ABSTRACT

We report the discovery of 45 beat Cepheids in the Large Magellanic Cloud (LMC) using the MACHO Project photometry database. The variables which are pulsating simultaneously in two radial modes are shown to break cleanly into two period-ratio groups, providing the first unambiguous evidence that the second overtone is indeed excited in real Cepheids. Thirty stars are beating in the fundamental and first overtone mode (F/1H, with a period ratio in the neighborhood of 0.72), and fifteen stars are beating in the first and second overtone (1H/2H, with a period ratio near 0.80). The F/1H period ratios are systematically higher than known Galactic beat Cepheids, indicating a metallicity dependence whose sense is in agreement with theory. Beat Cepheids in the LMC are found to select the 1H/2H mode for fundamental periods shorter than 1.25 days. We find the fraction of Cepheids excited in two modes to be about 20% for stars with fundamental periods shorter than 2.5 days. We fail to confirm any of the proposed beat Cepheid candidates common to our sample from the surveys of Andreasen (1987) and Andreasen & Petersen (1987). We also present finder charts and find several of the beat Cepheids to be in or near LMC clusters.

Key Words: Stars – Intrinsic Variables; Stars – Variable Stars; Stellar Systems – Magellanic Clouds

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1. Introduction and Motivation

Cepheids pulsating in more than one radial mode provide an excellent test of our understanding of the atmospheres of supergiant stars. Indeed, to match the observed period ratios for known beat Cepheids, models employing Cox & Tabor (1976) opacities by Petersen (1979) appeared to require masses between 1.0 and 3.0 $M_\odot$, far below the 5.0 to 7.0 $M_\odot$ predicted by evolution. This became known as the 'Cepheid mass discrepancy', which was first discussed in detail by Rodgers (1970) using the available data for the four known galactic 'beat Cepheids'. (A more complete review of the situation at that time is provided by Cox, 1980). More recently, Petersen (1990) has shown that the use of the Livermore OPAL opacities (published in Rogers & Iglesias, 1992) which are substantially more opaque in the critical driving region of a Cepheid atmosphere predicts masses consistent with evolution.

From an observational perspective, the situation is not ideal. When Balona (1985) wrote his review, only 11 galactic double-mode Cepheids were known. Since that time the star EW Sct has been found to be a beat Cepheid by Cuypers (1985) and confirmed by Figer *et al.* (1991). Two additional objects may be added to this list: CO Aur and AC And. The first was discovered by Mantegazza (1983) and subsequently characterized by Antonello & Mantegazza (1984) and Antonello, Mantegazza, & Poretti (1986) who claimed that it was a Cepheid beating in the first and second overtone modes. Balona (1985) reanalysed their data and disputed this conclusion, claiming that the peak identified with the second overtone is not distinct from the noise in the power spectrum. AC And has been identified by Fitch and Szeidl (1976) as pulsating simultaneously in the fundamental, first overtone, and second overtone modes. A third principal frequency was also claimed for TU Cas by Faulkner (1977), the recent history of the investigation of this variable being described by Matthews *et al.* (1992) who concluded that there is no second overtone present.

The difficulty of establishing the existence (or non-existence) of second overtone pulsation in Cepheid variables is the result of a number of circumstances. First, it is very

difficult, in practice, to acquire the long time-series needed to unambiguously identify power at the appropriate frequencies and their combinations. This problem is exacerbated by the short periods of many candidates which are frequently close to multiples of a day. Second, the tools to remove the undesirable effects of non-uniform sampling of the lightcurves have only recently become widely available. Third, candidates are not readily recognized in photographic variable star surveys (the primary source of variable star discoveries in the field) as a result of their apparent irregularity and intervals of low photometric amplitude. Fourth, the lack of convincing cases argues that only a small percent of beat Cepheids are pulsating in the second overtone and so a large survey would be required to provide a meaningful yield. (Only of order 750 galactic Cepheids are known). Last, even without the preceding difficulties, these stars are generally found alone and hence independent determinations of their reddenings and luminosities is not possible. (The sole exception is the star V367 Sct which lies in the cluster NGC 6649, see Barrell, 1980). The only surveys undertaken in the Large Magellanic Cloud (LMC) to date, those of Andreasen (1987) and Andreasen & Petersen (1987), were inconclusive.

