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Research Note

Discovery of a variable star population in NGC 2808

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Abstract. We have applied the image subtraction method to images of the peculiar, bimodal-horizontal branch globular cluster NGC 2808, taken over a total of six nights over a range of five months. As a result, we have found, for the first time, a sizeable population of variable stars in the crowded inner regions of the cluster, thus raising the known RR Lyrae population in the cluster to a total of 18 stars. In addition, an eclipsing binary and two other variables with periods longer than 1 day were also found. Periods, positions and (differential) light curves are provided for all the detected variables. The Oosterhoff classification of NGC 2808, which has recently been associated with a previously unknown dwarf galaxy in Canis Major, is briefly discussed.

Key words. Galaxy: globular clusters: individual: NGC 2808 – stars: horizontal-branch – stars: variables: RR Lyr

1. Introduction

Adequate interpretation of the color–magnitude diagrams of globular clusters (GCs) in terms of age, metallicity and other evolutionary parameters is one of the most important goals of stellar astrophysics, constraining both the formation history of the Galaxy and the age of the Universe. Yet, there are still several open problems in the interpretation of these diagrams, one of the most outstanding being the so-called "second-parameter problem".

The prominent sequence that is seen as a "horizontal branch" (HB) in the visual color–magnitude diagrams of Galactic GCs generally changes from being predominantly comprised of stars to the red of the RR Lyrae (RRL) instability strip at high metallicities to having mostly blue HB stars at the low end of the [Fe/H] scale. However, Sandage & Wildey (1967) and van den Bergh (1967) noted that, at a given metallicity, one may find very different HB types. Perhaps the best known examples are the second-parameter pairs NGC 288/NGC 362 and M 13/M 3, comprised of GCs which have very closely the same metallicity, and yet dramatically different HB morphologies.

Scenarios for the formation of the Galaxy whereby it may have grown through the accretion of protogalactic fragments have been based, to a large degree, on the interpretation that age is the second parameter of HB morphology (e.g., Searle & Zinn 1978; van den Bergh 1993; Zinn 1993). Indeed, there is now some strong evidence that age may play an important part in explaining the syndrome, at least in the paradygmatic case of NGC 288/NGC 362 (Catelan et al. 2001 and references therein). On the other hand, the case of M 13/M 3 suggests that age is unlikely to be the sole explanation (Stetson 1998, 2000).

Indeed, several additional parameters have not been ruled out and may also play a role, including mass loss (Catelan 2000), primordial abundance variations (D'Antona et al. 2002), stellar rotation (Norris 1983), deep mixing on the red giant branch (RGB; Sweigart 1997), core density (Buonanno et al. 1997), and even planetary systems (Soker & Harpaz 2000). In this sense, it has also been argued that GCs presenting the second parameter syndrome *internally* – that is, those with *bimodal* HBs – could provide a key to understanding the phenomenon (e.g., Rood et al. 1993; Catelan et al. 1998a,b). Conversely, a fully satisfactory solution to the problem will not logically have been reached until bimodal-HB GCs have been properly accounted for.

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RR Lyrae (RRL) stars may be able to assist us in our quest for an answer. In particular, some models for the origin of bimodal HBs require that blue HB and RRL stars be unusually bright, whereas others do not. On the other hand, the period-mean density relation tells us that the RRL pulsation period, at a given $T_{\rm eff}$ (or amplitude), is strongly sensitive to the star's luminosity. Therefore, if RRL variables in bimodal-HB GCs follow similar period-temperature relations as do the RRL in GCs that do not show the second-parameter effect, without significant *period shifts* that may be attributed to luminosity effects, their HB bimodality is likely to be caused by mass loss variations among RGB stars, and/or by internal age variations within the cluster. This is due to the fact that both these parameters affect only the mass with which a star will arrive on the zero-age HB s(ZAHB), differences in which may cause a star to "slide" horizontally along the $T_{\rm eff}$ axis but not shift vertically along the $\log L$ axis. Conversely, period shifts with respect to the RRL in "well-behaved" GCs should be indicative of second parameters that do directly affect HB luminosity (Catelan et al. 1998b).

