Fundamental Mode and First Overtone Mode Cepheids in the Small Magellanic Cloud

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Abstract

We report results of a new photographic survey of variable stars in a 1 x 1.3 degree region near the Northeast Arm of the Small Magellanic Cloud. We have discovered 133 new variable stars in this field and have determined periods and B lightcurves for 78 new and 72 previously known variables. At periods shorter than about 3 days, the Cepheid period-luminosity relation splits into two sequences. The brighter sequence is believed to be populated by stars pulsating in the first overtone radial mode, whereas the fainter sequence is populated by fundamental mode pulsators. The peak in the Cepheid period-frequency distribution occurs near a period of 1.8 days. The surface density of RR Lyrae stars in this field is comparable to that in an outlying SMC field near NGC 121.

1. Introduction

In the eight decades since Henrietta Leavitt (Pickering 1912) discovered that Cepheid variable stars in the Small Magellanic Cloud obey a period-luminosity relation, there have been numerous studies of Magellanic Cloud Cepheids. Most of these studies, however, have concentrated upon the brighter Cepheids, leaving the fainter Cepheids and RR Lyrae stars rather neglected. We have carried out a new photographic survey of variable stars in the SMC designed in part to remedy this neglect.

Our survey is based upon 29 B-plates obtained between 2 July and 29 September 1970 with the 1.5-m telescope at CTIO. These plates cover a 1 x 1.3 degree region and have a limiting magnitude near B = 21. Centered at 1975 coordinates $\alpha = 1^h02^m$ δ=-71^{o}30', this photographic field is located near the Northeast Arm of the SMC and includes the cluster NGC 361 (Fig. 1). For brevity, we shall refer to this region as the NGC 361 field.

This investigation is a companion study to that reported by Graham (1975), who used similar plate material to study variable stars in an outlying field near the old SMC cluster NGC 121. Graham found many RR Lyrae stars but few Cepheids in

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the field around NGC 121.

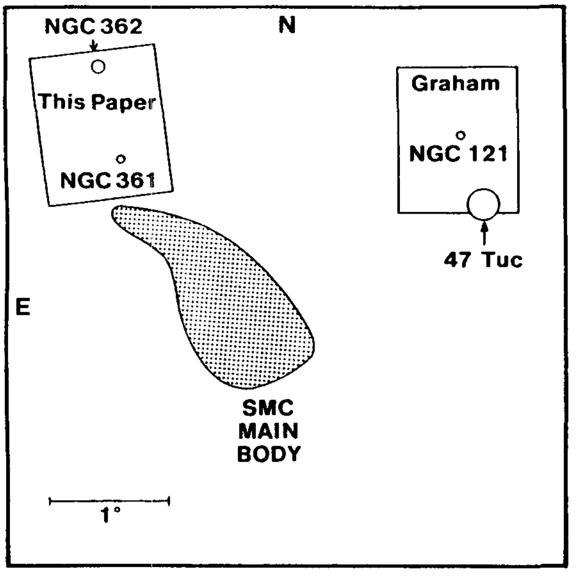

Figure 1. Diagram of the Small Magellanic Cloud, showing the locations of the outlying field studied by Graham (1975) and the NGC 361 field.

2. Variable Stars in the NGC 361 Field

By visually blinking 8 plate pairs, and by intercomparing scans of an additional plate pair obtained with the Automatic Plate Scanner at the University of Minnesota, we identified 276 candidate variables in the NGC 361 field. 209 of these were later confirmed as definitely or probably variable. 133 of these were new variable stars.

Candidate variable stars were scanned with the PDS machine at the Dominion Astrophysical Observatory. Standard stars selected from those observed by Harris (1982) and Da Costa & Mould (1986) were also scanned and used to calibrate the photographic photometry. Periods and lightcurves were determined for 78 new and 72 previously known variables.

In Figure 2 we plot <B> against the logarithm of the period in days for all of the variables for which we determined lightcurves. Four groups of variables are visible in this diagram. Near 20th magnitude and having periods shorter than one day are the field RR Lyrae stars which belong to the SMC. A second group of variables with RR Lyrae-like periods extends nearly vertically from <B> =15.5 to 18. The brighter of these are likely foreground RR Lyrae stars in the galactic halo, though the status of the fainter members of this group is more ambiguous. Finally, there are the Classical Cepheids of the SMC which, at periods shorter than about 3 days, seem to divide into two distinct sequences of period versus luminosity.

