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Cepheids in the Magellanic Clouds

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Abstract. In the past few years, the Magellanic Clouds have been the targets for several major variable star surveys. The results of these surveys are now becoming available and it is clear that a Renaissance in LMC and SMC variable star research will result. In this review, I will describe the results of such surveys and review the questions that are likely to be answered by further work.

With respect to results, I will concentrate on LMC MACHO Project data, including beat Cepheids, discovery statistics, mode identification,

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Fourier decomposition of lightcurves, and the differences between the LMC and galactic sample.

1. Introduction

The Magellanic Clouds continue to play a central role in our understanding of Cepheid variables. Long duration, wide-field surveys have now begun to yield large volumes of high-quality photometric data which will replace and extend the results of photographic surveys published over thirty years ago. Unlike these past surveys, the individual photometric measurements for each star will be available to all researchers. The impact of these surveys on our understanding of pulsating stars is not likely to be surpassed for decades to come.

2. Recent work

Let me briefly mention work carried out since the review of Welch, Mateo & Olszewski (1993). The largest and most comprehensive published work is that of Smith et al. (1992) who surveyed 1.3 square degrees in the SMC for new variables using automated photographic photometry techniques. They discovered 78 new variables, many of them new Cepheids. Their mean B period-luminosity relation clearly shows two sequences of points which are interpreted as being due to Cepheids pulsating in the fundamental (F) and first overtone (1H) modes. They also find that 34% of the total sample are 1H pulsators. Sebo & Wood (1995) report on the detection of Cepheids in the rich, young clusters NGC 1850 and NGC 330. Storm et al. (1995) have undertaken Baade-Wesselink solutions for several SMC Cepheids. Poretti, Antonello & Mantegazza (1995) have produced the first results from a study of 21 short-period LMC Cepheids which compares the Fourier sequences in the Galaxy and the LMC in the neighbourhood of the long-period s-Cepheid sequence.

The two major intensive photometric surveys of LMC fields reported at this meeting are those of the EROS project by Beaulieu (1995) and the MACHO Project, described in more detail later in this paper, and by Cook (1995). The EROS project obtained some 15,000 images of a single 0.4 square degree field in both B_J and R_C. They found 96 Cepheids in their field, 72 of which are new and found that 1H pulsators were 30% of their sample.

3. The MACHO Project

The work I would like to describe in somewhat more detail involves a portion of the MACHO Project photometry database. This survey project has been described by Alcock et al. (1992). Its principal goal is to detect microlensing events in order to estimate the mass spectrum of objects in the disk and halo. Due to the rarity of such events, it is necessary to observe large numbers of stars repeatedly, and in the process large numbers of variable stars are also detected and recorded. The 1.27m telescope at Mount Stromlo, Australia is currently dedicated full-time to this project. A camera built specifically for the project

(Stubbs et al. 1993), has a field-of-view of 0.5 square degrees and images in a 'blue' (450-630nm) and 'red' (630-760nm) bandpass simultaneously.

To date the first 5500 frames, distributed over 22 fields and 400 nights, have been analysed. At present we have identified over 1500 Cepheids in these fields. Typical datasets contain between 100 and 320 two-colour observations.

3.1. Beat Cepheids

The passage of time is one of the few things in extragalactic research that can be measured with high precision. Beat Cepheids are stars which pulsate in two radial modes simultaneously. Only about 14 are known in our Galaxy, with CO Aur and EW Sct (Cuypers 1985; Figer et al. 1991) added to the list of Balona (1985). The ratio of the two periods can be determined with high precision and is expected to be dependent on metallicity. Beat Cepheids are difficult to discover, in practice, because of the large number of datapoints required to recognise and characterise them. Existing surveys for Cepheid variables in other galaxies have not detected beat Cepheids because they have lacked either the total number of observations required, the photometric precision, or both.

