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Period and light curve fluctuations of the *Kepler* Cepheid V1154 Cyg

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ABSTRACT

We present a detailed period analysis of the bright Cepheid-type variable star V1154 Cygni (V=9.1 mag, P≈4.9 d) based on 600 days of continuous observations by the *Kepler* space telescope. The data reveal significant cycle-to-cycle fluctuations in the pulsation period, indicating that classical Cepheids may not be as accurate astrophysical clocks as commonly believed: regardless of the specific points used to determine the $O - C$ values, the cycle lengths do change by about 0.01 days (0.2 per cent) seemingly randomly over the 120 cycles covered by the observations. We compare the measurements with simulated light curves that were constructed to mimic V1154 Cyg as a perfect pulsator modulated only by the light travel time effect caused by low-mass companions. We show that the observed period noise in V1154 Cyg represents a serious limitation in search for binary companions. While the *Kepler* data are accurate enough to allow the detection of planetary bodies in close orbits around a Cepheid, the astrophysical noise can easily hide the signal of the light-time effect.

Key words: stars: variables: Cepheids – stars: individual: V1154 Cyg – techniques: photometric – planets and satellites: detection

1 INTRODUCTION

Cepheids are luminous, F and G type supergiant stars, exhibiting radial pulsations driven by the κ-mechanism with periods from a few days up to about 100 days. Owing to their high luminosity and well-defined period-luminosity relations, they are primary distance indicators. The pulsation period is one of the most important parameters of a Cepheid variable and it is assumed to be stable on short time scales. However, on the evolutionary time-scales, Cepheid periods are subject to variations but these period changes become detectable only over several decades or even longer timescales (Szabados 1983; Turner, Abdel-Sabour Abdel-Latif & Berdnikov 2006).

Observations of Cepheids with ground based instruments provide very poor light curve sampling, usually 1-2 data points per night which is mainly due to the long pulsation period of these variables. In addition, except whole Earth campaigns, observations usually cover a few weeks at most. The three phases of the Optical Gravitational Lensing Experiment (OGLE) project produced years of observations of Cepheids in the Magellanic Clouds (e.g. Soszynski et al. 2008ab, 2010) but again, the OGLE light curves contain one point per night. While this is perfectly enough to characterize the general variability of the few thousand Cepheids in the OGLE fields, detailed insight into the light curve shape changes or short-term period fluctuations are prevented by the daily sampling. The quasi-continuous observations of *Kepler* give us a unique opportunity to study such variables as never before.

Cepheids are often regarded as clockwork-precision, regular pulsators and with a few exceptions (V473 Lyr: Burki et al. (1982),

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Polaris: Turner et al. (2005); Bruntt et al. (2008); Spreckley & Stevens (2008)) this is usually a valid approximation to the limits set by the sampling and precision of ground-based observations. Poleski (2008) has analysed the period change of Cepheids based on the OGLE and MACHO datasets and found variability on the scale of a few years. State-of-the-art one-dimensional hydrocodes (Florida-Budapest: Kolláth et al. (2002), Warsaw: Smolec & Moskalik (2008)) have been supporting this view, because after reaching their limit-cycle (in case of a single-mode pulsation) they are able to repeat pulsational cycles essentially forever. This of course assumes that no evolutionary or additional processes acting on longer time scales are included in the set of equations solved numerically.

Photometric time series data obtained by space based telescopes have been available on a few Cepheids: Spreckley & Stevens (2008) analysed photometric data of Polaris observed with the SMEI instrument on board the Coriolis spacecraft; independently, Bruntt et al. (2008) also studied Polaris using the SMEI and WIRE star tracker photometry; Berdnikov (2010) studied the periodicity of eight Cepheids based on SMEI photometry; while the existing WIRE data on δ Cephei are currently being analysed (Bruntt 2007). Although the precision of these data is superior to that of their ground based counterparts, the 0.0001 relative accuracy still hides the subtle effects to be discovered from the *Kepler* data.

