A Search for Eclipsing Binary Lightcurve Variations among MACHO Project Lightcurves of 3256 Fundamental-Mode RR Lyrae Variables in the Galactic Bulge

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ABSTRACT

The MACHO Project collected photometry of many RR Lyrae stars from its observations of the Milky Way's bulge. We examined the lightcurves of 3256 stars identified as RRab Lyr variables by Kunder et al. (2008), subtracting an empirical model of the pulsation lightcurve and searching for periodic variation in the residuals. There are no systems which show the brief dips in light characteristic of detached eclipsing binary systems. We discuss the results for objects which show the largest residual periodic modulation, most of which are probably due to aliases of the fundamental period.

Subject headings: binaries: eclipsing – RR Lyrae stars

1. Introduction

Measuring the distances to objects is one of the most fundamental tasks in astronomy, yet it is also one of the most difficult. Among the many indirect methods astronomers have devised for dealing with this problem is the technique of “standard candles:” identifying a class of sources which have the same luminosity and are easy to recognize. RR Lyrae stars fit into this category: they vary in brightness by a considerable amount (amplitudes of order half a magnitude) in a short time (periods of order half a day). Moreover, their light curves exhibit a characteristic shape: a rapid rise in brightness followed by a leisurely fall (Preston 1964; Jameson 1986; Smith 1995).

Although RR Lyr stars have become important tools for the investigation of galactic structure, they are not as well understood as one would wish for such fundamental calibrators. For example, we cannot compare rigorously our models of stellar structure and their predictions for pulsation to observations, because we do not know precisely the mass of any RR Lyr star. The reason is simple: despite a few false alarms (Soszyński et al. 2003; Prsa et al. 2008), and one case – TU UMa – of what may be a very wide binary containing an RR Lyr (Wade et al. 1999), we have found no RR Lyr stars in eclipsing binary systems which can be studied via photometric and spectroscopic methods. The discovery of even a few RR Lyr in eclipsing binary systems would provide a very valuable check to our understanding of these stars and improve our use of them as distance indicators. On the other hand, if comprehensive searches reveal that RR Lyr stars occur in binary systems at rates far below that of other, similar, stars, such as the pulsating W Vir variables which *have* been seen in eclipsing binary systems (Soszyński et al. 2008), we may deduce some features of the evolutionary sequence which leads to RR Lyr stars.

2. Analysis of the MACHO photometry

We begin with the collection of data described in Kunder et al. (2008), which includes measurements of 3256 stars in the Galactic Bulge made during the course of the MACHO project (Alcock et al. 1997, 1999). The data are available freely from the MACHO collaboration[1], but we could not find the detailed description of their analysis promised by the reference "Cook et al. (2007, in preparation)." We therefore do not know the particular procedures used to identify these stars as RR0 (= RRab) Lyr variables, nor to determine their fundamental periods. All we have are the results of that analysis: photometry of several thousand RR0 Lyr stars in the B_M (blue) and R_M (red) passbands of the MACHO project.

Each star in this dataset is listed with its Right Ascension and Declination and a MACHO identifier of the form $NNN.xxxxx.sssss$, in which NNN identifies the field, $xxxxx$ the tile, and $sssss$ the star within that tile. We will use this MACHO identifier as a label for particular stars throughout this paper. The data for each star consists of a fundamental period, a mean $V-$band magnitude, and a series of measurements: the Julian Date, red magnitude and estimated uncertainty, blue magnitude and estimated uncertainty. The mean $V-$band magnitudes fall largely in the range $16 < m_V < 19$, but the red and blue magnitudes listed for each measurement are on an instrumental system and lie between -5 and -8. Figure 1 shows a histogram of the number of epochs of measurements of each star, which is typically several hundred.

For the benefit of readers who may decide to use this database for their own work, let us mention that some caution is required. Some measurements ought to be discarded: for example, those marked with magnitude values of -99 or magnitude uncertainties of 9.999. We found that others are so noisy that they provide no significant information. Both the "crowding" and "FWHM" attributes associated with each measurement can be used to identify data of low

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[1] http://wwwmacho.anu.edu.au/

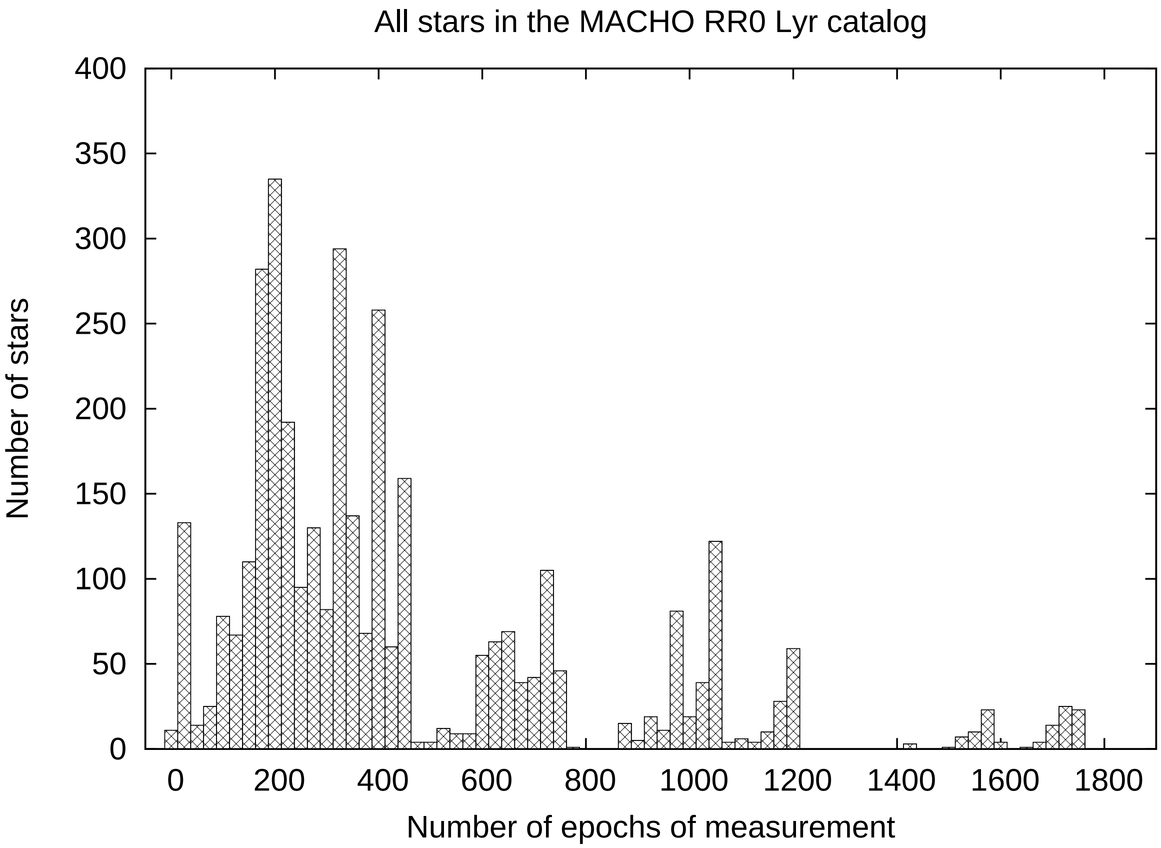

Fig. 1.— Number of epochs of measurement for stars in the MACHO Bulge RR0 Lyr catalog.

significance. After examining the pattern of outliers in several test cases, we decided to discard any measurements in which the "FWHM" values for both the red and blue images was larger than 6.5 pixels.

This catalog includes measurements made over a span of seven austral winters, starting in April, 1993, and ending in October, 1999, but most fields were not observed during all seven seasons. Let us choose a single star as an example, and follow it through our analysis. Star 101.21167.00060 is one of the brighter stars in the catalog, with a mean $V-$band magnitude of 16.34. A graph of its photometry, Figure 2, reveals that its field was not part of the regular observing sequence during the second season.

The goal of this work is to seek evidence of eclipses in the light curves of RR Lyr stars. It would be easier to find such evidence if the large variations in light due to the RR Lyr pulsations are removed. Therefore, we created a model for the regular RR Lyr light curve of each star and subtracted it from the measurements, leaving the residuals for further consideration. Our method to create the model for each star was simple: we phased the data with the period given in the MACHO catalog, divided the data into 20 bins of equal size in phase, and computed the median magnitude within each bin. We assigned this median magnitude to the phase in the middle of its bin. Finally, we interpolated linearly between these median values to determine the magnitude at any phase. Figure 3, shows the resulting models – one for the red magnitudes, one for the blue magnitudes – for star 101.21167.00060.

Note that this simple approach has an obvious drawback: it does not match the actual light curve well in places where there is sharp change, such as phase 0.7 in Figure 3. However, it does provide a reasonable model for stars with relatively few measurements, and it handles noisy data very well.