The MACHO photometric database was searched for stars whose phased lightcurves exhibited a photometric scatter in excess of that expected from photometric errors. A total of 45 beat Cepheids were discovered and are reported in Alcock et al. (1995). The mode identification was based on analysis of CLEAN'ed power spectra and position in the P-L and reddening-free P-L-C relations. MACHO Project lightcurves for a singly-periodic LMC Cepheid and an LMC beat Cepheid are shown in Figure 1. While the photometric calibration to a standard system is not complete, a number of conclusions can be drawn:

- Thirty are F/1H pulsators, fifteen are 1H/2H pulsators.
- The ratio of the shorter period (P_S) to the longer period (P_L) is near 0.7 and 0.8 for the F/1H and 1H/2H pulsators, respectively.
- The period ratios for LMC beat Cepheids are systematically higher than galactic beat Cepheids.
- The period ratio difference is presumably due to metallicity and is in the sense predicted by theory.
- Beat Cepheids seem to be found in bands across the instability strip (a result which must be confirmed by the photometric calibration).
- About 20% of the stars with fundamental periods shorter than 2.5 days are beat Cepheids.
- Several of the beat Cepheids were found in or near young clusters which will allow their evolutionary state to be determined.
- None of the previously reported beat Cepheid candidates common to our fields were confirmed.

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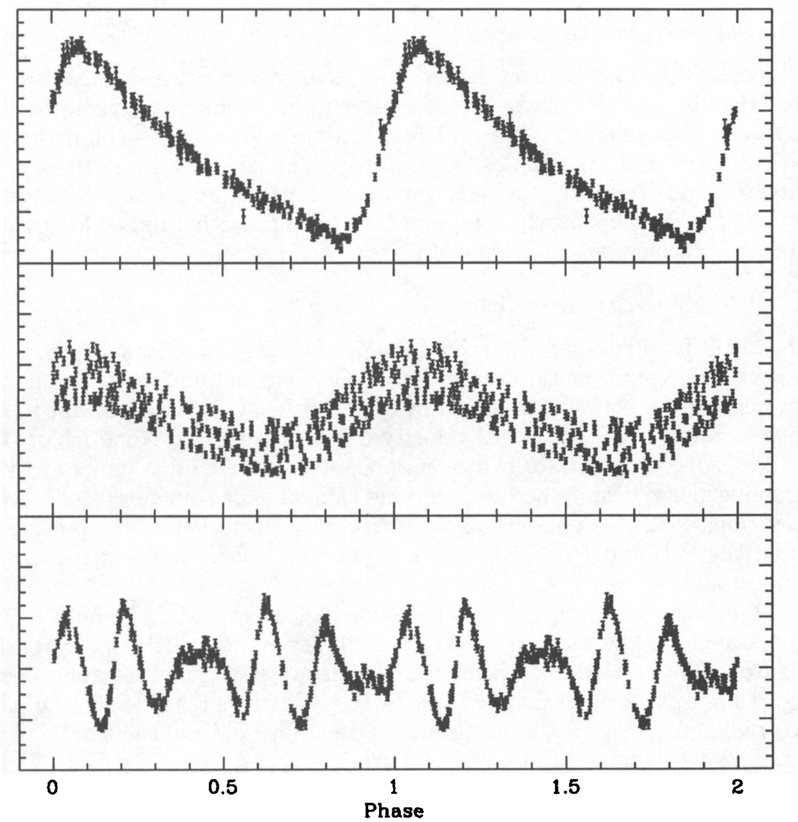

Figure 1. A V_{MACHO} lightcurve of one of the 1500 Large Magellanic Cloud Cepheids in the MACHO Project photometry database is shown in the top panel. This fundamental pulsator has a period of 4.1 days. The middle panel illustrates the lightcurve of a so-called 'beat' Cepheid which is pulsating with two different periods simultaneously, when it is phased with on of the two periods (4.84 days). The bottom panel shows what the lightcurve would look like if followed continuously. The pattern in the lightcurve of this 'beat' Cepheid repeats every 24.2 days. There are a total of 249 observations for the normal Cepheid and 319 for the 'beat' Cepheid. Each point is plotted twice to reveal continuity. The vertical scale for each lightcurve is 1.0 mag.

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Petersen & Christensen-Dalsgaard (1995) have already begun work on the theoretical implications of the LMC beat Cepheid data and hopefully will provide predictions for the expected period ratios for such stars with SMC-like metallicities.

3.2. Discovery statistics

Of the 1500 Cepheids identified to date, 950 of these are F pulsators and 550 are 1H pulsators. We have cross-correlated our variable list with the catalogue of Payne-Gaposchkin (1971) and find that new discoveries comprise 57% and 94% of the F and 1H samples, respectively. The lack of 1H pulsators in existing surveys is due to their relatively small photometric amplitudes. This survey is expected to be very nearly complete for Cepheids with amplitudes greater than 0.05 mag throughout the Cepheid period range.