Of all the bimodal-HB Galactic GCs, NGC 2808 (C0911-646) stands out as the best known, and most dramatic, example. Being one of the most luminous GCs in our galaxy, with $M_V = -9.39$ mag (Harris 1996), it was early noted to have very prominent blue and red HB components, with very few if any stars in between (Harris 1974; 1975; 1978). Searches for RRL stars in the cluster have indeed confirmed that the cluster is largely devoid of these variables, photographic work culminating with the paper by Clement & Hazen (1989).

However, appropriate searches utilizing CCD detectors have apparently never been conducted in this cluster. To date, the only CCD study tackling the cluster RRL to appear in the literature seems to have been the report by Byun & Lee (1991), utilizing images obtained with the CTIO 0.9 m telescope, which however does not seem to be based on time-series photometry. No actual RRL candidates were reported in that study. Accordingly, the Clement et al. (2001) catalogue currently lists a mere 5 variables in the cluster, only two of which are actually RRL stars – the remaining being a BL Herculis star and two semi-regular variables.

Recent success at detecting sizeable numbers of RRL variables in crowded GC fields (e.g., Kaluzny et al. 2001; Borissova et al. 2001; Kopacki 2001; Corwin et al. 2003), based on high-quality CCD images and image subtraction techniques (ISIS: Alard 2000; Alard & Lupton 1998), has motivated us to revisit the variable star population in NGC 2808. Additional motivation is provided by the suggested association of NGC 2808 with the recently discovered Canis Major dwarf galaxy (Martin et al. 2004), given the constraints that RRL stars may pose on the formation history of the Galaxy (Catelan 2004; Kinman et al. 2004). Accordingly, the present paper reports on the first detection of a sizeable population of variable stars in the cluster, mainly comprised of RRL stars.

2. Analysis

The CCD images used in this study were obtained with the Danish 1.54 m telescope located at the European Southern Observatory at La Silla, Chile. The field was observed for a total of six nights, including two nights in October 2002 (14/15 and 15/16), two nights in December 2002 (11/12 and 12/13), and two nights in February 2003 (18/19 and 19/20). The seeing in October was not particularly good, generally around 1.5 to 2.0 arcsec, and images were generally elongated; whereas the December and Feburary seeing was much better, around 1.0 arcsec or less, and image elongation problems were not as severe. Unfortunately, the October B data turned out to be severely affected by fringing. Consequently, our adopted image subtraction analysis (based on ISIS2.1; Alard 2000) of the October data either did not produce useful results or was unable to locate the variables found in the December and February data. For these reasons, results for the October run are not reported here. The December run included 65 B, V image pairs, whereas the February run contained 83 B, V image pairs.

The ISIS2.1 analysis measures the difference in flux for stars in each image of the time series relative to their flux in a reference image obtained by stacking a suitable subset of images, and after convolving the images with a kernel to account for seeing variations and geometrical distortions of the individual frames (Alard 2000). We used the 10 B images with the best seeing in each of the December and the February runs, respectively, to build up the reference images. In the case of V, we used 3 images obtained in the December run, closely spaced in time. Unfortunately, because of rotation between the two sets of images, we were not able to use the same reference image in B for both of the runs. This resulted in offsets in the differential flux light curves for the two runs, which prevented us from consistently fitting B light curves using the same periods as for the V light curves, for which we were able to properly align the images and use a single reference frame for both the December and February data. For these reasons, in what follows, unless otherwise noted, we will be addressing only the results based on the V data. A full analysis of the B data will be reported on in the future, along with a discussion of possible long-period variables.

3. Results

The ISIS analysis identified 18 new variables in NGC 2808, including 16 RRL variables and two longer-period variables. Positional information and periods for these variables are provided in Table 1. Using the V-band data for the December and February runs, periods were computed using a variety of methods, including a period-finding program based on Lafler & Kinman's (1965) "theta" statistic; the phase dispersion minimization technique (Stellingwerf 1978); information entropy minimization (Cincotta et al. 1995); Period98 (Sperl 1998); and CLEANest (Foster 1995). However, because of the relatively poor phase coverage and the long time interval between the December and February observing runs, we have found that we are typically unable to decide among period aliases to within the ±0.01 d level, particularly in the cases of the RRab and longer-period stars. Therefore, periods in Table 1 are only provided to within this level of accuracy.

Light curves for the newly detected RRL variables are provided in Fig. 2, where ISIS relative V fluxes were used in all cases except when otherwise noted in the Appendix. Likewise,

Table 1. Variable stars detected in NGC 2808.