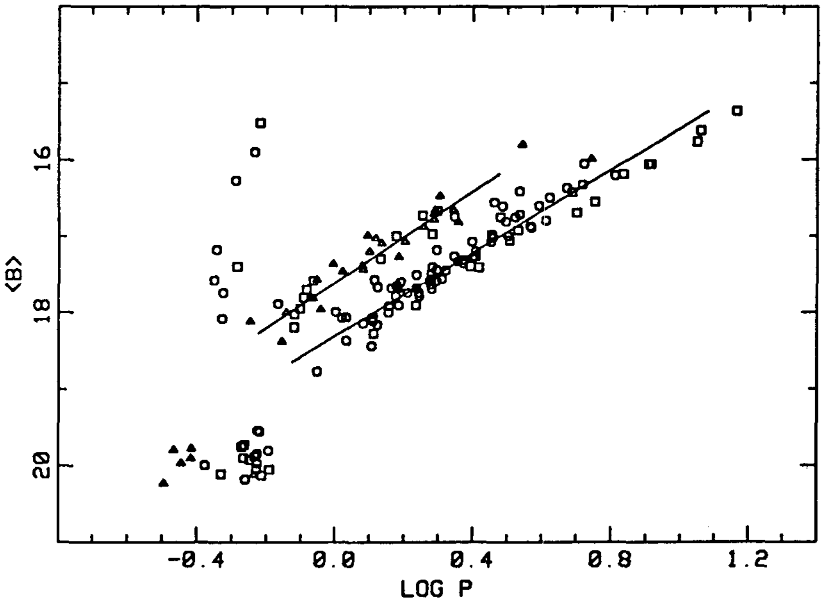

Figure 2. Period-apparent magnitude relation for variable stars in the NGC 361 field. Symbols are explained in the text.

Cepheids in the two P-L sequences are distinguished not only by differing luminosities at equal periods, but also by lightcurve shape. This difference is well illustrated in Figure 3, which depicts the lightcurves of two Cepheids of nearly equal period - one from the upper and one from the lower sequence. HV1871, the lower sequence variable, has a greater amplitude and more asymmetric lightcurve than HV11449, the upper sequence variable. In Figure 2 we have plotted as circles those Cepheids which have relatively large-amplitude, asymmetric lightcurves similar to those of ab-type RR Lyrae stars. Cepheids with smaller amplitude, more symmetric lightcurves similar to RR Lyrae stars of type c have been plotted as triangles. Stars with significant gaps in phase coverage or otherwise difficult to classify on this scheme have been plotted as squares.

By analogy with the RR Lyrae stars, we might suppose that Cepheids in the brighter sequence are pulsating in the first overtone radial mode, while Cepheids in

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the fainter sequence pulsate in the fundamental mode. This would be consistent

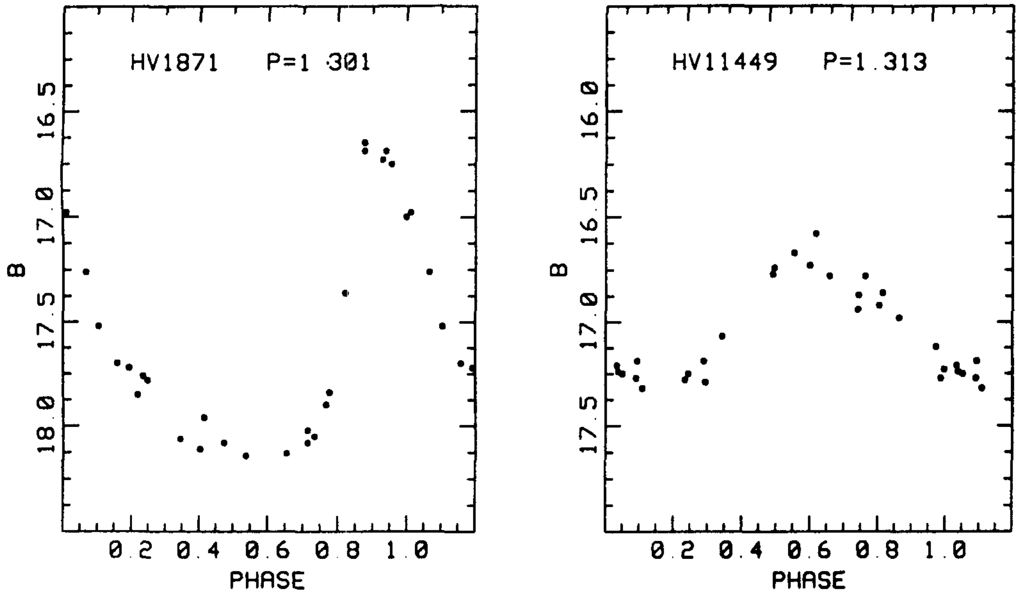

Figure 3. Lightcurves of the upper sequence Cepheid HV11449 and the lower sequence Cepheid HV1871. Both have periods near 1.3 days.

with the shift in period between the two sequences, approximately $P_1/P_0 = 0.72$. That some of the shortest period SMC Cepheids were first overtone pulsators has been suspected at least since the work of Arp (1960) and Payne-Gaposchkin & Gaposchkin (1966). That case now seems very strong.

