Cepheids in Magellanic Cloud Clusters

D.L. Welch[1], M. Mateo[2], E.W. Olszewski[3]

[1]*McMaster University, Hamilton, Ontario, Canada* [2]*Observatories of the Carnegie Institution of Washington, Pasadena, CA* [3]*Steward Observatory, University of Arizona, Tucson, AZ*

Abstract

The Magellanic Clouds remain an ideal place to study the properties of Cepheid variables. In this paper, we review historical and current work on Cepheids in LMC and SMC clusters, present new results for NGC 1866 and NGC 2164, and describe a new technique for automated selection of Cepheid variables using two-color photometry. We also emphasize the numerous advantages of high-precision radial velocities in the study of Magellanic Cloud variables.

1. Introduction and Historical Review

It has been over forty years since Thackeray (1951) first called attention to the Cepheid variables associated with the LMC cluster NGC 1866. Yet it has only been possible to study these stars with sensitive panoramic linear detectors in the last decade. In this paper, we will review the work to date and report new results for the young cluster NGC 2164. Furthermore, we highlight how current software developments are likely to influence work in the coming years and provide a glimpse of a highly sensitive, yet automated means of detection variables from photometry lists.

2. Modern Surveys

The first intensive studies of Cepheid variables in a Magellanic Cloud cluster were published by Arp and Thackeray (1967) and Arp (1967) for NGC 1866. Not long thereafter, Robertson (1974) published photoelectrically calibrated photometry of clusters listed in Table 1. Some periods were mentioned for probable Cepheid variables, but no lightcurve data were listed. More recently, Walker (1987) published BVI lightcurves for seven NGC 1866 Cepheids. In Table 1, Cepheid variables are listed in boldface and red supergiant variables in slant font.

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Table 1
Variables Reported in Robertson (1974)

SMC	NGC 330	None
LMC	NGC 1818	*D3*
	NGC 1850	**D34, A86**
	NGC 1854	**A83**
	NGC 1866	No new variables
	NGC 2004	None
	NGC 2100	*B4, C32*
	NGC 2136	**HV 12230, 2868, 2870, B21**
	NGC 2157	None
	NGC 2164	None
	NGC 2214	**B1**

3. Current Status

To date, we have obtained BVRI CCD photometry of young clusters in the LMC and SMC during three (or more) observing seasons using the 1.0m Swope reflector at Las Campanas, Chile. (Some of the earliest epochs were obtained with the CTIO 0.9m or 4.0m telescopes). Typically, we have more than fifty BV pairs per cluster. These data were reduced using the photometric reduction routine DoPHOT (see Mateo and Schechter 1989) which is nearly ideal for the required reductions due to the minimal interaction required by the researcher. In all, more than 50 Gbytes of data have been reduced for this program.

In Table 2, we list the clusters which have been included in our survey or reported previously. This table contains only data for Cepheid variables. The columns N_C and N_F refer to the number of cluster and field Cepheids found, respectively. The distinction between these categories is not extremely well-defined — a case in point being the 10.8-day Cepheid found near NGC 2156. In all, some 60–70 Cepheids have been found in or near clusters. Note that this is a significant fraction of all Magellanic Cloud Cepheids with CCD or photoelectric photometry, recently estimated to be about 141 for the LMC and 186 for the SMC by Caldwell and Laney (1991). A '?' indicates that the data is reduced but that a careful search for variables has not yet been undertaken.

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Table 2
Magellanic Cloud Cluster Cepheid Statistics

Object	Cluster	N_C	N_F	Comments
SMC	NGC 330	0	1	Balona 1992
	NGC 376	?	$\geq$4	
LMC	NGC 1711	?	?	
	NGC 1755	2	0	
	NGC 1774	?	?	
	NGC 1818	0	0	
	NGC 1850	$\geq$1	?	
	NGC 1854	1	0	
	NGC 1866	21	1	Welch *et al.* 1991
	NGC 2004	0	0	Balona 1992
	NGC 2010	4	1	
	NGC 2025	0	1	
	NGC 2031	14	0	Olszewski, Mateo and Madore 1991
	NGC 2041	0	0	
	NGC 2100	0	0	Balona 1992
	NGC 2134	2	0	
	NGC 2136	6	0	Olszewski, Mateo and Madore 1991
	NGC 2156	1	0	
	NGC 2157	3	0	Mateo, Olszewski, and Madore 1990
	NGC 2164	1	1	Welch *et al.* 1993
	NGC 2214	1	0	

