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NEW VARIABLE STARS IN MESSIER 13 (II)
STUDY OF TEN RED GIANT STARS

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Abstract: We have studied ten red giant stars, located in Messier 13, using *V* band CCD images obtained in a campaign during 2024: all of them are located at the top of the Red Giant Branch such as other conspicuous variable stars (V11, V17, V24, V33...), between magnitudes 12.130 and 12.807 in Johnson *V* band according to our photometry. Of these, four stars are constant in brightness and the remaining six are variables between 0.066 and 0.114 magnitudes. The data and the light curves suggest that three of them are binary systems with periods between 25.6 and 35.4 days; two seem to pulsate with periods of 21.9 and 24.8 days, while the last variable does so with a very long period, 88.6 days, similar to that which obtained from the ASAS-SN measurements: 92.3 days. We calculate the absolute magnitudes of these variables between M_V = –2.20 and –1.55. We also analyzed the variable V41: our data suggests that it is a binary system with a period of 85.32 days. Since the last one in the electronic version of the *Catalogue of Variable Stars in Globular Clusters (CVSGC) is V69 (January 2024), we suggest the remaining names be* V70, V71, V72, V73, V74, and V75.

1 Introduction

The purpose for this paper, the second in a series of three, is to investigate the variability of ten stars in the cluster (all of them relatively bright stars of magnitude 12.130-12.807 *V*) located at the tip of the Red Giant Branch, for which we have determined mean magnitudes, amplitudes (both in *V* Johnson band) and periods, and also plotted their light curves in phase. All these stars are red giants belonging to Messier 13, as determined by Gaia parallaxes (Bailer-Jones *et al*., 2021). Although our first study of Messier 13 began in the spring of 2000, with Kodak photographic filters (not *B* and *V* Johnson), we did not focus our attention on the search for new variable stars until 2019: previously we obtained light curves, amplitudes, periods and we plotted the light curves of the already known variables, and published these results in various Spanish papers and websites. However, when using a dozen check stars in all the campaigns, with which we could verify the quality and precision of the photometry obtained, we observed in some of them very small brightness oscillations (less than a tenth of a magnitude in all cases), which made us suspect that a good part of the brightest stars in the cluster (mag < 12.81 *V*) were variable stars not recognized as such for two reasons: because of their reduced amplitude (ΔV < 0.09 mag) and because a large number of photometric measurements are needed, over several months, to obtain a sufficiently large set of data from which to determine their periods and draw their phased light curves.

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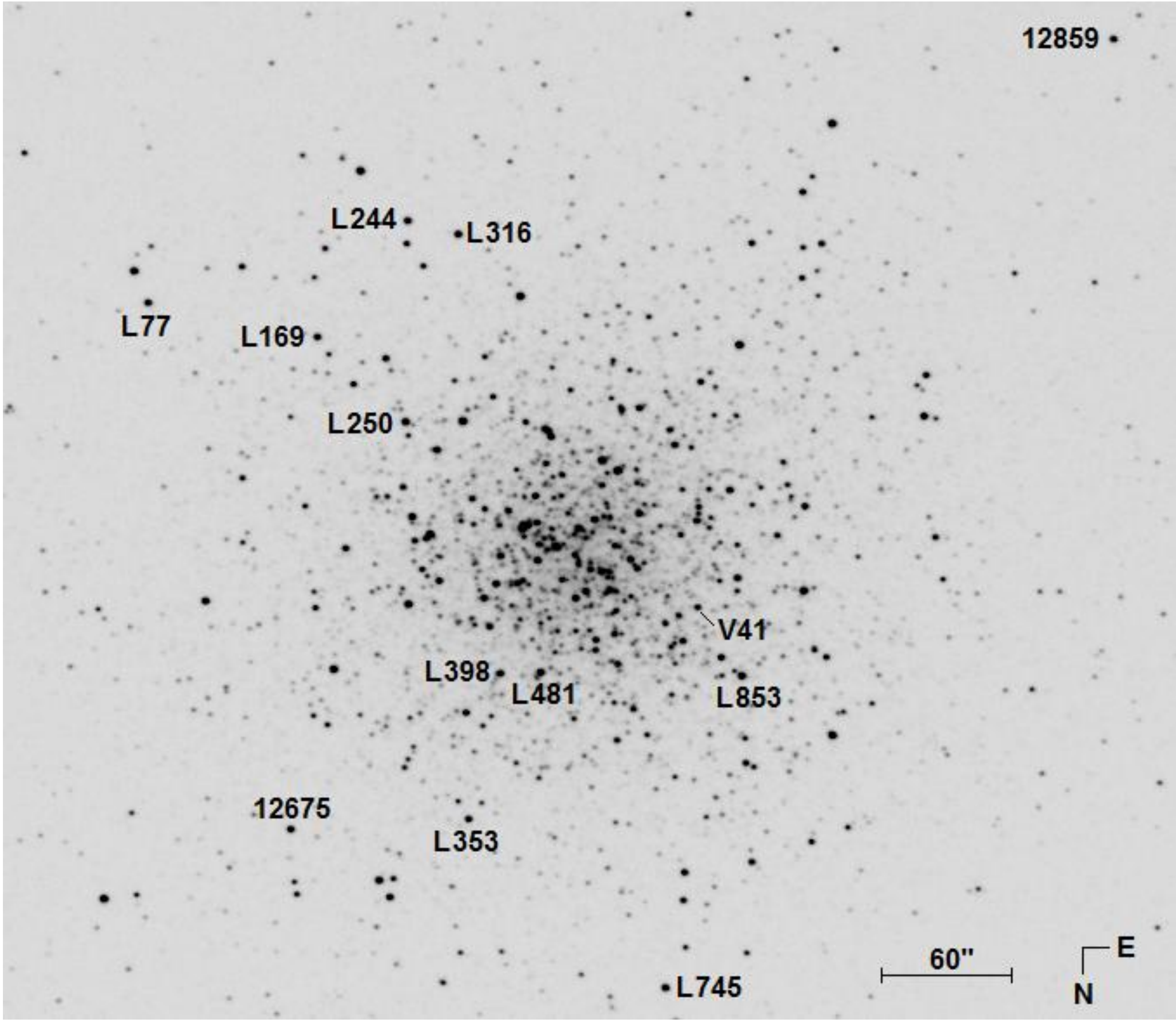

Figure 1: The CCD observed field with labeled stars: V41, ten stars studied and two photometric calibration stars with their magnitude (in Johnson *V* band). North is down, East to the right.

Messier 13 is one of the brightest (*V*~ 5.8 mag.) and best known of the globular clusters in the constellation of Hercules (α = 16h 41' 41.24", δ = +36º 27' 35.5", J2000); the distance to the cluster was estimated as 7.1 ± 0.1 kpc, with an average metallicity of [Fe/H] = –1.58 ± 0.09 and an age of 12.6 Gyrs (Deras *et al*., 2019, hereafter DER19). Its proximity allows small diameter telescopes (20 to 40 cm) to obtain photometry from their stars, on condition that the focal length is sufficient to separate their components even close to their nucleus. If the accuracy of this photometry is high and the campaign is long enough (greater than 90-150 nights or even something else), we can identify and study new variables not recognised to date. Figure 2 shows light curves of the variables V38 and V63 during the 2024 campaign: having observed almost every clear night, our precise photometry has allowed us to detect micro-changes of a few hundredths of magnitude in sixty different stars,

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including the variables already known, variable candidates (from DER19) and bright stars not detected as variables to date in the range 12.13-13.50 *V*.