3.3. Fourier decomposition

The MACHO photometry database is a near-ideal sample for studying lightcurve behaviour. A systematic description of Cepheid lightcurve shapes in terms of Fourier series was first introduced by Simon & Lee (1981) as a means to compare observational light and radial velocity curves with the predictions of pulsation models. One drawback of the galactic Cepheid data sample is its observational inhomogeneity, despite heroic observing campaigns by numerous observers. Observations of LMC Cepheids allow a direct interpretation on the pulsation mode using the P-L and P-L-C relations - something not possible for their galactic counterparts.

We have undertaken Fourier decomposition of LMC Cepheid lightcurves. An example of the the run of the phase difference ϕ_{21} with $\log_{10} P$ is shown in Figure 2. In addition to allowing a comparison with theory, we are producing an algorithm by which the shape of a lightcurve of a given period and amplitude may be predicted. This will aid in the estimation of mean brightness of incompletely-sampled extragalactic Cepheid lightcurves.

3.4. Young clusters containing Cepheids

It is easy to get the impression that all young clusters containing Cepheids in the LMC and SMC have been surveyed. However, the work reviewed by Welch, Mateo & Olszewski (1993) covers only a small fraction of known young clusters and concentrates on those far from the bar of the LMC. We have cross-correlated positions of catalogued clusters with the existing set of 1500 Cepheid variables and find many new Cepheid-rich clusters. We plan to publish a list of these objects in the near future, with finder charts.

4. Future avenues of research

The mining of the MACHO Project photometric database has only begun. There are many avenues of research which we plan to explore. These include:

- We will search for evidence of singly-periodic 2H pulsators, and, if found, determine their lightcurve properties.

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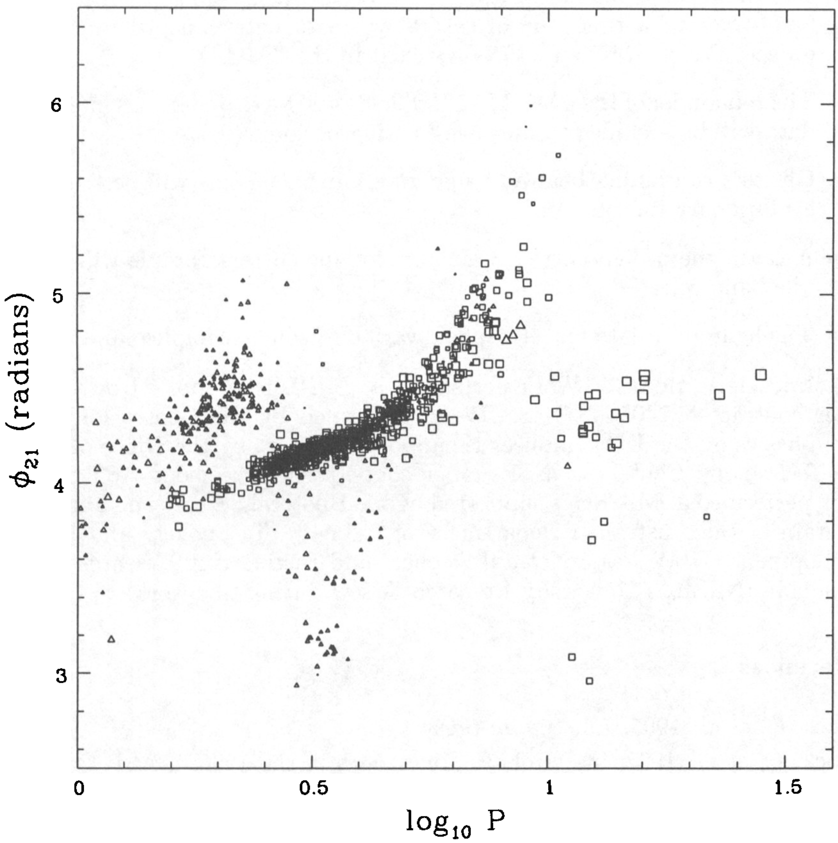

Figure 2. The Fourier parameter ϕ_{21} plotted as a function of $\log_{10} P$ for over 1500 Cepheids. This particular sample was selected by requiring the photometry lists to contain over 100 datapoints with fewer than 4 5-σ outliers (which were excluded from the fit), a fitted RMS error smaller than 0.025 mag, and an error in $\phi_{21} < 0.15$ radians. The sample has not been carefully culled for contaminating objects such as foreground Type II Cepheids. The triangles and squares indicate an early (and imperfect!) classification of overtone and fundamental pulsation mode. The size of the symbols is proportional to the Fourier amplitude R_1. The sequence of long-period s-Cepheids is definitely present and the well-known resonance at 10 days are also clearly visible.

