

# New $\beta$ Cephei stars in the young open cluster NGC 637<sup>★</sup> (Research Note)

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## ABSTRACT

**Context.** Studying stellar pulsations in open clusters offers the possibility of performing ensemble asteroseismology. The reasonable assumption that the cluster members have the same age, distance, and overall metallicity aids in the seismic modelling process and tightly constrains it. Therefore it is important to identify open clusters with many pulsators.

**Aims.** New pulsating stars of the  $\beta$  Cephei type were searched for among the members of the open cluster NGC 637.

**Methods.** Thirty-one hours of time-resolved  $V$  filter CCD photometry were obtained.

**Results.** The measurements confirmed two previously known variables, and revealed three new  $\beta$  Cephei stars and one more candidate. All four pulsators have sufficiently large amplitudes for easy mode identification and are multiperiodic.

**Conclusions.** With four certain pulsating members, NGC 637 is now among the open clusters that are richest in  $\beta$  Cephei stars. It is thus an excellent target for ensemble asteroseismology, and to examine the differences between pulsating and apparently constant stars in the  $\beta$  Cephei domain.

**Key words.** stars: early-type – open clusters and associations: general – techniques: photometric – stars: oscillations – asteroseismology

## 1. Introduction

Asteroseismology is the study of the interiors of pulsating stars by using their modes of oscillation as seismic waves. The mode frequencies depend on the physical conditions in the regions where the oscillations propagate. Measuring these frequencies therefore provides information about the deep inner structure of stars, which is impossible in any other way. An overview of the methods and results of asteroseismology can be found in the monograph by Aerts et al. (2010).

To make asteroseismic investigations possible, one needs to know the surface and interior geometries of the observed oscillation modes. This poses the problem of mode identification (e.g., see Handler 2008; Teltig 2008). In addition, knowledge of the effective temperatures and luminosities of the target stars is important. However, absolute magnitudes of field stars can often only be determined with unsatisfactory accuracy.

The study of pulsating stars in clusters and associations alleviates this problem. The distances to stellar aggregates can be determined accurately, and because stars belonging to open clusters have originated in the same interstellar cloud, they can be assumed to have the same age and metallicity. Consequently, the asteroseismic modelling process of pulsating stars in clusters is tightly constrained.

The potential of asteroseismology has been recognized for the  $\beta$  Cephei stars (e.g., Pamyatnykh et al. 2004), which are pulsating main sequence variables with early B spectral types and typical periods of several hours (Stankov & Handler 2005; Pigulski & Pojmański 2008). These young massive

stars naturally occur in open clusters and stellar associations, and extensive observing campaigns have been organized (e.g., Saesen et al. 2010).

Searches for  $\beta$  Cephei stars in open clusters have increased the total number of such objects to about 50 out of a total of some 200 galactic  $\beta$  Cephei stars known (Pigulski 2006; Pigulski & Pojmański 2008). The relative number of pulsators to nonpulsators is considerably lower in northern hemisphere open clusters, which has been attributed to a metallicity gradient in our Galaxy (Pigulski 2004).

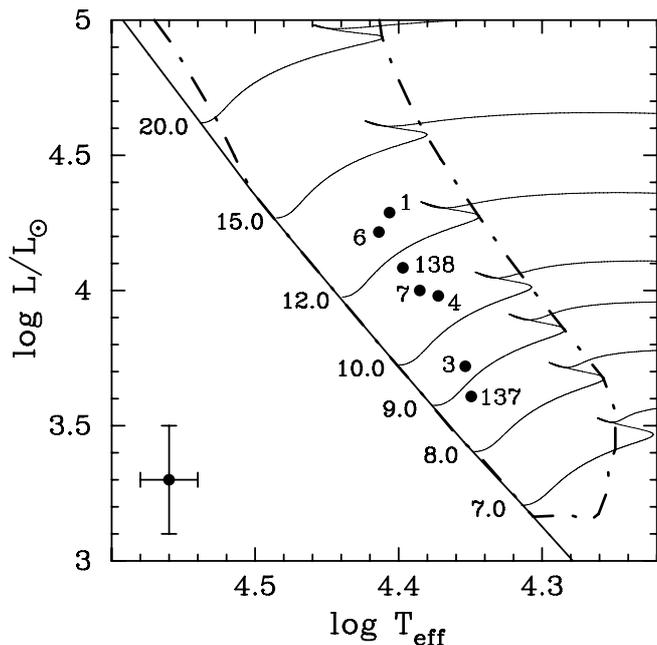
NGC 637 is a young (age  $10 \pm 5$  Myr, Yadav et al. 2008) open cluster whose seven brightest stars are of 10th magnitude. Apart from some radial velocity measurements (Liu et al. 1991, and earlier papers), this cluster has only been photometrically studied. In particular, no membership information is available in the literature.