What questions might profitably be answered by a such a survey? There are many. Is the second overtone excited? If so, what are the lightcurve characteristics of this pulsation and is it observationally distinct from fundamental and first overtone behavior? What are the actual ratios of periods between the fundamental, first overtone, and second overtone modes, preferably as a function of period. Are the ratios a function of metallicity? Do second overtone pulsators appear in specific regions of the Hertzsprung-Russell diagram? Have second overtone pulsators been mistaken for first overtone variables in the past?

To settle these questions, an ideal survey would study a system where all stars are at a common distance, differential reddening is low, and large numbers of observations on a common photometric system are available over a continuous time interval of many hundreds of cycles. In this paper, we present the results of such a survey. In section 2, we describe how the observations were obtained. In section 3, we outline how our sample of

beat Cepheid candidates was chosen, In section 4, we analyse the sample and in section 5 we summarize our results, describe work in progress, and suggest future avenues of research.

2. Observations

The MACHO Project (Alcock *et al.* 1992) is an astronomical survey experiment designed to obtain multiepoch, two-color CCD photometry of millions of stars in the LMC (also, the galactic bulge and SMC). The principal goal of the project is to search for massive compact objects whose presence between the observer and a background source will result in an amplification of received flux due to gravitational lensing. The expected rate of detectable events is very low, requiring large numbers of background sources, in this case, LMC stars, to be measured over many years. The survey makes use of a dedicated 1.27m telescope at Mount Stromlo, Australia and because of its southerly latitude is able to obtain observations of the LMC year-round. The camera built specifically for this project (Stubbs *et al.* 1993) has a field-of-view of 0.5 square degrees which is achieved by imaging at prime focus. Observations are obtained in two bandpasses simultaneously, using a dichroic beamsplitter to direct the 'blue' (approximately 450-630 nm) and 'red' (630-760 nm) light onto 2×2 mosaics of 2048×2048 Loral CCD chips. (Hereafter, these bandpasses will be referred to as V_{MACHO} and R_{MACHO}, respectively). Images are obtained and read out simultaneously. The 15 μm pixel size maps to 0.63 arcsec on the sky. The data were reduced using a profile-fitting photometry routine known as Sodophot, derived from DoPhot (Mateo & Schechter, 1989). This implementation employs a single starlist generated from frames obtained in good seeing.

The results reported in this survey comprise only a fraction of the planned data acquisition of the MACHO project. At present we have processed most of the first year's LMC data, consisting of some 5500 frames distributed over 22 fields; this sample contains a total of approximately 8 million stars. This data has been searched for variable stars and microlensing candidates and over 40,000 variables have been found, most newly discovered.

The great majority of these fall into four well-known classes: there are approximately 25000 very red semi-regular or irregular variables, 1500 Cepheids, 8000 RR Lyraes and 1200 eclipsing binaries (Cook, 1995). Typically the dataset for a given star covers a timespan of about 400 days and contains 150-320 photometric measurements (multiple observations are obtained on a given night whenever conditions allow). Two of our candidate beat Cepheids fall in the overlap region between two fields and hence have twice the above number of measurements. The output photometry contains flags indicating suspicion of errors due to crowding, seeing, array defects, and radiation events. Only data free from suspected errors was employed for this work, resulting in output photometry lists of length 100-320. Typical photometric uncertainties are in the range 1.5-2 percent.

3. Detection of Multimode Cepheids

Photometry produced by the MACHO Project is currently available in the form of amplification relative to the median brightness. No transformation to a standard system was applied prior to our inspection for beat Cepheids. A star was judged to be variable if it had at least 7 simultaneous red and blue measurements, with a large χ^2 fit compared to a constant brightness star in both red and blue, and a reasonable rank correlation between the red and blue lightcurves. A total of about 2900 variable stars were identified with median $R_{KC} < 18.7$ and $0.2 < (V - R) < 0.6$, where the KC subscript refers to the Kron-Cousins system. (The transformation to the standard system is only approximate and is being refined). The V_{MACHO} and R_{MACHO} lightcurves were searched for periodicities using a period-finding code developed by Reimann (1994). This code fits either cosines, "super-smoother" (Friedman 1984), or periodic cubic splines to the folded light curve data. These lightcurves were all fit using super-smoother. A weighted sum of absolute residuals was calculated as a measure of fit which was minimized in a two-step procedure going from a coarse frequency grid to a fine one. For these variables, the best five periods for each light curve were output along with statistics of the fit. Since beat Cepheids are expected to be fit poorly by a single period, about 2900 lightcurves were examined for evidence of periodic

scatter. The Reimann routine very frequently identified the pattern repetition period as one of the fits with the least scatter. A total of 51 stars were judged to have abnormally large scatter in their lightcurves. Examples of fundamental and overtone Cepheid V_{MACHO} lightcurves are shown in Figure 1. Lightcurves for four LMC beat Cepheids for the longest principal period and the pattern repetition period are shown in Figure 2.