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- When reductions for the six SMC fields observed by the MACHO Project become available, they will be searched for beat Cepheids and their period ratios will be compared with the LMC and galactic samples.
- We will make a systematic search for objects which change their lightcurve amplitude on a timescale of several years to determine whether or not objects like α UMi and V473 Cyg exist in the LMC.
- The remainder of the LMC MACHO fields will be searched and more recent data will be included to improve existing period ratios.
- Clusters containing beat and singly-periodic Cepheids will be studied for evolutionary information.
- A catalogue of lightcurve parameters for the current sample will be compiled and released.
- The lightcurve data for all Cepheid variables will be compiled and released.

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Discussion

Stift: What is the period-number distribution like? It should tell you something about metallicity and mass loss.

Welch: The most prominent feature in the period-number distribution seems to be due to burst of star formation about 2 10^8 yr ago. We will be making the catalogue of mean properties available soon.

Sasselov: On your period-ratio diagram - is there an overlap at P = 1.25d ? If there is, could it be used to determine a scale of mode selection, whether it is an evolutionary time scale or some other scale.?

Welch: Yes, there is an overlap - a small one. I haven't checked the percentage relative to the evolutionary time scale.

Moskalik: The 1.25d period is not very significant; it is just a coincidence. For one group (F/1H) it is an F-mode period, for another group (1H/2H) it is a 1H-mode period. You cannot compare them directly, you have to use fundamental (or overtone) periods for both groups in order to have a meaningful comparison.

Poretti: In our studies of galactic Cepheids we found three stars (DT Cyg, V1334 Cyg, V1726 Cyg) whose light curves are perfectly sinusoidal, i.e., the amplitude of the $2f_1$ term is not significant. Have you found similar light curves in the LMC Cepheids?

Welch: Yes, there are many near-sinusoidal light curves.

Antonello: I am happy with the results on the first overtone pulsators (Fourier parameters), because they confirm the analogous results on Galactic Cepheids obtained by our group, and definitely confirm the first overtone pulsation of these Galactic Cepheids. Now it is important to improve the models in order that they are able to reproduce satisfactorily the observed features of the Fourier diagrams.

Matthews: (i) Is the fraction of first overtone to fundamental pulsators relatively constant from field to field, or does it depend on position within the LMC? (ii) Have you examined the V-R colour curves for the Cepheids for temperature and phase lag information?

Welch: (i) I have not looked at that distribution yet. (ii) I have also not examined the phase lag or transformed the observations to the theoretical plane. As you can imagine, there are plenty of things to do with this database!

Morgan: Have purely 2nd overtone mode pulsators been detected, and if not, why not?

Welch: They *may* be in our database - there are occasional stars with unusual light curve shapes, but I have not yet checked them on a case-by-case basis.

Kanbur: (i) To my knowledge, no non-linear models can reproduce double-mode pulsation, so we still have a problem to explain the switch in period ratio from P_1/P_F to P_2/P_1 from theory. (ii) Does the steep rise in the $\phi_{21} - P$ plot seen in galactic Cepheids at 10 days occur at the same period for your LMC data?

Welch: (i) Not my problem. (ii) Yes, it occurs at very close to 10 days and the difference between the LMC and galactic plots is not obvious.

Christensen-Dalsgaard: Have you looked for additional frequencies in the data, beyond the two dominant modes?

Welch: Yes, and there are a few that appear to show additional frequencies. The analysis of these stars would benefit from the more complete set of reductions now available (3 years).

Goldreich: What fraction of light curves in the Cepheid region of the H-R diagram is not interpretable? For example, could there be non-radial pulsators?

Welch: A very small percentage in the Cepheid region. At fainter magnitudes there are more, but I can't give you meaningful percentages from memory.

Bono: Did you try to transform the colours of your sample to a temperature scale?

Welch: No, but this may be done using published work once the MACHO data are standardised.

Moskalik: Calibrating period ratios in terms of metallicity is not so simple. For fixed M and L the period ratios *increase* with decreasing metallicity. But, evolution theory theory tells us that the M-L relation depends on Z. The change of luminosity predicted from evolutionary theory causes the period ratios to *decrease* with decreasing Z. So, the net result is a difference between these competing effects. Thus, calibrating Z from period ratios depends on the evolutionary calculations, not only on the envelope pulsation models.

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