After creating separate models for the red and blue measurements of each star, we subtracted the model from the data, leaving a set of residual magnitudes. We show an example of these

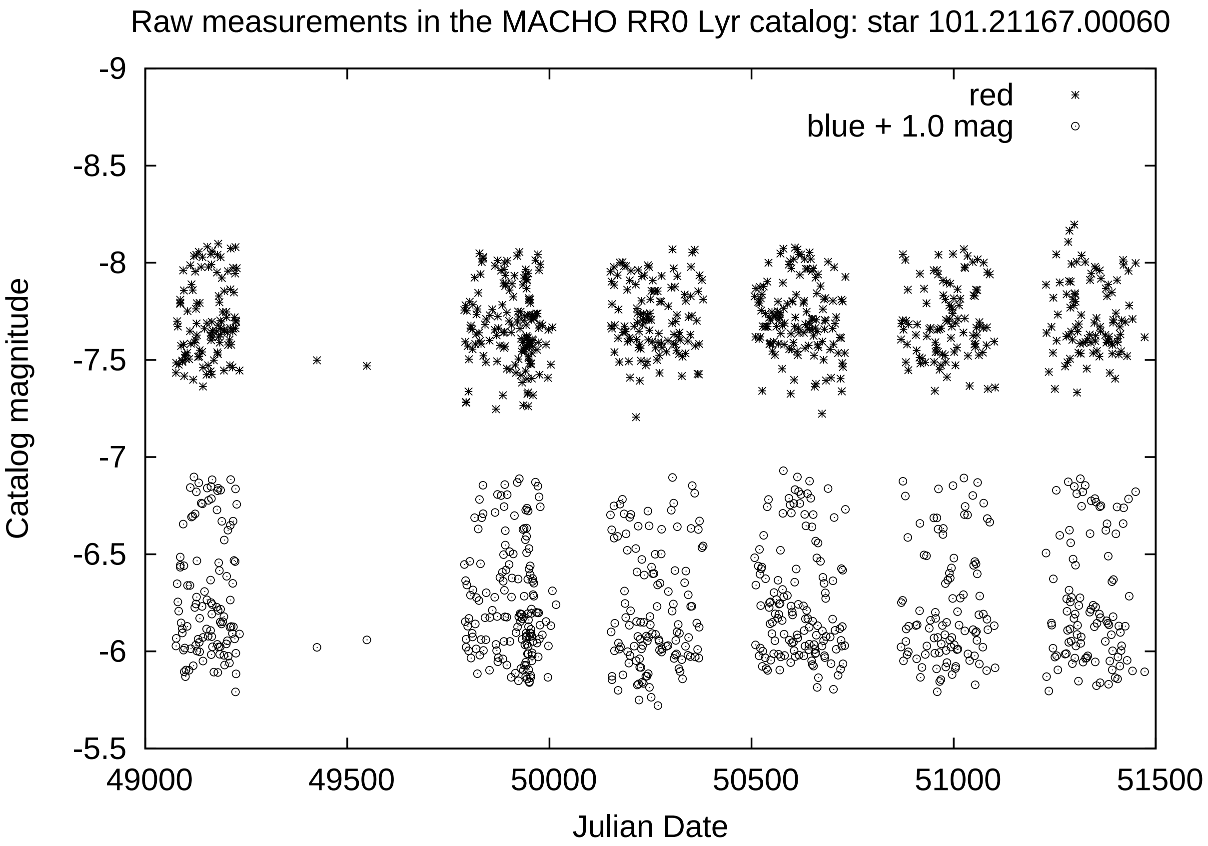

Fig. 2.— Photometry of one bright star.

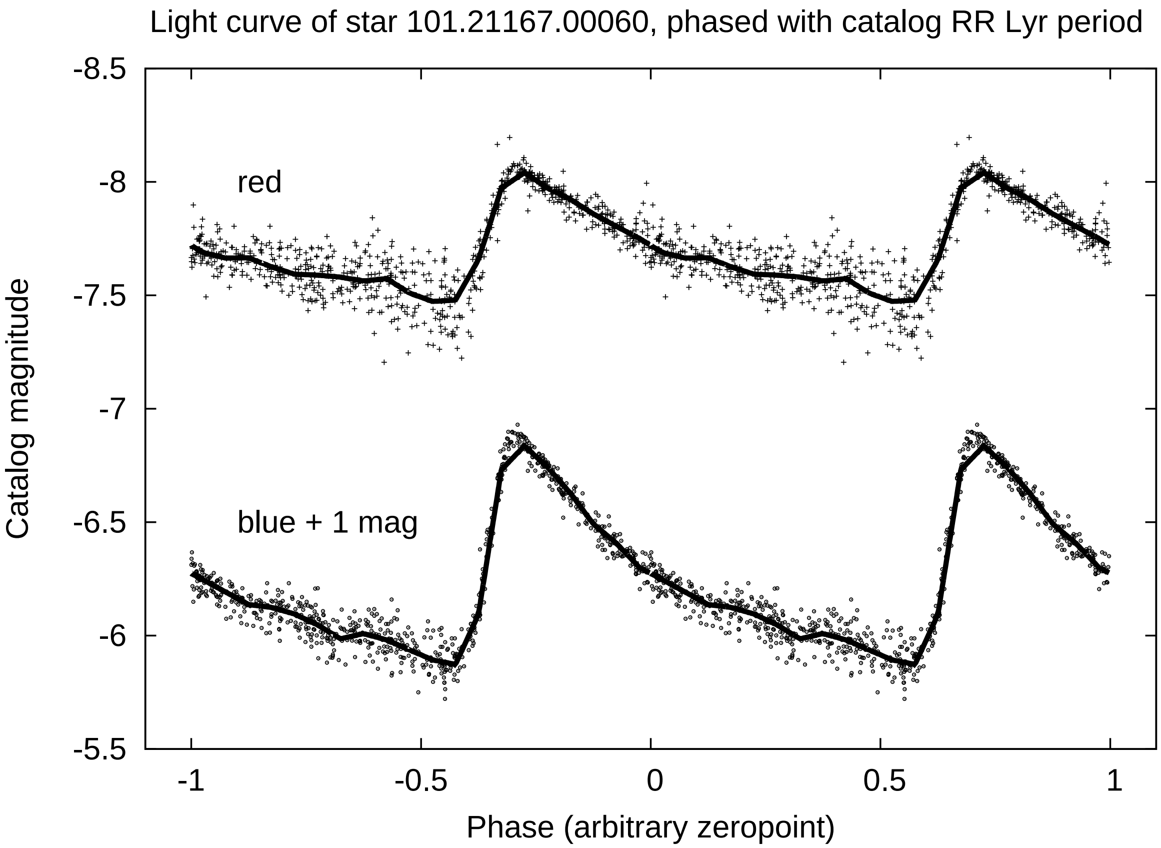

Fig. 3.— The model light curves for one bright star.

residuals, phased with the RR Lyr period, in Figure 4.

3. Identifying eclipsing binary candidates

Having subtracted model RR Lyr light curves from the measurements of each star in the red and blue passbands, our next task was to search for patterns in the residuals which might indicate eclipses. There are many approaches to this problem, in general, but given the nature of our data – very inhomogeneous sampling with large gaps and often high noise levels – and the uncertain nature of our expected signal – which could range from sharp, narrow dips in light to smooth, continuous variation – we chose the "string length" method (Dworetsky 1983; Bhatti et al. 2010).

Our implementation of this technique follows closely the description given in Bhatti et al. (2010). We generated string lengths for periods between 0.10 and 100 days, using steps equally spaced in frequency of size 0.0001 cycles per day. For each possible period, we computed a string length separately for the red and blue measurements, then added the two lengths to form an overall figure of merit for that period. We set thresholds for significance following the suggestions of Dworetsky (1983) and ignored periods which exceeded these thresholds. We saved the periods which yielded the 10 shortest string lengths for further consideration. In addition, we computed the string length for a period of 9999 days; since this was much longer than the actual span of observations, it yielded a "phased" light curve which was simply in chronological order. Stars with very long periods of variation would show a short string length for this artificial period.

