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Stellar activity and stellar pulsations in ground- and space-based observations

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Abstract. The research on variable stars has significantly benefited from the availability of long-term photometric time series data from ground- and space-based surveys. Precise and long-term stable data allow the investigation of variable stars with small amplitudes and long periods, and the research on multi-periodic objects has profited greatly from the availability of quasi-uninterrupted time series data from space-based mission. To illustrate this situation, we have chosen to present our efforts to investigate the photometric variability of magnetic chemically peculiar stars using data from six different survey sources (ASAS-3, CoRoT, KELT, Kepler, Kepler-K2 and SuperWASP). Due to their range of periods (0.5 days to several years) and photometric amplitudes (sub-mmag range to about 0.1 mag), these objects constitute a challenge to observers. Long-term instrumental stability and a sufficient phase coverage are needed to detect and investigate this kind of variability.

Key words: stars: chemically peculiar – stars: variables: general – surveys – techniques: photometric

1. Introduction

The advent of ground- and space-based photometric surveys during the last two decades has led to the accumulation of a wealth of data that is mostly publicly available and constitutes a valuable resource for variable star research. The available surveys cover different time bases, observing cadences, magnitude ranges, wavelength ranges, and accuracies. Thus, a direct comparison of the available photometric data is often not straightforward.

For this paper, we haven chosen to present survey light curves of the group of α^2 Canum Venaticorum (ACV) variables. These objects are photometrically variable magnetic chemically peculiar (mCP) stars of the upper main sequence (spectral types early B to early F), whose spectra show abnormal line strengths indicating peculiar surface element abundances for elements such as Si, Cr, Sr, He or the rare-earth elements (Preston, 1974). As their name implies, mCP stars exhibit strong, globally-organized magnetic fields reaching strengths of up to several tens of kiloGauss (Mathys, 2017). The observed chemical peculiarities are generally attributed to diffusion of chemical elements as a result of the competition between radiative pressure and gravitational settling (Richer et al., 2000; Turcotte, 2003). The photometric variations of ACV variables are explained in terms of the oblique rotator model (Stibbs, 1950); the observed photometric period is the rotational period of the star.

ACV variables exhibit periods ranging from about 0.5 days to several years and amplitudes from the sub-mmag range to about 0.1 mag, depending on the bandpasses of the employed photometric filters. The observed period and amplitude range of ACV variables presents a challenge because of the problem of daily aliasing and the need for long-term stable observations. Several investigations have been concerned with the study of the photometric variability of ACV variables in the recent past (Paunzen et al., 2016). In the following, we present typical light curves of several such objects from different survey sources which offer the possibility to directly compare the quality of these data.

2. Data sources

In this section, we shortly describe six photometric survey sources (ASAS-3, CoRoT, KELT, Kepler, Kepler-K2 and SuperWASP) that we have already employed for studying the variability of ACV stars. In addition, exemplary light curves are shown. This list is by no means complete, but the presented data are publicly available, which is why they have been chosen for this paper. Another important aspect to consider is the processing of the data, and the amount of effort involved. From our experience, almost all survey data need to be further reduced, or at least carefully inspected. Instrumental trends need to be identified, and the data have to be cleaned of outliers; sometimes time binning may be helpful. This data treatment has to be done with care in order to preserve the intrinsic variability of the star. When dealing with a new survey source, it has proven helpful to procure and analyze data for known variable stars with well-determined parameters before setting out on the search for new variable stars, as this will provide a good idea what can be expected from (and achieved with) the employed data source.

2.1. ASAS-3

The All Sky Automated Survey (ASAS) is a project that aims at continuous photometric monitoring of the whole sky, with the ultimate goal of detecting and investigating any kind of photometric variability. The typical exposure time for ASAS-3 V-filter observations is three minutes, which results in reasonable photometry for stars in the magnitude range $7 < V < 14$ mag (about 10^7 objects). In general, a field is observed each one, two, or three days (Pigulski, 2014). Using ASAS-3 data, Bernhard et al. (2015a) and Hümmerich et al. (2016) investigated

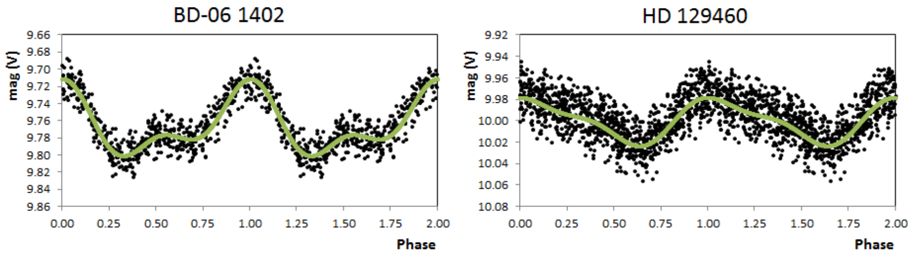

Figure 1. The ASAS-3 light curves of BD–06 1402 (period of 1.13063 days, left panel) and HD 129460 (1.76444 days, right panel), taken from Hümmerich et al. (2016).

the photometric variability of mCP stars and identified more than 650 new ACV variables. Two examples from the latter source are given in Fig. 1, which shows the light curves of BD–06 1402 ($V = 9.75$ mag, period of 1.13063 days, left panel) and HD 129460 ($V = 10.06$ mag, 1.76444 days, right panel).

