A case study of ACV variables discovered in the Zwicky Transient Facility survey[★]

N. Faltová¹, K. Kallová¹, M. Prišegen¹, P. Staněk¹, J. Supíková², C. Xia¹, K. Bernhard^{3,4},
S. Hümmerich^{3,4}, and E. Paunzen¹

¹ Department of Theoretical Physics and Astrophysics, Faculty of Science, Masaryk University, Kotlářská 2, 611 37 Brno, Czech Republic

e-mail: epaunzen@physics.muni.cz

² Faculty of Informatics, Masaryk University, Brno, Czech Republic

³ Bundesdeutsche Arbeitsgemeinschaft für Veränderliche Sterne e.V. (BAV), Berlin, Germany

⁴ American Association of Variable Star Observers (AAVSO), Cambridge, USA

Received 12 June 2021 / Accepted 17 August 2021

ABSTRACT

Context. Magnetic chemically peculiar (mCP) stars exhibit complex atmospheres that allow the investigation of the interplay of atomic diffusion, magnetic fields, and stellar rotation. A non-uniform surface distribution of chemical elements and the non-alignment of the rotational and magnetic axes result in the variability of several observables. Photometrically variable mCP stars are referred to as α^2 Canum Venaticorum (ACV) variables.

Aims. The present work presents a case study of known variables from the Zwicky Transient Facility (ZTF) survey, with the aim of investigating the survey's suitability for the detection and study of new ACV variables.

Methods. Using suitable selection criteria based on the known characteristics of ACV variables, candidate ACV stars were selected from the ZTF Catalog of Periodic Variable Stars. All light curves were inspected in detail to select the most promising candidates. Where available, low-resolution spectra from the Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST) were employed to classify the stars on the MK system and confirm their status as mCP stars.

Results. We have identified 86 new promising ACV star candidates. Fifteen of these stars have LAMOST spectra available that, in all cases, confirm them as classical mCP stars, which highlights the viability of our approach. We present astrophysical parameters for all sample stars that can be sorted into four subgroups characterized by distinct light curve shapes. Anti-phase variations in different photometric passbands, in particular, are a unique characteristic of a subset of ACV stars readily usable for their identification. The availability of data in three different passbands (g , r , and i) is a major advantage of the ZTF survey.

Conclusions. On the basis of our experience with other photometric surveys and the analysis of light curves, we conclude that the ZTF is well suited to the search for, and the analysis of, ACV variables that are not considered in the available ZTF variable star catalogs. Further work will focus on the development and refinement of a search algorithm to correctly identify these stars in ZTF data and, subsequently, in massive photometric time series databases in general.

Key words. stars: chemically peculiar – stars: variables: general – stars: rotation – binaries: eclipsing

1. Introduction

The magnetic chemically peculiar (mCP) stars, which encompass the groups of the Ap/CP2 stars and the He-peculiar stars (Preston 1974), are upper main-sequence objects (spectral types B to early F) that exhibit anomalous surface abundances and a non-uniform distribution of chemical elements. They are further characterized by the presence of a strong and global magnetic field. The CP2 stars show overabundances of Si, Sr, Cr, Eu, and the rare-earth elements as compared to the solar composition (Preston 1974; Saffe et al. 2005). The He-peculiar stars comprise the B5 to B9 He-weak (CP4) stars that show anomalously weak He I lines for their temperature type and the more massive B1 to B3 He-strong stars with anomalously strong He I lines (Andrillat & Jaschek 1998).

In addition, there are also the CP1 stars (the metallic-line or Am/Fm stars; Qin et al. 2019) and the CP3 stars (the mercury-

manganese or HgMn stars; Paunzen et al. 2021). These groups are believed to possess only very weak, if any, magnetic fields (Bychkov et al. 2003).

The non-uniform distribution of chemical elements characteristic for mCP stars is responsible for the formation of spots and patches of enhanced element abundances on their surfaces (Michaud et al. 1981). Several mechanisms and their interplay may be responsible for the development of these spots, such as a weak stellar wind (Krtićka 2016), the characteristics of the stellar magnetic field (Romanyuk 2014), the occurrence of a weak convective zone, and the implications of slow rotation.