Name	x	y	RA	Dec (J2000)	Period (d)	Type	Comment
V1	+107	−35	9:12:20	−64:52:21.3		SR	
V6	+39	−66	9:12:30	−64:56:39.0	0.53897	RRab	
V10	−42	−98	9:11:57	−64:53:24.0	1.76528	Cepheid	
V12	−45	94	9:11:56	−64:50:10.2	0.30578	RRc	
V13	124.32	323.04	9:12:24	−64:57:11.4	0.21	RRc	RRe? W UMa?
V14	79.48	−50.60	9:12:13	−64:51:04.3	0.60	RRab	
V15	60.92	−39.60	9:12:11	−64:51:15.1	0.61	RRab	
V16	46.32	56.64	9:12:09	−64:52:51.9	0.59	RRab	
V17	35.76	0.88	9:12:07	−64:51:57.4	0.38	RRc	
V18	31.92	21.08	9:12:07	−64:52:17.2	0.58	RRab	not phased in V
V19	30.00	14.36	9:12:06	−64:52:10.5	0.51	RRab	
V20	27.48	−25.96	9:12:06	−64:51:30.9	0.29	RRc	
V21	17.24	−31.64	9:12:04	−64:51:26.2	0.60	RRab	
V22	15.52	−1.68	9:12:04	−64:51:56.7	0.54	RRab	large scatter in V
V23	10.40	22.80	9:12:03	−64:52:19.6	0.27	RRc	
V24	7.08	13.68	9:12:03	−64:52:11.4	0.27	RRc	
V25	−16.52	−30.92	9:11:59	−64:51:28.8	0.49	RRab	Blazhko?
V26	−52.46	−30.12	9:11:53	−64:51:30.8	0.37	RRc	
V27	−53.64	59.76	9:11:54	−64:53:00.0	0.57	RRab	
V28	−68.60	−33.84	9:11:51	−64:51:28.0	0.28	RRc	
V29	−9.83	−19.08	9:12:00	−64:51:38.8	1.97	Cepheid?	
V30	39.09	−13.14	9:12:08	−65:51:44.6	1.47	EB	β Lyr?

light curves for the longer-period variables, one of which (V30) is likely to be an eclipsing binary of the β Lyrae type, are given in Fig. 3. The light curves for V1, V6, V10 and V12, the only previously known variable stars in NGC 2808 that were detected in our study, are shown in Fig. A.1. Additional comments about individual variables can be found in the Appendix. The location and period of all the newly detected variables are given in Table 1, where the x and y values have the same meaning as in the Clement et al. (2001) catalogue.

4. Discussion

With our newly detected variables, we can recompute the specific frequency of RRL variable stars in NGC 2808. This quantity is defined as

$$S_{\rm RR} = N_{\rm RR} \times 10^{0.4\,(7.5+M_V)}, \qquad (1)$$

where M_V is the integrated visual magnitude of the cluster, or $M_V = -9.39$ according to the Harris (1996, Feb. 2003 update) catalogue. Given our newly discovered variables, one finds that the specific frequency of RRL variables in NGC 2808 is $S_{\rm RR} = 3.2$ (or 3.0, if V13 is not an RRL), compared with the value 0.3 as currently listed in the Harris catalogue.

Even though the number of known RRL variables in the cluster has been increased by a factor of 10 with respect to previous estimates, the HB of NGC 2808 is still firmly classified as bimodal, since the numbers of both blue and red HB stars are much larger than the number of RRL present in the cluster (see, e.g., Table 1 in Lee et al. 1994). Likewise, the increase in the number of RRL stars implies but a small increase in the Lee-Zinn parameter that describes HB morphology in terms of the numbers of blue, red, and variable (RRL) stars; using the Lee et al. number counts as a guide, we estimate that the value provided in the Harris catalogue should be increased by only about 0.03.