2.2. CoRoT

The CoRoT (Convection, Rotation and planetary Transits) space mission (2006 – 2012) focused on high-precision photometry, taking advantage of the boons of space-bound photometry by observing given targets continuously for up to 150 days (De Medeiros et al., 2013). A set of light curves is available for about 170 000 stars. Observations have been performed in two modes optimized for targets with $6 < V < 9$ mag and $11 < V < 16$ mag, respectively. Paunzen et al. (2015) analyzed the high-quality CoRoT light curve of the CP2 star HD 49310 (Fig. 2) and photometrically modeled the star spots by applying a Bayesian technique. As can be seen in the available light curve, 'jumps' and linear trends are still visible in the data which have to be corrected for. However, the accuracy of the data is very high and comparable to data from the *Kepler* mission. Up to now, no statistical analysis of the ACV variables based on CoRoT data has been published.

2.3. KELT Transit Survey

The Kilodegree Extremely Little Telescope (KELT) is an all-sky survey boasting data for stars with $7 < V < 11$ mag in several filters and a time basis of up to 10 years (Pepper et al., 2008). Two combined dedicated telescopes observe over 70% of the entire sky with a 10 to 30 minute cadence. A detailed analysis of ACV variables using KELT data is in preparation but has not been published yet. In Fig. 3, we present the KELT light curves of two known CP stars, GSC 1773–00211 (HD 14522, $V = 8.79$ mag, period of 1.837182 days, left panel) and GSC 1875–00552 (HD 39865, $V = 8.62$ mag, 26.36 days, right panel). The scatter in the light curve is about 0.02 mag.

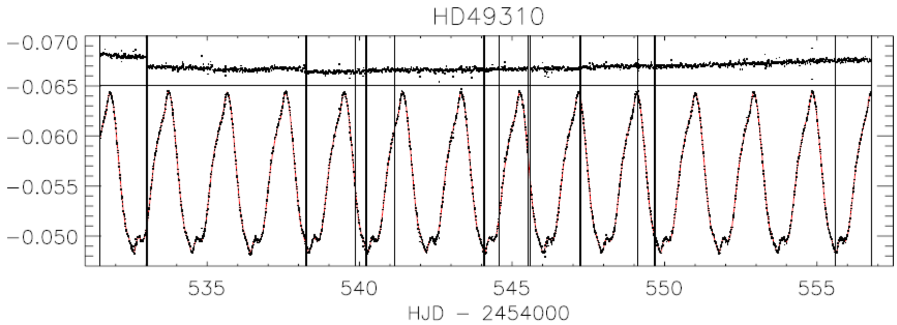

Figure 2. The CoRoT light curve of HD 49310 taken from Paunzen et al. (2015) and fitted by a six-spot model (red line). Residuals (arbitrary offset) are shown in the upper part of the figure. Jumps and linear trends have been accounted for automatically by using a likelihood function that integrates over all possible magnitude offsets and trends (lower part). The period of this star is 1.91909 days.

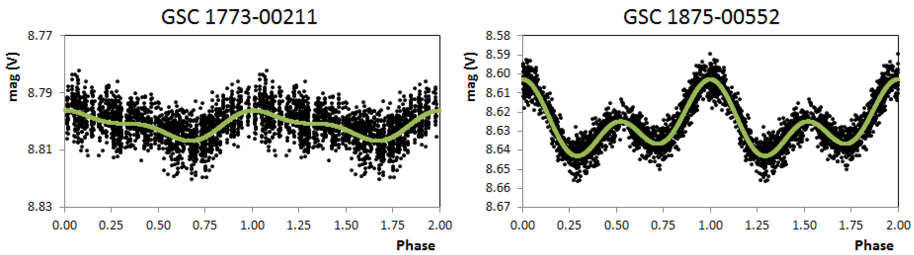

Figure 3. The KELT light curves of GSC 1773–00211 (period of 1.837182 days, left panel) and GSC 1875–00552 (26.36 days, right panel).

2.4. Kepler

During the first part of the *Kepler* space mission, the brightness of about 150 000 stars was continuously monitored for 4.5 yr in a 105-square-degree fixed field of view (Borucki, 2016). The mean top-of-the-noise level in the periodogram for a star of 10th magnitude is about 3 ppm for an observing run of 30 d, dropping to about 1 ppm after one year. For a star of 12th magnitude, the corresponding noise level is about 6 ppm for one month and 3 ppm after one year. This unprecedented level of precision allows the discovery of new CP stars and a detailed study of their photometric variability (Fig. 4).