As a result of the abundance inhomogeneities, the rotation of mCP stars necessarily results in periodic variations of the observed flux (known as photometric spots; Krtićka et al. 2007) and periodic changes in their spectra. This variability can be explained by the oblique rotator model, which was proposed by Babcock (1949) and developed by Stibbs (1950). The period of the observed variations is hence identical with the rotational period of an mCP star. α^2 Canum Venaticorum was the first CP2 star that was identified as a photometric variable (Guthnik & Prager 1914), which is the reason why photometrically variable mCP stars are

[★] LAMOST spectra are only available at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via <http://cdsarc.u-strasbg.fr/viz-bin/cat/J/A+A/656/A125>

generally referred to as α^2 Canum Venaticorum (ACV) variable stars (Samus' et al. 2017).

Several elements play a part in the observed variations. For instance, Krtićka et al. (2007) demonstrated that the variability of the He-strong star HD 37776 is caused by spots of He and Si, whereas Krtićka et al. (2009) produced evidence that the variability of the CP2 star HR 7224 is the result of an inhomogeneous surface distribution of Fe and Si. Other elements such as Si, Cr, Sr, or Eu may contribute to the observed variations in CP2 stars (Bernhard et al. 2015a).

The ACV variable stars are perfectly suited for direct measurement of the rotational period without the need for any additional calibrations. With astrophysical parameters such as stellar masses, effective temperature, radii, inclinations, and critical rotational velocities, it is possible to analyze the conservation of angular momentum during the main-sequence evolution (Netopil et al. 2017).

Although many excellent data sources on stellar variability are now available, the class of the ACV variables is only rarely considered in the algorithms employed for the automatic classification of variable stars into astrophysically meaningful classes (Blomme et al. 2010; Kügler et al. 2015; Bass & Borne 2016). In this paper we present a case study of new ACV variables discovered in data from the Zwicky Transient Facility (ZTF), and show that the accuracy and cadence of the ZTF allows us to detect previously unknown stars of this kind. This survey reaches fainter magnitudes than most corresponding programs (Hümmerich et al. 2018), which means that we can probe the population of ACV variables at larger distances from the Sun. To date, the automatic detection and classification methods employed with the ZTF data have not included this class of variable stars (Chen et al. 2020; Ofek et al. 2020).

2. Data selection and time series analysis

The ZTF is a time-domain survey that is located at Palomar Observatory and in operation since 2017. It is a successor of the successful Palomar Transient Factory (PTF). The ZTF camera employs e2v CCD231-C6 devices and is mounted on the Palomar 48-inch Samuel Oschin Schmidt Telescope. It is able to scan 3750 square degrees an hour in three different passbands (g , r , and i) to a limiting magnitude of 20.5 mag. The main aim is to discover young supernovae and other types of transients. With its current strategy, the ZTF survey provides nearly 300 observations each year per object in the northern hemisphere. ZTF data are therefore ideally suited for studies of variable stars, binaries, AGN, and asteroids (Bellm et al. 2019; Masci et al. 2019).

Chen et al. (2020) exploited the ZTF Data Release 2 and compiled a catalog of 781 602 periodic variable stars (The Zwicky Transient Facility Catalog of Periodic Variable Stars¹). We systematically searched this catalog for candidate ACV variables by examining the light curves of an extended sample of stars in detail. Since the catalog does not contain a category for ACV-type variables, it can be assumed that any such objects were assigned to other categories of short-period variables, especially to the class of the RS Canum Venaticorum (RS CVn) stars which was the focus of our analysis. RS CVn stars are rotational variables whose light curves, at least on first impression, look similar to the light curves of ACV variables (Kozhevnikova & Alekseev 2015). They are, however, close binary stars with active chromospheres and enhanced spot activity (Eaton et al. 1993).

As there are 81 393 RS CVn stars listed in Chen et al. (2020), further restrictions were made based on the known characteristics of the group of ACV variables (Netopil et al. 2017; Jagelka et al. 2019): (i) photometric period between one and ten days; (ii) amplitude in the r band smaller than 0.3 mag; (iii) presence of a single independent variability frequency and corresponding harmonics; (iv) stable or marginally changing light curve throughout the covered time span; (v) T_{eff} (taken from Andrae et al. 2018) between 6000 K and 25 000 K.

