.31	...
3818.670	9.64	0.49	0.65	0.31	...
3832.707	9.63	0.49	0.68	0.31	0.60
3833.758	9.63	0.53	0.68	0.31	0.61
3834.800	9.64	0.49	0.68	0.31	0.60
3848.709	9.62	0.50	0.68	0.30	0.59
3894.579	9.59	0.46	0.65	0.31	0.58
3895.825	9.56	0.46	0.64	0.30	0.60
3899.788	9.59	0.47	0.64	0.29	0.57
3902.660	9.57	0.44	0.65	0.30	0.57
3906.574	9.59	0.48	0.60	0.30	0.61
4218.798	9.69	0.55	0.66	0.23	0.62
4226.604	9.69	0.51	0.69	0.33	0.63
4227.796	9.66	0.52	0.70	0.33	0.65
4255.539	9.72	0.33	0.67	0.31	0.63
4255.590	9.74	0.39	0.65	0.32	0.62
4573.773	9.61	0.48	0.60	0.30	0.58
4579.734	9.59	0.38	0.62	0.29	0.56
4583.723	9.60	...	0.61	0.29	0.58
4585.760	9.59	0.43	0.61	0.29	0.53

roughly 250 days is found from a periodogram analysis. The new observations of S65-48 are presented in Table 2, and all observations phased to this period are displayed in Figure 2. Ardeberg *et al.* (1972) give the radial velocity of S65-48 as $+311$ km s^{-1}, confirming its membership in the LMC. They also quote a spectral type of F8 Ia, while Morgan and Keenan (1973) consider it to define the super-supergiant type F8 0. Hagen, Humphreys, and Stencel (1981) give a discussion of high-dispersion echelle spectrograms of this star and also tabulate single-phase optical and infrared photometry, which has been included in Table 3.

In Figure 3, we present the V P-L relation for LMC Cepheids observed photoelectrically as compiled by Madore (1985). Neither individual nor statistical corrections for foreground or external reddening have been applied to the data. Also plotted are the intensity-averaged V magnitudes of

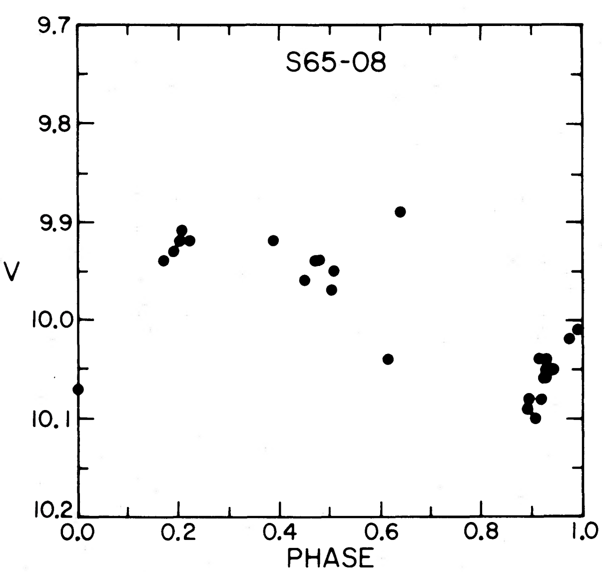

FIG. 1.—V observations for S65-08 listed in Table 1 phased to a period of 250 days.

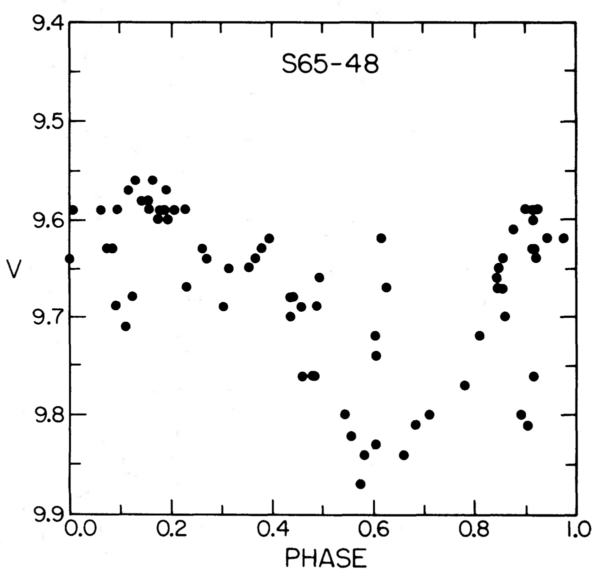

FIG. 2.—V observations for S65-48 listed in Table 2 phased to a period of 250 days.