The next step was to examine the results for each star visually. We created a graphical representation of the star's light phased with the best three periods, as shown in Figure 5. In addition to the measurements, the graph displayed the candidate periods, both in days and as a fraction of the star's RR Lyr period. A relatively quick view of this graph was sufficient to decide if any of the candidate periods yields any significant signal, and if the candidate periods are simply

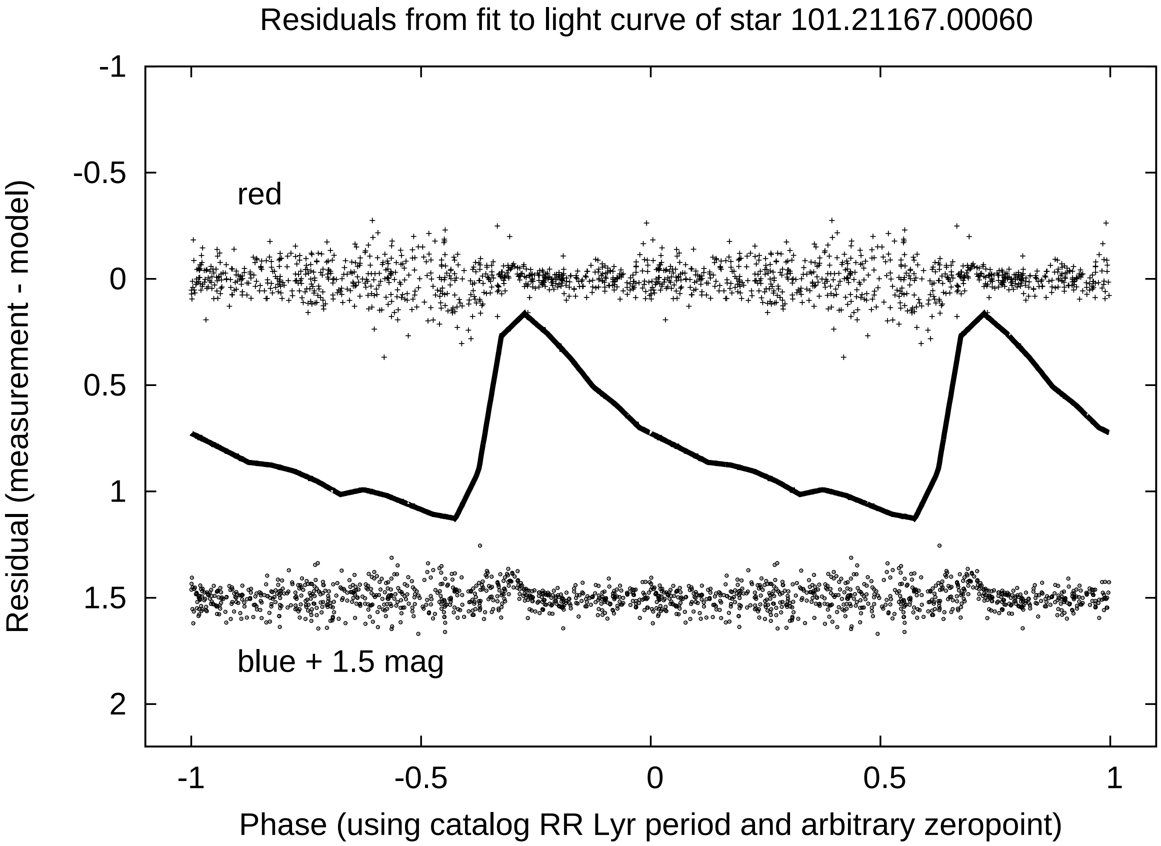

Fig. 4.— Residuals from the model light curves for one bright star; the blue model curve is shown, offset from the measurements for clarity.

multiples or fractions of the RR Lyr period. The author examined graphs for all 3256 stars in the catalog and noted those which deserved further consideration.

Stars which did show promising signs were subjected to additional tests. First, light curves were generated for all 10 of the best candidate periods, in order to see which candidate period looked most significant to the eye. Second, we sometimes tried new periods, generating graphs and string lengths manually, in order to yield a phased light curve with 2 maxima. For example, if the best period P created a light curve with 5 maxima, we checked the period $0.4P$. When the results looked good, we replaced the best automatically generated candidate period with the manually chosen period.

The final step was to improve the value of the best candidate period, and to derive an estimate for the uncertainty in that period. We set a small range around the best candidate period, extending 0.05 days in both directions, and divided the range into 10,000 pieces. After computing string lengths for each piece, we identified the range of periods which led to a local minimum in string length (see Figure 6). Following the precepts of Belserene (1983) and Fernie (1989), we fit a parabola to this local minimum and used the parameters of the fitted curve to estimate both the period and the uncertainty in the period.

Based on a visual scan of the phased light curves of the residuals for the best three candidate periods, we selected 25 of the 3256 stars in the RR0 Lyr catalog for further analysis. After additional checks, we found that 11 stars show clear, periodic patterns in their residuals. We list these 11 stars, which we shall call “candidates”, in Table 1. Values in the column labelled “main period” are taken from the catalog of Kunder et al. (2008), while those in the column labelled “residual period” were determined by this paper. Phased light curves of each candidate are shown in Figures 7 to 17.

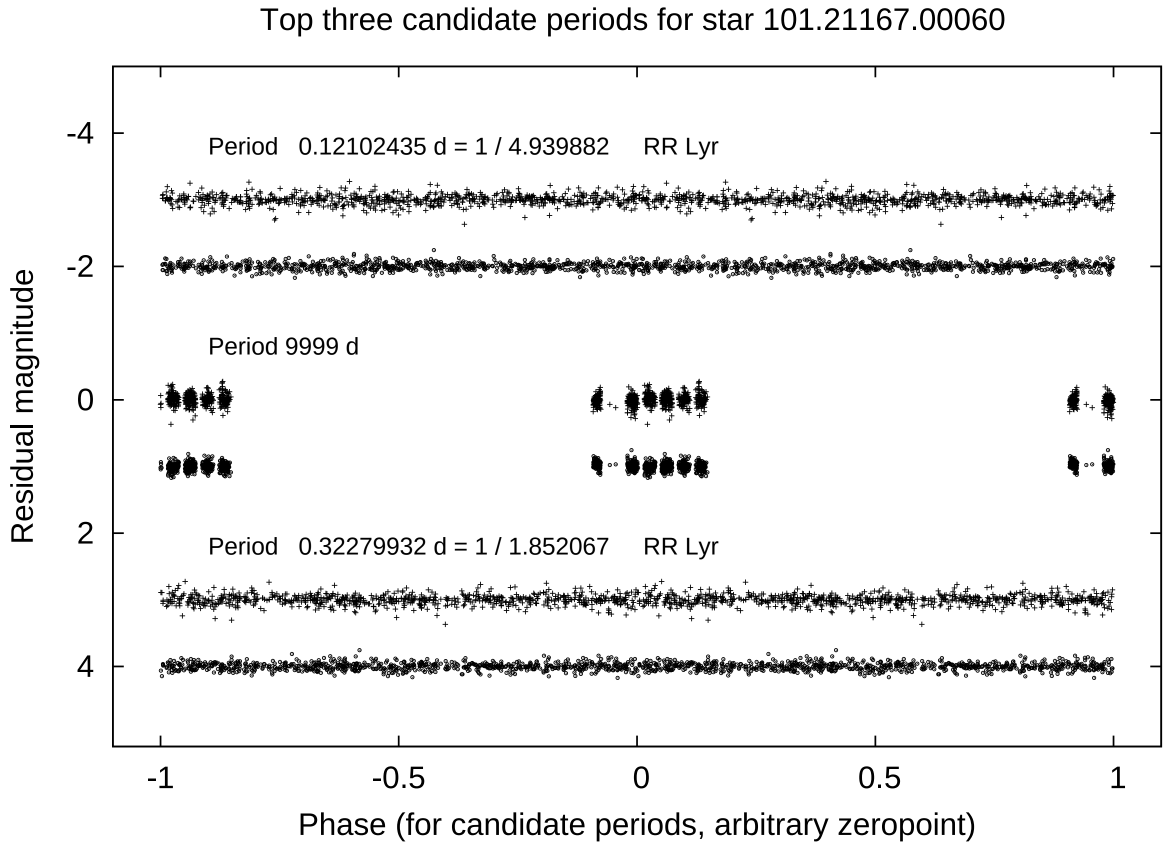

Fig. 5.— Light curves for the residuals of a bright star, phased with the best three candidate periods.