Items (iii) and (iv) are helpful to distinguish ACV variables from, respectively, pulsators (which are often multi-periodic) and other types of rotational variables, such as RS CVn stars. In contrast to ACV variables, whose light curves remain stable over very long periods of time (decades or more), most spotted stars show significant light changes as spots form and decay.

A total of 1400 objects passed these selection criteria, whose light curves were downloaded from the ZTF website² and visually inspected. The most promising ACV candidates were selected, which resulted in the 86 candidates presented in this paper. The big advantage of the ZTF survey is that photometric data are available in at least two filters, which facilitates the differentiation from other similar groups of variable stars, such as the ellipsoidal variables.

The published periods by Chen et al. (2020) were inspected using the program package PERIOD04 (Lenz & Breger 2005), which performs a discrete Fourier transform. Furthermore, we used the CLEANEST and phase dispersion minimization (PDM) algorithms as implemented in the program package PERANSO (Paunzen & Vanmunster 2016). The same results were obtained within the derived errors, which depend on the time series characteristics (i.e. the distribution of the measurements over time and photon noise).

The complete set of phased light curves in the available filters is presented in Table A.1.

3. Sample characteristics

In the upper panel of Fig. 1, the distribution of the stars on the sky is shown. All stars are located in the Galactic disk with distances between 1000 and 6000 pc from the Sun. They are also, on average, fainter than the known ACV variables (see Fig. 1, lower panel) investigated with other ground-based surveys (Bernhard et al. 2015a,b, 2020).

3.1. Spectral classification

In order to validate the selection process of our target star sample (Sect. 2) and assess its efficiency, we searched for matches in DR7 of the Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST) database (Zhao et al. 2012).

The LAMOST project employs a four-meter quasi-meridian reflecting Schmidt telescope capable of observing up to 4000 targets per exposure simultaneously in a field of view of 5° (Cui et al. 2012). Recently, in March 2020, the DR7 released more than ten million low-resolution spectra in the wavelength range 3690–9100 Å, with a resolution of $R \sim 1800$.

In total, we found spectra for 15 stars, of which five (ZTF J040517.81+335007.7, J050755.19+495727.2, J054009.21+120945.1, J183551.46+334749.7, and J212905.49+142755.5) have more than one spectrum available. Only the spectrum with the highest signal-to-noise ratio was considered for the analysis in these cases. We note that the available sample is not biased by

¹ <http://variables.cn:88>

² <https://www.ztf.caltech.edu/>

Fig. 1. Mollweide projection in right ascension and declination (*upper panel*) and the G magnitude distribution (*lower panel*) of our sample stars. All stars are located within the Galactic disk.

the spectral type range, but by the apparent magnitude. It should therefore be a representative sample of 86 ACV stars.

The spectral classification was performed in the framework of a revised MK system by visually comparing, with the help of a simple graphical program, spectra in the spectral range from 3700 Å to 9100 Å to the spectra of standard stars using the notation of [Gray & Garrison \(1987, 1989a,b\)](#), and [Garrison & Gray \(1994\)](#). As ACV stars are mainly early B- to early F-type main-sequence stars, the spectral range of the standard star spectra was chosen to extend from 3800 Å to 4600 Å because the majority of the relevant spectral lines are situated in this wavelength region.

In the spectral classification we focused on several relevant indicators: the profile of the H lines, the ratio of the Ca II K to the H ϵ line, and the presence and strength of several well-known metallic lines ([Hümmerich et al. 2020](#)). The spectra of all of our sample stars show the characteristic signature of mCP stars: the well-known flux depression at around 5200 Å ([Kupka et al. 2003, 2004](#)). The Ca II K/H ϵ line ratio lies in the range 0.3–0.75 for all of our sample stars, which is typical for the spectral classes A0 to A5. In most cases the H lines present the broad profiles of luminosity class V objects, confirming that the majority of our sample stars belong to the main sequence. The two hotter stars in our sample (J050755.19+495727.1 and J053725.00+382012.2) show narrow H-line profiles best fit by standards of luminosity class III.

The spectral classes in our sample are listed in Table 1. Peculiarities are listed in order of importance. Peculiarity types in parentheses or followed by a colon denote, respectively, mild or questionable peculiarities. With the two exceptions mentioned

Table 1. Spectral types of the 15 sample stars with spectra in LAMOST DR7.