In this paper we present the first evidence that the pulsation period of V1154 Cyg is jittering, i.e. it is not as stable as the present models predict. In Sect. 2 we briefly describe the data used, with details of pixel-level photometry of the saturated *Kepler* observations, and then the methods of the analysis. In Sect. 3, our findings on the period fluctuations in V1154 Cyg are described, while the implications are discussed in Sect. 4. We conclude with a short summary in Sect. 5.

2 DATA ANALYSIS

The data we use in this paper were provided by the *Kepler* space telescope. The telescope was launched in March 2009 and designed to detect transits of Earth-like planets. A detailed technical description of the *Kepler Mission* can be found in Koch et al. (2010) and Jenkins et al. (2010a,b).

The *Kepler* space telescope observes 105 square degree area of the sky in the constellations Cygnus and Lyra, and has two observational modes, sampling data either in every 58.9 s (short-cadence which characteristics was analysed by Gilliland et al. (2010)) or 29.4 min (long-cadence), providing quasi-continuous time series for hundreds of thousands of stars. The data are divided into quarters: the commissioning run, Q0 ($\sim$10 d), then Q1 ($\sim$34 d) followed by Q2, Q3, Q4, Q5, Q6, and Q7 ($\sim$90 d for each); when this paper is written $\sim$418 days of observations are available to us.

In the field of view of *Kepler*, there is only one genuine Cepheid variable so far (Szabó et al. 2011a), V1154 Cyg (KIC 7548061) which has been observed in long-cadence mode in all quarters and short-cadence mode in Q1, Q5, Q6. V1154 Cyg has a mean V magnitude of $\sim$9.1 mag and period of $\sim$4.925 d. Previous observational studies of this Cepheid are listed and discussed by Szabó et al. (2011a).

2.1 Cepheid pixel photometry

In Szabó et al. (2011a) we demonstrated that the apparent large amplitude variations (especially in Q2) are not intrinsic to the star, because some of the flux was lost from the assigned *optimal aperture* (Bryson et al. 2010) of V1154 Cygni. The usual output of the *Kepler* photometer is the integrated flux (light curve). However, to correct for this instrumental effect we have to rely on additional information to which we had no access at the time of writing the Szabó et al. (2011a) paper.

Besides the extremely precise measurements of *Kepler* it is equally important that recently the individual pixel time-series data have been made available[1] by the *Kepler* Team. In a number of cases the pixel data provided crucial information (1) on the photocenter of the transit variations (Batalha et al. 2010) thereby confirming planetary candidates, (2) helped to devise a custom aperture for RR Lyrae (Szabó et al. 2010), which is too bright and is located very close to the edge of one of the CCDs, thereby providing a way to observe this important prototype Blazhko variable with *Kepler*, or (3) in a recent paper (Szabó et al. 2011b) based on pixel data we were able to determine which component of a close visual CPM binary is transited by a 'hot' brown dwarf.

We have downloaded all the long cadence target pixel files (Q0-Q7) of V1154 Cygni. We assigned a much larger aperture than the original optimal aperture to sum the pixels to ensure that we do not loose flux, see Fig.1. It is worth noting that V1154 Cygni is heavily saturated on the *Kepler* CCDs, so an elongated aperture is applied. It is also noticeable that the central (saturated) column is not contained in its entirety with the original optimal aperture. We took care to exclude additional stars captured in the downloaded pixels. Later it proved to be a wise decision, because by adding up its pixels the additional star centered at (3,13) turned out to be a previously unknown variable star showing frequency peaks in the [2,3] c/d frequency range.

The resulting light curve is very similar to the *Kepler* light curve, except that the spurious amplitude drop has disappeared. Although light curve sections of different Qs had to be shifted vertically because of the different sensitivities of the CCDs (occurring due to the quarterly roll of the space telescope), we did not have to adjust the amplitudes which is reassuring. The only exception is Q0 (commissioning phase containing only two pulsational cycles), where inspection of the downloaded pixels confirmed that some flux was lost in the maximum phases, because the flux spilled out of the downloaded pixels, and this affected the pulsation amplitude and the $O-C$ values as well.