NGC 637 has been examined for stellar variability. Two of the seven brightest stars turned out to be variable (Pietrukowicz et al. 2006). One has been classified as a  $\beta$  Cephei star, and the other was said to be an ellipsoidal variable. New standard  $uvby\beta$  photometry (Handler 2011) puts all seven bright stars into the  $\beta$  Cephei instability strip (Fig. 1). To evaluate the prospects of NGC 637 as a target for ensemble asteroseismology, it was decided to re-examine the cluster for pulsating stars.

## 2. Observations and data reduction

Time series photometric measurements were carried out with the 0.8-m “vienna little telescope” (vlt) at the Institute of Astronomy of the University of Vienna. The telescope is located at an altitude of 241 m, some 5 km away from the city centre. It was used in combination with an SBIG STL-6303E CCD camera, with a focal reducer and a 3 K  $\times$  2 K front-illuminated Kodak Enhanced

<sup>★</sup> Photometric lightcurves are only available in electronic form at the CDS via anonymous ftp to [cdsarc.u-strasbg.fr](mailto:cdsarc.u-strasbg.fr) (130.79.128.5) or via <http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/533/A70>



**Fig. 1.** The positions of the seven brightest stars in NGC 637, as derived in Sect. 4, and labelled with their WEBDA (<http://www.univie.ac.at/webda/>) numbers, in a  $\log T_{\text{eff}} - \log L$  diagram. Some model evolutionary tracks computed with the Warsaw-New Jersey code (e.g., see Pamyatnykh et al. 1998) are shown for comparison, marked with the corresponding masses. The slanted full line is the zero-age main sequence. The dashed-dotted line is the theoretical  $\beta$  Cephei star instability strip (Zdravkov & Pamyatnykh 2008). Error bars of the individual positions of the stars are given in the lower left corner.

KAF-6303E chip. The pixel size of  $9 \times 9$  microns translates to  $0.41''$  on the sky and gives a total field of view of  $20.8' \times 13.9'$ . The measured value for the gain is  $2.32 \pm 0.02 e^-/\text{ADU}$  in  $2 \times 2$  binning. The read noise was determined with  $11.2 e^-$  and the dark current with  $0.07 e^-/\text{pix/s}$  at  $0^\circ\text{C}$ .

Given the typical seeing in Vienna (between  $1.4''$ – $6''$  FWHM, with a median of  $2.8''$  during the present measurements), the chip was binned  $2 \times 2$ , resulting in a readout time of 8 s. Owing to technical problems with the filter wheel, only the V filter was used. Integration times of 10 or 15 s were chosen, depending on seeing. NGC 637 was observed on nine nights from December 2010 to March 2011 in which a total of 4776 usable science frames were collected.

The journal of the observations is given in Table 1. Due to constraints from other observing programmes, the camera was rotated twice during the project. Care was taken that after the second rotation the observed field matched the original orientation as closely as possible. The time base of the total data set is 61.2 d.

The CCD frames were reduced with standard IRAF tasks, comprising corrections for bias level, dark current, and flat field. Flat-field frames were obtained by exposing the CCD to the evening twilight sky. Heliocentric Julian Dates were computed for the middle of each exposure. The photometry of the reduced frames was carried out using the MOMF (Multi-object multi-frame, Kjeldsen & Frandsen 1992) package. MOMF applies combined point-spread function/aperture photometry relative to an optimal sample of comparison stars, ensuring the highest quality differential light curves of the targets.

