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Monitoring Period Variations of Variable Stars using Precise Photometric Surveys

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Abstract. The period variations of rotating, pulsating and eclipsing variable stars bear valuable astrophysical information about the presence of companions, evolutionary effects, and the inner structure of the stars. This talk described a universal method for de-trending and re-scaling precise photometric data (*Kepler*, MOST, CoRoT, OGLE, ...) appropriate for period-change diagnostics of periodic variables. We demonstrated the potential of the method by analysing the period variability of one of the newly-identified *Kepler* magnetic chemically-peculiar (mCP) stars. We showed that, surprisingly, our target star displays near-sinusoidal changes in its observed light-variations, with a period of 2.85(6) years, which is apparently the result of the presence of a nearby stellar companion. The expected long-term changes of the rotational period, as have been observed in several mCP stars, have not been identified among the sample of *Kepler* mCP stars.

Keywords. Methods: statistical, surveys, stars: chemically peculiar, stars: rotation, stars: spots, binaries: general, stars: low mass.

1. Introduction

The majority of variable stars exhibits more or less periodic brightness variations with constant or predictable light-curve shapes. Such variations may be caused by various mechanisms, especially the rotation of objects with axially anisotropic radiation (such as magnetic chemically peculiar stars (mCPs), stars with sun-like spots, or pulsars), by pulsations (Cepheids, RR Lyrae variables), or by eclipses. The observed periods of these cyclic changes may vary owing to the gravitational influence of other bodies in the system, apsidal motion in binaries, internal differential rotation, mass loss, etc. The parameters of period variations carry essential astrophysical information about the variable stars or the systems in which they occur.

To reveal period variations, observations that span a sufficient period of time are needed. Such systematic series of observations are rare, while archived data (if any) can suffer from a lack of quality control and sometimes from failures in data processing. However, the advent of a new generation of highly and moderately precise photometric surveys observed over years from space or from sophisticated ground-based observatories such as *Kepler*, CoRoT, ASAS, SuperWASP, OGLE, and others, has greatly assisted the detection of variables with changing periods.

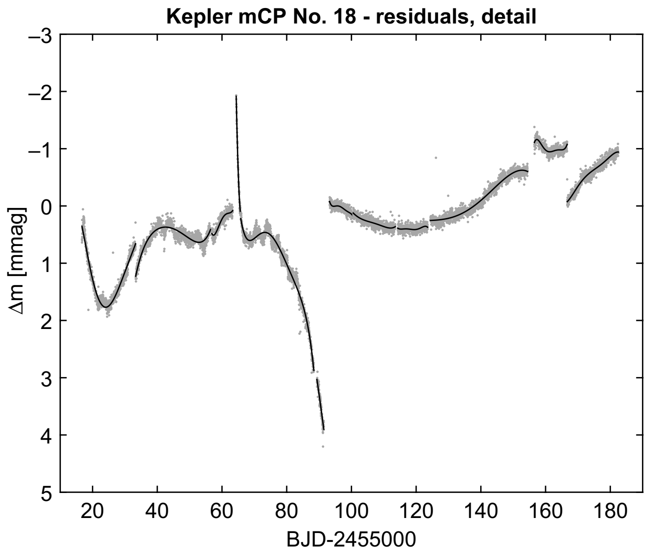

Figure 1. The dependence of individual residuals upon time (shadow dots), in days. The full lines denote Chebyshev polynomials up to the 6^{th} order that were fitted to the segments. After correction for those trends, we obtained a detrended, very accurate, light-curve with an uncertainty around 0.1 mmag.

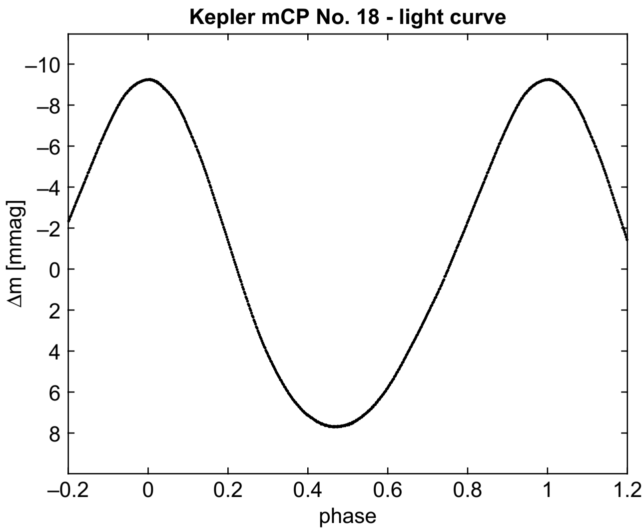

Figure 2. Phased light-curve of our target star, represented by normal points. Each point represents the median of 700 individual detrended observations of the rotational phase, corrected for the period variations. For a satisfactory fit to the light-curve, a harmonic polynomial of the 20^{th} order is needed.

2. Magnetic Chemically Peculiar Stars

MCP stars display variations in light, spectrum and magnetic field that are strictly periodic and synchronous with rotation period. Photometric changes are caused by vast persistent surface spots.