2.2 The $O-C$ diagram

We studied the period stability of V1154 Cyg applying the classical $O-C$ diagram method (Sterken 2005). Thanks to the continuous observations of *Kepler*, we could determine the $O-C$ values for all cycles. For a thorough analysis, we used 4 different methods to calculate the $O-C$ values that are described below.

The first and second methods were to determine the times of maxima and minima of the light curve by fitting tenth-order polynomials around the extremes. The calculated $O-C$ diagram for the times of maxima and minima are shown in Fig. 2 plotted with square and triangle symbols, respectively.

We also determined the moments of the median brightness of the light curve. Their $O-C$ diagram are plotted with red crosses in Fig. 2.

The fourth method was to measure phase shifts of each pulsational cycle and transform this to an $O-C$ diagram. This was done

[1] MAST, http://archive.stsci.edu/kepler/

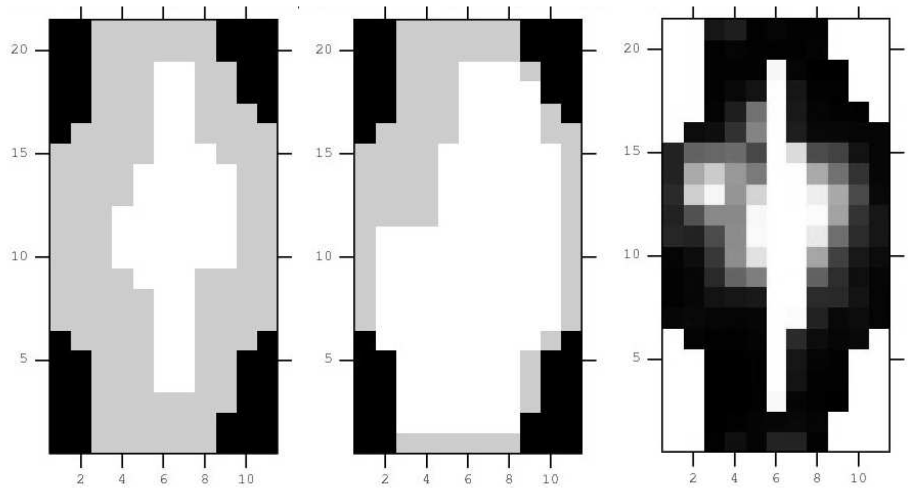

Figure 1. Left: original optimal aperture mask in Q2 (white), all the downloaded pixels (grey), pixels that were not downloaded (black). The axes label row and cloumn pixel numbers. Middle: our custom mask designed to retain all the flux. Right: Flux distribution around one of the maxima of V1154 Cyg in Q2 (greyscale).