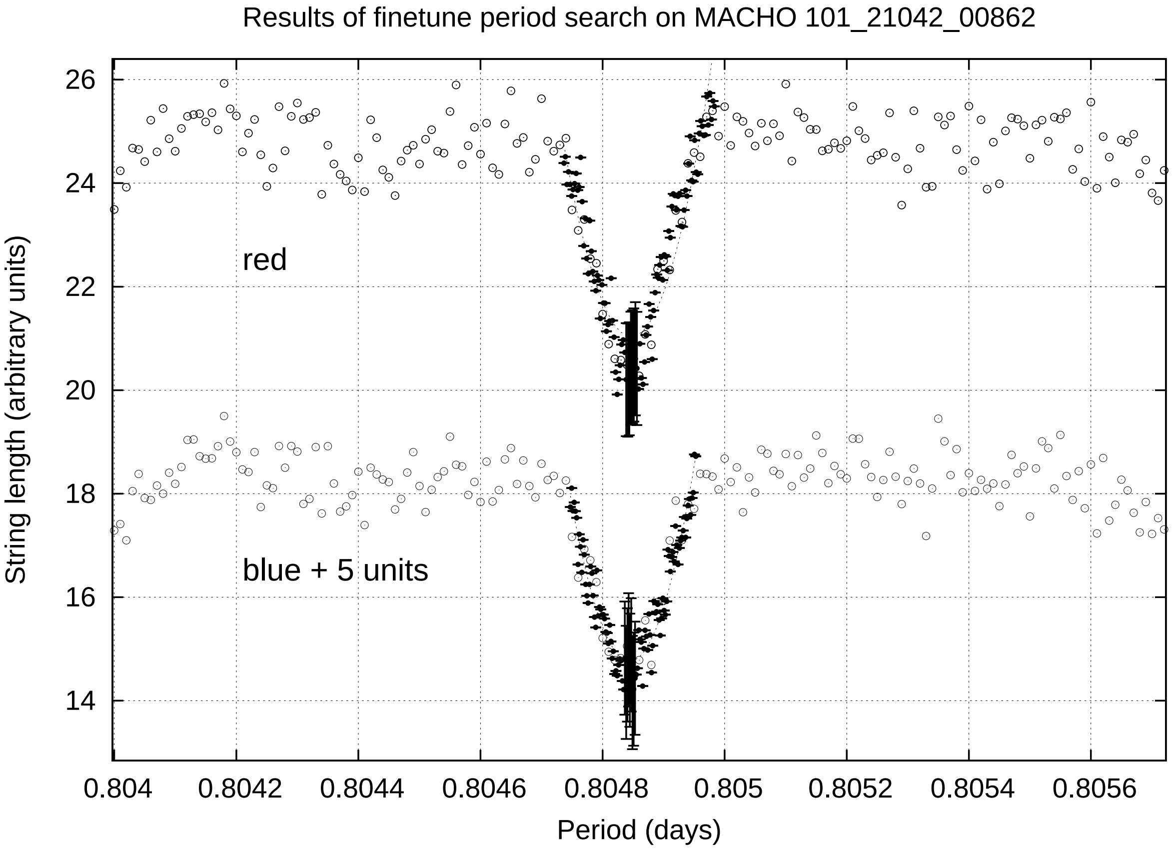

Fig. 6.— Determining the uncertainty in the best candidate period; the symbols with vertical errorbars span the uncertainty in period.

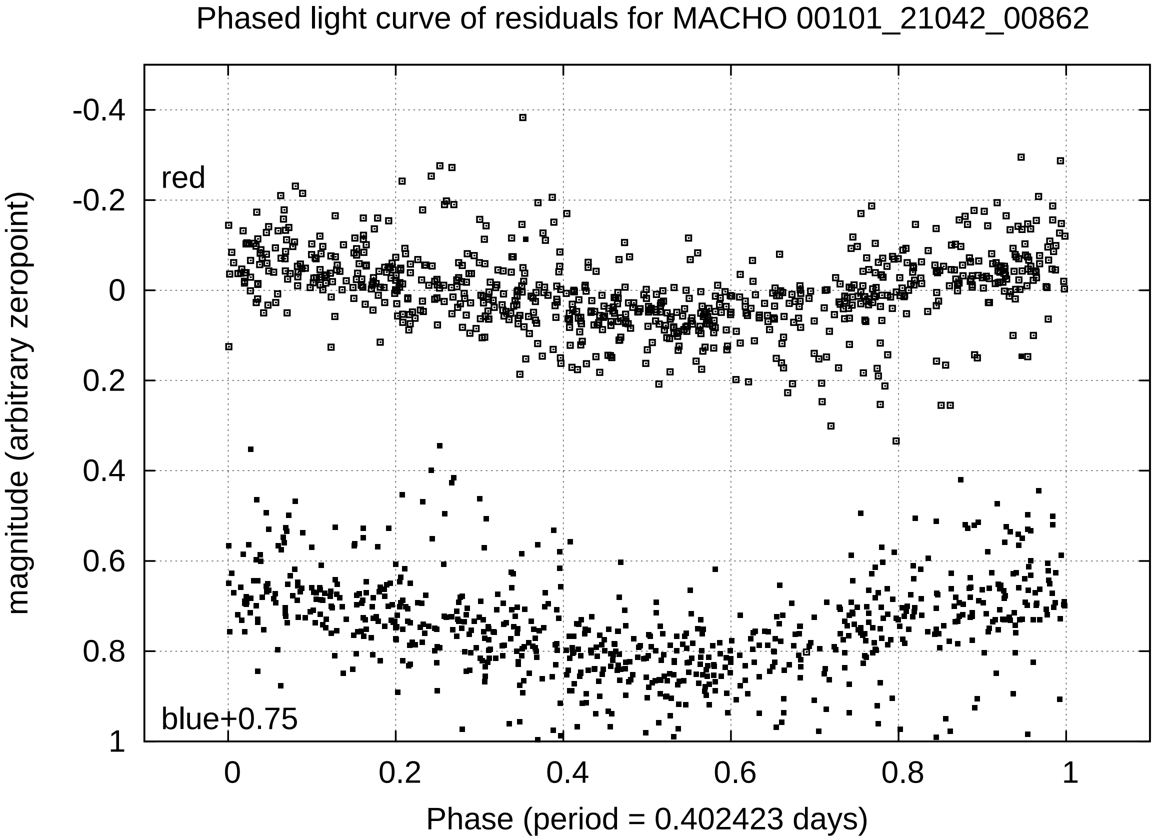

Fig. 7.— Phased light curve of star 101.21042.00862.

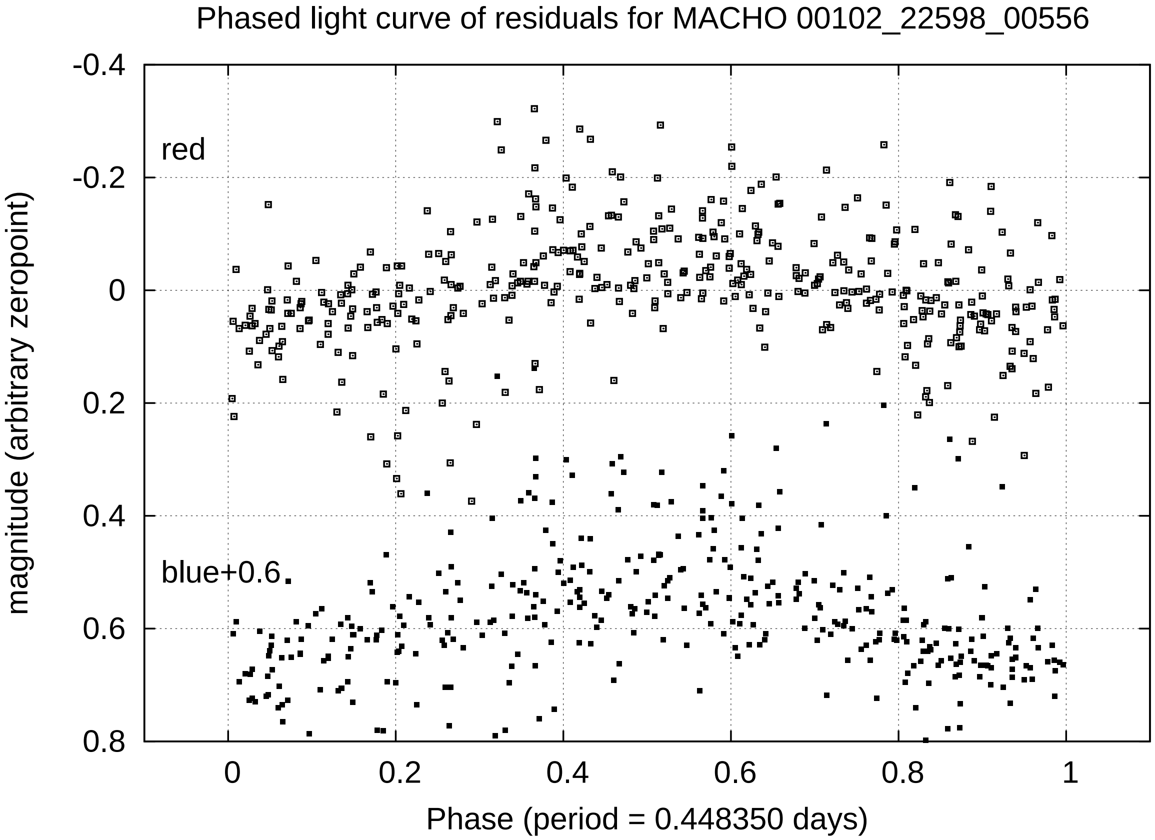

Fig. 8.— Phased light curve of star cand 102.22598.00556.