3. Period-Luminosity Relations

Linear least squares fits to the two Cepheid sequences give the relations

$$< B >= 18.29(\pm 0.04) - 2.71(\pm 0.09) log P_0 \tag{1}$$

$$< B >= 17.61(\pm 0.04) - 2.98(\pm 0.17) log P_1 \tag{2}$$

which are shown in Figure 2. The standard deviations around relations (1) and (2) are about 0.18 mag. This relatively small scatter is indicative of small differential reddening and modest back-to-front depth among Cepheids in the NGC 361 field.

Previous work indicates that reddening is relatively small in the NGC 361 field (Da Costa & Mould 1986, Harris 1982). We assume E(B-V) = 0.06 ± 0.03. RR Lyrae stars in the SMC appear to be about 0.4 ± 0.1 mag fainter than those in the LMC (this paper, Graham 1975, 1977, Nemec & Hazen 1992, Walker 1991). If this difference can be entirely attributed to distance, and if we adopt an LMC distance modulus of 18.5, we can transform apparent to absolute magnitudes for the SMC variables. The observed P-L relations then become

$$< M_B >= -0.87(\pm 0.21) - 2.71(\pm 0.09) log P_0 \tag{3}$$

$$< M_B >= -1.55(\pm 0.21) - 2.98(\pm 0.17) log P_1 \tag{4}$$

Relations (3) and (4) remain, however, somewhat tentative.

Nemec et al. (1988) found that the so-called anomalous Cepheids in dwarf spheroidal galaxies fell along two distinct period-luminosity relations. They interpreted these as indicating the presence of both first overtone and fundamental mode pulsators among the anomalous Cepheids. The period-luminosity relations for these anomalous Cepheids (Nemec 1989) are not, however, identical to those found here for the SMC classical Cepheids. Because most stars in dwarf spheroidal systems are very old, it has been suggested that the anomalous Cepheids, with masses near 1.5 solar masses, are not evolved single stars, but are instead coalesced binaries (Renzini, Mengel, & Sweigart 1977). A range of ages, from old to young, is present in the SMC, so that no such hypothesis is necessary to explain the large majority of the short period Cepheids in the NGC 361 field.

4. Period-Frequency Distribution

The period-frequency distribution for variables which are believed to be

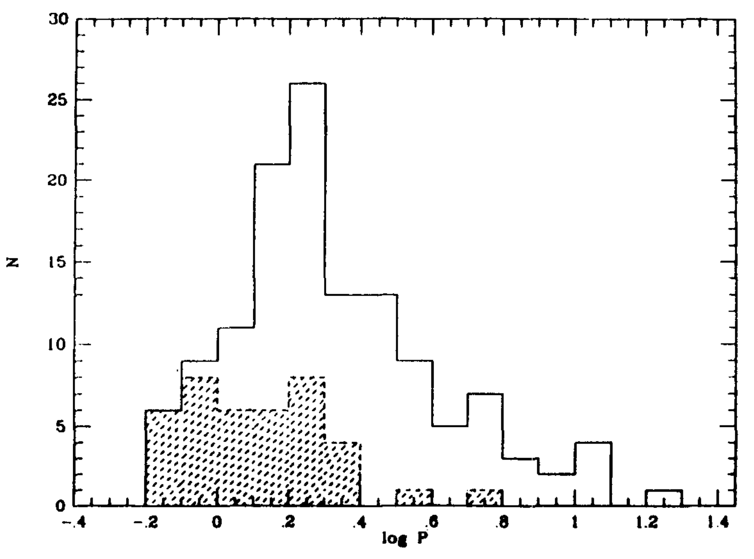

Figure 4. Period-frequency distribution for Cepheids in the NGC 361 field. The hatched area denotes Cepheids which are belived to pulsating in the first overtone mode

SMC Cepheids is shown in Figure 4. Incorporated into this figure are data for 12 additional Cepheids which fall within the NGC 361 field but which, for various reasons, were not measured by us. For these stars, the decision as to whether a Cepheid is a first overtone or fundamental mode pulsator is based upon the lightcurves in Payne-Gaposchkin & Gaposchkin (1966).

The peak in Figure 4 occurs near a period of 1.8 days. This is consistent with the studies of Dessy (1959) and Wesselink & Shuttlewoth (1965), which found similar peaks near a period of 1.5 days. It is, however, somewhat at odds with the extensive survey of Payne-Gaposchkin & Gaposchkin (1966). The Payne-Gaposchin & Gaposchkin survey did find a secondary peak in the SMC period-frequency distribution near 1.6 days, but also found a higher peak near 3 days. It seems quite possible that the 3 day peak is not real, but is instead a consequence of the limiting magnitude of the Harvard plate material used by Payne-Gaposchkin & Gaposchkin. With a limiting magnitude near B = 18, much of the Harvard plate material may not go deep enough to reveal the faintest SMC Cepheids, thus underrepresenting the frequency of short period Cepheids.