All sets of frames, grouped by field orientation, were searched for variables as a first step. Then, the optimal apertures,

**Table 1.** Journal of the observations.

Civil date	Run start UT	Length h
30/12/2010	16:19:38	0.89
06/02/2011	16:51:19	4.99
07/02/2011	17:13:29	4.34
23/02/2011	17:19:55	4.25
24/02/2011	17:09:03	1.13
25/02/2011	17:11:58	4.37
26/02/2011	17:59:19	3.02
28/02/2011	17:16:56	4.34
01/03/2011	17:17:47	4.01
Total		31.34

**Notes.** Times of CCD rotation are identified with thick horizontal lines.

in terms of minimizing the scatter in the resulting light curves, were determined for all targets of interest from the most extensive subset of data (Feb. 23–Mar. 1). These apertures were then used for all data subsets, and differential magnitudes were computed for all stars. The light curves of the data subsets were combined and the relative zeropoints adjusted between them because the comparison star sample varied with field orientation, but not between individual nights. The resulting final light curves were cleaned for statistically significant outliers and first searched for variability up to the Nyquist frequency. No evidence of periodic signals with periods between 47 s and 90 min was found. Consequently, the data were merged into 3-min bins and subjected to variability analysis.

### 3. Analysis

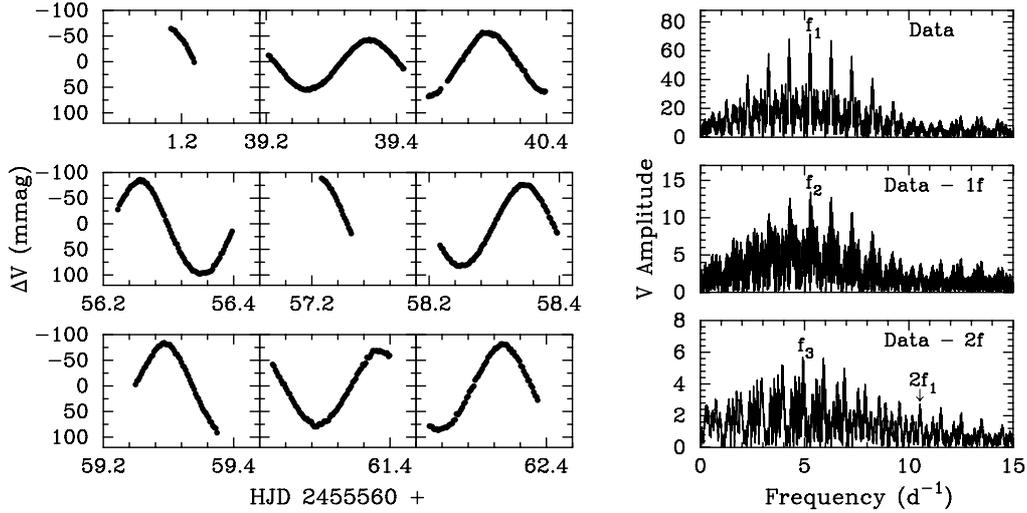
Unless otherwise noted, frequency analyses were performed with the program package Period04 (Lenz & Breger 2005). This software uses single-frequency Fourier and multifrequency nonlinear least-squares fitting algorithms. Amplitude spectra were computed and the frequencies of the intrinsic and statistically significant peaks in the Fourier spectra were determined. Multifrequency fits were calculated with all detected signals, and the corresponding frequencies, amplitudes, and phases were optimized. The resulting fit was subtracted from the data before residual amplitude spectra were computed. These were examined in the same way until no significant further periodicity could be detected. In what follows, this procedure is called prewhitening.

The frequency solutions derived from the new light curves are given in the consequent subsections. On suggestion by the referee, formal error estimates of the individual parameters following Montgomery & O'Donoghue (1999) are given. However, they will be systematically overoptimistic: our frequency analyses are affected by aliasing and more signals may be present in the data.

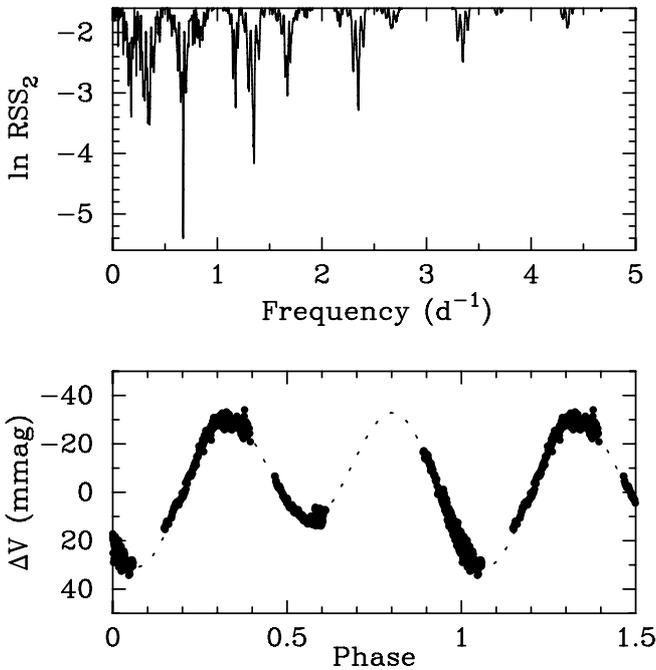
#### 3.1. Previously known variable cluster members