4. New Results for NGC 1866

Photometric precision in Magellanic Cloud cluster work is limited by two factors: starlist differences from night-to-night and estimation of the underlying sky. A new routine written by Peter Stetson called ALLFRAME has recently been tested on NGC 1866 frames and promises to significantly improve our ability to work under the very crowded conditions in the cores of young Magellanic Cloud clusters. It produces photometry based on a single, optimized starlist and estimates sky 'under' the image of the star (rather than in an annulus around the star). In this test, 29 B and 27 V frames were reduced together. These frames were a subset of the frames used by Welch *et al.* (1991) which were selected for being centered on the cluster and

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representing many different observing nights.

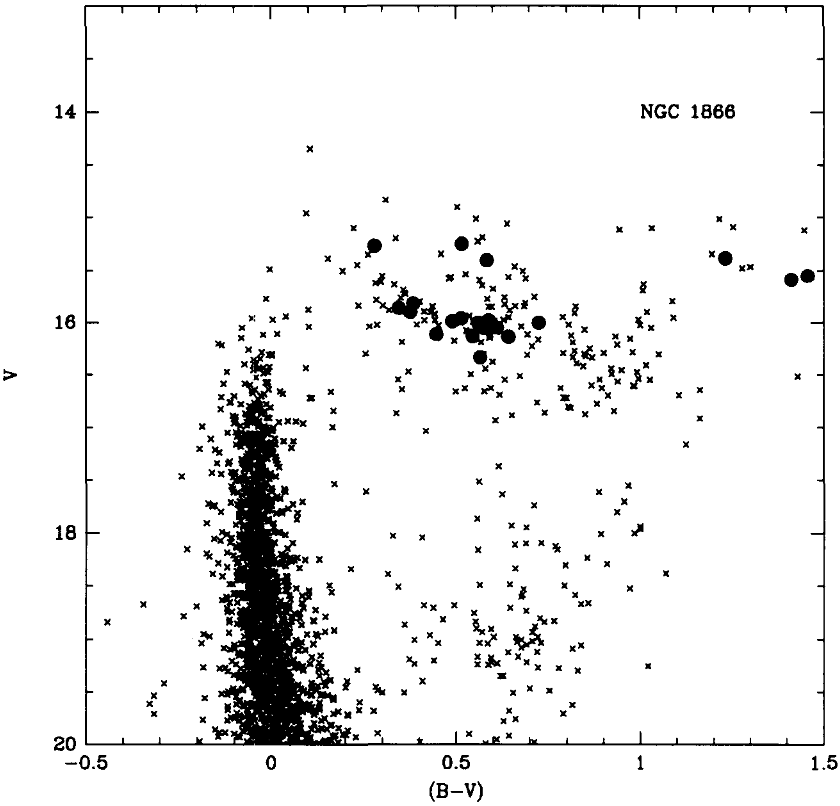

Figure 1 The color-magnitude diagram for NGC 1866 from 29 B and 27 V frames, using Peter Stetson's ALLFRAME. The filled circles are variable stars.

Our results can be summarized as follows:

- Periods for *all* reported Cepheids.
- Two additional low-amplitude Cepheids.
- One erratum: We 1 = V 7.
- Large number of apparently stable stars in the CIS.

