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A New Look at the Blazhko Effect in RR Lyrae Stars with High-Quality Data from the MACHO Project

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Abstract. We present the first results of the analysis of 22 Blazhko stars. We find: 1) Blazhko RRab stars that are nearly pure amplitude modulators; 2) Blazhko RRab stars that have both amplitude and phase modulation; 3) A Blazhko RRab star that has an abrupt period change; 4) Proof of the Blazhko effect in RRc stars. Our data show the character of the amplitude and phase modulations of the light curves over the Blazhko cycles far better than has been previously possible.

1. Introduction

RR Lyrae stars are giant A and F stars which pulsate in the fundamental radial mode with periods typically near 12 hr and/or in the first-overtone radial mode with periods typically near 7 hr. Their peak-to-peak V amplitudes range between 0.2 and 2 mag (Kholopov et al. 1985). Because of their brightnesses, longevity and large amplitudes, they are among the most numerous known of all the classes of variable stars and are important to several fields of astrophysics:

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as standard candles at the base of the extragalactic distance scale; as tracers of galactic dynamics and chemical evolution among the older population of stars; as test objects for stellar evolution theory of low mass stars; and as test objects for stellar pulsation theory. The RR Lyrae stars are divided into several subclasses: RRc stars have nearly sinusoidal light curves; they are the first-overtone pulsators. RRab stars have larger amplitude, non-sinusoidal light curves; they are the fundamental mode pulsators. For pulsation theory and stellar evolution theory the RRd class is of particular interest since these stars pulsate simultaneously in the fundamental and first overtone radial modes, the ratio of which places a strong constraint on the stellar structure.

The most intriguing subclass consists of stars which show the "Blazhko effect". These stars have light curves which are modulated on a longer time scale with periods that range from 11 to 533 d. There have been many models put forth for the Blazhko effect. The two prime contenders are the Oblique Pulsator Model (Shibahashi 2000) and the Resonant Mode Interaction Model (Van Hoolst 2000).

The first requirement for making progress on this problem is high-quality data. Complete light curves are needed over the pulsation period (about 12 hr typically) and the Blazhko period (months typically). To obtain such data means either: 1) a multi-site campaign with observers stationed at sites around the globe continuously for more than one Blazhko cycle – months of work for probably half a dozen observers, all to get data for only a few stars at best; or 2) a very long-term observing project from one site to build up a sufficient dataset, or 3) a revolutionary new way to tackle the problem.

Remarkably, the second method has shown some success. Kovács (1995) has shown that the frequencies of the circumpolar RR Lyrae star RV UMa comprise an equally spaced triplet plus its harmonics. Similar results were found by Nagy (1998) for RS Boo, and by Smith et al. (1999) for AR Her. In nearly a century of observations of Blazhko stars, these are the three best datasets and frequency solutions that have been obtained.

That has now changed. The MACHO dataset is novel: it has been gathered to study a completely different problem, and our data sampling would previously have (incorrectly) been considered inappropriate to the solution of the Blazhko problem. In this paper we present the first results of the analysis of two dozen Blazhko stars. Our light curves and frequency solutions are of a higher quality than has previously been obtained. We find: 1) Blazhko RRab stars that are nearly pure amplitude modulators; 2) Blazhko RRab stars that have both amplitude and phase modulation; 3) A Blazhko RRab star that has a period change; 4) Proof of the Blazhko effect in RRc stars. Our data and frequency solutions also show the character of the amplitude and phase modulation of the light curves over the Blazhko cycles far better than has been previously possible.

2. The MACHO Observations

The MACHO project (Alcock et al. 1992) is an astronomical survey experiment designed to obtain multi-epoch, two-color CCD photometry of millions of stars in the LMC, 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 caused by 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 1.27-m telescope at Mount Stromlo, Australia and because of its southerly latitude is able to obtain observations of the LMC year-round. This lack of seasonal aliasing is one factor which makes these observations so suitable for studying the Blazhko effect in RR Lyrae stars.