Pietrukowicz et al. (2006) discovered the variability of NGC 637 4<sup>1</sup> and identify it as a  $\beta$  Cephei pulsator. The light curves of this star from the present study are shown in the left part of Fig. 2. The light range varies from 0.1 to 0.2 mag during different nights, suggesting beating of several pulsation modes.

<sup>1</sup> All stars are identified with their WEBDA designations, whenever available.



**Fig. 2.** *Left:* light curves of the known  $\beta$  Cephei star NGC 637 4. *Right:* amplitude spectra of the data with successive prewhitening.



**Fig. 3.** *Upper panel:* residualgram analysis of the light curves of the previously known variable NGC 637 3. *Lower panel:* phase diagram of these data with the best fit to it (dotted line).

This is confirmed by the Fourier analysis of the light curves (Fig. 2, right half). The corresponding frequency solution, leaving behind an rms residual of 3.4 mmag per single data point, is listed in Table 2 (top). The two strongest oscillations and the harmonic were previously found by Pietrukowicz et al. (2006), consistent with the present results. The third oscillation frequency is new.

NGC 637 3 was also recognized as a variable star with a main period of 0.7432 d (Pietrukowicz et al. 2006). These authors preferred the explanation of an ellipsoidal variable (with an orbital period of  $2 \times 0.7432$  d) for the star over the one of a slowly pulsating B star, because of its high luminosity.

Fourier analysis of the present data set reveals the same dominant period. However, pushing it further leads to difficulties because the subharmonic of this frequency ( $0.673$  d $^{-1}$ ) cannot be

**Table 2.** Frequency solutions for the known variable cluster members.

WEBDA	ID	Frequency (d $^{-1}$ )	V Amplitude (mmag)	S/N
4	$f_1$	$5.26350 \pm 0.00002$	$65.2 \pm 0.2$	64.6
	$f_2$	$5.28770 \pm 0.00007$	$22.5 \pm 0.2$	22.6
	$f_3$	$4.9073 \pm 0.0002$	$7.0 \pm 0.2$	6.7
	$2f_1$	$10.52699 \pm 0.00004$	$2.3 \pm 0.2$	4.1
3	$f_1$	$0.67266 \pm 0.00008$	$9.9 \pm 0.1$	13.5
	$2f_1$	$1.34532 \pm 0.00004$	$26.2 \pm 0.1$	36.5

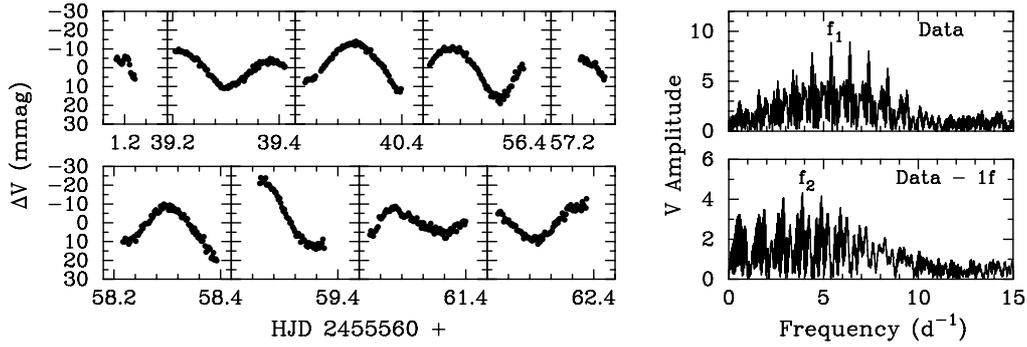
**Notes.** Error estimates are formal and to be used with caution.

distinguished from its first harmonic ( $2.691$  d $^{-1}$ ) owing to daily aliasing. Even worse, the  $-2$  d $^{-1}$  alias of the strongest signal is not fully resolved from the possible subharmonic. Residualgram analysis (Martinez & Koen 1994), consisting of fitting a sine wave with  $M$  harmonics to the measured time series and evaluating the residuals at each trial frequency, provides the solution (Fig. 3, upper panel). Fitting a signal with one harmonic to the data clearly shows that the base frequency is  $0.673$  d $^{-1}$ . The resulting frequency solution is given in Table 2 (bottom), and no other signal is significantly present in the light curves. The rms of the residual time series is 2.2 mmag per point.