LAMOST_ID	Obs_ID	S/N	Spectral type
J012145.51+443625.8	168003189	98	kA1 hA5 V SrEu(Cr)
J040517.81+335007.7	189415040	37	kA0 hA5 V EuSrCr
J050755.19+495727.1	290903161	64	A0 III SiSrCrEu
J051331.05+393032.4	294302231	103	kA1 hA7 V SrEuCr
J052856.69+475711.7	253703006	67	kA1 hA7 V SrCrEu
J053725.00+382012.2	316409236	87	A0 III SiEuSrCr
J054009.21+120945.0	476111206	106	kA2 hA3 V SrCrEu
J055527.76+152315.3	98805041	88	kA2 hA5 V SrCrEu
J065551.61+174248.1	372816239	75	kA1 hA7 V SrCrEu
J182441.87+485404.6	155808159	17	kA0: hA5: V SrCrEu
J190408.38+445439.1	362115243	110	kA0 hA6 V EuCrSr(Si:)
J190831.72+511959.7	575716189	153	kA0 hA3 V EuCrSr(Si:)
J194356.39+470831.0	572806020	96	kA1 hA5 V SrEu(Cr)
J212905.49+142755.4	592409127	113	kA1 hA7 V SrCrEu(Si:)
J213347.82+451647.6	476310217	51	kA2 hA7 V SrCrEu

Notes. Also indicated are the LAMOST observation ID (Obs_ID) and the signal-to-noise ratio in the g band (S/N).

above, all objects are cool mCP stars, which is also reflected by their astrophysical parameters (Sect. 3.2). Example spectra are provided in Fig. 2.

Cool CP2 stars and CP1 stars overlap in the temperature domain, and care needs to be taken in the differentiation of their spectra, which may look similar at first glance. CP1 stars are characterized by significant underabundances of Ca and Sc and general overabundances of iron-peak and heavier elements ([Gray & Corbally 2009](#)). Therefore, in relation to the spectral type as derived from the hydrogen lines, they show weak Ca II K lines and a pronounced metallic-line spectrum, which also applies to most cool CP2 stars.

The enhancement of heavy elements in CP1 stars is general, whereas selected elements generally dominate the spectra of CP2 stars. Strong lines of the iron-peak element Cr are a common feature of both groups; strongly enhanced lines (e.g., Si and Eu), however, are a diagnostic feature of CP2 stars, which also generally show broader and more diffuse Ca II K lines. Figure 3 illustrates the subtle differences between the spectra of a CP1 star ([Qin et al. 2019](#)) and a CP2 star of the present sample in the traditional blue-violet spectral region. While Sr II 4077 Å is strong in both stars, the Sr II 4216 Å line, which is used to confirm Sr peculiarity ([Gray & Corbally 2009](#)), is only enhanced in the CP2 star.

More important, however, is the morphology of the 5200 Å region. CP2 stars show a characteristic flux depression around 5200 Å, which is not observed in CP1 stars ([Paunzen et al. 2005](#)), and is therefore an important criterion to differentiate between these groups of objects.

Some of the stars, for example LAMOST J190408.37+445439.3, are very peculiar objects whose general spectral pattern resembles that of HD 101065 (Przybylski's Star), which is a rapidly oscillating Ap (roAp) star with a unique abundance pattern showing, for example, lines of Pm I, Pm II, Tc I, and Tc II ([Hubrig et al. 2018](#)). The cadence and accuracy of the ZTF measurements does not allow us to search for roAp pulsations, which have periods below 30 min and amplitudes of only a few mmags ([Cunha et al. 2019](#)). Unfortunately, most of our sample stars are also too faint to be observed by the TESS satellite ([Sikora et al. 2019](#)). Therefore, new ground-based observations are needed to search for this

Fig. 2. Blue-violet spectral region of three newly identified mCP stars, based on spectra from LAMOST DR7. Some prominent lines of interest are identified.

Fig. 3. Spectra of a CP2 star (*upper panel*) of the present sample and a CP1 star (*lower panel*) taken from [Qin et al. \(2019\)](#) in the traditional blue-violet spectral region. Some prominent lines of interest are identified.

type of variability in our sample stars (Paunzen et al. 2015a, 2018).

3.2. Astrophysical parameters

As the next step, we determined and analyzed the astrophysical parameters of our sample stars, namely the effective temperature and luminosity, from which we deduced the evolutionary status.