The results reported in this paper comprise only a small fraction of all the RR Lyrae stars found by the MACHO project. In the first instance, we sought stars which were likely foreground RR Lyrae stars according to Alcock et al. (1997). Many more Blazhko RR Lyrae stars have been identified (and many remain to be confirmed) based on goodness-of-fit statistics for single-cycle periods for variable stars with appropriate magnitudes and colors toward the LMC and SMC. Statistics of many of these other stars are discussed in this volume by Kovács et al. (2000). All of the stars presented in this paper lie in the direction of the LMC. Typically, the dataset for a given star covers a time span of about 2000 days and contains 750 photometric measurements (multiple observations are obtained on a given night whenever conditions allow). Typical photometric uncertainties are in the range 15 to 20 mmag (1.5 to 2% in intensity).

With only one or two points per night, it would not seem at first thought to be possible to do a definitive frequency analysis for stars with pulsation periods on the order of 8 to 12 hr. For equally spaced data it is well known that the frequency solutions from Fourier Analysis are ambiguous with equally probable solutions occurring above and below the Nyquist frequency, twice the Nyquist frequency, etc. This is simply because of beating between the real frequencies and the sampling frequency. However, with unequally spaced data, such as the MACHO data, the ambiguities disappear for large enough datasets. "Large enough" is easy to define: it means that the data gathered are well-spread over all phases of all frequencies present in the data. These criteria are met for many of the Blazhko stars in the MACHO dataset.

3. Analysis, Results and Discussion

We have performed frequency analyses on 22 RR Lyrae stars from the MACHO data using standard Discrete Fourier Transforms (Deeming 1975; Kurtz 1985). We show here only a sample of the kinds of behavior we have found. The results of our frequency analysis for star 82.8410.55 show an equally-split frequency triplet, plus its triplet harmonics. These give a complete fit to the data to a standard deviation per observation of 0.028 mag, which is close to our estimated error. Our results for star 82.8410.55 show almost pure amplitude modulation. Two more stars, 6.5722.3 and 5.5376.3686, behave in a similar manner. Fig. 1 plots the 82.8410.55 data against pulsation phase with a period of 12.35 hr. Fig. 2 plots the 82.8410.55 data against Blazhko phase with a period of 85.71 d.

It can be seen in Fig. 1 that there is very little phase modulation from the sharpness of the rising branch. It can also be seen that most of the amplitude modulation occurs near maximum, with a much lower modulation amplitude near minimum. Those latter effects are more easily seen in Fig. 2, where the data are plotted against the Blazhko period of 85.71 d.

We show the amplitude and phase modulation of the fundamental frequency triplet in Fig. 3, which shows the pulsation amplitude and pulsation phase for 82.8410.55 plotted against Blazhko phase for 10 equal phase bins. In this plot and subsequent similar plots the top points are amplitude in mmag with the scale shown on the left ordinate; the bottom points are phase with the scale shown on the right ordinate. The phase is measured with respect to a time when the outside pair of frequencies in the low-frequency triplet are equal. This is close to amplitude maximum in most cases; it has been chosen because it is a useful reference time for the oblique pulsator model which, in its simplest form, predicts all members of the frequency triplet to have equal phase at magnetic maximum. The error bars are $\pm 1\sigma$. As can be seen, the modulation is mostly in the amplitude with a small variation in phase.

Finally, because some RR Lyrae stars show period changes, we have tested for the stability of the amplitude and phase of the central frequency of the fundamental frequency triplet by dividing the data into 10 subsets equally spaced in time (about 200 d each) and fitted the central frequency of the fundamental triplet to those subsets by linear least squares. Fig. 4 plots the pulsation amplitude and phase for 82.8410.55 against Julian Date for 10 equal time bins of about 200 d each. This shows that the amplitude and phase for 82.8410.55 are constant over the 5-yr time span of our data. This is not true of other stars, as will be seen.

The RRab star 12.11285.419 illustrates two additional effects we see in the Blazhko stars. Fig. 5 shows the behavior of the amplitude and phase in the 200-d data subsets. The phase in this plot is equivalent to an O$-$C diagram: a constant frequency gives a straight line. Fig. 5 shows that the frequency in 12.11285.419 underwent a sharp change at the eighth phase bin which is centered on JD2450358. The amplitude also seems variable with time. Some RR Lyrae stars are known to show frequency changes. See the discussion by Szeidl & Kolláth (2000) for RR Lyrae itself, and the paper by Kovács et al. (2000) discussing the statistics of the MACHO RR Lyrae stars.