A color-magnitude diagram for this field is shown in Figure 1, with variables indicated. B and V lightcurves for one of the newly discovered low-amplitude Cepheids are shown in

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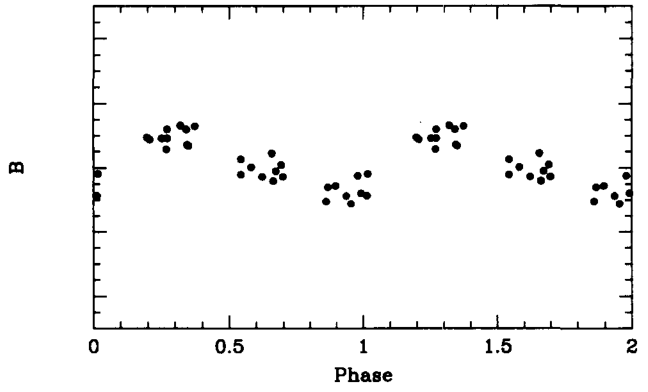
Figure 2. These results will be reported in more detail by Welch and Stetson (1993).



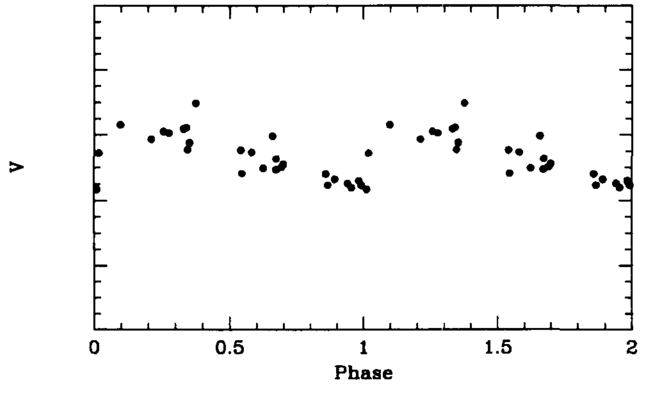


Figure 2 A previously unknown Cepheid in the central regions of NGC 1866, discovered with Peter Stetson's ALLFRAME. This variable is the bright, blue variable in Figure 1. The lightcurve is almost certainly being diluted by the light of an upper main sequence star. Major tick marks on the magnitude axis are separated by 0.2 mag.

5. Radial Velocities

In the last few years it has become possible to obtain high-dispersion spectra of Magellanic Cloud Cepheids from which, using cross-correlation techniques, radial velocities with errors of order 1 km s^{-1} can be extracted. Such velocity precision can be obtained for Cepheids of all periods. Among the uses for high-precision radial velocities are:

- Membership — the internal velocity dispersion of most young Magellanic Cloud clusters is $\leq$1 km s^{-1}, whereas the line-of-sight velocity dispersion of the massive disk population is about 5 km s^{-1}.
- Binarity — Several Cepheids are already known to be single-lined spectroscopic binaries.
- Period Determination — When crowded by main-sequence stars, the cross-correlation

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peak is only minimally affected by photon noise. Hence there may be significantly greater dynamic range in the radial velocity curve than the lightcurve.

- Baade-Wesselink Analyses — Providing that light and color curves of sufficient quality are available, fundamental properties of Magellanic Cloud Cepheids can be directly compared with their Milky Way counterparts.
- Mode Identification — The radial velocity curve can be studied to extract mode information in the same way as the lightcurve. Under crowded conditions, the radial velocity curves are less effected.

A velocity curve for the 7.7156-day variable NGC 2157-2 is shown in Figure 3.