As explained in the introduction, future analysis of the detailed properties of the calibrated RRL light curves may reveal precious information about the origin of the bimodal HB of the cluster. In the future, we will attempt to employ resolved images of the core of the cluster, obtained from the ground or from space, to put the ISIS relative fluxes in the standard system, thus yielding reliable amplitudes and Fourier decomposition parameters for the cluster variables. The reason why this is not possible for most of the detected variable stars based solely on the available data is that we cannot obtain reliable photometry for these stars on our ISIS reference images, due to the extreme crowding that characterizes this cluster – one of the brightest in our galaxy. The difficulty in performing accurate photometry in the inner cluster regions is, in fact, undoubtedly the main reason why a mere two RRL variables had previously been found towards NGC 2808 until we applied the image subtraction technique to our images. Note, in this sense, that even the finding chart for the cluster that we present in this note (Fig. 1) is based on a 0.2 s exposure, obtained with the sole purpose of producing a finding chart for the crowded cluster fields where the variables were detected.

In any case, we can already attempt a preliminary classification of the cluster into an Oosterhoff (1939) type on the basis solely of the mean period of its RRab and RRc stars, as well as on the c-to-ab number ratio.

The number fraction of c-type RRL, including the candidate RRe, is $N_{\rm c}/N_{\rm RR} \simeq 0.44$ (0.41, if V13 is not an RRL). This relatively large number ratio of c-type stars would clearly favor an Oosterhoff type II (OoII) classification for the cluster. On the other hand, the mean period of the 10 ab-type pulsators is $\langle P_{\rm ab}\rangle \simeq 0.563$ d, which indicates instead an OoI classification

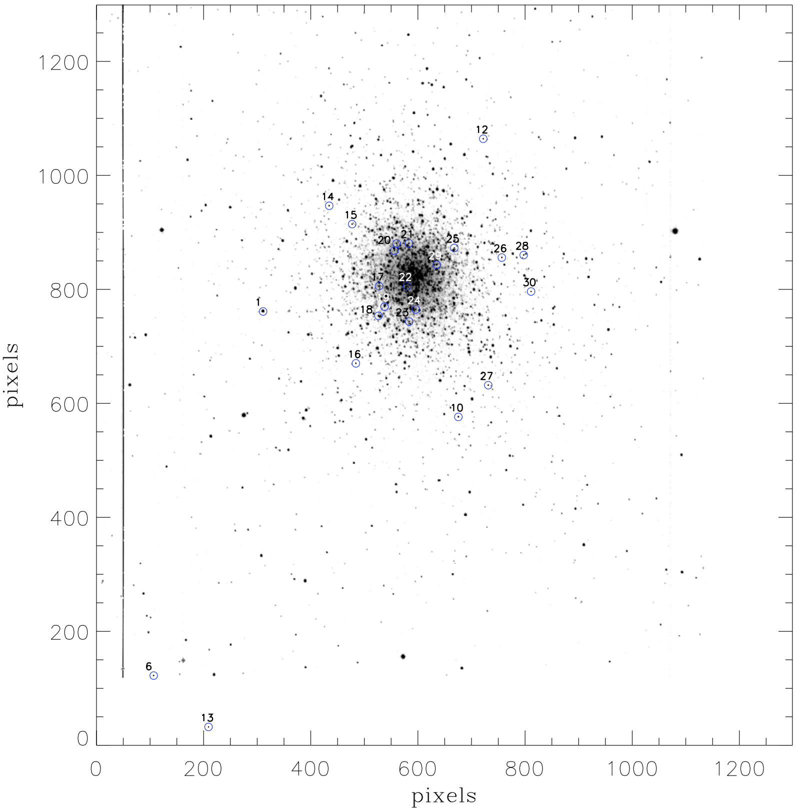

Fig. 1. Finding chart for the NGC 2808 variables in our observed field.