As our sample stars are members of the Galactic disk and are situated beyond 1000 pc from the Sun, interstellar reddening (absorption) needs to be taken into account. Unfortunately, Strömgren-Crawford indices, which allow a reliable reddening estimation, are not available for our sample stars (Paunzen 2015). We therefore relied on the reddening map of Green et al. (2019) and on the *Gaia* EDR3 photogeometric distances and their errors from Bailer-Jones et al. (2021) in order to interpolate within this map.

To derive the T_{eff} values, we used the photometric data from 2MASS (Skrutskie et al. 2006), APASS (Henden & Munari 2014), and *Gaia* DR2 (Arenou et al. 2018). Then several independent calibrations were applied, as listed in Paunzen et al. (2006, 2017), and Netopil et al. (2008). Furthermore, all available photometric data (ultraviolet, optical, and near-infrared bands) were employed to analyze the spectral energy distribution (SED) of our sample stars. For the SED fitting, the VO SED Analyzer was used (Bayo et al. 2008, VOSA), which is a browser-based online tool. The photometric data were derived from the available VO catalogs. Two different stellar atmosphere models were used to determine the effective temperatures: the blackbody model and the Kurucz ATLAS9 model (Castelli et al. 1997) using new opacity distribution functions (Castelli & Kurucz 2003) and solar metallicity. The derived values are generally in good agreement with the photometrically calibrated values. The errors were derived by calculating the standard deviations from all available individual T_{eff} values.

The luminosity of our target stars was calculated using the photogeometric distances and their errors (directly transformed to the error for the luminosity) from Bailer-Jones et al. (2021) and the bolometric corrections from Flower (1996). ZTFJ232952.58+501457.3 was excluded from further analysis because of its large luminosity uncertainty.

Ages, masses, and evolutionary phases were estimated by the Stellar Isochrone Fitting Tool³, which follows the methods described by Malkov et al. (2010). PARSEC isochrones (Bressan et al. 2012) for a solar metallicity of $[Z] = 0.020$ were used in this context. We favor this value because it has been shown to be consistent with most recent results of helioseismology (Buldgen 2019; Vagnozzi 2019).

In Fig. 4 the distributions of the T_{eff} , mass, and evolutionary phase values are shown. The last are taken from the evolutionary models by Bressan et al. (2012), and Chen et al. (2014). They divided their tracks and isochrones in 15 phases from the pre-main sequence to the thermally pulsing AGB stage, respectively. In line with the spectral classifications presented in Sect. 3.1, most of the stars have T_{eff} values between 7300 and 8500 K (spectral types between F0 and A3). The masses are also consistent with the derived spectral types. Except for a single star (ZTFJ071633.43–020221.4), all objects are located between the zero age main sequence (ZAMS, phase 5) and the terminal age main sequence (TAMS, phase 6). Therefore, they are all hydrogen-burning main-sequence objects, which is additional

Fig. 4. Distribution of determined effective temperatures (*upper panel*), estimated masses (*middle panel*), and estimated evolutionary phases (*lower panel*). The labeling in the lower panel follows the format of the employed models (Bressan et al. 2012), in which phase 5 represents the zero age main sequence (ZAMS) and phase 6 the terminal age main sequence (TAMS). The large uncertainty in luminosity for one star (ZTFJ232952.58+501457.3) prevented us from calibrating the corresponding mass and phase values.

³ <https://github.com/Johaney-s/StIFT>

Fig. 5. Comparison of estimated masses and evolutionary phases for $[Z] = 0.020$ and $[Z] = 0.014$.

Fig. 6. Distribution of periods among our target star sample, which reflects the selection process described in Sect. 2.

evidence that the catalog classification as RS CVn stars is clearly incorrect (Chen et al. 2020).

A recent article by Asplund et al. (2021) estimated the solar metallicity to $[Z] = 0.014$, which is significantly lower than the value used in this work. We have therefore recalculated the corresponding values using $[Z] = 0.014$. A comparison of the results based on the two different metallicities is provided in Fig. 5. The mass differences between $[Z] = 0.020$ and $[Z] = 0.014$ amount on average to about $0.1 M_{\odot}$, in the sense that a lower metallicity results in lower masses. In addition, adopting the lower metallicity value results in a 10% increase in the derived ages. From a statistical point of view, these differences are negligible.