Power spectra for the data were generated using the CLEAN algorithm for time-series developed by Roberts, Lehár & Dreher (1987). Briefly, the raw power spectrum of an irregularly sampled time series is the convolution of the the actual power spectrum and the spectral window (due to the set of observing times). The CLEAN algorithm is a way of iteratively removing the spectral window from the power spectrum to obtain a good approximation of the actual power spectrum. In our implementation, a gain of 0.5 and 30 iterations were employed. Due to the large number of observations and long sampling period, the CLEAN algorithm worked very well.

The power spectra of beat Cepheids are distinct from the power spectra of unresolved double Cepheids. In the latter case, there is significant power at the two principal frequencies and their multiples. Beat Cepheid power spectra have significant power at frequencies corresponding to combinations of the two principal frequencies, as well. A second discriminant is that double Cepheids appear unusually bright for the chosen fundamental period in the period-luminosity (P-L) and period-luminosity-color (P-L-C) diagrams. In fact, their position reflects the contribution of two sets of fluxes.

In all, we identify 45 LMC beat Cepheid variables. The properties for these stars are listed in Table 1, where the columns, from left to right are: right ascension and declination for equinox J2000.0, longer principal period, shorter principal period, identification of the strongest peak in the power spectrum as either the longer period (L) or the shorter period (S), median R_{KC} and $(V-R)$ using the available (and approximate) transformation from V_{MACHO} and R_{MACHO}, mode identifications where F indicates fundamental mode, 1H

indicates the first overtone, and 2H indicates the second overtone, and comments. The table is ordered by increasing principal period. (Note that we have used the term principal period to avoid the initial classification of the period as fundamental or overtone). The positions have uncertainties less than 2.0 arcsecs. Listed separately at the bottom are the three double Cepheid candidates. The remaining three stars of the original 51 candidates had unusually large photometric scatter due to other causes or were not Cepheids. Finder charts for the 48 stars in Table 1 are given in Figure 3.

The power spectra for these stars are plotted in Figure 4. Note that asymmetric lightcurves will result in the principal frequency and its integer multiples being present, whereas a near-sinusoidal shape will result in most of the power being in the principal peak. The strength of the frequencies corresponding to mixing modes will be correspondingly affected.

Of the double-mode candidates found by this survey, only six have previous identifications in Payne-Gaposchkin (1971). All six have notes indicating abnormally large scatter in the phased lightcurves. (Cross-identifications are given in the comments column of Table 1).

We have examined the three LMC double-mode Cepheid candidates proposed by Andreasen (1987) which are common to our fields. HV 12500, 5694, and 2345 are all normal fundamental mode pulsators with no evidence for a second (non-commensurate) periodicity. (HV 2345 was considered one of the two best candidates in that study.) We have also examined the two stars in common with the list of beat Cepheid candidates given by Andraesen and Petersen (1987). Neither HV 5664 nor HV 913 show evidence for a second periodicity.

4. Analysis

a) Strategy

The fact of the stars being at a common distance (50 kpc) is an enormous advantage in the interpretation of the observed properties. The total absorption at R_{KC} is known to be of order 0.15 mags for field Cepheids and the differential reddening is also correspondingly low. Hence, the interpretation of observed brightnesses is relatively straightforward. Before describing our strategy in more detail, it is useful to briefly review the observational properties of Cepheids.

Cepheid variables are radial pulsators which are found in a regime of luminosity and effective temperature popularly known as the Cepheid Instability Strip (CIS). This strip has a finite width in effective temperature which results in a finite width in observed color. Lines of constant period and constant luminosity are not parallel and hence a sample of Cepheid with identical periods can display a range of luminosities. Since the luminosity is a function of two variables (radius and effective temperature), we expect that the luminosity of a Cepheid will be better predicted by the use of a color and a period. Indeed this is found to be the case — the P-L-C relation is generally a much tighter fit than the P-L relation. As is well known, the change in color due to a difference in effective temperature and due to differential absorption by interstellar dust grains is very similar. Hence, if we form a projection of the P-L-C relation which removes the effects of differing effective temperature, we automatically remove most of the effects of differential absorption.