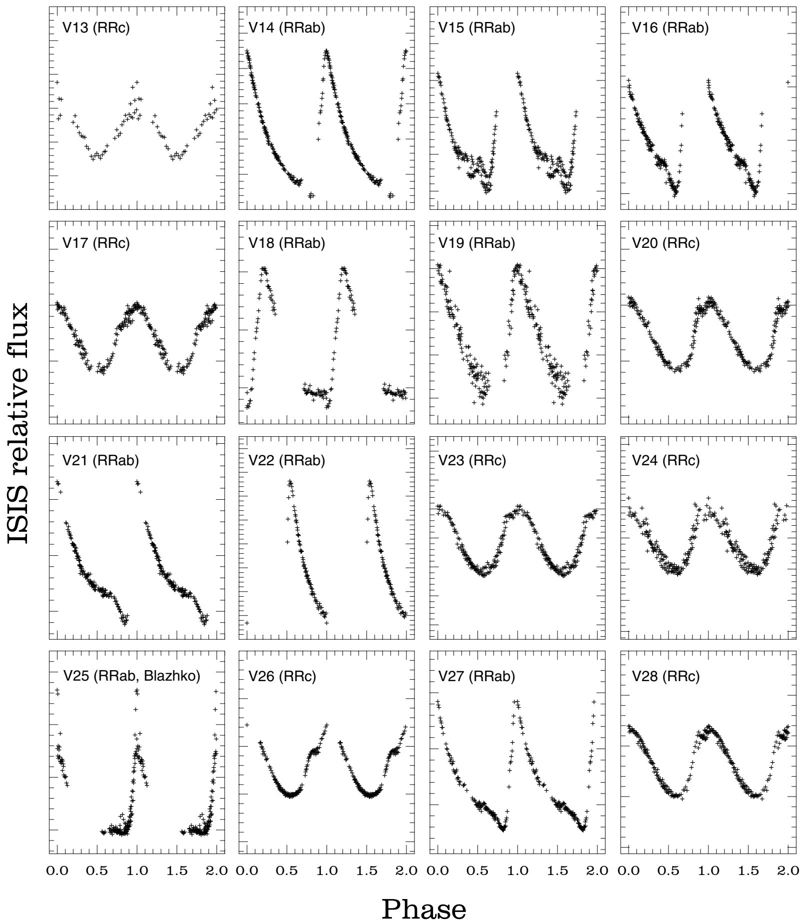

Fig. 2. Light curves for newly discovered NGC 2808 RRL variables. ISIS relative fluxes obtained using *V*-band images were used in all cases except V18, V22, and V25.

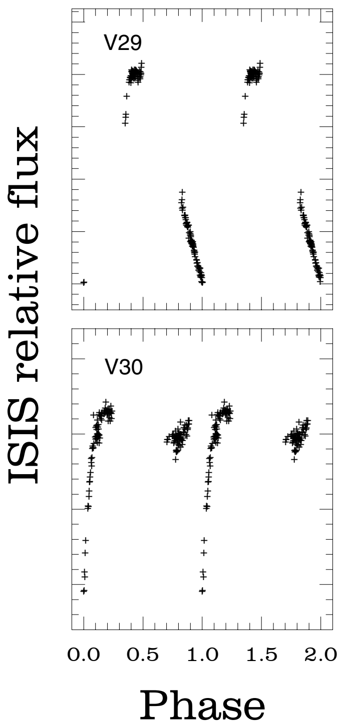

Fig. 3. Light curves for newly discovered longer-period variables in NGC 2808. ISIS relative fluxes obtained using V-band images were used in both cases. V30 is likely to be a β Lyrae-type EB.

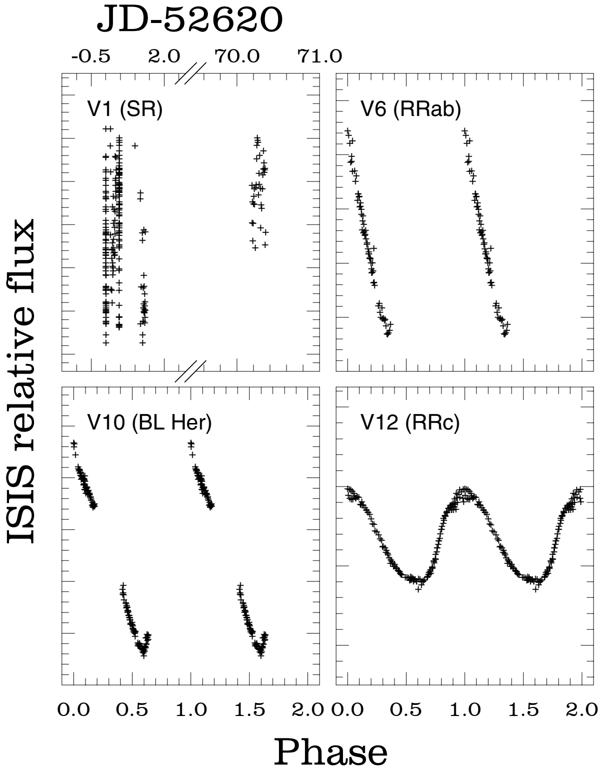

Fig. A.1. Light curves for V1 (*upper left*), V6 (*upper right*), V10 (*lower left*) and V12 (*lower right*), the previously known variable stars in NGC 2808 for which light curves could be obtained in the present study. For V1, relative fluxes are plotted as a function of the Julian Date (note the break in the horizontal axis scale), whereas for other stars the light curves are phased using the period values indicated in the main text.