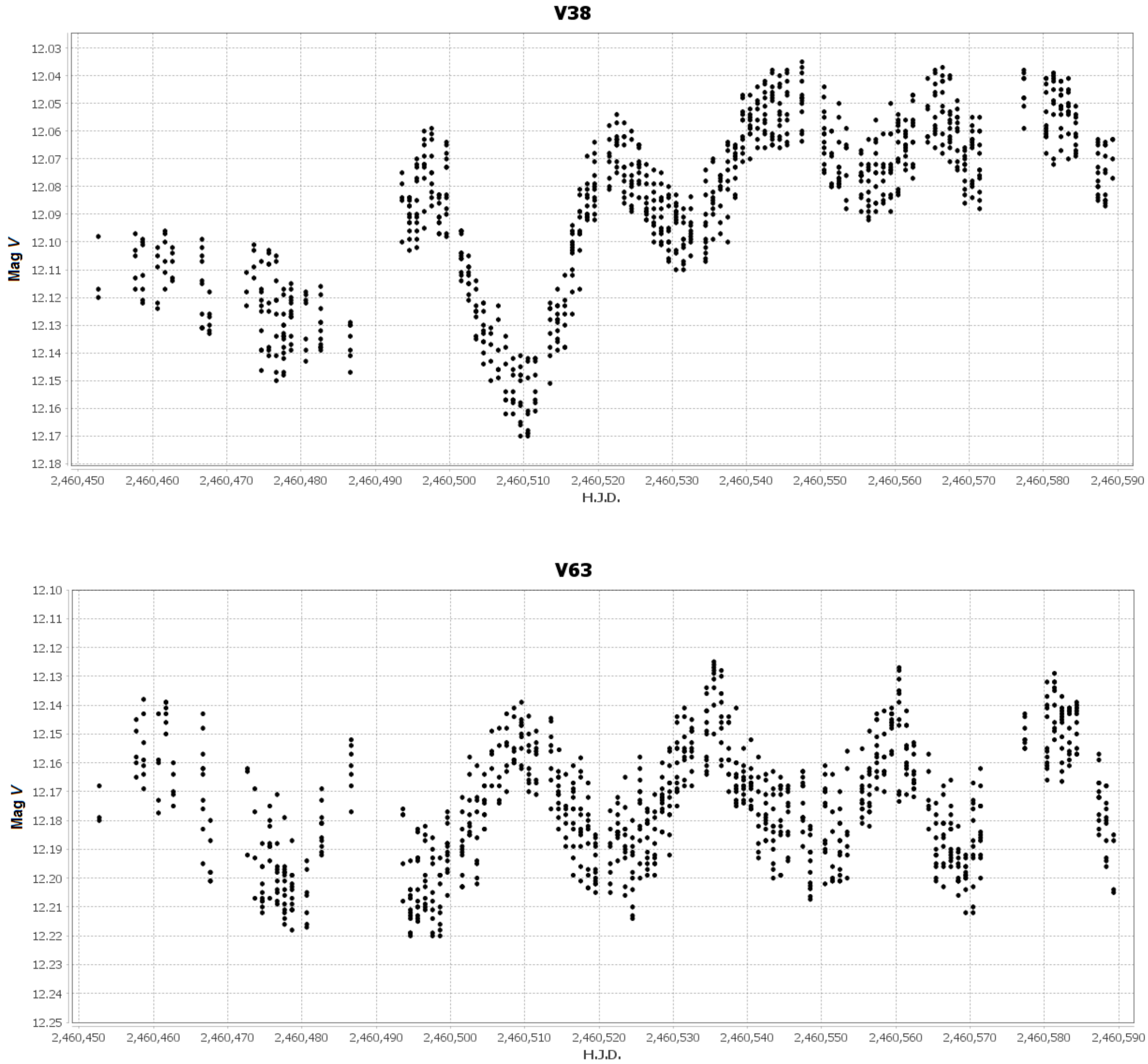

Figure 2: Light curves of the variable stars V38 (upper panel) and V63 (lower panel) obtained throughout the 2024 photometric campaign (140 nights): the two stars are semiregular red giants. Our equipment has enabled us to capture very small oscillations (or microchanges) represented in each panel and drawn using VStar, software developed by the AAVSO (the American Association of Variable Star Observers).

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2 Stars: Identification, position and magnitudes *V* and *B* – *V*

In Table 1, we have identified all the stars by their Ludendorff's number (1905), which has allowed us to locate their magnitudes and other interesting parameters in SIMBAD. Stetson *et al*. (2019, hereafter STE19) include in their paper these stars and tabulate their magnitudes *B* and *V*, which allows us to determine their B–V colour indices:

Table 1: Comparison, variables and check stars

Star	ID	RA (J2000) [h:m:s]	DEC (J2000) [° ' "]	*V* [mag]	*B* – *V* [mag]
L158	2MASS J16413053+3629434	16:41:30.52	+36:29:43.44	12.675	1.144
L1073	2MASS J16420085+3623338	16:42:00.84	+36:23:33.67	12.859	1.087
L169	2MASS J16413107+3625587	16:41:31.06	+36:25:58.80	12.769	1.188
L250	2MASS J16413448+3626365	16:41:34.47	+36:26:36.43	12.349	1.288
L398	2MASS J16413831+3628301	16:41:38.31	+36:28:30.10	12.654	1.239
L481	2MASS J16413983+3628291	16:41:39.82	+36:28:29.02	12.331	1.300
L745	2MASS J16414486+3630514	16:41:44.85	+36:30:51.37	12.490	1.293
L853	2MASS J16414744+3628284	16:41:47.42	+36:28:28.33	12.189	1.374
L77	2MASS J16412464+3625449	16:41:24.63	+36:25:45.11	12.735	1.202
L244	2MASS J16413437+3625048	16:41:34.36	+36:25:04.76	12.602	1.225
L316	2MASS J16413629+3625104	16:41:36.28	+36:25:10.30	12.536	1.240
L353	2MASS J16413725+3629368	16:41:37.24	+36:29:36.77	12.809	1.138

We have chosen as comparison stars two non-variable stars, used in previous studies (Violat-Bordonau, 2021; Violat-Bordonau, 2022; Violat-Bordonau, 2024a), whose *B* – *V* colour indices are low; the same is true for the four check stars, all of which are non-variable stars that have remained stable throughout the campaign: their light curves are shown in Figure 2. Their linearity over the 140 nights we have studied the cluster demonstrates two essential facts: first, that the use of the two comparison stars was successful, since no unusual effects (microchanges) are seen in any of the four light curves; and second, that the check stars are not variable, as we assumed and have verified in other photometric studies of the cluster published by us previously.

In our images, we could study just over 600 stars between magnitudes 11.8 and 17.1 *V* to discover new variable stars in the captured field; however, this would require significant computing resources and time. To select candidate stars that could be new variables, we used two parameters published in previous work: their radial velocities and the Variability Index (V.I.) published by STE2019, and based on the Welch-Stetson test (1993).

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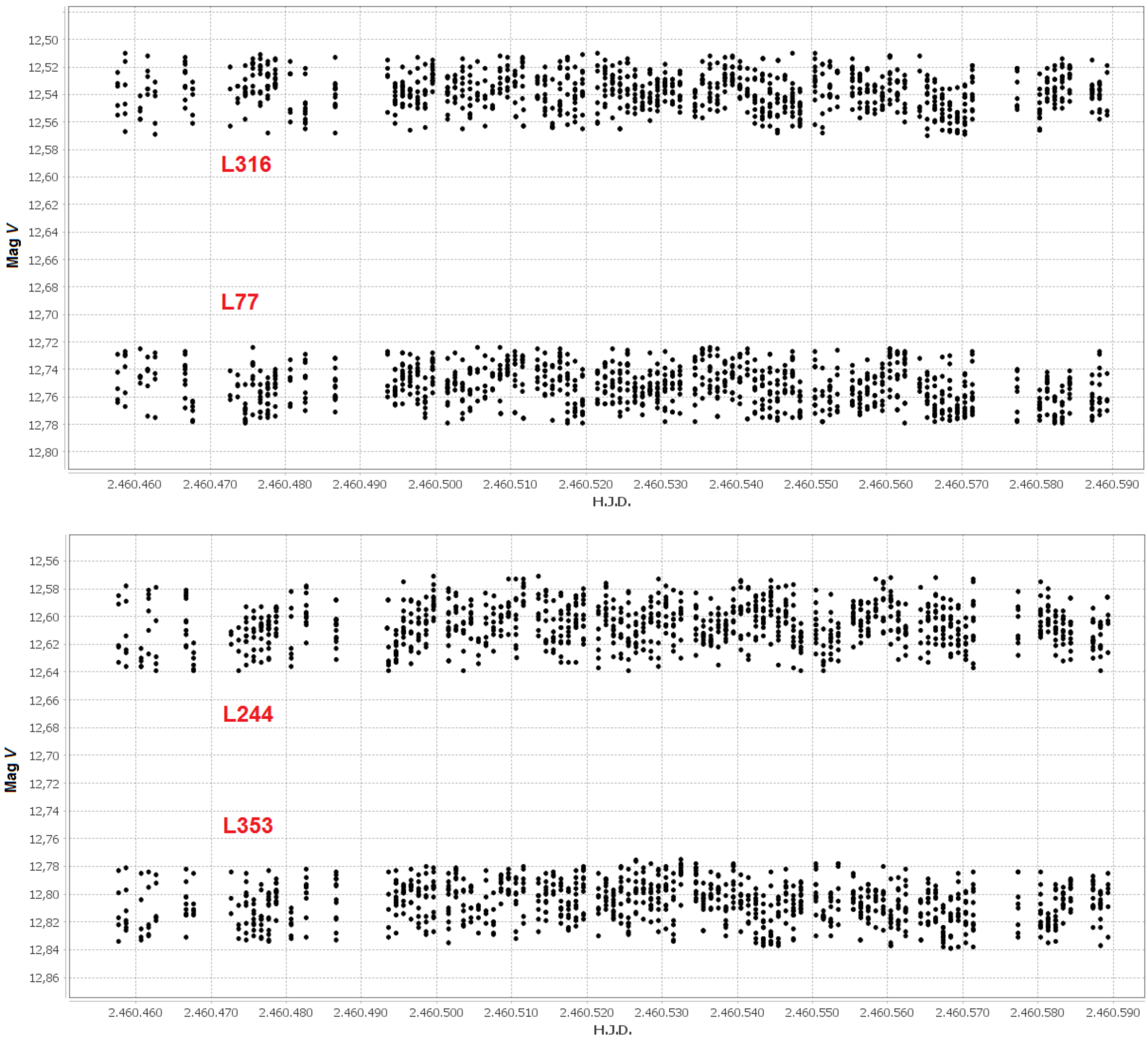

Figure 3: Light curves of the four comparison stars L77, L244, L316 and L353: none of them showed any variability or *microchanges*.

Lupton *et al*. (1987) published a work in which they determined radial velocities of 147 stars in the cluster Messier 13 with a very low error (1 km s^{-1}): according to these authors, at least six of them were new variables (for example L782, now V41, discovered in 2003). This work presents different data, of which three are of particular interest to us: the chi-square test value (χ^2), the number of measurements used, and the degrees of freedom; classical variable stars (V2, V6, V11, et.) present high chi-square values ($\chi^2 > 12.5$), while for the remaining non-variable stars these values are very low. STE19, on the other hand, presents *UBVRI* magnitudes and Variability Indices (V.I.) for most of the stars in the cluster: this index represents the probability that a star is variable, using the well-known Welch-Stetson test; high values (V.I. > 1.5) indicate possible variability, which increases as the star's photometric variation amplitude increases: variables with very small amplitude have very small values

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(V.I. < 1.5), similar to those of constant-light stars. Using both values, we have prepared Table 2, which presents the following data: star name, chi-square value (χ^2), number of measurements (Velocities), degrees of freedom (Nu), variability index (V.I.), and use of the star in this work, which may be a comparison star (COMP), a candidate variable star (STAR), or a photometric check star (CHK).