The lower panel of Fig. 3 shows a phase diagram of the light curve with the base frequency. Unfortunately, there is only about 56% phase coverage, however, a fit to this phase diagram (cf. Fig. 3) suggests a light curve resembling an ellipsoidal variable, with equal light maxima and unequal minima. Although we cannot rule out that the variability is induced by rotation, we prefer the interpretation of ellipsoidal light variations for NGC 637 3.

### 3.2. New $\beta$ Cephei stars

The brightest member of NGC 637, WEBDA 1, is a new  $\beta$  Cephei star. Its light curves (Fig. 4, left-hand side) can reach light ranges of about 0.045 mag in  $V$ . Multiperiodicity is evident from the light variations and from a Fourier analysis with prewhitening (Fig. 4, right-hand side). The frequency analysis for these data is summarized in Table 3 (top). There are aliasing uncertainties, and the residual amplitude spectrum suggests the



**Fig. 4.** *Left:* light curves of the new  $\beta$  Cephei star NGC 637 1. *Right:* amplitude spectra of these data with successive prewhitening.

**Table 3.** Frequency solutions for the new  $\beta$  Cephei stars in NGC 637.

WEBDA	ID	Frequency ( $\text{d}^{-1}$ )	V Amplitude (mmag)	S/N
1	$f_1$	$5.3899 \pm 0.0002$	$9.3 \pm 0.2$	8.0
	$f_2$	$3.8962 \pm 0.0004$	$4.5 \pm 0.2$	4.0
7	$f_1$	$5.1982 \pm 0.0001$	$10.7 \pm 0.2$	14.1
	$f_2$	$5.7634 \pm 0.0003$	$4.9 \pm 0.2$	7.0
138	$f_1$	$4.5364 \pm 0.0002$	$11.5 \pm 0.2$	13.9
	$f_2$	$5.7941 \pm 0.0004$	$5.0 \pm 0.2$	6.9

**Notes.** Error estimates are formal and to be used with caution.

presence of more, or unresolved, frequencies in the light variations of the star.

Most of the previous comments apply to the variability of NGC 637 7 as well. The star is also multiperiodic with a slightly narrower light range (up to 0.041 mag, Fig. 5). However, although the aliasing is as severe as for the previous star, it was easier to find the most probable intrinsic frequencies (Table 3, middle), and the prewhitening residuals are lower (2.8 vs. 3.7 mmag rms per point), suggesting that this star has a simpler oscillation behaviour than does NGC 637 1.

The variability of NGC 637 138 is similar to the two stars discussed above. The  $V$  light range can reach 0.045 mag (Fig. 6). Results from the frequency analysis are listed in Table 3 (bottom), and the rms residual scatter is 3.4 mmag per data point. A re-analysis of the time series photometry by Pietrukowicz et al. (2006) shows the pulsations of these three stars to be marginally present, but these data alone were unfortunately insufficient for confident detections.

### 3.3. A $\beta$ Cephei suspect and an apparently constant star in the $\beta$ Cephei domain

The light curves of NGC 637 6 (Fig. 7) raise the suspicion that it is a low amplitude  $\beta$  Cephei star. During almost all nights, there is some variability on the time scale expected for pulsation, and the star is separated well from others in the field, implying no blending problems in the photometry. However, the Fourier analysis is inconclusive since the light curves are dominated by nightly variations in the mean stellar magnitude, most likely of instrumental origin<sup>2</sup>. Nevertheless, the rms scatter per single point in this light curve is only 2.6 mmag. Individual

<sup>2</sup> Nightly zeropoint variations at the same level are also present in the data for the other bright stars, but are smaller than their intrinsic variability.

$\beta$  Cephei pulsation modes, if present, would not exceed a level of 1.5 mmag in amplitude.