We therefore removed the last 400 days of data for 12.11285.419 and analyzed the remainder for which there is a constant slope in Fig. 5, hence a constant frequency. A pure frequency triplet plus harmonics were found. Fig. 6 illustrates the results. There is strong amplitude and phase variation over the Blazhko cycle in this star.

There has been controversy whether RRc stars show the Blazhko effect, or not. We resolve that controversy here: the Blazhko effect does occur for some RRc stars. We find a frequency triplet for the RRc star 82.8049.746 which has a pulsation period of 7.17 hr and a Blazhko period of 13.898 d. Fig. 7 shows that this star is purely phase modulated over the Blazhko cycle. At first thought, this might seem to indicate a simple Doppler shift in a binary system. But the phase modulates by about 1 radian which implies a minimum mass for the secondary star of 55,000 $M_\odot$. Not very likely! Thus we conclude that 82.8049.746 shows the Blazhko effect with pure phase modulation.

Even more conclusive is the RRc star 13.6810.2992. It has a pulsation period of 6.97 hr, a Blazhko period of 24.089 d and yields a frequency triplet. Fig. 8

shows that it has both amplitude and phase modulation, thus removing any lingering doubts from the pure phase modulation of 82.8049.746. We have several other Blazhko RRc stars placing the conclusion that the Blazhko effect occurs in these stars on a firm foundation. Some readers may have noted the relatively short Blazhko periods for the above two RRc stars. The star 14.8376.548 has a frequency triplet with a pulsation period of 7.00 hr and a Blazhko period of 273.86 d.

With the MACHO data for RR Lyrae Blazhko stars we have shown the character of the frequency content, amplitude and phase modulation better than has been previously possible. All theories for the Blazhko effect must confront and explain the complex variations of which we have shown samples in this paper, and the presence of the Blazhko effect in RRc stars. We can look forward to a flood of more information for the Blazhko stars as we mine the vast data source of the MACHO project.

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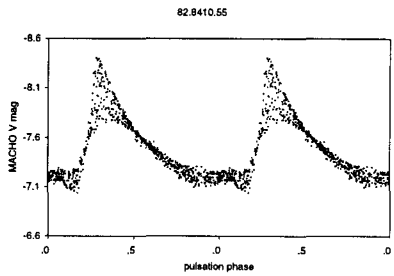
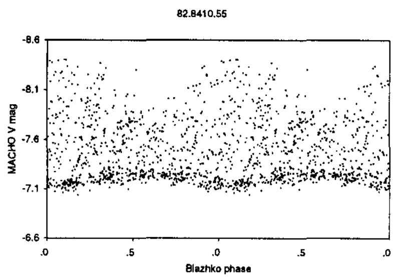


Figure 1.



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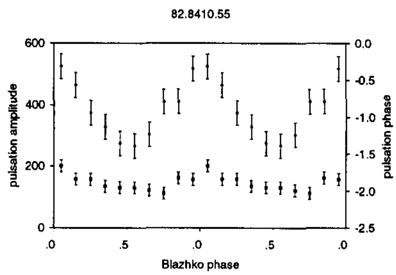

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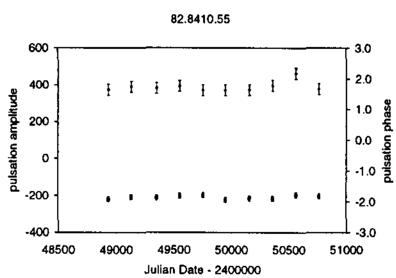

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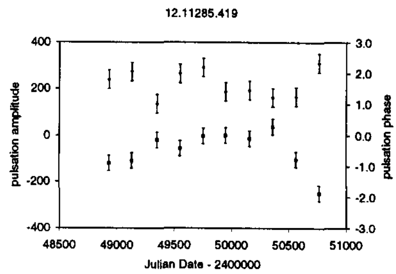