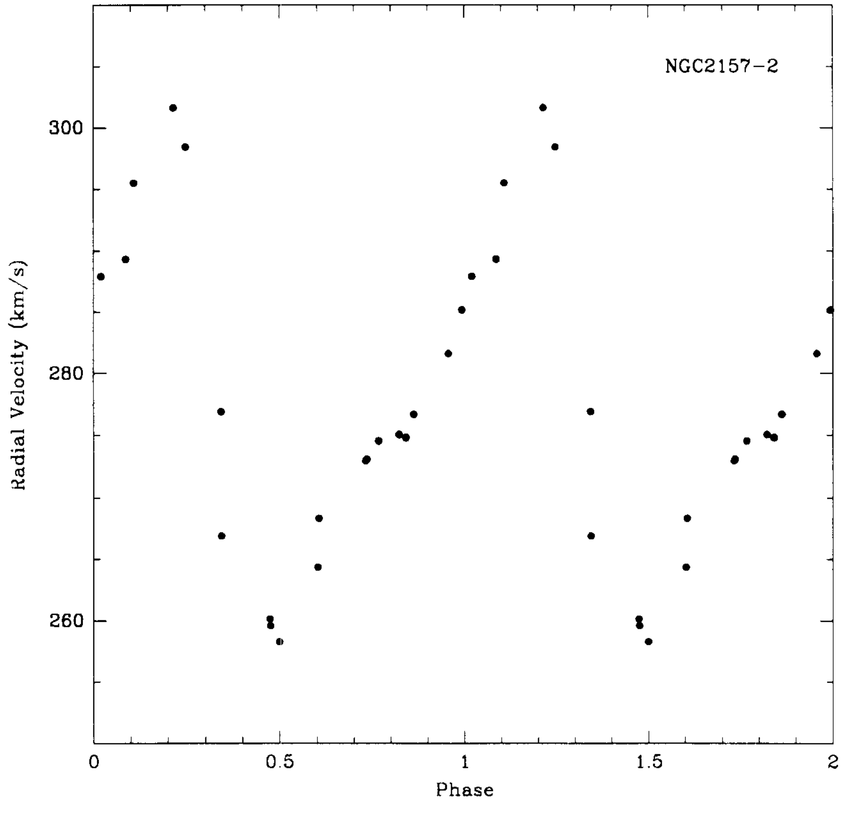

Figure 3 The radial velocity curve for NGC 2157-2, obtained using the 2D-Frutti plus echelle spectrograph on the 2.5m Dupont reflector at Las Campanas, Chile.

4. New Results for NGC 2164

We have recently completed a survey of the young cluster NGC 2164. The turnoff mass for this cluster has been estimated to be 7.7 $M_\odot$ by Elson, Fall, and Freeman (1989), so we expect the Cepheids to have longer fundamental periods than those in NGC 1866 where the turnoff mass is closer to 5 $M_\odot$.

Our survey made use of 64 B and V frames taken over the 1989, 1990, and 1991 observing seasons. Our results can be summarized as follows:

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- A cluster member Cepheid — B11 in Robertson (1974) — which is a first overtone pulsator with $P_1 = 3.772$ days, confirmed to be a member with radial velocities.
- A new field first overtone pulsator with a period of 3.4262 days.
- Full phase coverage of the known 10.6878 day Cepheid HV 12078 which is sufficiently close to NGC 2156 that it may be a member.
- A measurement of the Fourier phase $\phi_{21} = 3.1$ radians for B11 which suggests that it is a so-called long-period s-Cepheid and confirms the assertion of Antonello, Poretti, and Reduzzi (1990) that such a distinct class of overtone pulsators exists.

A complete description of this work is contained in Welch *et al.* (1993).

5. Search Algorithms for Pulsating Stars

Search techniques for variables stars have evolved little with the years. The traditional technique of 'blinking' is still widely used with CCD frames. Other well-known algorithms are: 1) 'scatter' searches, where every star showing an unusual degree of photometric scatter is examined, and 2) 'brute force' searches, where every star of appropriate magnitude and color is examined. In an era of large detector format, large surveys, and short proprietary periods, it would be especially useful if a sensitive and selective technique for detecting pulsating variables from photometry lists were available.

One such technique has been identified which we call 'surface brightness change'. Simply put, the magnitude and color change of a star are correlated if the variation in flux is primarily the result of a change in surface brightness. This is not true of random photometric error. The most trivial demonstration of this technique involves combining two-color photometry from two epochs and examining the pattern of residuals. In Figure 4, we plot the V and (B–V) residuals for two sets of frames containing the SMC cluster NGC 376. Plotted in this way, random photometric errors result in an elliptical error distribution (since the V photometry appears on both axes). However, the objects which have changed their surface brightness scatter in a direction which is essentially uncontaminated by random errors. In this simple two-epoch comparison, probable Cepheid variables can be selected with changes in V mag as small as 0.10–0.15 mag. This compares to the 0.6–0.8 mag variation typically required for detection by blinking. Surface brightness change detection can be simply extended to an arbitrary number of epochs and the sensitivity increases correspondingly.