Finally, NGC 637 137 did not show any sign of intrinsic variability. The star is a close double ( $\approx 10''$  separation) with NGC 637 138 in the very centre of the cluster. Our images under the best seeing conditions suggest another faint star in between the two. In either case, the photometry of NGC 637 137 became poor under poor seeing conditions, but even taking only the best light curves (about 2/3 of the data) shows no trace of variability within a limit of 3 mmag in total or 1 mmag in the  $\beta$  Cephei frequency domain.

### 3.4. Other (claimed) variable and interesting stars in the field

There are some other objects in the field of NGC 637 that deserve special attention. These are briefly discussed here, together with newly detected variables from the present study.

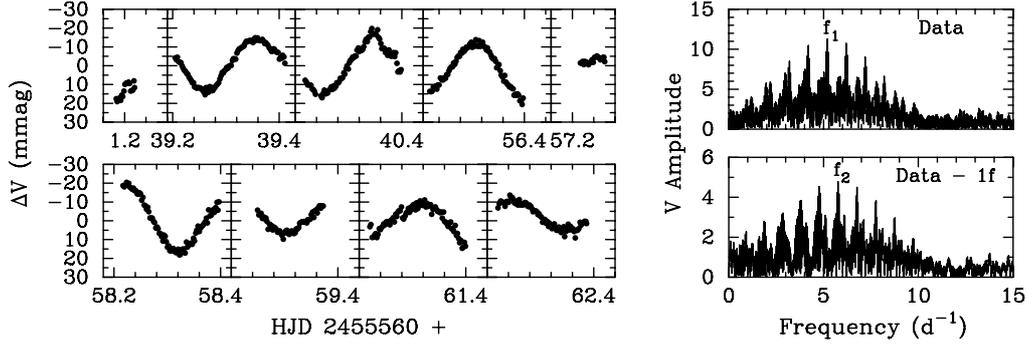
NGC 637 13 is variable in the present data, with a main frequency of  $2.46 \text{ d}^{-1}$  and an amplitude of 17 mmag. Star WEBDA 18 was claimed to be variable (Huestamendia et al. 1991). The present measurements show no evidence of variability within a limit of 5 mmag, or 2 mmag for periods shorter than 2.5 h.

NGC 637 27 is a Be star (Yadav et al. 2008). Because these stars are often variable, we consequently examined our data. However, no variability within a limit of 5 mmag, or within 1.4 mmag for periods shorter than 2.5 h, was found.

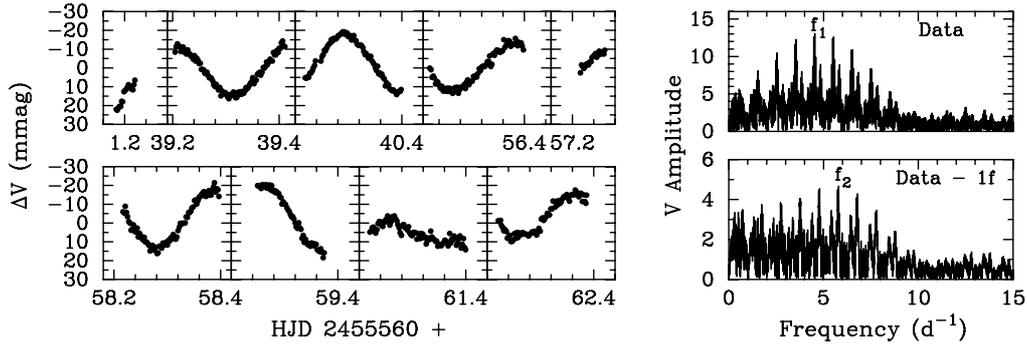
WEBDA 33 in NGC 637 is also variable, with a dominant frequency of  $0.703 \text{ d}^{-1}$ . The light curve is asymmetric, as also implied by the presence of a first harmonic from combining Fourier and residualgram methods, and reaches a total light range of 0.053 mag.

NGC 637 68 showed an egress from an eclipse in one night of measurement (Fig. 8). Finally, two new  $\delta$  Scuti stars were discovered, GSC 04039–00930 with a dominant frequency of  $14.36 \text{ d}^{-1}$  (modulo daily aliasing) and an amplitude of about 2.5 mmag, and GSC 04040–01606 with apparent multiple frequencies between 6 and  $8 \text{ d}^{-1}$  with amplitudes around 12 mmag.