Table 2: Variability detection: radial velocities and Variability Indices

Star	χ^2	Velocities	Nu	V.I.	Type
L158	0.60	2	1	0.940	COMP
L1073	0.34	3	2	0.647	COMP
L169	0.58	2	1	2.585	STAR
L250	16.03	4	3	5.422	STAR
L398	2.07	2	1	11.932	STAR
L481	20.41	4	3	0.760	STAR
L745	0.50	2	1	1.011	STAR
L853	1.73	3	2	0.894	STAR
L77	1.72	3	2	1.339	CHK
L244	4.32	3	2	0.866	CHK
L316	0.34	2	1	1.390	CHK
L353	0.32	2	1	0.953	CHK

Examining the table we see that, based on the radial velocities, there are two very notable candidates for variable stars: L250 and L481; the Variability Indices point to three new variable stars: L169, L250, and L398. Both parameters are high for star L250, which, according to our hypothesis, indicates that it is undoubtedly a new variable star. A clarification is in order: since chi-square values depend on the number of radial velocities (degrees of freedom), new variable stars with a reduced number of speed measurements will have very low chi-square values ($\chi^2 < 5$), and may appear to be non-variable stars. We will see this later when we present the light curves of six new variables, of which only two (L250 and L481) stand out in the table. Variability Indices, for their part, point to the existence not only of three new variables (as already mentioned) but also suggest variability of very small amplitude for the stars L77 (V.I. = 1.339) and L316 (V.I. = 1.339), two of the four check stars. By downloading and drawing the ASAS-SN measurements (Jayasinghe, T. *et al.*, 2018; Shappee, B. J. *et al.*, 2014; Kochanek *et al.*, 2017) obtained in the period 2018-2024, in the SLOAN-g band, we will see that in both cases, variability is apparent, but this is due to the contamination produced by classical variable stars: V18 in the case of L77 and V38 in the case of L316. Figure 4 shows the photometric measurements of V18 (top) and L77 (bottom) between 2018 and 2024; both are identical: this is due to the low resolution of this optical

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system (7.8 arcseconds pixel^{-1}) and the proximity of both check stars to the variables, which are relatively slightly brighter stars.

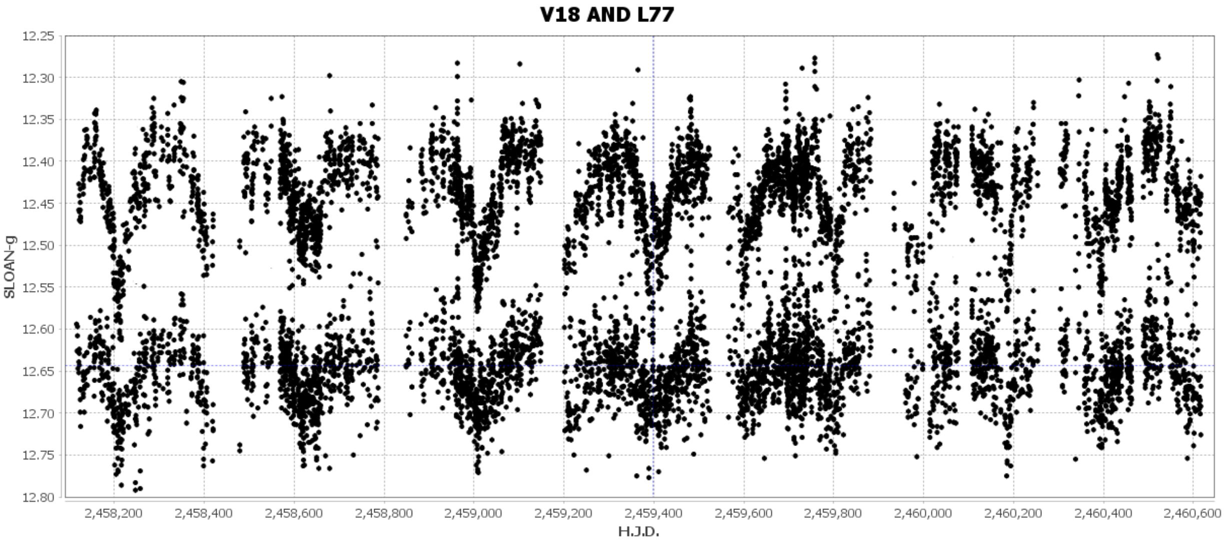

Figure 4: Light curves of the variable star V18 (above) and L77 (below) obtained by the ASAS-SN robotic system in the period 2018-2024: both are identical.

3 Photometry. Observations and data reductions

We obtained *V*-band photometry during a 2024 campaign from Cáceres (Spain), carried out between May and October. Since the spring of 2019 we have studied carefully the variable and suspected variable stars of Messier 13: we employed the 0.2-m telescope f/10 of the Observatorio Astronómico *Norba Caesarina*, at Cáceres, Spain, located at 455 m above sea level, to obtain time-series imaging of the globular cluster: all cluster frames were calibrated using bias and flat field frames through standard procedures; bias and twilight flats were taken every observing night. The image data were obtained during several runs where we collected a total of 971 frames through Johnson *V* filter; Table 3 shows a detailed log of the observations: the exposure times were 120 s; on most nights the weather was very good and he seeing varied over a rather wide range, between 2.5 and 3.3 arcsec, with a typical value of 2.9-3.1 arcsec. The CCD camera is an ATIK 414EX, of 1391 × 1039 pixels (squares, 6.5 microns), with a scale of 0.68”/pixel and a field of view of 15.9 × 11.8 arcmin^2 (Figure 1). We have also observed other variable stars in the cluster, obtaining light curves and determining periods and amplitudes in *V* band: Figure 2 is a good example. We have studied all the Red Giants, the three Cepheids in the cluster and most of the RR Lyrae stars.

Table 3: Observational log

Year	H.J.D. Start	H.J.D. End	Nights	Images
2024	2460450.672	2460589.330	140	971

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The photometric data were reduced using the software *FOTODIF*[1] (FOTOmetría DIFerencial, differential photometry) and calibrated using two stars of very well determined *B* and *V* magnitudes published in the photometric study by STE19. The CCD finder chart (with labelled stars) is shown in Figure 1: the magnitudes were determined relative to L158 and L1073, whose constancy during the run was confirmed using L77, L244, L316 and L353 as check stars. We show in Table 4 the photometric measurements obtained on the night of July 4, 2024 of the brightest star (L853) and the faintest (L353): the reader will see the magnitude *V*, the error (σ), the Signal/Noise Ratio (SNR), the air mass, the FWHM and the frame number on the night:

Table 4: Photometric measurements and other data

H.J.D.	*V* [mag]	+/- [mag]	SNR	*V* [mag]	+/- [mag]	SNR	Air	FWHM [“]	NUM
	L853			L353					
2460495.57572	12.115	0.008	131	12.799	0.013	82	1.332	3.11	0001
2460495.57692	12.116	0.008	131	12.798	0.013	84	1.339	3.10	0002
2460495.57817	12.118	0.009	120	12.808	0.012	88	1.346	3.13	0003
2460495.57948	12.125	0.009	126	12.804	0.012	92	1.353	3.13	0004
2460495.58156	12.121	0.008	131	12.805	0.011	96	1.366	3.07	0005
2460495.58295	12.121	0.008	133	12.784	0.011	98	1.374	3.11	0006
2460495.58396	12.113	0.008	134	12.785	0.011	98	1.380	3.12	0007
2460495.58492	12.112	0.008	131	12.795	0.011	96	1.386	3.12	0008
2460495.58651	12.112	0.008	133	12.785	0.011	97	1.396	3.08	0009
2460495.58743	12.122	0.008	133	12.793	0.011	98	1.402	3.13	0010
2460495.58869	12.122	0.008	133	12.797	0.011	97	1.410	3.06	0011
2460495.58954	12.115	0.008	134	12.799	0.011	98	1.416	3.08	0012

Our photometry is very precise and allows us to detect oscillations of few hundredths of magnitude ($\Delta V > 0.01$ mag) in these light curves: with a signal-to-noise ratio above 85 for the faintest star (L353), our optical system has been able to detect very small microchanges in the stars studied. Figures 5 shows the light curves of the stars L169, L250 and L398; Figure 6 shows the light curves of the stars L481, L745 and L853: all of them are new variable stars.