In this paper, we are most concerned with mode determination and lightcurve shape than absolute calibration, so a useful projection of the P-L-C is the quantity W_R, where:

$$W_R \ = \ R \ - \ 4.0(V - R).$$

The exact value of the color coefficient is relatively unimportant, since as long as it is close to the correct value, the largest part of the small amount of differential reddening and effective temperature differences will be removed. The value given was chosen by determining the ratio of total-to-selective absorption for the R bandpass and the $(V - R)$ color index, given $A_V/E_{B-V} = 3.3$ (appropriate for the Magellanic Clouds) using the

algorithm of Cardelli, Clayton & Mathis (1989). This class of function is described by van den Bergh (1975).

Note that additional light from an unresolved companion will result in an unusual value of W_R. The most common circumstance for contamination is the presence of an early type (hence bluer) star in the same resolving element. Since the addition of the light of a blue star will make the $(V - R)$ color index smaller and increase the brightness at R marginally, we expect such stars to fall below the main locus of points in the W_R-$\log_{10} P$ diagram. A sensitive test for this contamination is to determine the ratio of amplitudes between the V_{MACHO} and R_{MACHO} bandpasses which will be different than for isolated stars. Note also that a comparison of this type is not possible with galactic Cepheids since they do not have a common distance.

b) Beat Cepheids

In Figure 5, we plot W_R versus $\log_{10} P_L$ for about 1500 stars identified as Cepheids in our sample. The periods assumed in this plot are photometric periods. Also shown are the appropriate values for our beat Cepheid candidates, assuming the longer of the two principal periods, P_L. There are several feature of this plot which are worthy of comment. First, there are two obvious loci of stars which are characterized by different lightcurve shape. The sequence which extends to longer period is due to stars pulsating in the fundamental mode and these stars typically have skewed lightcurves. The sequence which appears at brighter W_R is largely due to stars pulsating in the first overtone. If the correct value of the fundamental period had been used for these stars, they would also lie along the fundamental sequence. The separation in $\log_{10} P$ between the two sequences therefore corresponds to $\log_{10} (P_{1H}/P_F)$. The plot first presented by Cook (1995) shows these same features, but is an R_{MACHO} P-L relation.

The beat Cepheids plotted in Figure 5 also fall along two different sequences. Since we have already used the power spectra of these stars to select the longer of the two principal periods, this indicates that the beat Cepheid points falling on the overtone sequence

are pulsating in the first and second overtones, rather than the fundamental anf first overtone modes. This assertion is borne out by inspection of the period ratio column in Table 1, where these stars are *all* found to have a higher period ratio than those stars falling on the fundamental sequence.

Since this database contains variables fainter than $R_{\mathrm{MACHO}} = 18.0$ mag, we expect that the survey is essentially complete throughout the period range examined. An examination of Figure 5 reveals that among short period Cepheids, the beat phenomenon is actually quite common. For $P_F < 2.5$ days, we detected beat Cepheids among 20% of the sample. If the beat Cepheid phase is a transition between the two dominant pulsation modes, then the fraction of time spent in a transition state is contrained by this number.

In Figure 6, we have plotted the ratio of the two principal periods, P_S/P_L versus $\log_{10} P_L$. Two very tight sequences of points are seen, dividing very neatly near $\log_{10} P_L = 0.1$ ($P_L = 1.25$ days). For P_L less than 1.25 days, the period ratios are all in the neighborhood of 0.80, whereas for P_L greater than 1.25 days, the ratios fall near 0.72. In both cases, there is a dependence of period ratio on P_L in the sense that the ratio gets larger with decreasing period. Linear fits to the LMC F/1H and LMC 1H/2H sequences give the following relations:

$$P_S/P_L \; = \; 0.733 \; - \; 0.034 \log_{10} P_L, \;\; 0.1 < \log_{10} P_L < 0.7,$$

$$= \; 0.803 \; - \; 0.022 \log_{10} P_L, \;\; -0.2 < \log_{10} P_L \leq 0.1.$$

The ratio of the fundamental to *second* overtone period can be found in the neighborhood of $P_L = 1.25$ days and its value is $P_{2H}/P_F = 0.585$. Hence, if Cepheids beating in the second overtone alone exist in the LMC sample, they will be found displaced in $\log_{10} P_L$ from the fundamental sequence by $\log_{10} 0.585 = $ -0.233. Since the displacement of the second and first overtone sequence is only $\log_{10} 0.80 = $ -0.10, any photometric scatter may result in these two sequences overlapping. Therefore, Cepheids pulsating solely in the second overtone may exist and may have been confused with first overtone stars to date.