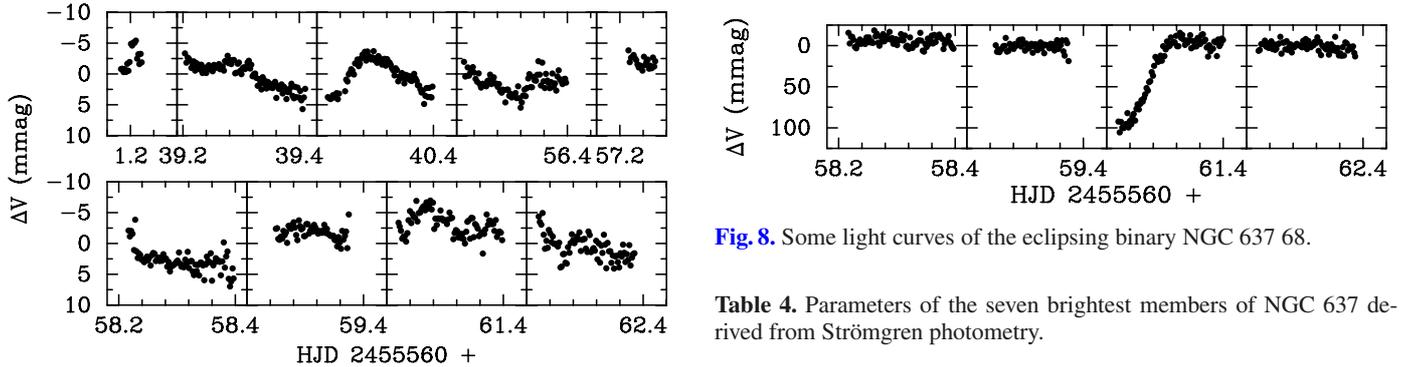
The positions of the new variables that have WEBDA identifications in a  $V$  vs.  $B-V$  colour–magnitude diagram, constructed with WEBDA, are consistent with cluster membership. On the other hand, the two  $\delta$  Scuti stars have no WEBDA designations and no accurate  $BV$  photometry. Their mean  $V$  magnitudes are  $\approx 12.7$  and  $\approx 13.9$  on our frames, respectively. In the following section, we estimate a distance modulus of  $V - M_V = 13.6$  to NGC 637, implying  $M_V = -0.9$  and  $0.3$ , respectively, if the two pulsators are cluster members. The period–luminosity–colour relation for  $\delta$  Scuti stars (Breger 1979) provides  $M_V = 1.7 \pm 0.7$  and  $0.7 \pm 0.7$ , respectively. The error estimates are dominated



**Fig. 5.** *Left:* light curves of the new  $\beta$  Cephei star NGC 637 7. *Right:* amplitude spectra of these data with successive prewhitening.



**Fig. 6.** *Left:* light curves of the new  $\beta$  Cephei star NGC 637 138. *Right:* amplitude spectra of these data with successive prewhitening.



**Fig. 7.** Light curves of the  $\beta$  Cephei suspect NGC 637 6.

by the unknown colours of the variables and represent the width of the instability strip. We conclude that GSC 04039–00930 is a foreground star. GSC 04040–01606 may be a cluster member, although it is some  $9'$  off centre. It would then be a pre-main sequence pulsator because of its long periods and the young age of the cluster.

#### 4. Discussion

The Strömgren  $uvby\beta$  photometry by Handler (2011) can be used to derive  $T_{\text{eff}}$  and  $M_V$ , thus  $\log L$  of the individual stars, but also their reddenings and distance moduli. The routines by Napiwotzki et al. (1993) were employed to this end. Bolometric corrections by Flower (1996) and a bolometric magnitude of  $M_{\text{bol}} = 4.74$  for the Sun (Livingston 2000) were used to obtain stellar luminosities. The results of this procedure are listed in Table 4 and were also used for constructing Fig. 1.