[1] Written by Julio Castellano, http://www.astrosurf.com/orodeno/fotodif/index.htm

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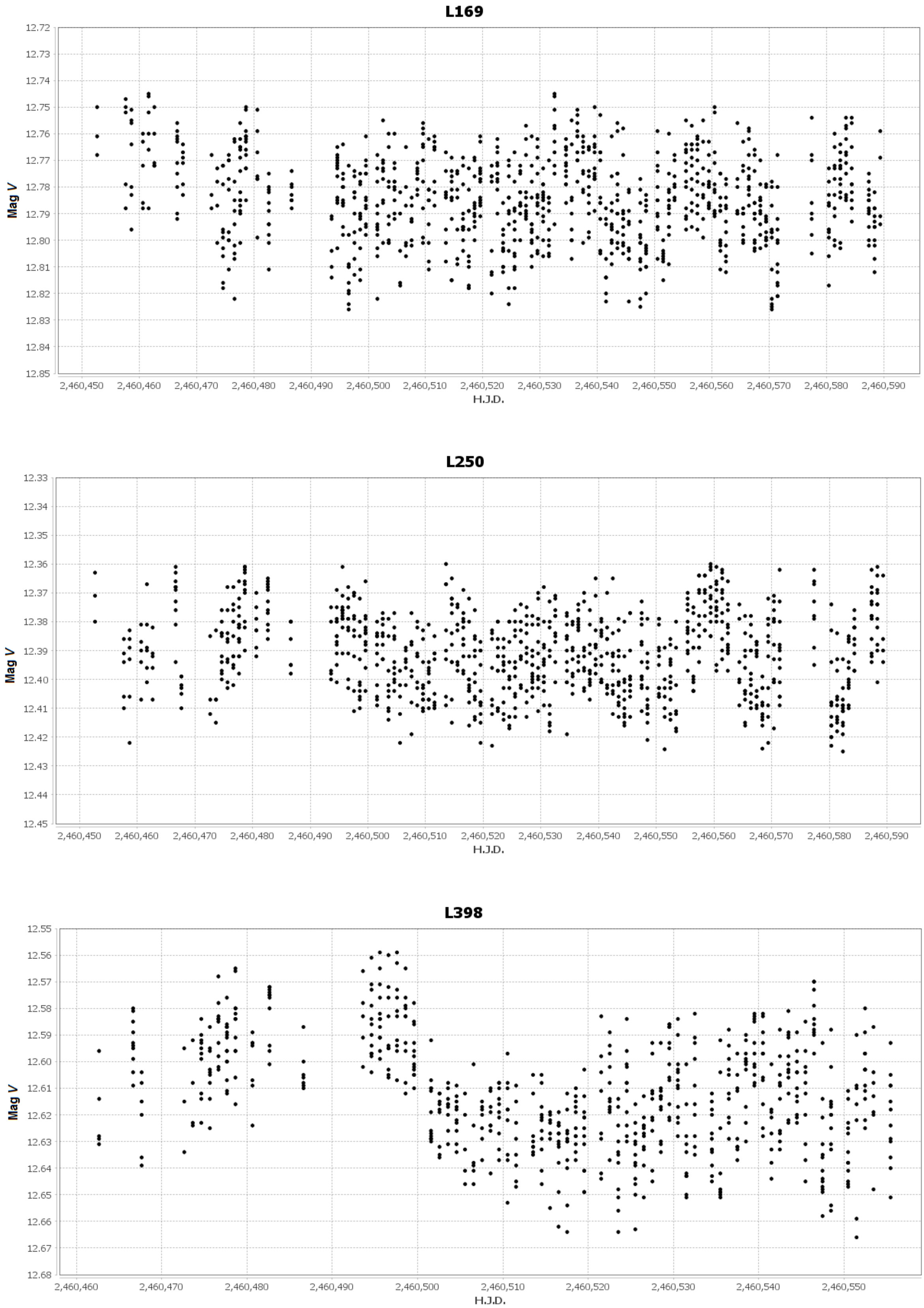

Figure 5: Light curves of the stars L169 (upper panel), L250 (middle panel) and L398 (lower panel) obtained throughout the 2024 photometric campaign.

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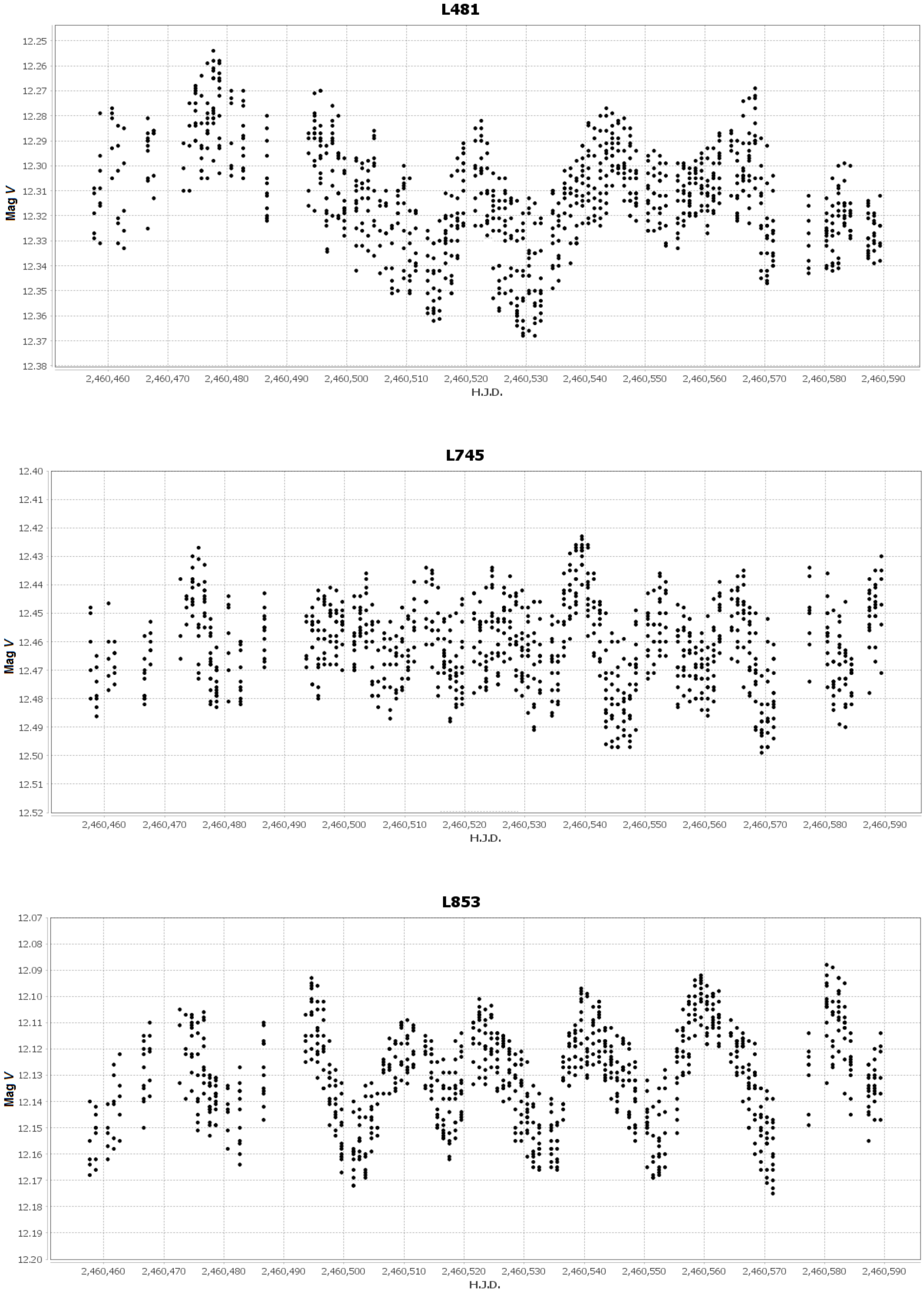

Figure 6: Light curves of the stars L481 (upper panel), L745 (middle panel) and L853 (lower panel) obtained throughout the 2024 photometric campaign.

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Table 5 shows the star name of all the stars, number of frames measured, average V magnitudes, measured amplitude ΔV, variation range V and its absolute magnitudes M_V using $(V - M_V) = 14.33$ and $E(B - V) = 0.02$ (Harris, 2010):

Table 5: Average V magnitudes, amplitudes, range V and M_V

Star	Images	V [mag]	Amplitude [mag]	Range V [mag]	M_V
L853	964	12.130 ± 0.018	0.087	12.088-12.175	–2.20
L481	962	12.313 ± 0.021	0.114	12.254-12.368	–2.02
L250	949	12.391 ± 0.014	0.066	12.360-12.426	–1.94
L745	959	12.462 ± 0.015	0.076	12.423-12.499	–1.87
L316	961	12.538 ± 0.013	0.060	12.510-12.570	–1.79
L244	961	12.606 ± 0.015	0.068	12.571-12.639	–1.72
L398	684	12.612 ± 0.021	0.107	12.559-12.666	–1.72
L77	960	12.752 ± 0.014	0.059	12.724-12.779	–1.58
L169	950	12.785 ± 0.016	0.081	12.745-12.826	–1.55
L353	964	12.806 ± 0.014	0.065	12.774-12.839	–1.52

An examination of the table shows that four stars (L77, L244, L316 and L353) have amplitudes in the range ΔV = 0.06-0.07 mag: they are non-variable stars whose light curves we have shown in Figure 3. The other six, new variable stars, present amplitudes in the range ΔV = 0.07-0.11 mag. None of these stars appear as variable in ASAS-SN Database.

4 Data analysis

The analysis of each of the candidates has been carried out with *Vstar* (Benn, 2012) using Date Compensated Discrete Fourier Transform (DC DFT): *Vstar* is a software, from the American Association of Variable Star Observers (AAVSO), that was originally developed as part of the *AAVSO's Citizen Sky* project. In Figure 7 we show the periodograms obtained for each variable: to better represent these periods, the drawn intervals range between 1-150 days (for L398 and L481) and 1-60 days for L169, L250, L745 and 853. In the case of L398, the period obtained (88.6 days) is very similar to the average period obtained from the ASAS-SN measurements between 2018 and 2024: 92.2 days. Table 6 presents the periods obtained from the analyzed measurements (also from V41): the name of the star, the number of frames analyzed, the most notable periods, the type of most probable variable (pulsating or binary) and the average period obtained from the ASAS-SN data (2018-2024) are included.