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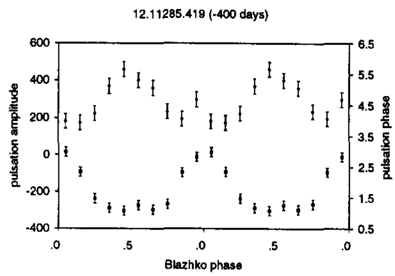

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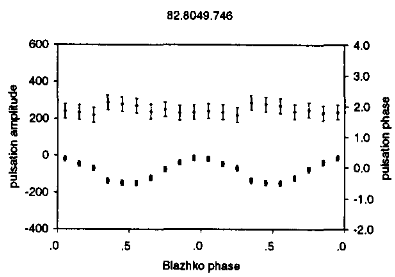

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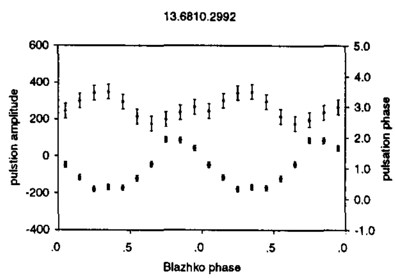

Figure 8.

Discussion

Mike Jerzykiewicz: Don, I believe the first analysis which showed equidistant frequency triplets was that of Borkowski on AR Her. The paper was published in Acta Astronomica in 1980.

Don Kurtz: Sorry, Mike. I was unaware of that. I will look it up.

Géza Kovács: What percentage of the MACHO RRab dataset did you sample in your selection procedure of Blazhko stars?

Don Kurtz: I don't know. We were selecting interesting stars to study in detail, rather than doing a systematic survey. For that, see the poster paper by Kovács et al. in these proceedings (p. 313).

Horace Smith: You make a clear case that surveys such as the MACHO survey will revolutionize this subject. I wish to make a plea for continued long-term observations of Blazhko stars as well. Such observations are important for identifying changes in the phase, amplitude, or period of the Blazhko effect on many-year time scales, changes which may help decide among alternative explanations.

Robert Buchler: Have you done any time-dependent Fourier decomposition of the light curves? The temporal variation of these light-curve shape parameters could give us important dynamical information about the Blazhko mechanism, and help us discriminate between some of the proposed models. In the proceedings of the previous pulsation conference in Los Alamos I presented such an analysis that I performed on the old data of Balázs-Detre and of Walraven. What was particularly striking was that the Fourier phase ϕ_{21} was oscillatory, rather than running.

Don Kurtz: I haven't done that yet, but I can and will. I'll send you the results.

Alex Schwarzenberg-Czerny: Important information in the data on the Blazhko effect is the coherence of the modulation. The present surveys are long enough to investigate that, either in the time domain (changes in Blazhko period and amplitude), or in the frequency domain (broadening of sidelobes with respect to the window function central peak).

Hiromoto Shibahashi: I noticed from your tables shown us that the relative ratio of the amplitudes of the side-components to the central component of the triplet becomes larger with the increase of the harmonic order. Is it the general tendency common in all the other stars which you have analyzed?

Don Kurtz: Yes, it is. The higher amplitude of the outside pair of frequencies in the harmonic triplets, relative to the central frequency, describes the fact that the light curve is more nearly sinusoidal at Blazhko minimum and more non-sinusoidal at Blazhko maximum. This can be seen in the light curves themselves.

Darragh O'Donoghue: Are the data you have presented consistent with the theories which will be presented at this meeting?

Don Kurtz: By fiddling with various parameters in those theories, the answer is probably yes. That means the solution to the Blazhko effect is still unknown.

Luis Balona: Have you seen any significant power in frequencies independent of the main pulsation frequency or the Blazhko frequency? These would be good candidates for nonradial pulsation.

Don Kurtz: Yes, we do sometimes see additional frequencies. However, I have not yet seen one when there is convincing evidence that it is real; i.e. they often are integral numbers of d^{-1}, or are associated with amplitude or phase variability.