The interstellar reddening of these stars is virtually the same, suggesting that they are all at the same distance and are therefore

**Table 4.** Parameters of the seven brightest members of NGC 637 derived from Strömgren photometry.

#	$T_{\text{eff}}$ (kK)	$\log g$ (dex)	$E(b-y)$ (mag)	$M_V$ (mag)	$\log L$ ( $L_{\odot}$ )	$V - M_V$ (mag)
1	25.5	3.6	0.470	−3.51	4.29	13.49
3	22.6	4.2	0.470	−2.39	3.72	12.97
4	23.6	3.9	0.499	−2.93	3.98	13.71
6	25.9	3.9	0.487	−3.29	4.21	13.64
7	24.3	4.0	0.469	−2.91	4.00	13.58
137	22.4	4.4	0.451	−2.13	3.61	12.92
138	24.9	3.9	0.439	−3.06	4.08	13.22

**Notes.** # is the WEBDA identification of the stars. The error on  $T_{\text{eff}}$  is about  $\pm 4\%$ , and 0.2 dex in  $\log g$ .

cluster members. The mean value is  $E(b-y) = 0.469 \pm 0.008$  mag, translating into  $E(B-V) = 0.65 \pm 0.01$  mag. This is in excellent agreement with the value by Yadav et al. (2008), but less consistent with Pietrukowicz et al. (2006).

Looking at the apparent distance moduli  $V - M_V$ , there are considerable differences of up to 0.79 mag between individual stars. However, it must be kept in mind that the absolute magnitude calibration of Strömgren photometry treats each star as if it was single. The spread in  $V - M_V$  is very close to the absolute

magnitude difference of a single star and a binary with equal components. It is therefore possible that stars WEBDA 3, 137 and 138 are members of binary systems. In fact, WEBDA 3 probably shows ellipsoidal variations due to a secondary component. In any case, determining a cluster distance from the four stars with consistent  $V - M_V$  (with a mean value of 13.6 mag) results in  $d \approx 2.1$  kpc, in reasonable agreement with the literature results, given our crude approach.

Of the  $\beta$  Cephei stars, NGC 637 4 is among the five highest amplitude pulsators of this type ever discovered (cf. Pigulski & Pojmański 2008). Such high-amplitude  $\beta$  Cephei stars often show a “stillstand” phenomenon in the rising branch of their light curves. This is not the case for NGC 637 4. A first harmonic was detected for this star, but it modifies the light curve shape from a sinusoid towards a higher and sharper maximum and a flatter and shallower minimum, such as observed in pulsating white dwarf stars (e.g., Montgomery 2005).

From an asteroseismic point of view, the large amplitudes of the two dominant modes of NGC 637 4 easily allow mode identification from multicolour photometry, once resolved from each other. The strongest modes in the three new  $\beta$  Cephei pulsators WEBDA 1, 7, and 138 reported here may also be identified with a rather modest data set.

Of the seven brightest stars in this cluster and their light variability as an ensemble, four are now known as  $\beta$  Cephei stars, and one is a suspect. There are currently too few observational constraints to pinpoint the distinction between pulsators and nonpulsators. However, it is interesting to note that the two apparently pulsationally stable stars may have binary companions, as implied by the difference between their apparent and absolute magnitudes from Strömgren photometry. They would therefore be less massive than the pulsators. More evidence in this direction would be provided by (spectroscopic) confirmation of the ellipsoidal variability of WEBDA 3.

## 5. Summary and conclusions

Thirty-one hours of time-resolved  $V$  filter CCD photometry of the open cluster NGC 637 resulted in confirming two previously known variable cluster members, one  $\beta$  Cephei pulsator and one probable ellipsoidal variable. Three new  $\beta$  Cephei stars were discovered in the cluster, and one more star is suspected of showing low-amplitude oscillations of the same kind. Other variable stars in the field are also reported. The present study shows that precise relative photometry can be obtained with a small telescope at an urban site.

NGC 637 is now among the six open clusters with most  $\beta$  Cephei stars known (together with NGC 884, NGC 3293,

NGC 4755, NGC 6231 and NGC 6910, Pigulski 2004; Stankov & Handler 2005; Saesen et al. 2010). The presence of at least four pulsators in a small portion of the sky (the seven brightest stars are located within  $3' \times 4'$ ), the large amplitudes of the dominant modes and the apparent presence of nonpulsating stars within the  $\beta$  Cephei domain make NGC 637 an attractive target for ensemble asteroseismology. Time-resolved photometric observations in several filters, including an ultraviolet band for pulsational mode detection and identification, are easily possible. Spectroscopic observations of the seven brightest cluster members are desirable for several purposes: to determine the rotational velocities, to look for binary companions and/or radial velocity variations, to derive more accurate  $T_{\text{eff}}$  and  $\log g$  values, and perhaps even to determine abundances of chemical elements.

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