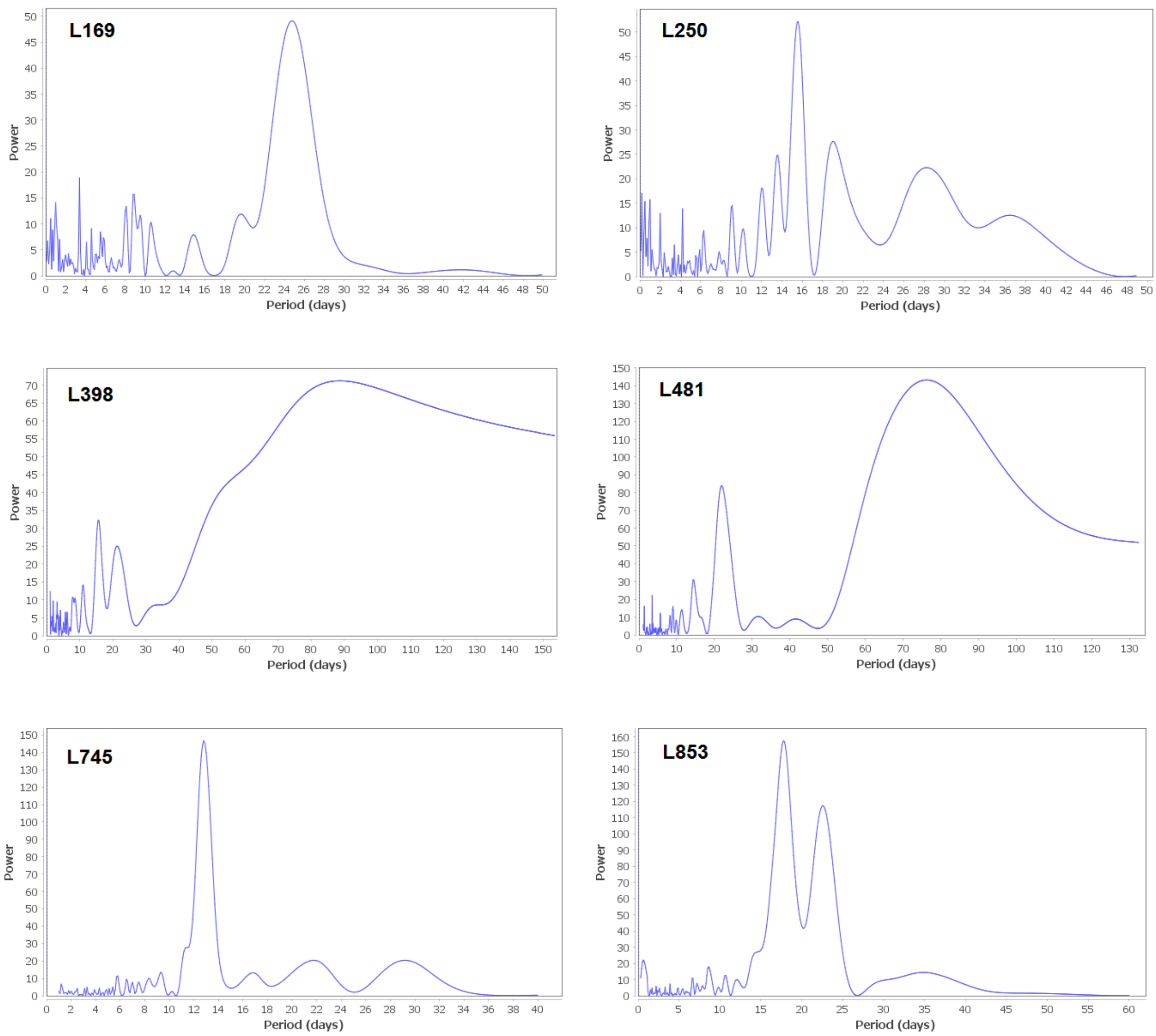

Figure 7: Periodograms obtained from each of the new variables: to better represent them the intervals analyzed are different for each of them (between 50 and 150 days).

Table 6: Periods of the new variables (and V41)

Star	Points	P1	P2	Type	ASAS-SN
L169	950	**24.8**	---	PUL	**27.3**
L250	949	15.6	**31.12**	BIN	**29.54**
L398	684	**88.6**	---	PUL	**92.2**
L481	962	**21.8**	76.2	PUL	**28.6**
L745	959	12.8	**25.62**	BIN	**27.31**
L853	964	17.8	**35.56**	BIN	**34.41**
V41	963	42.16	**85.32**	BIN	**85.40**

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We've included the variable V41 because it's a binary system (not a pulsating star) with a true period twice the official one: 85.32 days according to our data; the ASAS-SN data agree with this value. We have highlighted the correct periods in bold, as well as those obtained from the ASAS-SN data between 2018 and 2024. Below we show the light curves, in phase, of the new variable stars with the periods obtained: in the binaries they have been drawn with the two periods obtained to appreciate their shape.

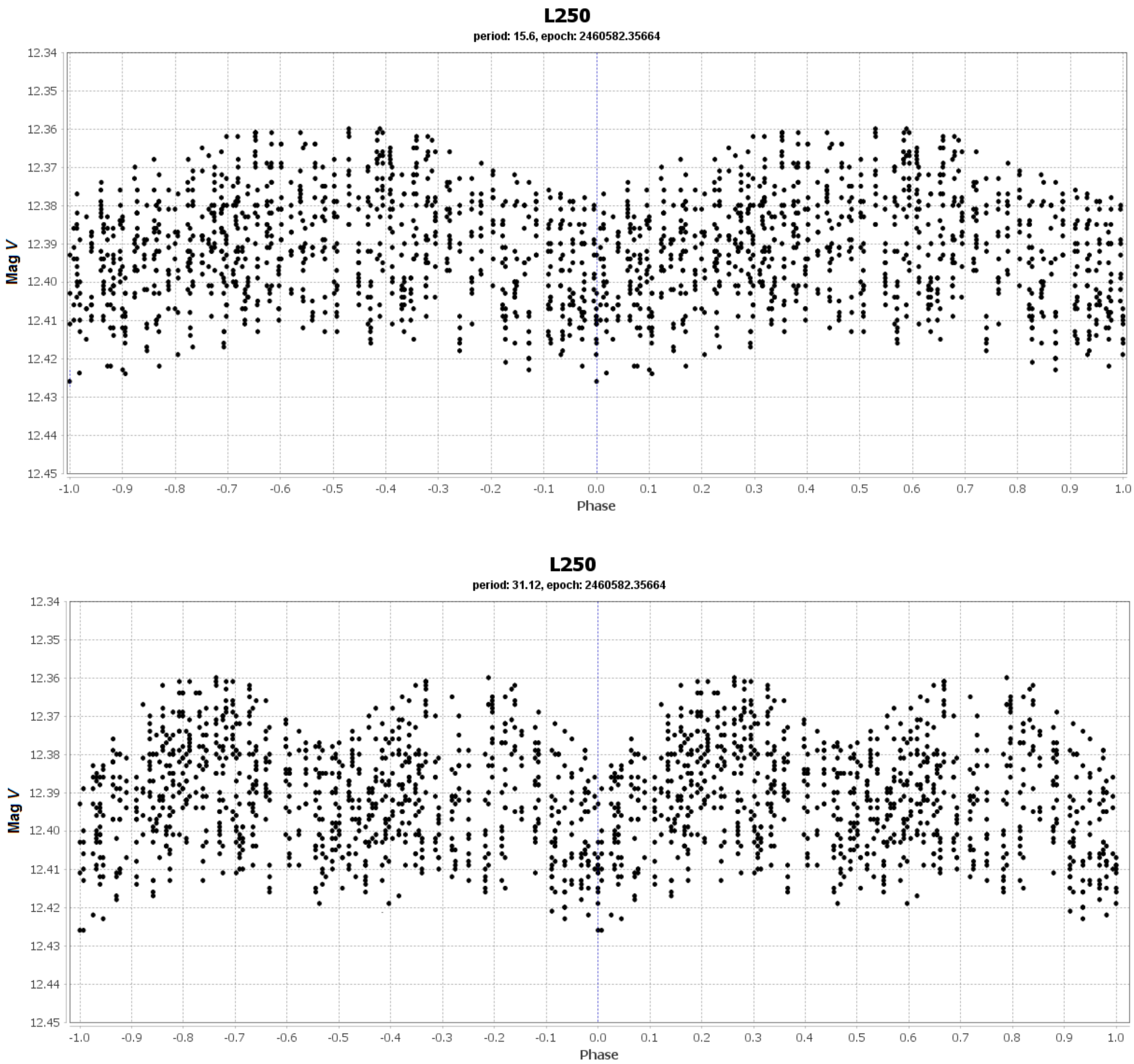

Figure 8: Light curve of L250, in phase, drawn with a period equal to 15.6 days (upper panel) and 31.12 days (lower panel): it is a binary system whose minima are deep and shallower alternately.