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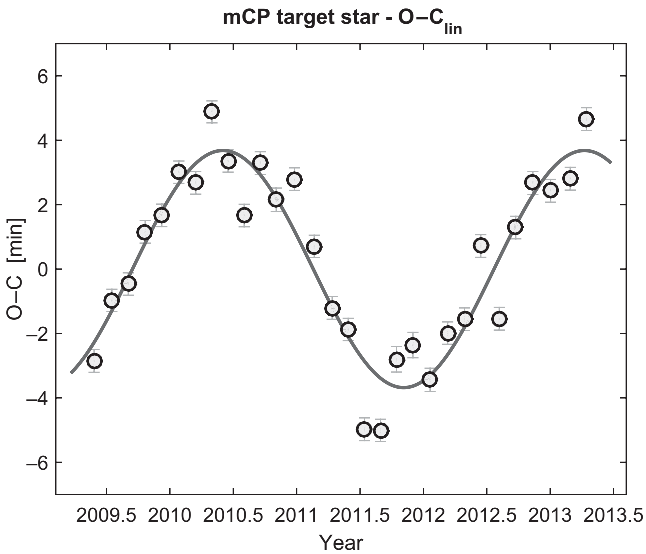

Figure 3. Shifts of the observed light-curves versus the model light-curve, assuming a constant variability period in minutes. The O–C time-dependence can be explained by the presence of a red-dwarf companion orbiting the more massive mCP star with a period of 2.85 years. To date, such a type of binarity has not been reported for any other known mCP star.

A few well-observed mCPs such as CU Vir, V901 Ori or BS Cir (Mikulášek 2016, and references therein) exhibit continuous long-term period changes of unknown origin. The rate of occurrence of these objects among other mCPs is not yet known, so we started period (timing) analyses of about fifty new mCPs that were identified by inspection of their *Kepler* light-curves and which were later confirmed spectroscopically (Hümmerich *et al.* 2018).

We illustrated our approach by selecting a cool mCP star displaying brightness changes with an effective amplitude $A_{\rm eff} = 17$ mmag and a mean period $P = 4.075\,081\,00(43)$ d. About $N = 65\,261$ data points with a typical scatter of $\sigma = 0.095$ mmag were gleaned from the *Kepler* database, which spans $\Omega = 4.03$ yr (1471 d). The expected uncertainty in the determination of the period derivative $\dot{P}$ ($\delta\dot{P}$) was estimated using a formula from (Mikulášek 2016):

$$\delta\dot{P} \cong \frac{10\,\sigma\,P^2}{A_{\rm eff}\,\sqrt{N}\,\Omega^2}. \tag{2.1}$$

For this target star we obtained $\delta\dot{P} \approx 1.7 \times 10^{-9}$, which is three times smaller than $\dot{P} = 5.4(4) \times 10^{-9}$ found in BS Cir, and it implies that period changes of a magnitude comparable to what was observed in that star would be detectable.

3. Applied Method of Timing (Period) Analysis

We used a phenomenological model of the observed light-curve consisting of three basic components:

1) A simple model of the phase function $\vartheta(t, \mathbf{b})$ (Mikulášek *et al.* 2008), bound with the variable period $P(t)$ through the relation $\dot{\vartheta}(t, \mathbf{b}) = P(t, \mathbf{b})^{-1}$, where $\mathbf{b}$ is a vector of free parameters of the model phase function.

2) A model of the light-curve – a periodic function of the phase function ϑ, $F(\vartheta)$. In the case of our target star, this was the harmonic polynomial of the twentieth order.

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3) Residuals of instrumental origin, which were modelled in about 120 segments (often separated by time gaps) that last typically for two weeks. The individual segments were approximated by Chebyshev polynomials up to the sixth degree.

By assuming constancy/predictability of the shape of the light-curve $F(\vartheta)$, we were able to detrend the 'raw' data considerably. The procedure outlined diminished the scatter by a factor of sixteen†. About 550 parameters were found by using robust regression derived from a least-squares approach. The method can also be applied to other types of periodic variables, as well as to ground-based observations.

4. Unexpected Period Variations in the Target Star

By using the method described, we established strong period changes of $\dot{P} = 27(3) \times 10^{-9}$ in our target star; the derivatives $\ddot{P}$ and $\mathrm{d}^3P/\mathrm{d}t^3$ are also large. The period shows near-sinusoidal variations with the period $\Pi = 2.85(6)$ years, and an (O–C) shift amplitude of 0.005 12 d = 7.36 min. That could well be explained by the presence of a nearby stellar companion. The mCP component orbits around the centre of gravity at a distance of $a_1 \sin i = 0.44\,\mathrm{au}$; that should manifest itself by radial-velocity variations of $9.2\ \mathrm{km\,s^{-1}}$, which should easily be detectable in a time-series of spectra. Assuming a mass of $M_1 = 2.0\,\mathrm{M_\odot}$ for the mCP component, we find $M_2 \sin i = 0.35\,\mathrm{M_\odot}$, where i is the inclination of the orbit. The mass of the secondary component corresponds to the mass of a normal M3 V red dwarf with $T_{\mathrm{eff}} = 3250\,\mathrm{K}$, $a \sin i = 3.0\,\mathrm{au}$.

5. Conclusions

The detection of a low-mass star in the close vicinity of our target star is surprising; such a double star has not been known before.

Among the newly-identified *Kepler* mCPs, none with intrinsic variations of the rotational period has been detected up to now. Our research in this project continues. Period analysis of periodically variable stars monitored by precise photometric surveys has proved to be an exciting tool for revealing outlying companions.

Acknowledgements

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† Several *Kepler* light-curves are corrupted by transient changes in the sensitivity of the apparatus that result in variations in amplitude. The effect on the investigation of period changes is only subtle. However, it escalates the uncertainty of the results to the point of being useless. The procedure of rescaling the light-curve assumes a constant light-curve; in fact the amplitude of the target star was constant throughout the observing run, so we could skip this step.

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