A full description of the surface brightness change algorithm (plus applications) will appear in Welch and Stetson (1993).

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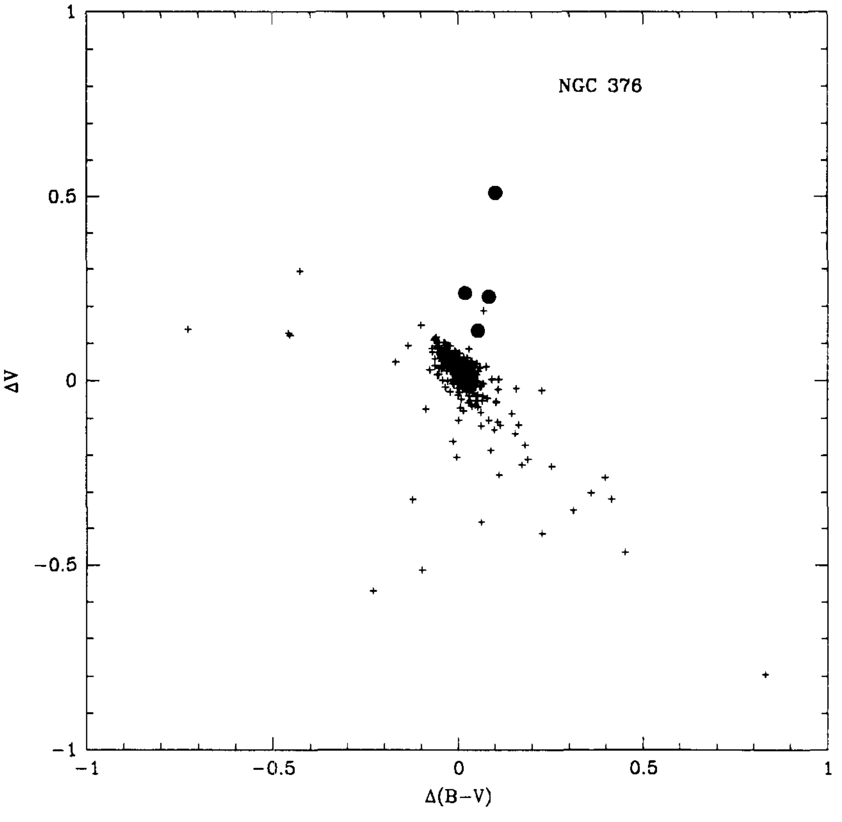

Figure 4 The magnitude and color residuals for the SMC cluster field taken on two consecutive nights. The five known Cepheids are indicated as filled circles (one of which appears in the thick of the zero-residual clump). The true variables are cleanly separated from random photometric scatter.

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P. Moshalik: Do you have Fourier coefficients for 1H Cepheids, and how well do they fit the s-Cepheid progression of Antonello? Are there any discrepant 1H Cepheids?

D. Welch: I have Fourier coefficients for the 1H Cepheids in both NGC 1866 and NGC 2164. Their ϕ_{21} values lie on the s-Cepheid progression. We should have coefficients for the other cluster 1H Cepheids shortly.

D. Fernie: If Polaris (amplitude 0.02 or 0.03 mag) were in NGC 1866, would you have detected it as a Cepheid? What is the limiting amplitude of detectability?

D. Welch: There are really two aspects to this question which need to be addressed separately. First, the amount of noise introduced into the photometry of a given star will depend both on the mean seeing of the data set and the position of the star in the cluster. In the innermost regions of NGC 1866, Polaris would not be detected with our data. Second, in uncrowded conditions, Polaris could almost certainly be detected to be variable using the surface brightness change technique, but a large (prohibitive?) number of epochs might be required to establish the period.

J. Nemec: What are the SWB classes or ages of the clusters in your sample?

D. Welch: The SWB classes are I–III, although the best hunting is in cluster types II and III where a combination of richness and evolutionary timescale produces the largest number of stars in the Cepheid Instability Strip.

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