(see, e.g., Fig. 1a in Catelan 2004). For the 8 RRc and candidate RRe, the mean period is $\langle P_c \rangle \simeq 0.30$ d (0.31 d, if V13 is not an RRL), which is also closer to the OoI type (e.g., Clement et al. 2001). Therefore, NGC 2808 presents characteristics of both Oosterhoff groups. As noted by Catelan (2004), however, more data are needed, particularly pulsation amplitudes, before the final word can be said in regard to the Oosterhoff type of the cluster.

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Appendix A: Notes on individual stars

A.1. V13

This star is located on the very southwestern edge of our field (Fig. 1). For this reason, it was not measured in about half of our images. The period that best phases the current data is very short; therefore, if not an RRc, this star might be an RRe – i.e., a second-overtone pulsator. One less likely possibility, which however cannot be conclusively ruled out by our data due to our poor phase coverage, is that this star is actually a W Ursae Majoris eclipsing binary (EB), with a period perhaps around 0.44 d.

A.2. V18

A good light curve for this star could not be obtained in V. In Fig. 2 is shown only the light curve obtained on the basis of the February B data.

A.3. V19

The V light curve presents significantly more scatter than the B light curve for each individual month, which could be due to imperfect subtraction of nearby bright RGB stars.

A.4. V22

Again like V19, the V light curve presents significantly more scatter than the B light curve for each month, which could also be due to imperfect subtraction of nearby bright red giants. In fact, this variable is the one closest to the cluster centre to be detected in the present study (Fig. 1). In Fig. 2 is shown only the light curve obtained on the basis of the February B data.

A.5. V25

Both the December and February B data are reasonably phased with a period near 0.49 d and an ab-type shape. However, one finds a large difference in amplitude between the two months. In addition, the two maxima appear slightly dephased. The star may be a Blazhko variable. To illustrate this, we show the star's light curve in *B* in Fig. 2, where both the February and December data were employed, but a single period was used. The *V* light curve presents significantly more scatter than the *B* light curve for each individual month, which could be due to imperfect subtraction of nearby bright RGB stars.

A.6. V29

This appears to be a longer-period variable, possibly a Cepheid. Our phase coverage is insufficient to derive a reliable period and light curve for this star. A light curve for a representative candidate period is shown in Fig. 3 (top panel).

A.7. V30

The light curve resembles that of an EB, most likely of the β Lyrae type. A W Ursae Majoris classification is also possible. However, our phase coverage seems to have been insufficient to derive a reliable period and light curve. A light curve for our best candidate period (Table 1) is shown in Fig. 3 (bottom panel).

A.8. Previously known variables

Of the previously known variables in the cluster, we have only been able to obtain a complete light curve for the RRc variable V12, which is shown in Fig. A.1 (lower right panel) using the same period as in Clement & Hazen (1989), or 0.30577705 d. This period clearly phases our data adequately. Clement et al. (2001) currently classify V12 as a possible RRe; we are unable at present to decide whether this is more suitable than a more straightforward RRc-type classification, and have thus adopted the latter until more data are available, including Fourier parameters and *I*-band magnitudes (Catelan 2004 and references therein). V1, which is also in our field, is classified as a semi-regular (SR) variable. In Fig. A.1, relative fluxes for this star are plotted as a function of the Julian Date. Obviously, our phase coverage is necessarily incomplete for this star. V6 is an RRab lying at the southwestern edge of our image; as it happens, it only fell within our field of view in the February run, resulting in an incomplete light curve as can also be seen in Fig. A.1 – where we have adopted the Clement & Hazen period of 0.5389687 d, which seems adequate. V10, for which we again were able to obtain only an incomplete light curve, is classified as a BL Her variable with a period 1.76528 d. This period appears to describe our data satisfactorily (Fig. A.1).

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