3.3. Stars in open cluster fields

Because the ZTF survey also targets the Galactic disk, we have searched for possible open cluster members among our sample stars following the approach presented in Prišegen et al. (2021). To this end, the angular distance from a given star to the cluster center together with proper motion and parallax con-

straints were applied. For the cluster parameters, the catalogs of Cantat-Gaudin et al. (2020), and Dias et al. (2021) were consulted. The astrometric data for our target star sample were taken from the *Gaia* EDR3 (Gaia Collaboration 2021).

We only found six matches with the newly discovered open clusters of Liu & Pang (2019, “sc” numbering scheme) and SAI 43 (Glushkova et al. 2010): ZTFJ014156.09+604451.3 (SC 1332), ZTFJ050755.19+495727.2 (SAI 43), ZTFJ060420.41+265942.2 (SC 1374), ZTFJ062801.26+162502.0 (SC 1381), ZTFJ 064847.25+ 020447.8 (SC 1392 and SC 1393), and ZTFJ071633.43-020221.4 (SC 1977). In the case of ZTFJ 064847.25+020447.8 we are unable to decide which of the two clusters it belongs to because the clusters are quite close together and have almost identical parameters. Comparing ages from our estimation (Sect. 3.2) with the corresponding cluster ages, we find excellent agreement. However, we note that the age estimates for the clusters from Liu & Pang (2019) exhibit quite large errors.

3.4. Light curves

The histogram of the periods (Fig. 6) reflects the selection process described in Sect. 2. Although ACV variables can have periods of decades and even longer (Mathys 2019), the detection of periods longer than ten days is hindered by gaps in the data and the rather low-variability amplitude (Hümmerich et al. 2016).

A note is due on the variability of the non-magnetic CP1 and CP3 stars. The CP1 stars are located in the classical pulsation strip and are known to exhibit γ Doradus and δ Scuti variability (Smalley et al. 2017). These variables were already excluded in the selection process (Sect. 2). Both groups also show indications of rotational variability, but with amplitudes of only a few mmags (Balona et al. 2015; Paunzen et al. 2021; Kochukhov et al. 2021). The amplitudes of our variable star sample are much larger (Fig. A.1), which excludes a possible contamination with CP1 and CP3 stars, respectively.

In general, concerning the characteristics of the light curves, our target star sample can be divided into four subgroups: (i) g and r data in anti-phase; (ii) the amplitude in r larger than in g and the light curves in phase; (iii) inconsistent light curves in g and r (i.e., they show different shapes); (iv) eclipses with possible additional ACV variability.

In Fig. 7 we present one typical example of each of these subgroups. The full set of light curves is shown in Fig. A.1.

Molnar (1973, 1975) reported anti-phase variations between the far-ultraviolet and optical spectral regions suggesting that the global flux redistribution caused by the phase-dependent absorption is the probable cause of the observed phenomena. If so, there is a point or a region in the spectrum where the flux remains almost unchanged (called the null wavelength region) and varies approximately in anti-phase on both sides of it (Mikulášek et al. 2007). The first subgroup of our sample stars (anti-phase variations in g and r), however, is unusual in that it shows anti-phase variations in the optical region, where in general the light changes are in phase in different photometric passbands (Paunzen et al. 2011). The null wavelength region of our ACV variables has to be somewhere between 4750 and 6200 Å, the central wavelengths of the g and r filters. One might speculate that the observed phenomenon is connected to the 5200 Å flux depression. ACV variables with anti-phase variations in the optical region are extremely rare (Gröbel et al. 2017); therefore, these stars are of special interest. Furthermore, it is obvious that this kind of anti-phase variation is a unique characteristic of ACV stars and very much suited to the

Fig. 7. Example light curves illustrating the four different subgroups among our sample stars: (i) g and r data are in anti-phase (*upper left panel*), (ii) the amplitude in r is larger than in g (*upper right panel*), (iii) the light curves in g and r are not consistent (*lower left panel*), and (iv) eclipses with possible additional ACV variability (*lower right panel*). Orange, red, and green symbols correspond to i , r , and g band data, respectively.

identification of this particular group of stars in massive photometric time series databases that contain observations in different passbands.