The relatively small scatter in the LMC ratios is remarkable and must be due to both the uniformity of the observations and a small spread in metallicity among the LMC sample. The scatter is not significantly greater than what is expected from the uncertainties in the periods themselves from the limited timespan of these observations.

Also, shown are data for the 12 galactic beat Cepheids listed by Balona (1985) plus EW Sct. There is a clear difference between the period ratios of galactic and LMC beat Cepheids, presumably due to the difference in metallicity between the two samples. Luck & Lambert (1992) found the LMC Cepheids to have [Fe/H] = -0.3 with a dispersion of 0.3, although this dispersion is inflated by one very metal-rich 100-day Cepheid in their sample. (The SMC, by comparison, has [Fe/H] = -0.7.) The trend in period ratio P_S/P_L for these Cepheids is given by:

$$P_S/P_L \; = \; 0.720 \; - \; 0.027 \log_{10} P_L, \;\; 0.3 < \log_{10} P_L < 0.8.$$

The sense of the period ratio change with metallicity can be derived from Petersen (1990) where the ratios predicted using the more recent opacities of Rogers & Iglesias (1992) are compared with models using the Cox & Tabor (1976) opacities. The older opacities, because of their lower absorption in the driving region, can be considered representative of a more metal-poor atmosphere. Figure 1 in Petersen shows that lower F/1H period ratios are associated with more opacity in the driving region of the Cepheid atmosphere and so our observationally derived sense of period-ratio change is in agreement with theory. More recently Moskalik, Buchler & Marom (1992) have calculated models for specific masses and luminosities which show this same dependence on metallicity. The period ratio for 1H/2H LMC beat Cepheids is also expected to be higher than for their more metal-rich galactic counterparts.

c) "Double Cepheids"

In our sample of beat Cepheid candidates, we have identified three stars whose photometric scatter appears to be due to the superposition of the light variations of two Cepheids. The two characteristics which result in this classification are the absence of power at frequencies corresponding to the mixing modes of the two principal frequencies and brightnesses which are clearly the sum of two normal Cepheids. The last three panels of Figure 4 contain the power spectra for these stars. Let us discuss these in turn.

MACHO*05:21:54.8-69:21:50 The lightcurve of this system is due to two 1H pulsators as evidenced by the weakness of the power spectra peaks at twice the principal frequencies (and lack of peaks that exceed the noise at higher multiples). There is no evidence for any excess power at the difference and sum frequencies. The 0.55 mag displacement brightward of the 1H sequence in Figure 5 is consistent with the sum of the light from two 1H pulsators of photometric period 2.48 and 1.96 days, which would result in a brightness difference of 0.61 mags.

MACHO*04:59:17.5-69:14:18 The power spectrum of this object is clearly the result of the light variations of a F and a 1H pulsator. The principal frequency and its second, third, and fourth multiples are seen in the power spectra, indicating a skew lightcurve. This is consistent with its identification as a fundamental pulsator. No higher multiples of the second principal frequency are seen, so the the second star is clearly a 1H pulsator. No excess signal is seen at the sum and difference frequencies of the two principal frequencies. The 0.59 mag displacement brightward of the F sequence in Figure 5 is consistent with these identifications. Using a period ratio of 0.715 for the 1H star, we predict a brightness increase of 0.72 mags for stars of the same color.

MACHO*05:04:02.3-68:21:32 The power spectrum for this system reveals it to consist of two F pulsators. The second, third, and fourth multiples of both of the two principal frequencies are evident and no mixing modes are seen. This object lies 0.41 mags above the ridgeline of fundamental sequence in Figure 5. This is consistent with the prediction of an increase of 0.47 mags for two fundamental pulsators with the given periods.

The question of whether or not these stars are physically related cannot be answered with these observations. It is clear that they must be very similar in age and mass, or they would not be sufficiently similar in period and luminosity to be detected in this search. A radial velocity study of these systems could provide evidence for orbital motion. Given the spectroscopic binary mass function and the assumption that the two stars have equal mass, it would be possible to derive lower limits for the masses of the stars. However, the shortest period Cepheid binaries in our galaxy have orbital periods of a year and a half, so such a programme would require long timescale monitoring.