5. RR Lyrae Stars

We have identified 42 probable RR Lyrae stars of the SMC within the NGC 361 field, although we have been able to determine periods for only 22 of these. Of those with periods, 17 appear to be RRab variables, while only 5 are RRc stars. The period-amplitude diagram for these RR Lyrae stars is similar to that found by Graham for RR Lyraes in the more outlying NGC 121 field.

Our survey of RR Lyrae stars in the NGC 361 field is probably seriously incomplete. An approximate correction for this incompleteness indicates that the NGC 361 field actually contains perhaps 80-85 RR Lyrae stars. This number is comparable to that obtained by Graham (1975) for RR Lyraes in the more outlying NGC 121 field. Excluding RR Lyraes which are members of NGC 121 itself, and those stars with RR Lyrae-like periods which are probably short period Cepheids, Graham's results indicate that there are about 90-95 RR Lyraes in the NGC 121 field. We thus confirm Graham's (1975) conclusion that RR Lyrae stars are not strongly concentrated to the main body of the SMC.

Future Observations

This study leaves many questions unanswered: What are the colors of the short period Cepheids? Do the fundamental mode and first overtone mode Cepheids overlap in color at a given luminosity? What are the periods of the variables identified, but still without reliable lightcurves? In an attempt to answer some of these questions, Alistair Walker and H. Smith plan to obtain B and V CCD photometry of most of the variables in the NGC 361 field. This photometry will be obtained with a CCD on the Schmidt telescope at CTIO.

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References:

Arp, H., 1960, Astron. J, **65**, 404.

Da Costa, G.S. & Mould, J.R., 1986, ApJ **305**, 214.

Dessy, J.L., 1959, **71**, 435.

Graham, J.A., 1975, PASP, **87**, 641.

Graham, J.A., 1977, PASP **89**, 425.

Harris, W.E., 1982, Ap.J. Suppl. **50**, 573.

Hazen, M.L. & Nemec, J.M., 1992, Astron. J. **104**, 111.

Nemec, J.M., 1989, IAU Colloq. No. 111, *The Use of Pulsating Stars in Fundamental Problems of Astronomy*, ed. E.G. Schmidt, Cambridge University Press, Cambridge, p. 215.

Nemec, J.L., Wehlau, A., & Mendes de Oliveira, C. 1988, Astron. J. **96**, 528.

Payne-Gaposchkin, C. & Gaposchkin, S. 1966, Smith. Contr. Ap. **9**, 1.

Pickering, E.C., 1912, Harvard Coll. Obs. Circ. No. 173, 3.

Walker, A.R. 1991, IAU Symp. 148, *The Magellanic Clouds*, ed. R. Haynes and D. Milne, Kluwer, Dordrecht, p. 307.

Wesselink, A.J., & Shuttleworth, M., 1965, MNRAS **130**, 443.

Discussion

G. KOVACS: Did you observe any bump progression among the fundamental mode Cepheids? Because of the resonance, a comparison with the Galactic Cepheid bump progression would constrain the chemical composition and M-L relation substantially.

SMITH: There is indeed some evidence for a progression of lightcurve shape with period among the fundamental mode Cepheids. However, some of our lightcurves still have gaps, and we would like to obtain additional data before drawing conclusions from this. It is also worth remembering that the Payne-Gaposchkin & Gaposchkin (1966) survey contains excellent lightcurves for SMC Cepheids.

D. WELCH: The intrinsic width of your <B> P-L relation for fundamental mode stars is so small that the line-of-sight depth in this field must be very small, which would be in contradiction to the large bulge giant scatter seen in the northeast portion of the SMC by Hatzidimitriou and Hawkins (MNRAS **241**, 645).

SMITH: This contradiction might have several explanations. The fields examined for bulge giants, although in the northeast part of the SMC, are somewhat farther from the main body of the SMC than is the NGC 361 field. Moreover, the bulge giants may belong to an older population than most of the Cepheids we have observed. The issue will need further observations to resolve.

S. HUGHES: Will you be obtaining I-band CCD frames in order to estimate individual extinctions to the Cepheids?

SMITH: It would indeed be very interesting to have I-band photometry for the Cepheids. However, our first CCD observations will be limited to the B- and V-bands.

D. TURNER: Presumably there are also a few double-mode Cepheids in the survey field. Could these stars lie in your sample of objects for which no definitive period was found?

SMITH: That is very likely the case, given our relatively small number of observations.