The *Kepler* K2 mission became operational in mid-2014, after a severe malfunction had deprived the satellite of its ability to stay pointed at a target without drifting off course. Data from the K2 mission are generally of some-

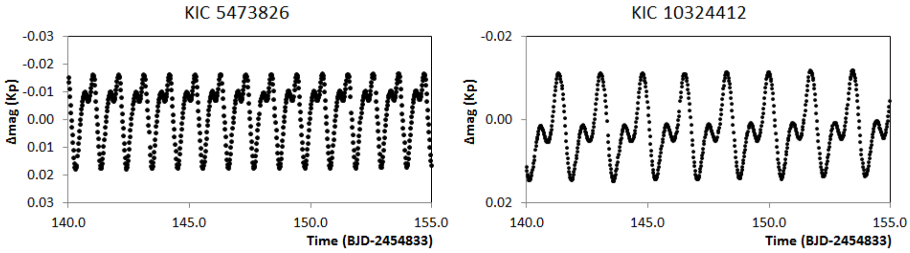

Figure 4. The Kepler light curves of KIC 5473826 (period of 1.05120 days, left panel) and KIC 10324412 (1.73150 days, right panel).

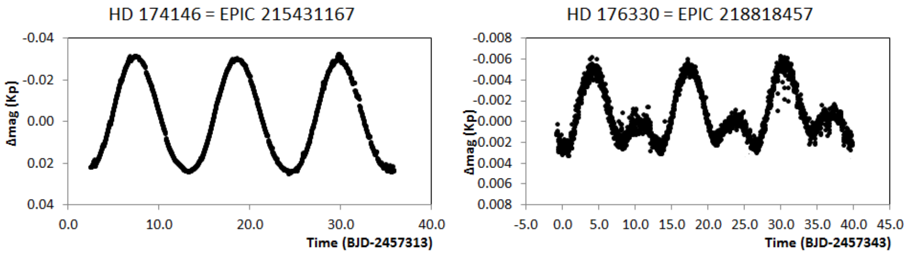

Figure 5. The Kepler–K2 light curves of HD 174146 (period of 11.185 days, left panel) and HD 176330 (13.16 days, right panel).

what lower quality but may approach a photometric precision similar to that obtained by the prime Kepler mission (Libralato et al., 2016). The K2 observing campaigns cover an approximate period of 80 days; target lists have been compiled from community solicitations for proposed targets. Fig. 5 illustrates the K2 light curves of two ACV variables. An investigation of ACV variables in K2 data is in progress.

2.5. SuperWASP

The SuperWASP survey started in 2004 and covers both hemispheres. It provides long-term photometric time series in a broadband filter (400–700 nm) with an accuracy better than 1% for objects in the magnitude range $8 < V < 11.5$ mag (Pollacco et al., 2006). Observations consist in general of two consecutive 30s integrations followed by a 10-minute gap. Bernhard et al. (2015b) analysed 3 850 000 individual photometric WASP measurements of 579 mCP stars and candidates. In total, 80 variables were found, from which 74 were reported for the first time (see Fig. 6 for exemplary light curves).

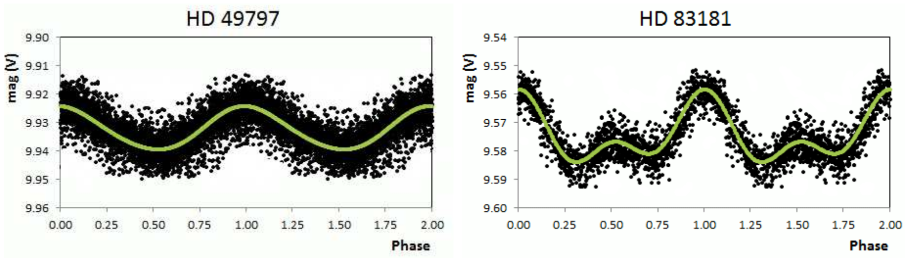

Figure 6. The SuperWASP light curves of HD 49797 (period of 1.2263 days, left panel) and HD 83181 (2.5241 days, right panel), taken from Bernhard et al. (2015b).

3. Conclusion

The present paper presents an overview over our recent efforts to investigate the photometric variability of ACV variables using data from diverse survey sources. Exemplary light curves are shown, which illustrate the capabilities of the employed surveys, which differ in parameters such as time base, observing cadence, accuracy and covered magnitude and wavelength range. After further processing (removal of outliers, instrumental trends etc.) and careful inspection, the survey data provide a wealth of information and constitute an important resource for variable star research. The research on variable stars with small amplitudes (such as ACV variables) and multiple periods (such as δ Scuti or γ Doradus stars), in particular, has benefited from the long-term and, in the case of space-based surveys, quasi-uninterrupted observations. New and exciting results are sure to come forth from the wealth of archival data that has been procured – and will be procured in future surveys.

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