There is one example of a double Cepheid in our galaxy: CE a+b Cas. Sandage and Tammann (1969) first discussed these two variables, which are located in the galactic cluster NGC 129. They are separated by about 8000 AU, so no detectable orbital motion is expected or seen. At the distance of the LMC, this pair of objects would be unresolved by this survey.

c) Beat Cepheids Near LMC Clusters

Our understanding of the evolution of stars and the evolutionary context of variable star phenomena has benefited from the discovery of variable stars in clusters. The Magellanic Cloud clusters are especially useful because there are many rich, young clusters which have few or no counterparts in the observable volume of our Galaxy. In preparing finder charts for the 48 stars in Table 1, it became clear that several of the beat Cepheids are found at positions very close to both known and uncatalogued clusters. We will discuss the associations we believe to be most promising.

MACHO*04:54:55.0-69:14:12 This star is found adjacent to the cluster NGC 1756. There are three additional Cepheids associated with this cluster. All of them are F pulsators with periods between 2.67 and 3.5 days.

MACHO*05:36:54.7-70:08:10 This variable is found near both NGC 2059 and NGC 2058, the latter being located just south of the boundary of the finder chart. NGC 2059 appears to be misidentified on chart 53B of Hodge & Wright (1967). There are five Cepheids associated with this relatively sparse cluster. Four are 1H variables with periods between 2.13 and 3.31 days, and one is a fundamental pulsator with a period of 5.58 days. There are at least 6 additional Cepheids associated with NGC 2058. Three of these are F pulsators with periods between 4.68 and 5.35 days, and three are 1H pulsators with periods between 1.92 and 2.09 days. Additional variables found in the immediate neighborhood may also belong. Bica, Clariá, & Dottori (1992) derive an equivalent cluster type of III on the Searle, Wilkinson & Bagnuolo (1980) classification scheme (SWB type). Class II and III clusters are where Cepheid variables are most likely to be found. Using the calibration of Elson & Fall (1985), NGC 2058 has an age of approximately 110 million years.

MACHO*05:33:39.4-69:54:55 This variable is found to be in the midst of the sparse cluster HS 353 (from the cluster catalogue of Hodge & Sexton, 1966).

5. Conclusions and Future Work

The principal conclusions of this work are: 1) we have identified 45 beat Cepheids in the LMC, thirty of which are F/1H pulsators, 2) fifteen of these stars are found to have a period ratio near 0.80 and a brightness which indictates that they are pulsating in the 1H/2H modes, 3) the F/1H period ratios are systematically higher in the LMC sample than in the galactic sample, indicating a structural difference between LMC and galactic Cepheids, 4) Cepheids in the LMC select the 1H/2H modes for periods shorter than 1.25 days, 5) among stars with fundamental periods shorter than 2.5 days, double-mode excitation is seen about 20% of the time, 6) the sense of the period-ratio/metallicity dependence agrees with that expected from pulsation theory, 7) we fail to confirm any of the beat Cepheid candidates proposed to date (which are common to our dataset), and 8) we find several beat Cepheids to be in or near LMC clusters, some of which contain other Cepheid variables.

There are many avenues of Cepheid research which may yet be explored with the MACHO photometry database. We will describe a few here.

The final analysis of some properties of the beat Cepheids reported in this paper must await the final photometric transformations between the instrumental MACHO photometry and a standard system. This analysis is underway and should be avilable soon.

There are almost certainly stars pulsating solely in the second overtone which have not been recognized thus far due to the overlap of the 1H and 2H sequences in the P-L relation. We have seen evidence for systematic differences in lightcurve shape and are actively pursuing the characterization of the three modes. Stellingwerf, Gautschy & Dickens (1987) have predicted that 2H lightcurves will be asymmetric like F pulsators but distinct.

The relative properties of SMC beat Cepheids (if they are found to exist) will be especially interesting in view of the much lower metallicity of this sample. Differences in the regions of the color-magnitude diagram occupied by Cepheids in different modes will provide strong constraints for pulsation models. The SMC fields which exist in the MACHO photometry database have not yet been searched for variables.