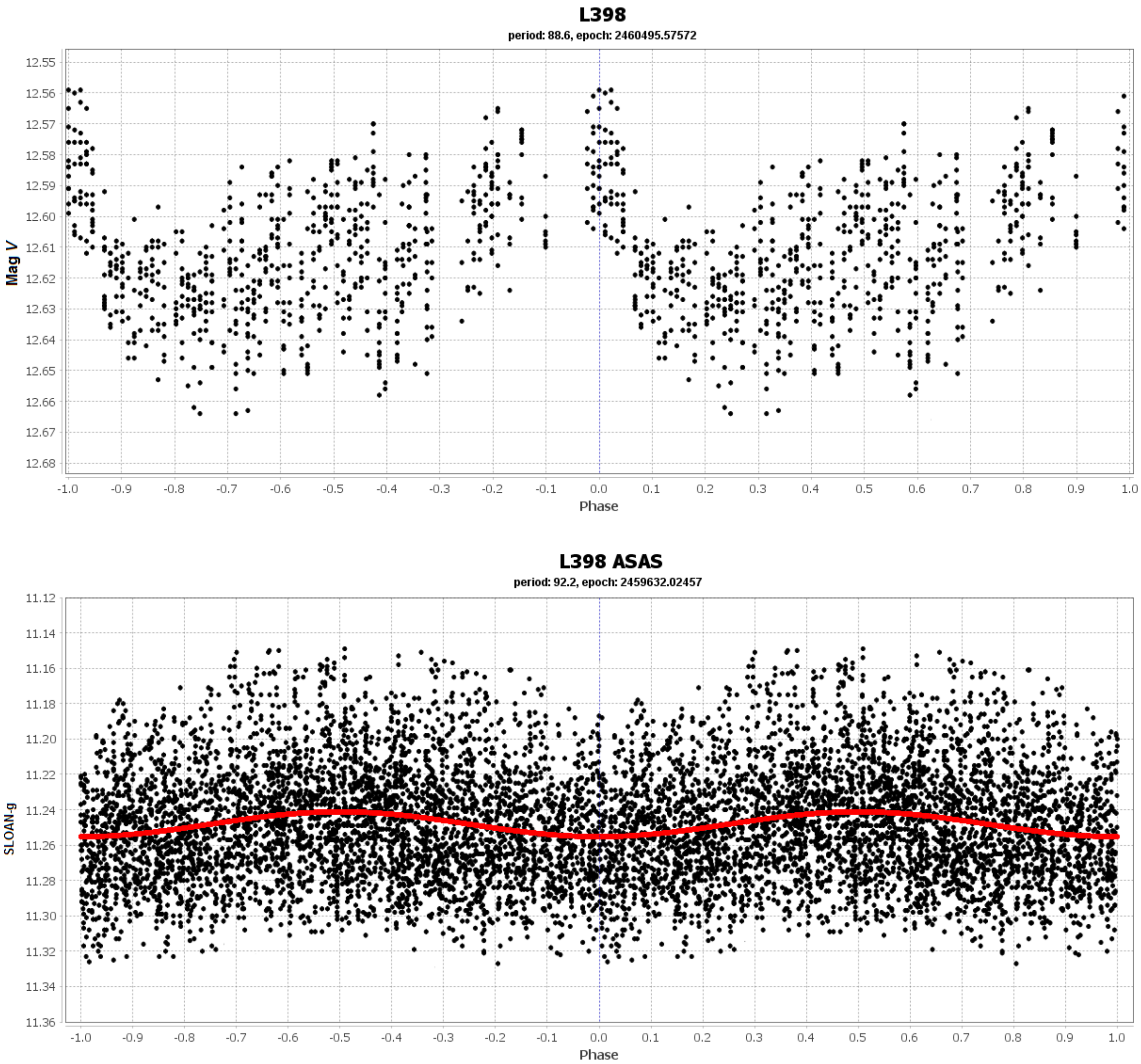

Figure 9: Light curve of L398, in phase, drawn with a period equal to 88.6 days (upper panel) compared to that obtained from the ASAS-SN data (low panel) drawn with a period equal to 92.2 days: in this case, the adjustment of the measurements is included. We can see that its real amplitude is very small, which explains why this variable has not been detected previously.

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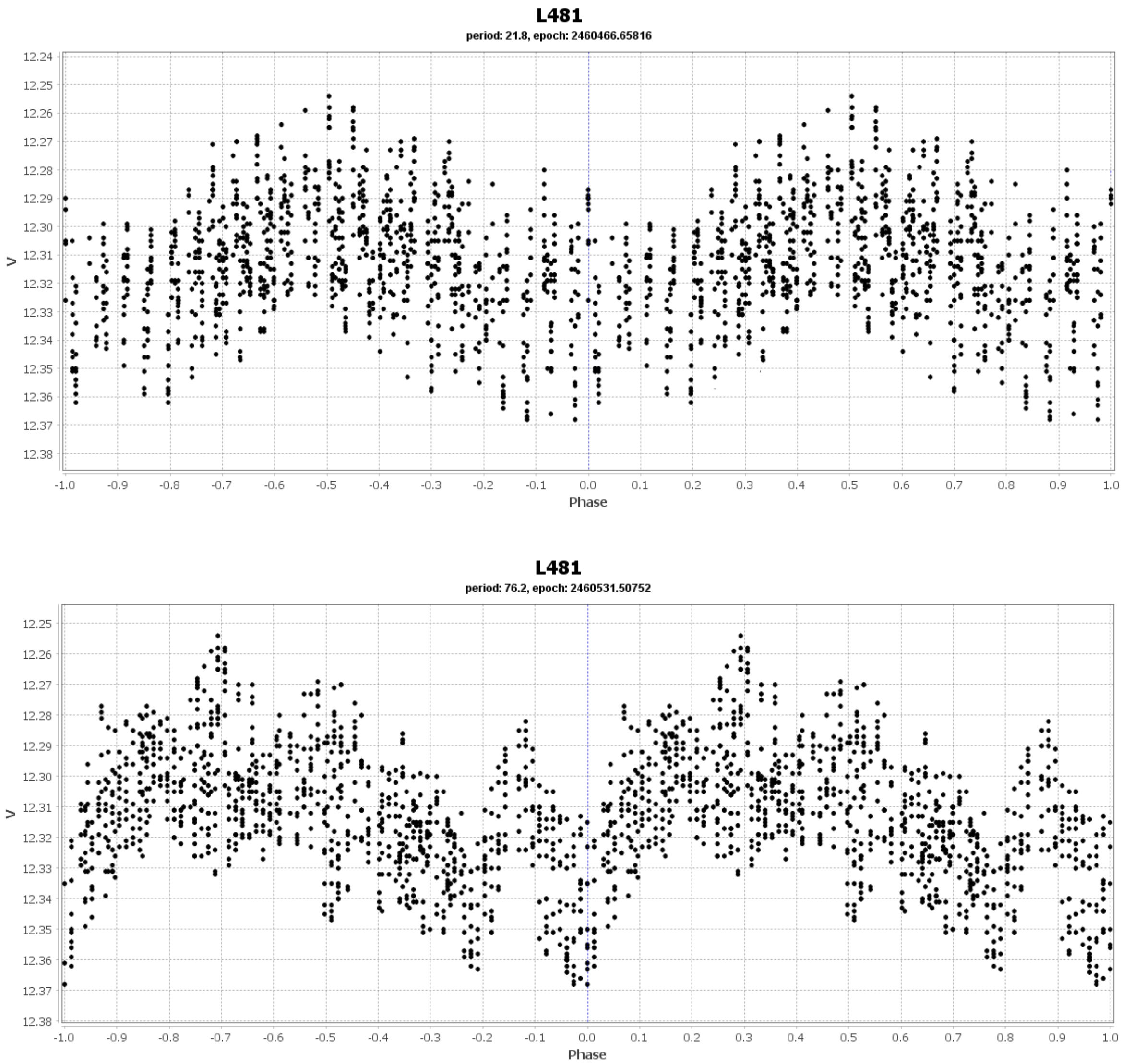
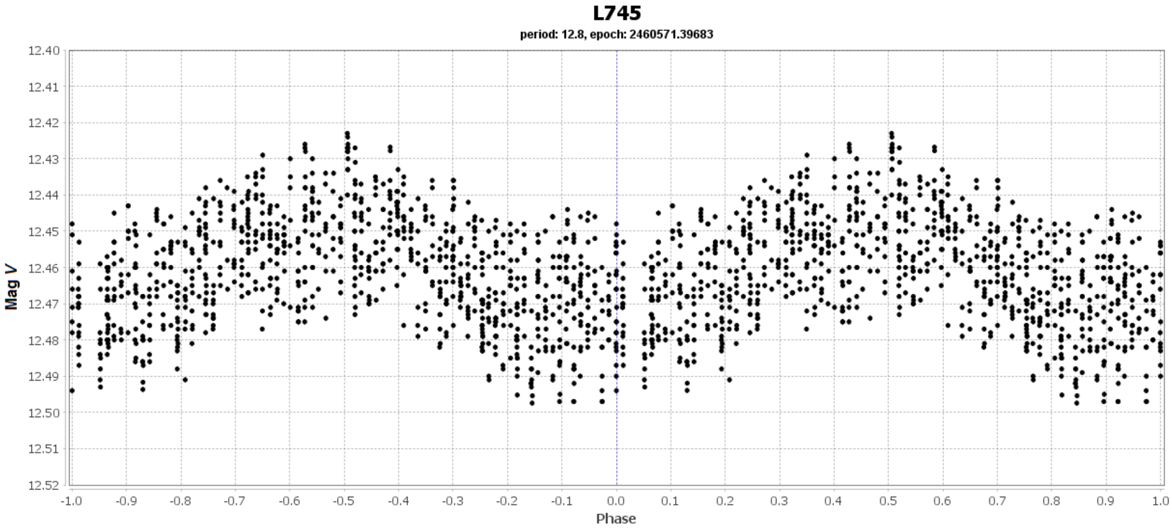


Figure 10: Light curve of L481, in phase, drawn with a period equal to 21.8 days (upper panel) and 76.2 days (lower panel): only with the first value we obtain a quality light curve, which suggests that it is not a binary system but a pulsating star.

The light curve of L481 is of good quality with the short period, but not with the long one: in this second case, a modulation produced by the existence of two different periods can be seen.