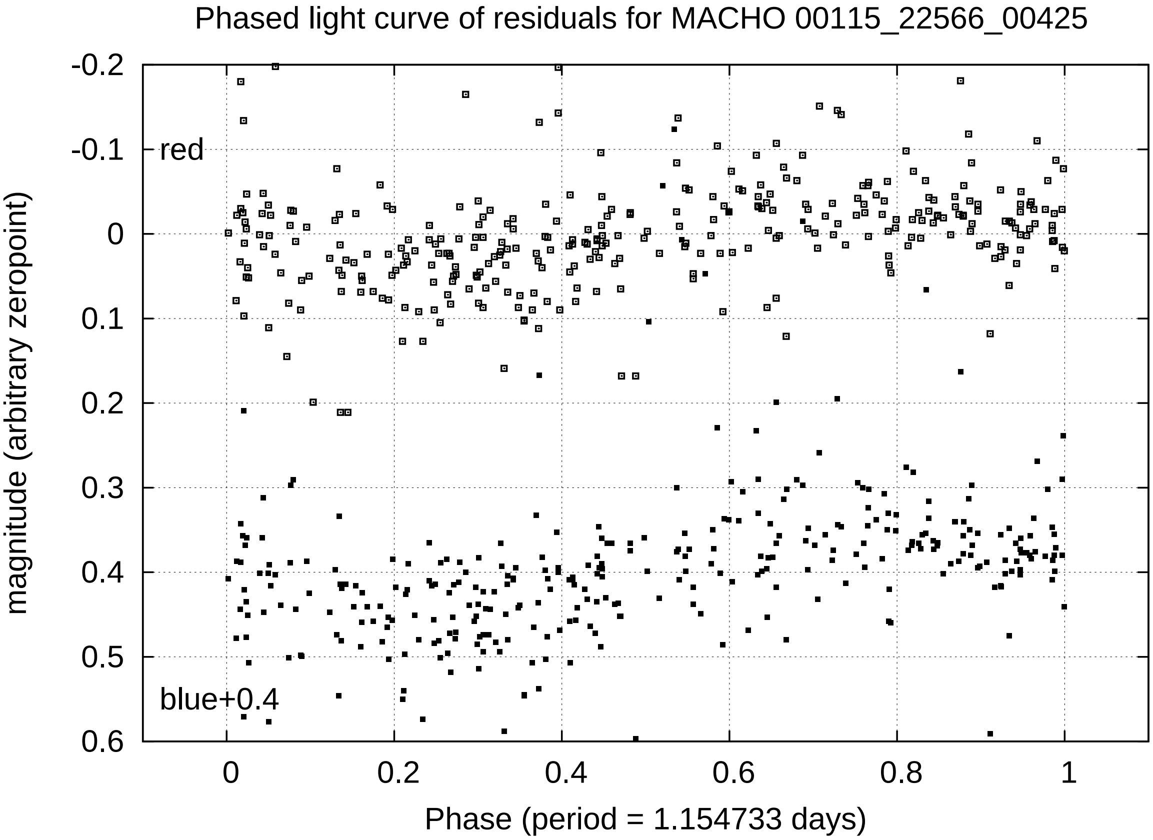

Fig. 9.— Phased light curve of star 105.22566.00425.

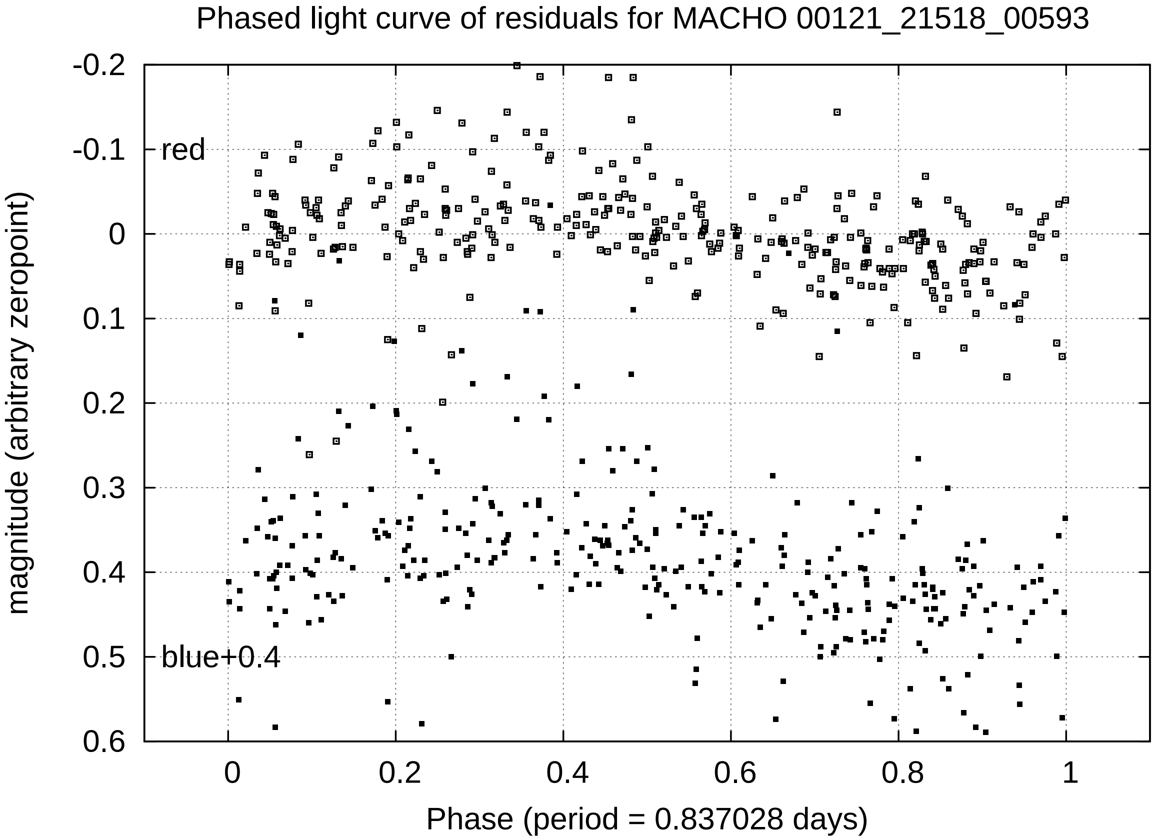

Fig. 10.— Phased light curve of star 121.21518.00593.

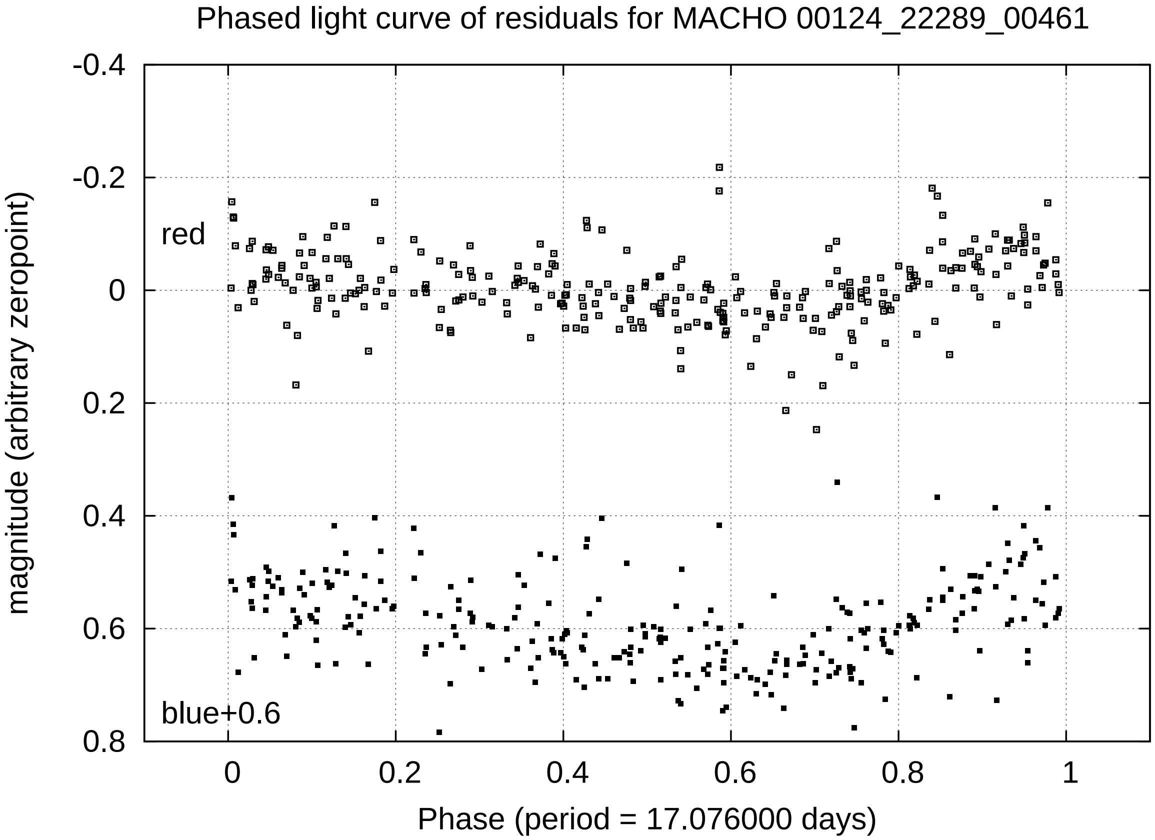

Fig. 11.— Phased light curve of star 124.22289.00461.