The difference in period ratios is evidence that LMC Cepheids metallicity affects the atmospheres of Cepheids in an observable way. With this knowledge in hand, we will explore the effects on the P-L and P-L-C relations.

The full MACHO dataset will span at least four years. During this time a sensitive test for time-variable mode strengths may be undertaken. This is the only dataset which is sufficiently long, contains sufficient numbers of stars and is of sufficient quality to test for such changes.

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Figure Captions

Figure 1— Lightcurves (V_{MACHO}) are shown for four fundamental mode (F) LMC Cepheids (left panels) and four first overtone (1H) Cepheids (right panels). The major tick marks on the ordinate are 0.5 mag apart. Each point is plotted twice (separated in phase by 1.0) to preserve continuity. Error bars are plotted. The star designation containing equinox J2000.0 coordinates is given on the upper left of each panel and the period used (to 0.01 days) is given in the upper right.

Figure 2— Lightcurves (V_{MACHO}) are shown for four LMC beat Cepheids. The left panel contains the lightcurve phased with period P_L from Table 1. The right panel is the same photometry phase with the pattern-repetition period $P = (2P_L P_S)/(P_L - P_S)$. The period used for plotting is not precisely that found from using the values from Table 1, but the period corresponding to the minimum 'string length' in the neighborhood of the expected pattern-repetition period.

Figure 3— Finder charts for the variables listed in Table 1. The size of the image portion of each chart is 120×120 arcsec. The label appears on the south side of the image, and west is to the right. The coordinates are the equinox J2000.0 positions for the variables - not the chart center. In cases where the star was near the edge of the image, the region was selected to show as much field as possible and consequently the star is not always at the chart center. These are R_{MACHO} images and have been stretched to show fainter stars. Known cluster identifications are shown. However, it is obvious that many of the beat Cepheids are found in or projected on uncatalogued clusters of stars. Both NGC 1976 and NGC 2058 contain other Cepheid variables.

Figure 4a-f — Power spectra for beat Cepheid candidates identified in this survey are shown. The ordinate is the logarithm of the power at that frequency. Based on the positions of the two principal frequencies, the mixing frequencies, as well as multiples of the principal frequencies, are identified with arrows. The symbols Ⓛ, Ⓢ, ⊖, ⊕, Ⓛ2, Ⓢ2, represent the longer and shorter principal frequencies, their difference and sum, and their second multiples, respectively. The star designation is also given. Note that if the shape of the lightcurve in one of the modes is nearly sinusoidal the higher multiples of the corresponding principal frequency (and their mixing modes) will be effectively absent. The last three panels contain power spectra identified as being due to "double Cepheids" – two Cepheids that appear within the same resolving element on the sky (and possibly related). Note the absence of mixing mode frequencies in the power spectra for these stars.

Figure 5— The quantity W_R, which removes the greatest fraction of brightness difference due to differential reddening and color difference, is plotted against the logarithm of the photometric period. Two sequences of Cepheids are seen in this diagram. For a given period, the lower sequence is due to stars pulsating in the fundamental (F) mode. The upper sequence is primarily due to stars pulsating in the first overtone (1H). This sequence appears brighter because the photometric period is shorter than the fundamental period appropriate for these stars. Beat Cepheids pulsating in the F/1H mode are shown as solid circles and stars pulsating in the 1H/2H modes are shown as open circles. Data for these stars are found in Table 1. The circles containing 'B' correspond to "double Cepheids" — two Cepheids which are seen in the same resolving element. Stars falling in the lower right-hand part if the diagram are Type II Cepheids and RV Tau stars for the most part.

Figure 6— The ratio of the shorter photometric period, P_S, to the longer photometric period, P_L, is plotted as a function of the logarithm of P_L for LMC and galactic

beat Cepheids. The stars with P_S/P_L near 0.72 are identified as beating in the fundamental and first overtone (F/1H) modes, whereas the stars near $P_S/P_L = 0.80$ are identified as pulsating in the first and second overtone (1H/2H) modes. Filled circles and open circles correspond to F/1H and 1H/2H LMC beat Cepheids, respectively. Open squares indicate galactic beat Cepheids — all F/1H pulsators. Near $P_L = 1.25$ days, the ratio of the second overtone to fundamental period is derived to be 0.585. The period ratios for LMC Cepheids are systematically higher than for galactic Cepheids, presumably due to differences in metallicity. The lines shown are unweighted linear least-squares fits to the appropriate data. The equations for these lines are given in the text.