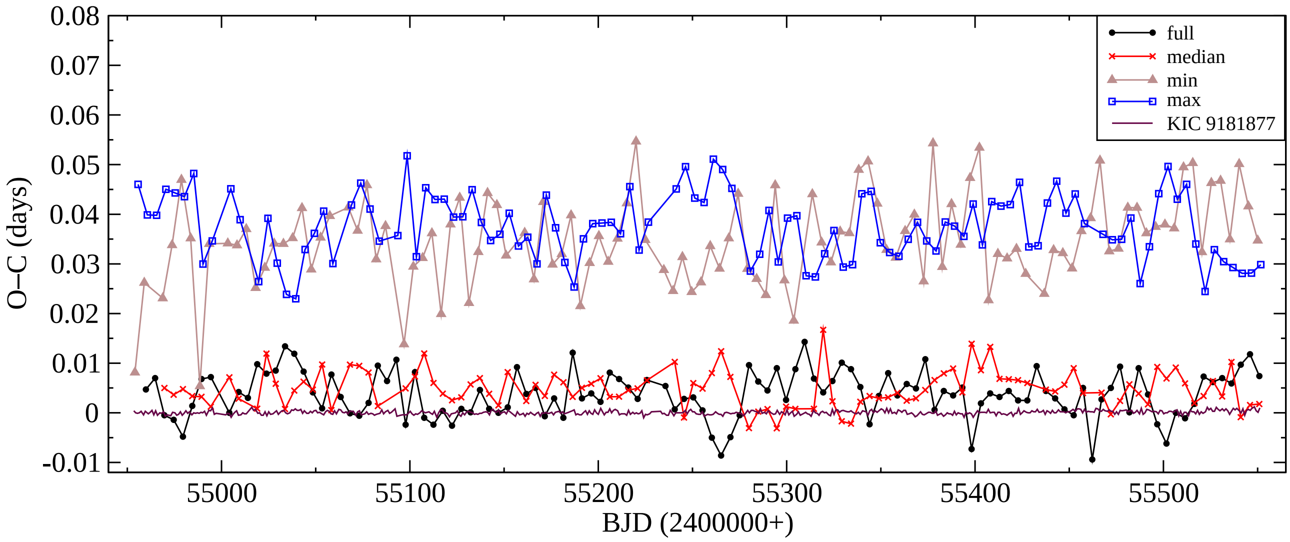

Figure 2. The $O-C$ diagram of V1154 Cyg calculated using 4 different methods and the $O-C$ diagram of the W UMa type eclipsing binary KIC 9181877. The $O-C$ diagrams of the times of minima and maxima are offset because the median brightness was used as an ephemeris for all $O-C$ calculations. The full description of these methods is in Section 2.2.

by fitting eighth-order Fourier-polynomial to the phase diagram of one pulsational cycle and used it as a master curve – allowing only vertical and horizontal shifts – to fit every other phase diagram. Combining the phase shifts and the period with the epoch, we calculated the $O-C$ values which are plotted with black dots in Fig.2.

For the calculation of the $O-C$ diagrams, we used the following ephemeris:

$$HJD = 2454969.70432 + 4.925454 \cdot E \qquad (1)$$

The $O-C$ values show a scatter of about $\pm$0.015 days ($\cong$20 min) for the full and the median and about $\pm$0.02 days ($\cong$30 min) for the maxima and the minima. The scatter of the $O-C$ diagram is far larger than we expect from a Cepheid variable (see Sect. 3 and Table 2).

To check that the detected period scatter is not originated from any observational artifact, we calculated the $O-C$ diagram of a W UMa type eclipsing binary in the *Kepler* field. The reason to choose this type of variable was that we do not expect fluctuations in the orbital period on short time scales in such a variable. We chose KIC 9181877 which is a 11.6 magnitude star and has an orbital period of 0.3210069 days. We calculate the $O-C$ diagram with the fourth method described above. The resulting $O-C$ diagram is plotted with maroon line in Fig. 2, along with the $O-C$ diagrams of V1154 Cyg. The diagram has a scatter of $\pm$0.0005 days ($\cong$43 sec) which is 15 times smaller than what V1154 Cyg shows. As we expected, the period is very stable and its $O-C$ diagram is a kind of illustration of the accuracy of the *Kepler* observations as well.

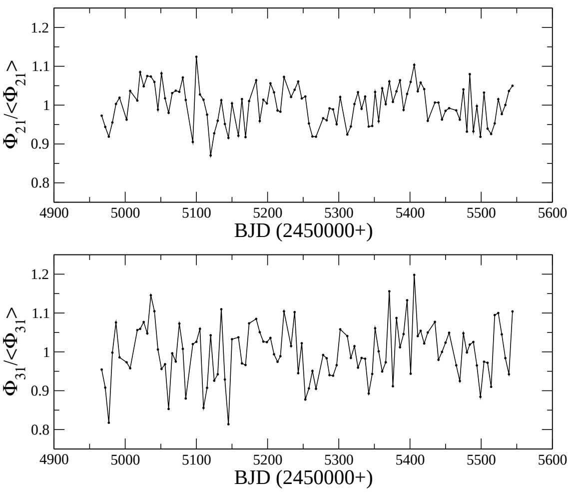

Figure 4. The relative phase variations of ϕ_{21} (top) and ϕ_{31} (bottom).