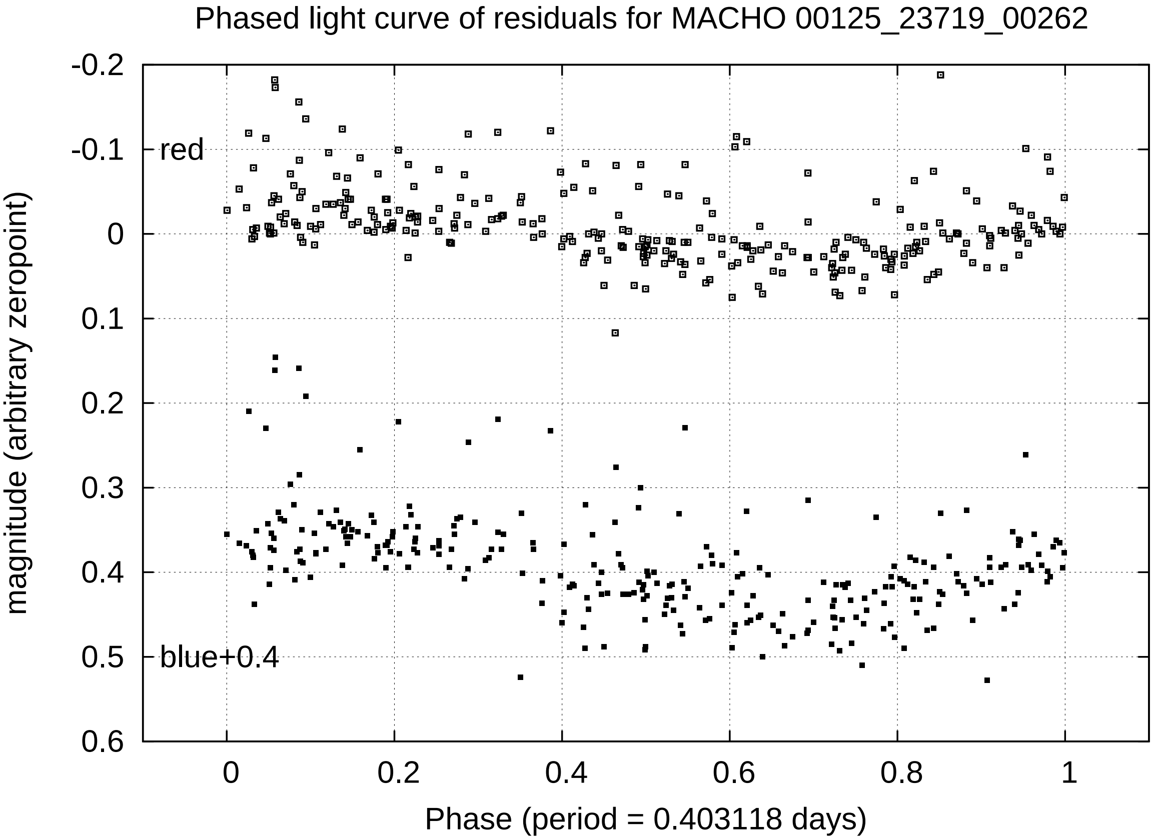

Fig. 12.— Phased light curve of star 125.23719.00262.

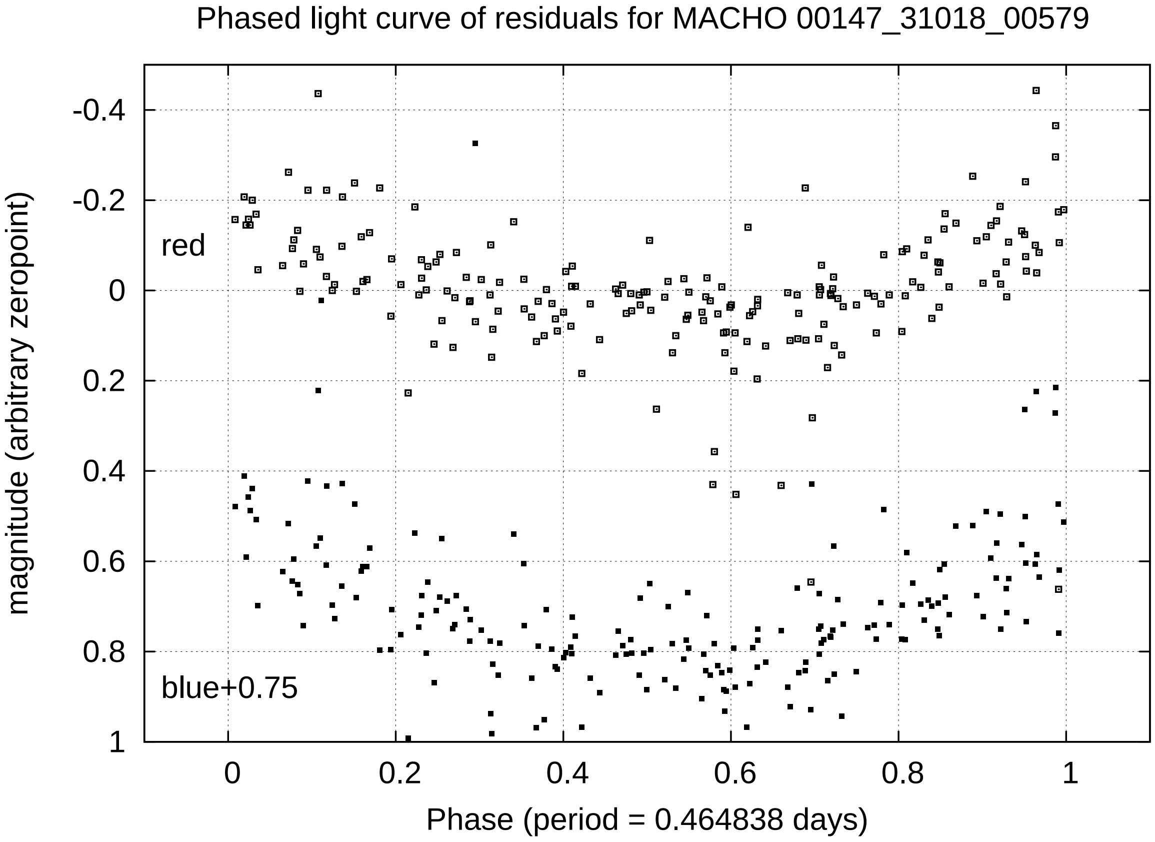

Fig. 13.— Phased light curve of star 147.31018.00579.

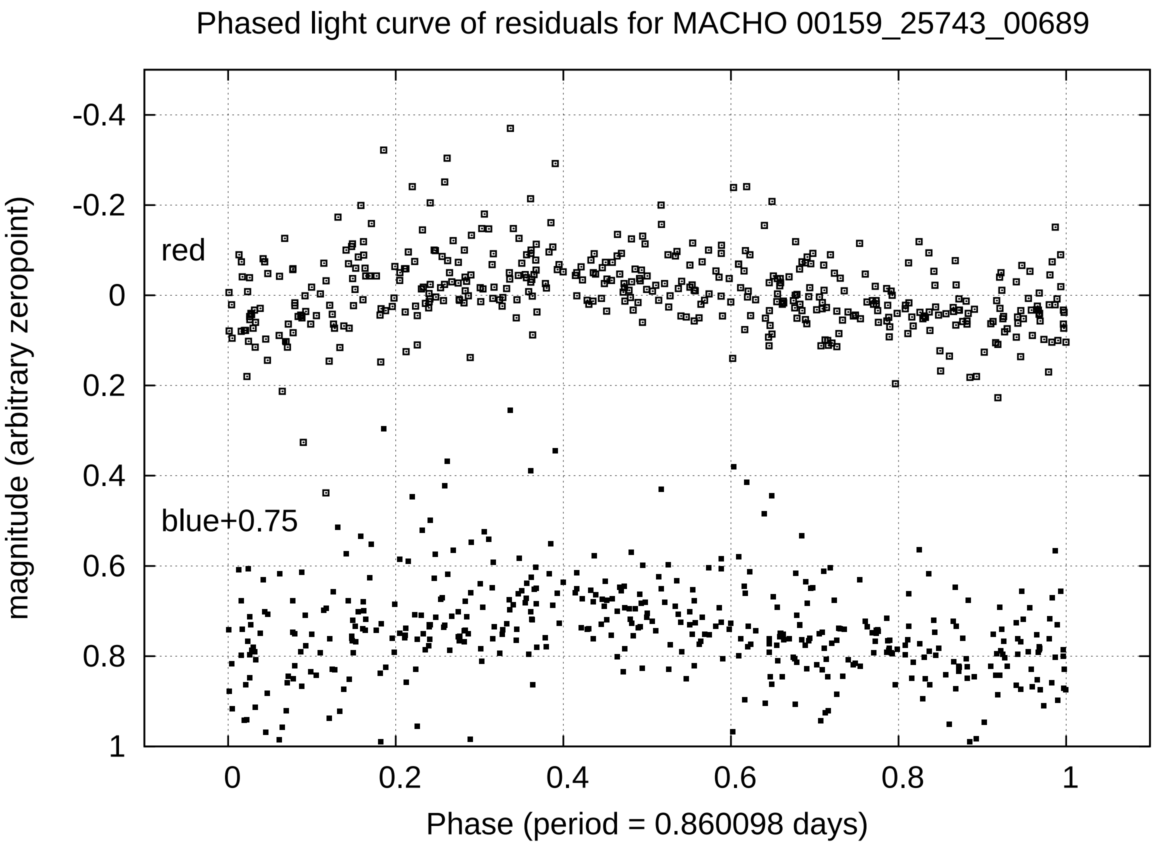

Fig. 14.— Phased light curve of star 159.25743.00689.