TABLE 3

Average Optical and Infrared Data on the Brightest Cepheids (mag)

Star	⟨V⟩	⟨B⟩ − ⟨V⟩	⟨V⟩ − ⟨R⟩	⟨V⟩ − ⟨I⟩	J	H	K
S65-08[a]	10.003 (0.066)	0.977 (0.060)	0.431 (0.26)	0.814 (0.036)	8.71	8.46	8.35[b]
S65-48[c]	9.640 (0.045)	0.657 (0.030)	0.312 (0.027)	0.604 (0.033)	{8.71	8.48	8.37[d]
					{8.51	8.40	8.32[e]

[a] S65-08 = HDE 270920 = CPD-65 398 = C64.
[b] JD = 2,445,338.644 Las Campanas, Dupont 2.5 m.
[c] S65-48 = HDE 271182 = CPD-65 457 = G266 = A198 = R92.
[d] JD = 2,445,338.579 Las Campanas, Dupont 2.5 m.
[e] Hagen, Humphreys, and Stencel 1981.

S65-08 and S65-48 listed in Table 3. As can be seen, the *V P-L* relation does in fact continue linearly from the shorter periods to the region unambiguously defined by these two new variables. The curvature in the *P-L* relation suggested by the previous data sample is not confirmed for substantially longer periods.

As a further powerful check in establishing that the intrinsic *P-L* relation extends out to 250 days in a linear fashion, we obtained *JHK* observations for S65-08 and S65-48, using the Dupont 2.5 m at Las Campanas, Chile, in 1983 January. These data are also given in Table 3. Figure 4 shows the position of these stars in the infrared *H*-band relation. The data defining this relation for the previously cataloged Cepheids are intensity-mean averages obtained by the techniques outlined in Welch *et al.* (1984), using the data in McGonegal *et al.* (1982) and additional data to be published. It should be stressed that while the defining relation is for mean light, the optical amplitude of the new stars is so low that at *H* the maximum phase-induced excursion from mean light should be less than 0.06 mag (Welch *et al.* 1984), consistent with the two independent observations of S65-08 given in Table 3. As can be seen in Figure 4, the new Cepheids again fall precisely where they would be expected to be, based on a simple linear extrapolation of the *H P-L* relation.

III. IMPLICATIONS AND DISCUSSION

Sandage (1984) has suggested that the flattening in his calibration of the apparent blue *P-L* relation can be put to good practical use, in the sense that only approximate periods are needed at the long-period end in order to obtain reasonable distances. Inspection of his Figure 1, or equivalenly, Figure 5 in Sandage and Tammann (1968), reveals that in practice this apparent flattening could be used to give distance moduli good to ±0.5 mag (full range) for periods in the interval 60 to 160 days (i.e., log $P = 2.0 \pm 0.2$).

However, a strictly linear *P-L* relation has a twofold advantage. First, the scatter in the infrared *P-L* relation is so small that periods need not be determined with great accuracy *anywhere* along the relation. For instance, for a Cepheid whose true period is 100 days, any determination between 80 and 125