2.3 Fourier parameters

We studied the change of the light curve shape as a possible cause of the scatter in the $O-C$ diagram by examining the time variation of the Fourier parameters of the light curve. For this, we fitted eighth-order Fourier polynomial at the primary frequency and its harmonics:

$$m = A_0 + \sum_{i=1}^{8} A_i \cdot \sin\left(2\pi i f t + \phi_i\right), \qquad (2)$$

where m is the magnitude, A is the amplitude, f is the frequency, t is the time of the observation, ϕ is the phase and index *i* runs from 1 to 8. Then we characterised the light curve shapes with the Fourier parameters (Simon & Teays 1982), of which we show particular results for $R_{21} = A_2/A_1,\ R_{31} = A_3/A_1$ as well as $\phi_{21} = \phi_2 - 2\phi_1$ and $\phi_{31} = \phi_3 - 3\phi_1$,

Fig. 3 shows the amplitude change and the relative variations of R_{21} and R_{31}, while Fig. 4 shows the relative variation of ϕ_{21} and ϕ_{31}. All of these parameters show significant cycle-to-cycle variations. Detailed study of these variations in the $O-C$ and the Fourier parameters is described in the next section.

3 RESULTS

3.1 Correlations between $O-C$ datasets

Different determinations of $O-C$ points show loose correlations, no correlation or even anticorrelations with each other. Results of a Spearman's rank correlation test (Lupton 1993) is summarized in Table 1; for each compared dataset pairs, the top row shows Spearman's ρ and the p-value is given below. This test is like a generalization of the correlation coefficient: the value of ρ measures the how well the dependence between two variables can be described with a general monotonic function. The value of ρ is 1 or -1 if there is a perfect fit with an increasing/decreasing function, respectively; values in between express the relative weight of residuals which cannot be explained by a monotonic law. The value of p shows how probable is that the suspected connection between the variables is due to a false recognition of simple numerical fluctuations. *Id est*, an intermediate value of ρ still safely expresses the slight monotonic connection between the variables if p is very little.

Table 1. Results of a Spearman's rank correlation test of different $O-C$ datasets. The sign ns means no correlation with a confidence exceeding 85%.

	Min	Max	Full
Med	ns	0.42 $p = 5 \cdot 10^{-6}$	-0.51 $p = 2 \cdot 10^{-8}$
Min	—	-0.14 $p = 0.15$	ns
Max	—	—	-0.73 $p = 2 \cdot 10^{-16}$

The most interesting is the general lack of strong dependences between the differently defined $O-C$ values derived for the same pulsation cycles. In particular, the minimum is practically not connected to any other $O-C$ measures; while $O-C$ of the maxima shows relatively good (but still somewhat stochastic) dependence on the $O-C$ of the whole cycle. Another remarkable feature is the anticorrelation between the $O-C$ of the whole cycle and that of the median brightness or the maximum.

This behaviour suggests two conclusions. At first, the scatter in $O-C$ values is somehow reproducible, at least certain kinds of $O-C$ values can be predicted to some accuracy if one knows the value of another $O-C$. Therefore, the scatter we observed in any $O-C$ is not due to some unrecognized stochastic error, e.g. coming from the sampling and/or the evaluation of data. So perhaps the phase of the pulsation is changing, or there are slight local irregularities in the light curve. But the second finding is that the process which acts on the $O-C$ values changes rapidly, this is why there are no strict correlations between the different determinations of $O-C$. These together suggest that the cause of the observed behaviour of $O-C$ data is the irregular local fluctuations of the light curve shape. We will explore this hypothesis in the followings.

3.2 Fourier parameters explain $O-C$ points

Local variations of the light curve can be described by higher-order Fourier-coefficients. Therefore one expects if changes in the light curve shape were the primary reason for $O-C$ variations, then there would be connections between the Fourier-parameters and the $O-C$ values. If linear models are taken into account, only approximate fits are expected because the light curve shape depends on the Fourier-parameters in a very complex and non-linear way. This was really observed: we generally found very slight correlations between the individual Fourier-parameters and the $O-C$ values.