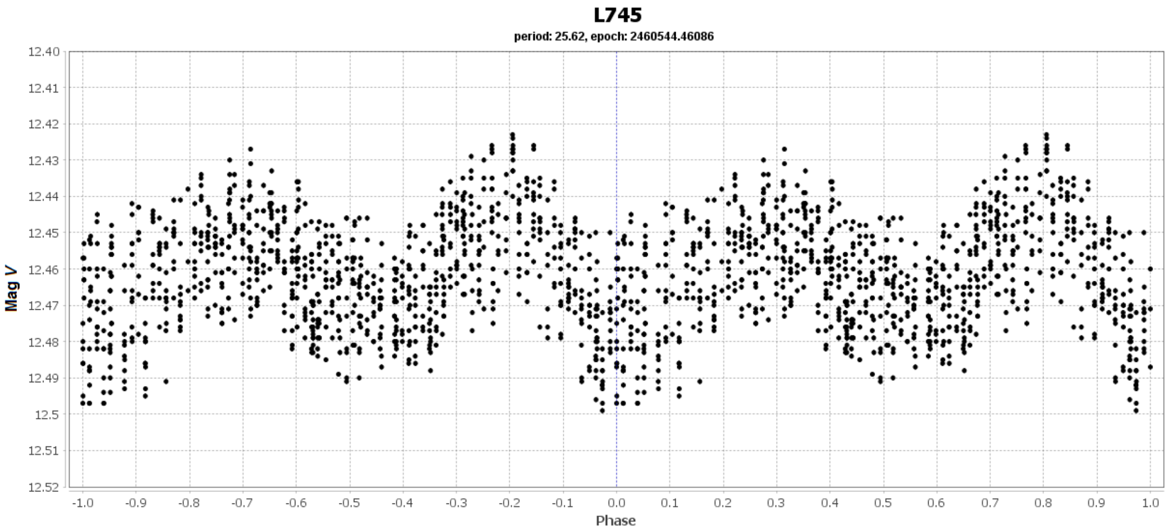


Figure 11: Light curve of L745, in phase, drawn with a period equal to 12.8 days (upper panel) and 25.62 days (lower panel): the deep and shallower minima suggest, as in previous cases, that this is a binary system.

In the case of L745, the curve obtained with the short period is of good quality; however, when drawn with the long period, the measurements suggest that it is a binary system and not a pulsating star, since the minima are alternately deep and shallower.

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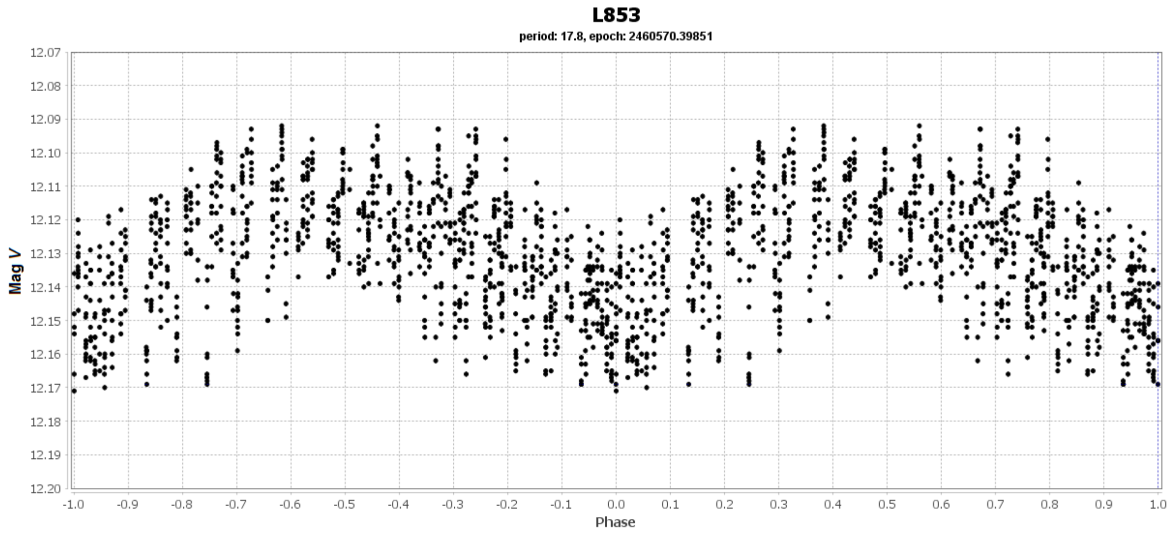

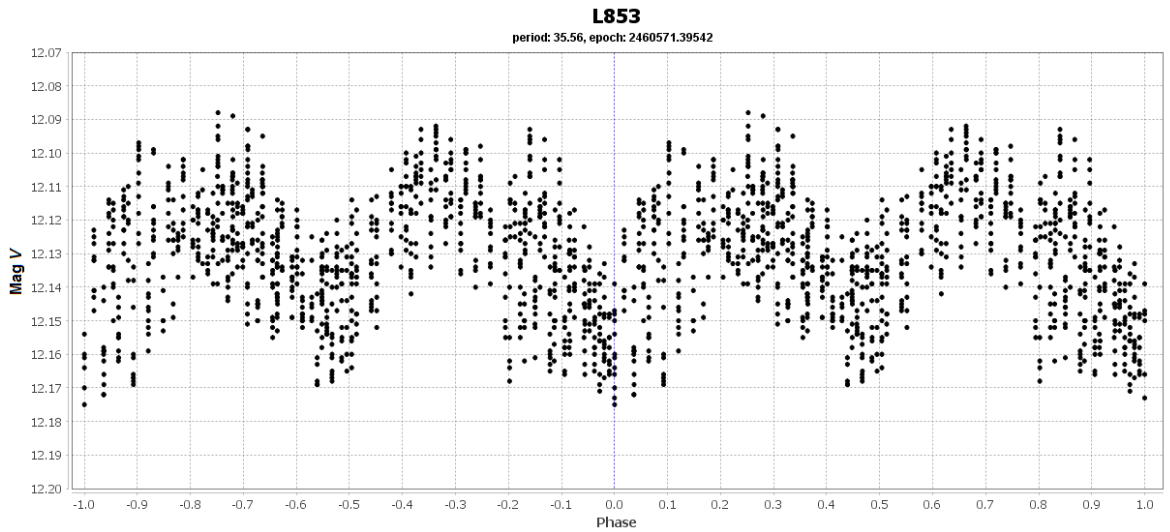

Figure 12: Light curve of L853, in phase, drawn with a period equal to 17.8 days (upper panel) and 35.56 days (lower panel): the data suggest, as in other cases, that it is another binary system and not a pulsating variable.

As in the previous case, the curve obtained with the short period (17.8 days) is of good quality; however, when drawn with the long period (35.56 days), the measurements suggest that it is a binary system and not a pulsating star since the minima are alternately deep and less deep. The same is true of the variable V41, which we show on the following page: its light curve drawn with the official period (42.5 days) is of good quality, but represented with a double period it clearly shows that it is a binary system that completes one orbit in 85.32 days.

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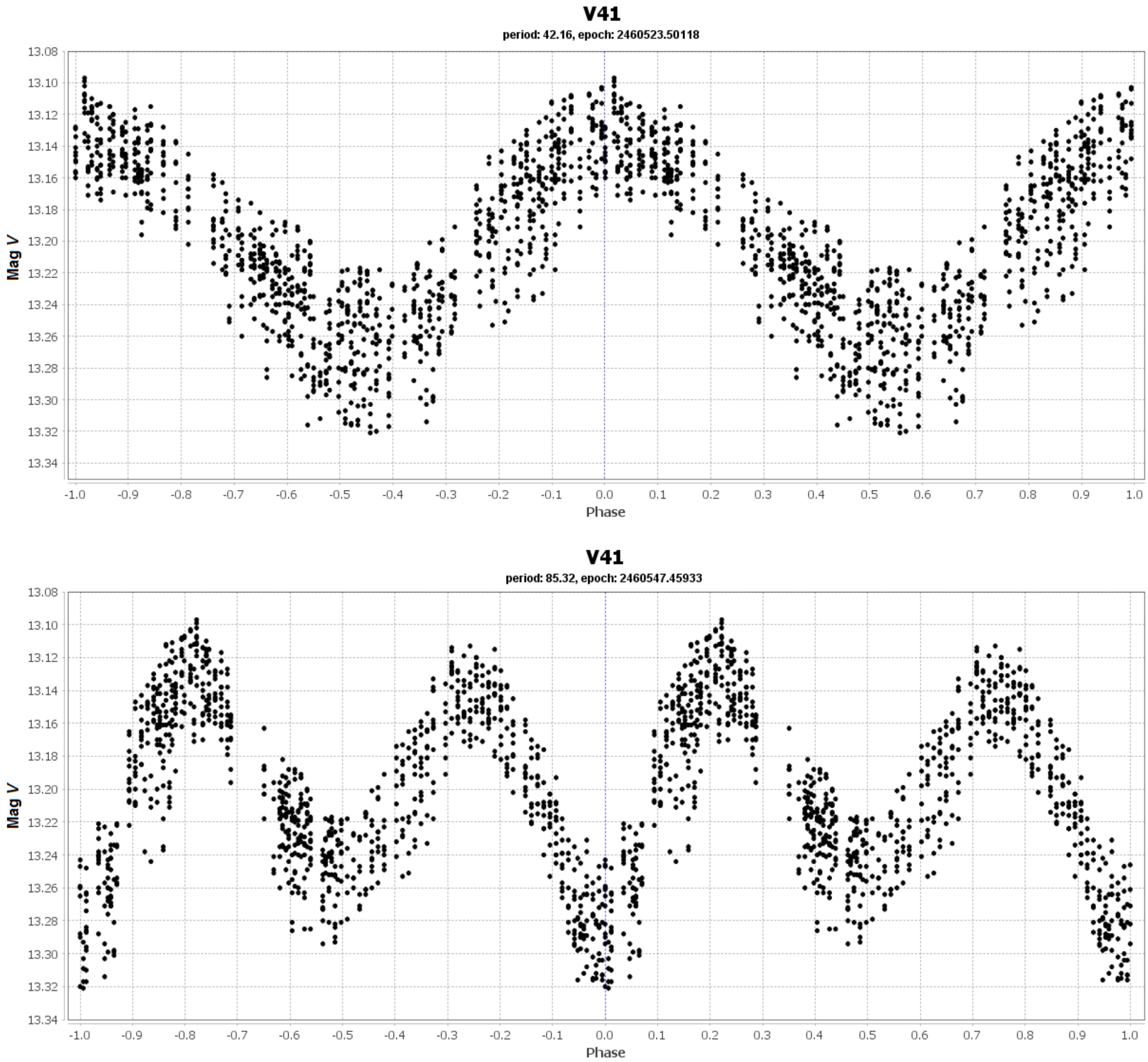

Figure 13: Light curve of V41, in phase, drawn with a period equal to 42.16 days (upper panel) and 85.32 days (lower panel): the data suggest, as in other cases, that it is another binary system and not a pulsating variable; the minima, of varying depth, corroborate this fact.