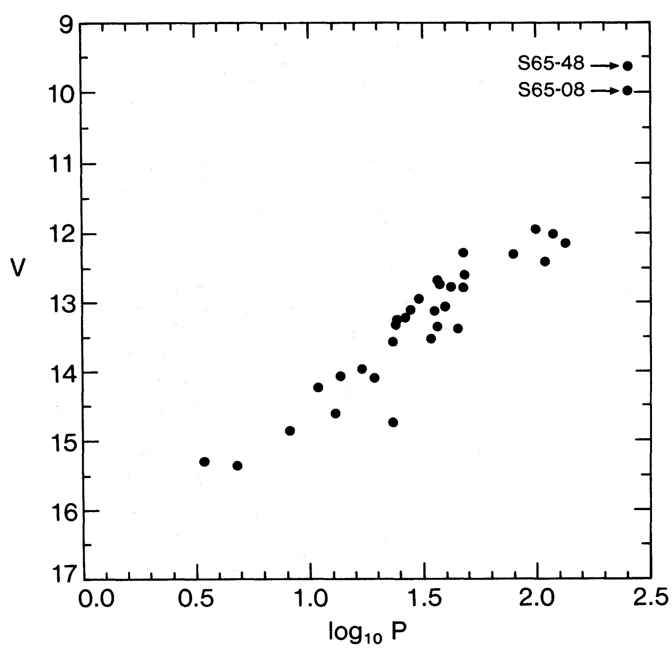

Fig. 3

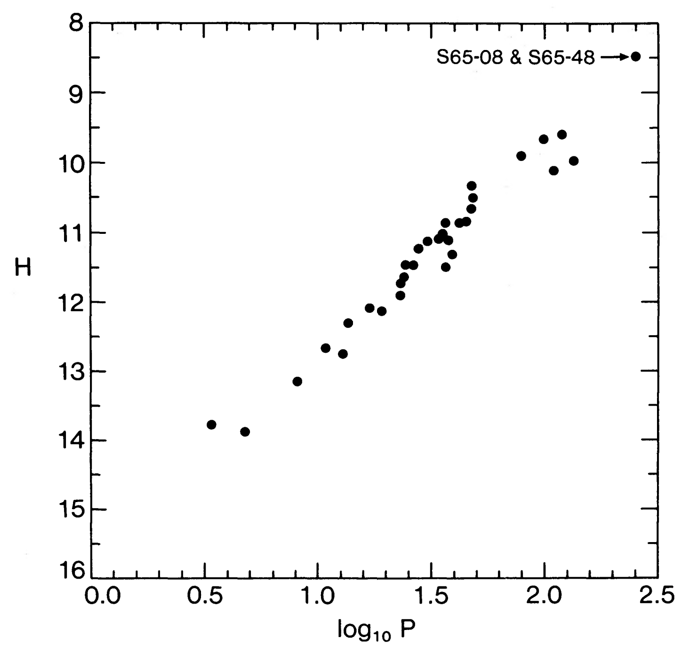

Fig. 4

Fig. 3.—The *P-L* relation for 33 Cepheids from Madore (1985). This subset of LMC Cepheids has been observed in both *V* and *H*.
Fig. 4.—The ⟨*H*⟩ *P-L* relation for 33 LMC Cepheids

days will also suffice to give an H-band distance modulus good to ± 0.5 mag (full range). Second, and perhaps more important, a linear P-L relation greatly extends the potential of Cepheids as distance indicators. At least an extra magnitude in distance modulus now becomes accessible to calibration by traditional methods.

The relatively low amplitudes of these particular Cepheids at very high luminosities and very long periods is a mixed blessing. The discovery of more such objects will require precision optical-wavelength photometry at faint magnitudes over long time intervals. Nonetheless, these stars will be detected a full magnitude brighter than their larger amplitude, shorter period counterparts. Once discovered in the optical, a *single* measurement in the near-infrared or even in the I band will yield a magnitude that, for all practical purposes, *is* the average intensity.

When Henrietta Leavitt (1907) plotted the periods and magnitudes of the variable stars that she had been studying in the Magellanic Clouds, "she realized that her discovery could be used as an indicator of intrinsic brightness, but was prevented from pursuing the subject any further" (Berendzen, Hart, and Seeley 1976). Not only did she discover a period-luminosity relation, but she discovered the longest period members of that class—none of which were known locally. Others soon identified Leavitt's Harvard variables with Galactic Cepheids and even the relation that she found does not now bear her name. Some 75 years later, as a tribute to the true discoverer of objects that have played and will continue to play a key role in the extragalactic distance scale, these variables found beyond $\log P \approx 1.8$ are now known as Leavitt variables (Grieve, Madore and Welch 1984).

Whether these stars should be thought of as Cepheids or pseudo-Cepheids (Eggen 1983) is probably academic. Aside from the fact that the latter term has already been used for a distinctly different class of objects (Lindblad 1922), we feel that there is a practical question to be asked: Independent of any label, do these stars show *sufficient* stability in period and magnitude for use as distance indicators, and do they smoothly merge with a preexisting data set? On both accounts we feel that they do, and therefore, in a purely practical vein, we plan to further explore the use of these objects as distance indicators for galaxies outside the Local Group.

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