Another possibility is a multilinear fit of the $O-C$ points using the Fourier parameters. Taking the first 8 amplitude and phase coefficients, and additionally, the height of the minimum and the maximum of the individual cycles, we found that the times of the mean amplitude can really be predicted with 90% accuracy via a linear – and therefore rather heuristic – model. The accuracy was less impressive in the other cases, e.g. it was only 30% when fitting the times of minima (i.e., the residuals decreased only by 30% after the fit).

The probable interpretation is that the $O-C$ variations are really due to the instability of the light curve shape, because the light curve shape alone is the best predictor of $O-C$ values. The existence of less impressive fits does not bother much this interpretation, because the light curve shape is a non-linear function of our parameter space, and it has been foreseen that the linear fit will

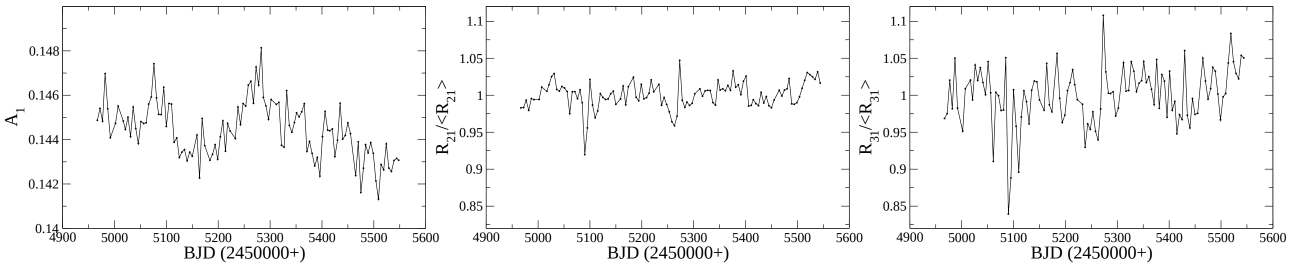

Figure 3. From left to right: the amplitude (A_1) change and the relative variations of R_{21} and R_{31} (definition is given in Sect. 2.3).

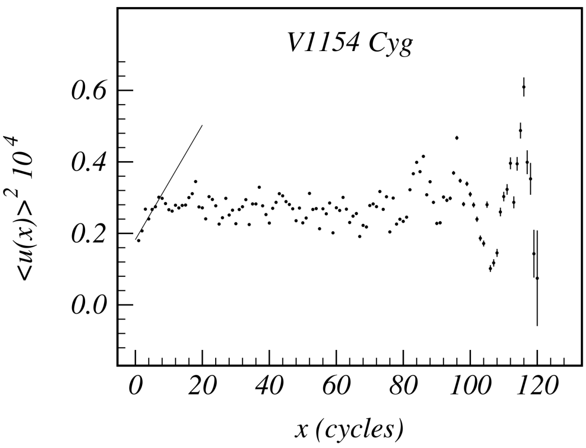

Figure 5. The result of the Eddington-Plakidis test.

not always work. In fact, good fits can be expected only in the case when the parameters are combined by fortune in such way that the local light curve irregularities can be effectively described with a multilinear approximation; as it happened for the times of median brightness.

3.3 Eddington-Plakidis test

The $O-C$ residuals (Fig. 2) were analyzed for the presence of random fluctuations in the pulsation period using the method described by Eddington & Plakidis (1929).

Eddington & Plakidis made the hypothesis that some or all of the $O-C$ variations are due to random fluctuations (ε) in period from one cycle to the next. There are also random errors (α) in the measured times of maximum light. These errors are each assumed to be accidental and uncorrelated. We define $z(r)$ as the $O-C$ residual of the r-th maximum, and $u(x) = \mid z(r+x) - z(r) \mid$ is the accumulated delay in x periods which, according to the hypothesis, is the sum of x uncorrelated random fluctuations. Eddington & Plakidis proposed that the average value $\langle u(x) \rangle$ over all values of r is given by

$$\langle u(x) \rangle^2 = 2\alpha^2 + x\varepsilon^2. \quad (3)$$

Hence a plot of $\langle u(x) \rangle^2$ against x should be a straight line with slope ε^2 and intercept $2\alpha^2$.