A careful examination reveals that the width of the same is not equal at the maximum and at the minimum (upper panel); the latter is wider. This is because the minima have different depths (lower panel).

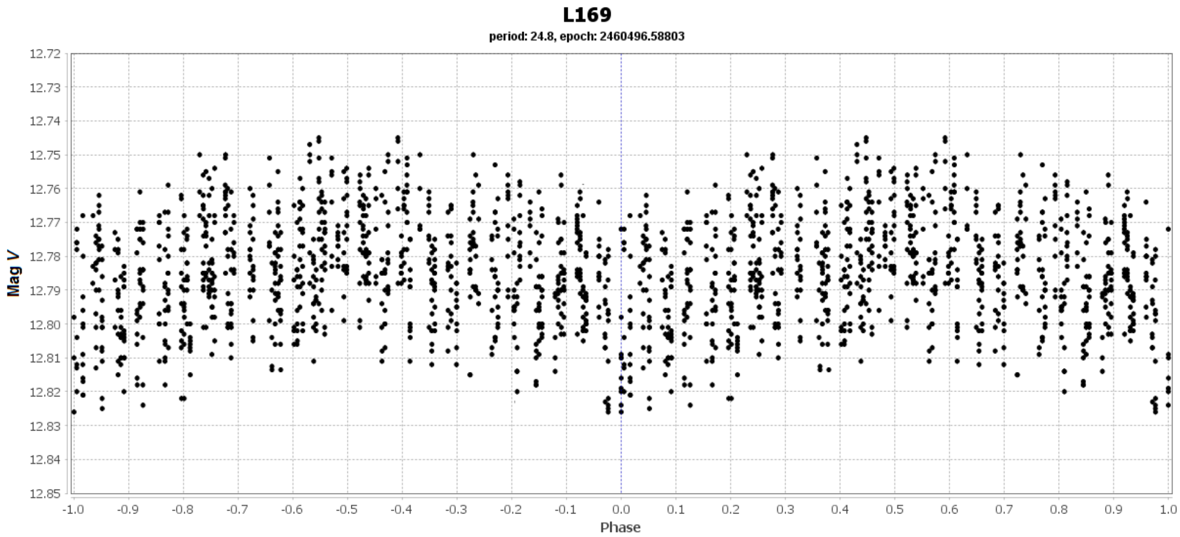

Figure 14: Light curve of L169, in phase, drawn with a period equal to 24.8 days: light curve corresponds to a pulsating Red Giant star with a reduced amplitude (0.08 mag), which explains why it has not been detected previously.

Using the average magnitudes just obtained, and the $B - V$ colour indices tabulated by STE19, we have determined its position in the colour-magnitude diagram (Figure 15) taken from the paper of Arp and Johnson (1955): L853, L481 and L250 lie at the top of the red giant branch, very close to the tip, next to the brightest variables of the cluster (V11, V42, V39, V24, V17, etc.) whose absolute magnitudes (from Osborn *et al.*, 2017) are between $M_V = -2.42$ (V11) and $M_V = -1.89$ (V43); L745, L398 and L169 appear a little lower with absolute magnitudes similar to those of V45 ($M_V = -1.74$) and something greater than V41 ($M_V = -1.19$), according to this paper. V41, with magnitudes 14.220 B, 13.126 V and $B - V$ = 1.094 (according to STE19), appears far from the top of the red giants because it is a binary system and not a pulsating red giant.

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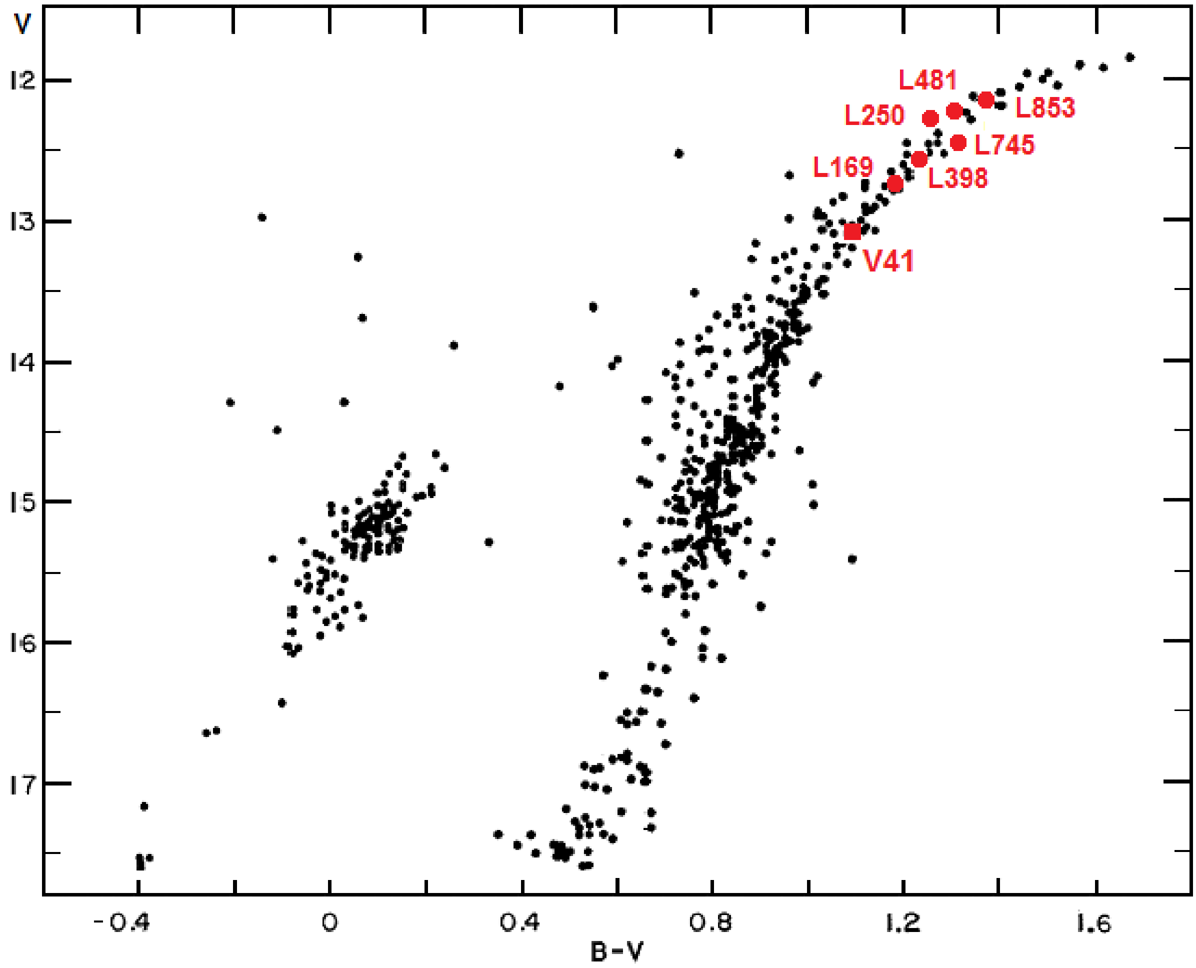

Figure 15: H-R diagram from the paper of Arp and Johnson (1955): the six new variable stars are located top of the red giant branch, very close to the tip, next to the brightest variables of the cluster. V41 appears far from the top of the red giants because it is not a pulsating giant but a binary system.

5 ASAS-SN photometry (2018-2024)

To confirm the periods we used ASAS-SN data (Jayasinghe, T. *et al.*, 2018; Shappee, B. J. *et al.*, 2014; Kochanek *et al.*, 2017), in SLOAN-g band, of each of the six variable stars (and V41) between 2018 January and 2024 November: 4577 for L169, 4541 for L250, 4416 for L398, 4560 for L481, 4512 for L745, 4582 for L853, and 4524 for V41. We eliminated some discordant measurements having a very low signal-to-noise ratio. The campaigns extended between 250 and 310 days, depending on the local meteorological condition and telescopes used, because ASAS-SN is a set of 24 robotic telescopes (whose diameter is 14 cm) distributed around the globe: Ohio and Texas in United States, Chile, South Africa and China. The search for the period was carried out in the same way as that used with our measurements in the interval 1-250 days.

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6 Conclusions

Using filtered CCD images obtained in 2024 we have studied ten red giant stars belonging to Messier 13. The data suggest that four of them (L77, L244, L316, and L353), used as comparison stars, are not variable within the detection range of our equipment (ΔV > 0.01 mag). Of the remaining six, three (L250, L745 and L853) are binary systems that complete orbits between 25.62 (L250) and 35.36 days (L853); finally, of the remaining three, two are pulsating stars with periods between 21.8 (L481) and 24.8 days (L169). The last one, L398, pulsates with a long period (88.6 days) similar to that of the bright variable V11: 92.0 days. The new variable stars present amplitudes in the range ΔV = 0.07-0.11 mag; we have determined their absolute magnitudes M_V which are in the range −2.20 (L853) to –1.55 (L169). We have analyzed the photometric measurements obtained by ASAS-SN between 2018 and 2024, in SLOAN-g band, and calculated their periods: the values are similar to those obtained by us. Since the last variable star recorded in the *CVSGC* is V69 (Violat-Bordonau, 2024b) we propose for them the names of V70, V71, V72, V73, V74, and V75.

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