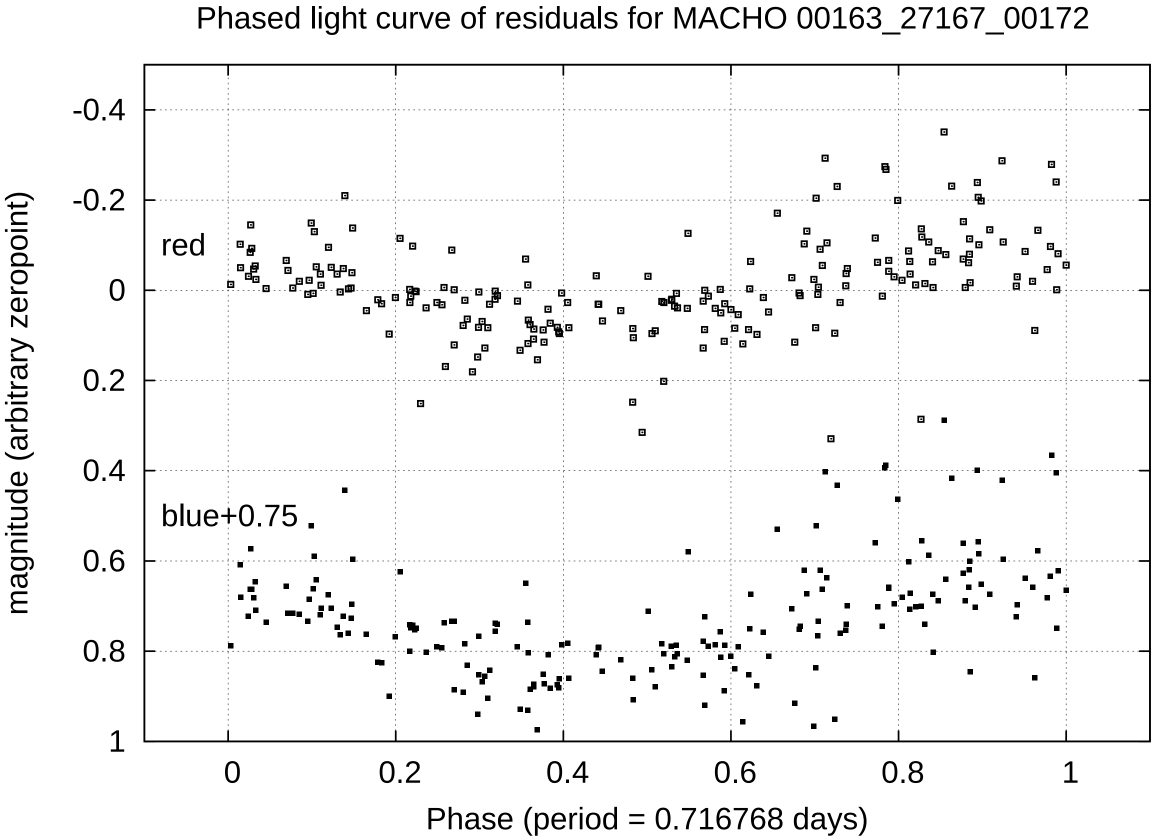

Fig. 15.— Phased light curve of star 163.27167.00172.

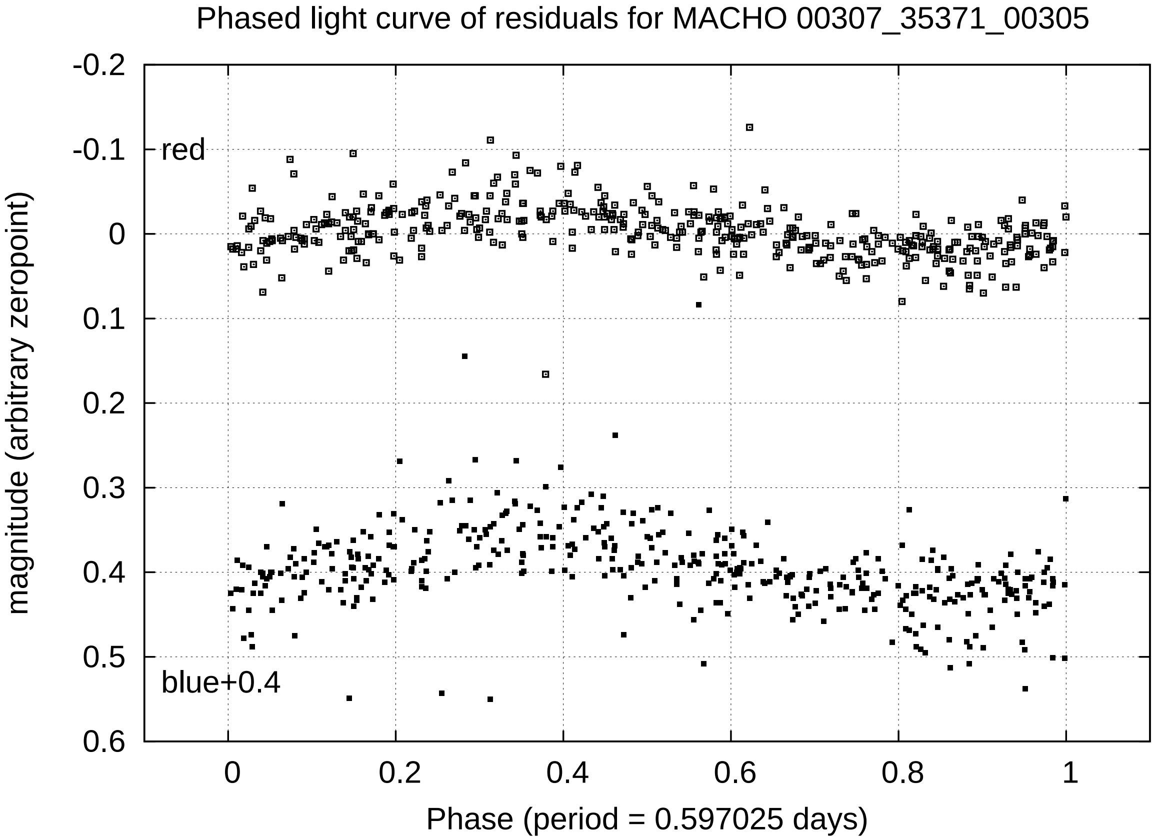

Fig. 16.— Phased light curve of star 307.35371.00305.

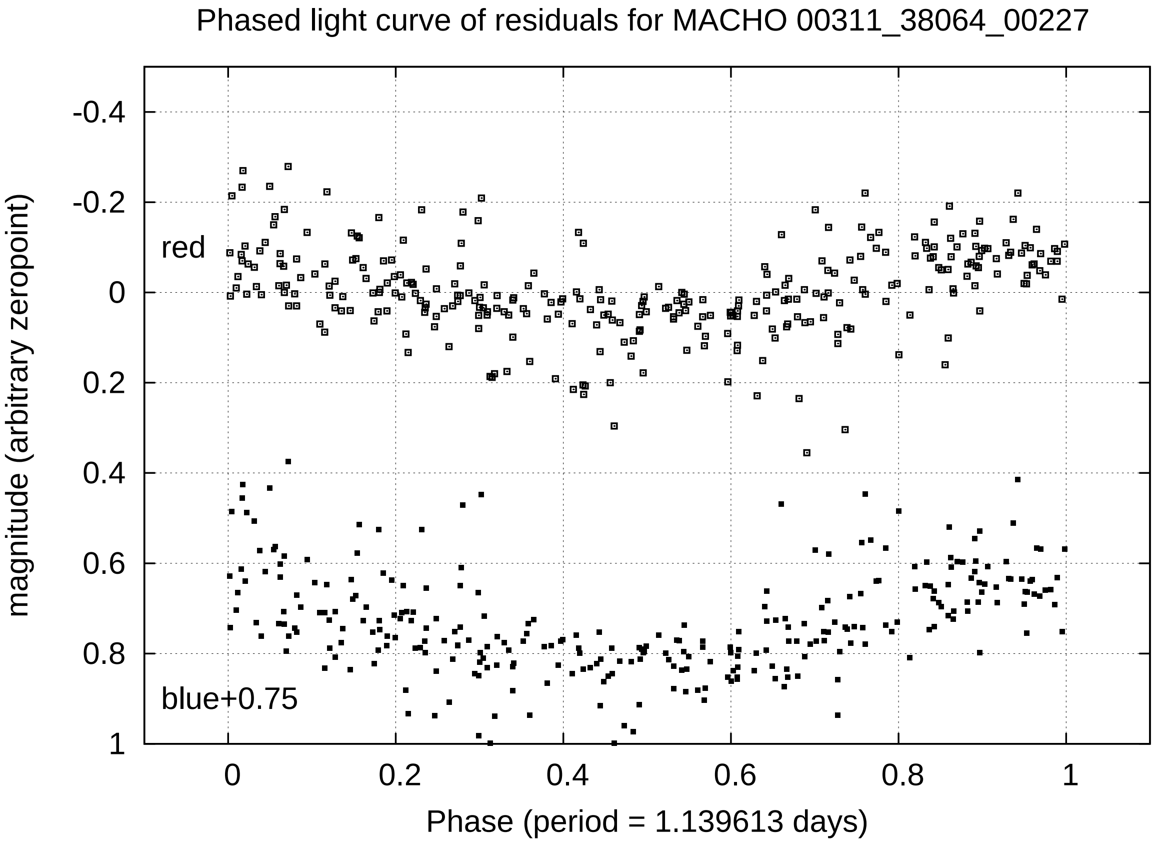

Fig. 17.— Phased light curve of star 311.38064.00227.