In practice, this means that if there is a linear trend in the plot of $\langle u(x) \rangle^2$ at low x (from several to several tens cycles), then it is assumed that random period fluctuations are present in the pulsations of a given star and this segment of the plot is used for a linear fit. In other words, all wave-like fluctuations in the $O-C$ residuals (after the removal of all trends) are assumed to be attributed to random fluctuations in the pulsation period.

Table 2. Results of the Eddington-Plakidis test.

Method	ϵ	$\epsilon_{\rm err}$	α	$\alpha_{\rm err}$
Full	0.0013	0.00054	0.0030	0.00085
Med	0.0008	0.00042	0.0023	0.00066
Min	0.0015	0.00058	0.0063	0.00141
Max	0.0015	0.00048	0.0043	0.00105

As it is shown in Fig. 5, a linear trend is revealed up to a cycle difference x$\sim$15. The mean random fluctuation parameters are summarised in Table 2 for the four different methods.

These results lead us to the conclusion that in short terms (up to a cycle difference x$\sim$15), the period changes randomly. However, for long term, there is an internal clock in V1154 Cyg which keeps the period around the mean period. This feature is also supported by the fact that the $O-C$ diagram of V1154 Cygni covering 15000 days indicates a constant mean pulsation period (see Fig. 13 in Szabó et al. (2011a)).

A similar Eddington-Plakidis test was performed for SMEI photometric data of 8 bright Cepheids by Berdnikov (2010). He found random period fluctuations, in some cases superimposed on period changes due to stellar evolution, but the period and its changes could not be studied on a time scale of individual pulsation cycles.

4 IMPLICATIONS OF THE RESULTS

If the results presented here for V1154 Cyg are common among Cepheids then the consequences might affect other areas of research.

4.1 Cepheids models

Numerical hydrodynamical models do not show such hectic period variations from cycle-to-cycle. This is primarily because these codes contain simplified description of turbulent convection (Florida-Budapest code Kolláth et al. (2002), Warsaw code Smolec & Moskalik (2008)), or before the early '90s contained radiative energy transfer only. Using this type of physics the pulsation usually reaches its limit cycle (or alternatively double-mode pulsation), then stays in this state essentially forever, because these codes are very good at conserving energy and momentum. Hence, the pulsation period is practically constant. Any deviation from this precise, regular machinery is due to choosing imperfect numerical scheme or coding errors. The above mentioned codes are free from these problems.

Present-day models are not capable of dealing with complex, magneto-hydrodynamic interaction (Stothers 2009) that could cause regular or irregular modulations of the stellar structure (hence in the period), because of the enormous difficulties of implementing and computing 3D MHD for full stellar envelopes.

Evolutionary changes are usually happening on a much longer timescale and in a regular manner, in addition the physics driving the evolution is usually missing from these models designed to follow only the pulsation.

Deviations from this precise clockwork mechanism do appear in certain high-luminosity models (Buchler & Kovács 1987; Kovács & Buchler 1988; Moskalik & Buchler 1990, 1991; Buchler & Moskalik 1992) namely they can show period doubling or a series of period doubling bifurcations en route to chaos. These types of dynamical phenomena also cannot be responsible for the observed period variations.

Clearly, a more precise (preferably multi-dimension) description of turbulent convection would be essential to model the observed large cycle-to-cycle period 'jitter'.

4.2 Searching for companions

The usually assumed stability of the pulsation period is a fundamental ingredient in finding low mass or substellar companions around Cepheids. In light of the period jittering found in V1154 Cyg, it is worth checking what kind of sensitivity can be expected for a perfect pulsator observed by *Kepler*. For this, we have calculated several simulations as follows. First we took a short subset of the long cadence light curve covering one pulsation cycle to fit a 4th order Fourier polynomial that represented the ideal light curve shape of the star. Then we took each time stamp of the combined Q0-Q7 long cadence light curve to calculate the analytic template, which was phase modulated by a sinusoidal term: the period of the modulation was set to 200 days, while the amplitude was set to representative values between 0.1 s and 60 s. The flux errors reported by the *Kepler* pipeline were used to add a random error to each point of the simulation. This way the properties of the random errors matched those of the original data. The simulated light curves were then analysed with the fourth method used in the $O-C$ analysis (see Sect. 2.2), namely with the local phase determination using a master curve represented by a Fourier polynomial.

In Fig. 6 we show the results for three simulations. The amplitudes of the phase modulations were 10 s, 1 s and 0.1 s, which can be connected to the mass ratio of the companion and the Cepheid using the third Kepler-law and assuming a mass for the Cepheid. Ignoring the $\sin i$ ambiguity of the unknown inclination angle (i.e. assuming an edge-on view of the system), the half-amplitude of the $O-C$ diagram depends on the Cepheid mass and the mass ratio as follows:

$$A_{OC} = \frac{1}{c}\left(\frac{G}{4\pi^2}\right)^{1/3} \frac{M_1^{1/3}\left(1+\frac{M_2}{M_1}\right)^{1/3}}{\left(1+\frac{M_1}{M_2}\right)} P_{\rm orb}^{2/3} \qquad (4)$$

where M_1 and M_2 are the masses of the Cepheid and its companion, respectively, $P_{\rm orb}$ is the orbital period, G is the gravitational constant, c is the speed of light. For a 5 $M_\odot$ Cepheid and a 200 days orbit, the given three $O-C$ amplitudes correspond to a companion mass of about 50 $M_{\rm Jup}$, 5 $M_{\rm Jup}$ and 0.5 $M_{\rm Jup}$. **check the numbers and the formula!**

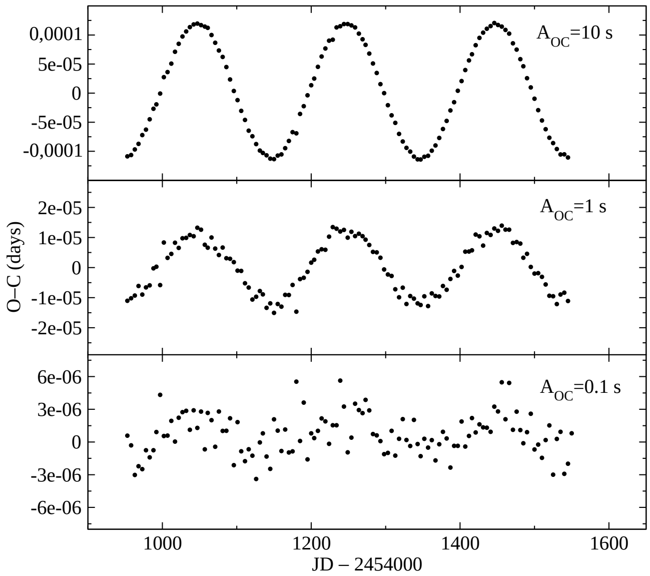

Figure 6. The $O-C$ diagram of three model light curves with sinusoidal phase modulations (modulation half-amplitudes shown in the upper right corner in each panel). See text for details.

The three simulated O−C diagrams in Fig. 6 clearly show that *Kepler*'s precision could be enough to detect planet-sized companions on short-period orbits around Cepheids, if the stars were perfect clocks. However, the astrophysical noise in V1154 Cyg is way too high to allow that kind of detections of substellar companions.

5 SUMMARY

The period variations for the Cepheid V1154 Cyg have been examined based on 600 days of photometric observations with the *Kepler* space telescope. Subtle variations in the pulsation period and shape of the light curve may be present in the pulsation of other Cepheids. Indirect evidence supporting the behaviour mentioned here was given by Klagyivik & Szabados (2009) who found that the photometric phase curves of some small amplitude Cepheids in our Galaxy show a wider scatter than expected from the measurement errors even if data are folded on the correct value of the pulsation period.

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