Table 1: Candidates with periodic residuals

MACHO ID	RA^a	Dec^a	V^b	main period^c	residual period^c	amp^d	notes^e
101.21042.00862	18:05:18.60	-27:16:14.5	17.55	0.413096	0.402423 ± 0.000005	0.13	A
102.22598.00556	18:08:54.96	-27:31:49.4	17.36	0.444434	0.448350 ± 0.000005	0.13	A
115.22566.00425	18:09:09.00	-29:40:30.4	16.83	0.530609	1.15473 ± 0.00004	0.08	D
121.21518.00593	18:06:25.92	-30:12:03.2	17.44	0.452635	0.83703 ± 0.00003	0.07	C
124.22289.00461	18:08:15.72	-30:50:30.5	17.72	0.498851	17.076 ± 0.002	0.12	
125.23719.00262	18:11:45.96	-30:50:13.2	16.47	0.684945	0.403118 ± 0.000005	0.10	B
147.31018.00579	18:28:43.68	-29:31:55.6	18.45	0.528649	0.46484 ± 0.00001	0.22	
159.25743.00689	18:16:18.12	-25:52:22.4	17.56	0.459778	0.86010 ± 0.00003	0.15	B
163.27167.00172	18:19:39.36	-26:15:58.0	16.98	0.428079	0.71677 ± 0.00003	0.16	
307.35371.00305	18:14:57.12	-24:04:48.7	17.62	0.611346	0.59703 ± 0.00001	0.07	A
311.38064.00227	18:19:33.60	-23:46:16.0	16.86	0.528800	1.13961 ± 0.00005	0.17	C

[a] J2000

[b] mean magnitude, from Table 3 of Kunder et al. (2008)

[c] days

[d] magnitude of residual variation, peak-to-peak in blue band

[e] A = residual period within 3% of main period ; B = residual period within 1% of 1-day alias; C = within 2% ; D = within 3%

4. Discussion

None of these candidates shows the sharp, narrow dips of a detached system. We suggest two reasons to explain the absence of such stars: first, stars with dips of large amplitude may have been excluded from the catalog of Kunder et al. (2008), if that catalog was constructed to contain only stars with light curve shapes of an isolated RRab variable. Correspondence with the first author of Kunder et al. (2008) suggests that this was not the case, but we cannot dismiss it as a possibility. Second, stars with dips of small amplitude may have escaped our analysis due to the relatively low signal-to-noise ratio of the individual measurements. The dataset of Kunder et al. (2008)

includes an estimated uncertainty with each magnitude measurement. We computed the mean value of the uncertainties for each star; the median over 3565 stars of all those mean uncertainties is 0.023 mag in the red band and 0.028 mag in the blue band. A system of shallow eclipses, with an amplitude of only two or three times the typical uncertainty and involving only a small fraction of the measurements, would not be found by our methods. The smallest amplitude among our 11 candidates is 0.07 mag peak-to-peak, and that variation involves all the measurements in the light curve, not just a few.

All the candidates have gently undulating light curves, rather than the sharp dips of a detached eclipsing system. What might cause this sort of periodic variation? Among the possibilities are artifacts from the subtraction of the model light curve; aliases of the RR Lyr frequency; an additional frequency of oscillation in the RR Lyr star; Blazhko variations in the RR Lyr star; blended light from another variable star(s); or the orbital motion of the RR Lyr star around a close companion. Let us examine these possibilities.

Our method for subtracting the main RR Lyr light curve from each star's measurements was based on a simple model made of linear segments. If the model failed to reproduce some features properly, the subtraction would leave a signal with the same period as the RR Lyr pulsation. Our 11 candidates include 3 stars for which the residual period is within 3 percent of the main RR Lyr period; we mark these in Table 1 with a "A" in the "Notes" column. It is possible that these candidates may be due to a low-amplitude version of the Blazhko effect, of which we say more below.

The majority of the measurements described in Kunder et al. (2008) were collected on a nightly basis; that is, each star was observed once per night, and often at roughly the same time. We therefore expect to see aliases of the true frequency ω_0 in the measurements with frequencies

$$\omega_{\text{alias}} = |\omega_0 \pm N\omega_{\text{sample}}| \tag{1}$$

where $\omega_{\rm sample} = 1\,{\rm day}^{-1}$ and N is some small integer. We computed the alias frequencies for all candidates using $N = 1$ and 2, and compared them to the frequencies of the residual variations. We found two cases in which the residual frequencies were within 1 percent of the main RR Lyr frequency (marked “B” in Table 1), two more cases within 2 percent (marked “C”) and one more case within 3 percent (marked “D”).

Some RR Lyr stars are known to oscillate at two frequencies; these double-mode stars always have a ratio of periods $P_1/P_0 \simeq 0.746$ (Nemec 1985; Szczygiel & Fabrycky 2007). None of our candidates have periods in their residuals which yield this ratio with the periods listed in Kunder et al. (2008). The lack of such double-mode pulsators may not be unexpected, since they appear to be very rare in the central regions of our Milky Way; Mizerski (2003) found only 3 such stars among a sample of 1942 RRab and 771 RRc stars observed near the center of the Milky Way in the OGLE-II database (Udalski et al. 1997). Their absence may also be a reflection of the selection criteria used by Kunder et al. (2008) to create the catalog of RR Lyr stars.

Some RR Lyr stars exhibit slow changes in the shape and amplitude of their light curves, with periods of tens to hundreds of days; this is known as the Blazhko effect. Mizerski (2003) finds roughly 25 percent of all RRab stars in a sample near the galactic center show the Blazhko effect. Could it be responsible for any of our candidates? MACHO 124.22289.00461, with a residual period of just over 17 days, is the only candidate for which this seems a possibility. Unfortunately, since the main RR Lyr period is almost exactly half a day, the measurements made during each observing season cover only a small range in phase; thus, we cannot see if the shape of the light curve changes over this 17-day interval. The three stars marked with an “A” in Table 1 have residual periods which could be produced by Blazhko-like periods of 15 to 50 days beating against the main RR Lyr period; however, we examined the phased light curves of these stars over each season and see no strong evidence of Blazhko variations.

The MACHO study area in the galactic bulge was, by design, chosen to have a very high stellar density. If the density is high enough, we may expect that blends of unrelated foreground or background variable stars may cause periodic signals in the residuals of RR Lyr light curves. Let us perform a very quick quantitative check on this idea. We examined one of the fields in this area, number 102, counting all the stars in the MACHO database (not just the variable ones) as a function of apparent V-band magnitude. Since the typical FWHM in these measurements is $3\overset{''}{.}5$, a rough estimate of the area of the seeing disk is about 10 square arcseconds. We find that, on average, there are 1.8 stars with $V \leq 20.1$ in each seeing disk, and about 0.5 stars with $V \leq 18.1$. The RR Lyr stars in the catalog of Kunder et al. (2008) range roughly $16 \leq V \leq 19$. so indeed a significant fraction of all the RR Lyr stars in the catalog must be contaminated by light from nearby stars at a level of 0.1 mag. It may in fact be surprising that we find so few objects with periodic variations in their residuals; however, since we do not know the details of the process by which RR Lyr stars were selected from the MACHO database, we cannot comment further.

Could any of the candidates be due to the effects of a binary companion of the RR Lyr star? If two stars orbit each other with a separation which is only slightly larger than their combined radii, their shapes may grow distorted enough that they produce a gently undulating light curve, even in the absence of eclipses. An RR Lyr star of mass $0.7 M_{\odot}$ with a companion of equal mass in a circular orbit of period 2 days would have a separation of about 7 $R_{\odot}$. The radius of a typical RR Lyr star varies from about 4 $R_{\odot}$ to 6 $R_{\odot}$ (Sodor et al. 2009), leaving little room for a companion. If an RR Lyr star did orbit a more compact companion with a period in this range, it would surely be greatly distorted, and so liable to vary in brightness as it moved in its orbit. Whether an RR Lyr star would have stable pulsations in such a close orbit is beyond the scope of this paper. Note that in this situation, the period listed in Table 1 would be *half* of the orbital period.

We conclude that our search through a sample of 3256 RRab Lyr stars failed to find any detached eclipsing binary systems, and very likely failed to find eclipsing systems of any sort with amplitudes of ≥ 0.07 mag. The implied disjunction between stars pulsing in the fundamental

RRab Lyr mode and stars in binary systems may provide clues to the evolution of RRab Lyr stars. Our simple technique for removing the ordinary variation of light in order to seek some signal in the residuals would be well suited to the more sinusoidal variations of RRc Lyr stars, many of which can be found in the catalogs of Soszyński et al. (2009) and Soszyński et al. (2003).

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