Due to a general lack of observations in the red optical region and the near-infrared (Catalano et al. 1998; Janík et al. 2011), the characteristics of the second subgroup (amplitude in r is larger than in g) are difficult to investigate. The ZTF survey will help analyze this phenomena in more detail, which may turn out to be helpful in the detection of ACV variables because pulsating variables, for example, are expected to show larger amplitudes at shorter wavelengths. However, we note that the light curves are in phase, which is the most common case for ACV variables (Paunzen et al. 2011).

The different characteristics of light curves in different filters and wavelength regions (third subgroup) have been well documented for ACV variables (Manfroid & Mathys 1986). To date, this phenomenon has almost exclusively been investigated in the narrowband Strömgren photometric system, which covers the spectrum up to 5700 Å. The ZTF data allows us to investigate the light curve behavior of ACV variables at even longer wavelengths, which, as the different light curve shapes in the r band demonstrate, opens up an interesting new window on this phenomenon. Additional data in the i band, in particular, will be important to further investigate the light curve characteristics of this subgroup and the correlation with spectral features.

The published overall binary fraction among CP2/4 stars is ranging from 20 to 51% (Paunzen 2020). However, eclipsing binary systems with such components are extremely rare (Kochukhov et al. 2018; Skarka et al. 2019). We therefore call particular attention to the fourth subgroup of stars (eclipses with possible additional ACV variability). We caution, however, that detailed high-resolution spectroscopy is needed to shed more light on the nature of these objects.

In summary, the quality of the ZTF data is comparable to that of other photometric ground-based surveys like ASAS-3, KELT, MASCARA, or SuperWASP (Bernhard et al. 2015a, 2020), while extending to much fainter magnitudes. The ZTF is therefore well suited to searching for new ACV variables and an analysis of their light curve characteristics.

4. Conclusions

The ZTF survey is regularly monitoring a large part of the sky in three passbands (g , r , and i) to the limiting magnitude of 20.5 mag. Observations also include the Galactic disk, which is important to the study of upper main-sequence stars. Extending to much fainter magnitudes, the ZTF is an excellent supplement to the TESS satellite mission.

In this paper we presented a first case study of the potential of the ZTF survey to find and investigate new ACV variables, which are upper main-sequence stars that show variability due to chemical surface spots. Employing selection criteria on the basis of known astrophysical and light curve properties of this group of stars, we identified 86 candidate ACV variables. Fifteen of these candidates could be confirmed as mCP stars with spectra from LAMOST DR7, which proves the viability of our approach.

Zwicky Transient Facility data come in three different passbands, which will allow us to apply the Bayesian photometric imaging technique (Lüftinger et al. 2010; Paunzen et al. 2015b) to a significant number of ACV variables in the future. This method allows the mapping of surface characteristics, and hence the study of the chemical spots. It is similar to a spectroscopic Doppler-imaging analysis, but it is not a tomographic method. The investigation of extensive sets of ground-based spectropolarimetric data for Doppler and magnetic Doppler imaging and photometric data has yielded an excellent correlation of the

surface maps from photometric and spectroscopic data in terms of spot location and size. The more data are available in different filters, the more accurate the description of the stellar surface can be conducted (Weiss et al. 2020).

Our search for ACV stars in the list of published variables from the ZTF survey has shown that ZTF data are very much suited to the study of this type of variability. However, the available automatic search and classification algorithms employed with the ZTF data do not include the relatively rare class of ACV variables. To reduce the contamination of other variability classes with ACV variables and to expand the sample size of these stars, it is imperative to be able to correctly identify these stars in survey data of different characteristics. By expanding the current sample of new ACV variables and candidates, we are intending to set up and calibrate a search algorithm to identify these stars, which can then also be applied to any other set of photometric times series. Anti-phase variations, in particular, seem to be an interesting characteristic of a subset of ACV variables that is readily usable for the identification of ACV stars in massive photometric time series databases with observations in different passbands.

Acknowledgements. The authors thank Sebastián Otero (VSX team) for helpful comments. EP acknowledges support by the Erasmus+ programme of the European Union under grant number 2020-1-CZ01-KA203-078200. Based on observations obtained with the Samuel Oschin 48-inch Telescope at the Palomar Observatory as part of the Zwicky Transient Facility project, which is supported by the National Science Foundation under Grant No. AST-1440341 and a collaboration including Caltech, IPAC, the Weizmann Institute for Science, the Oskar Klein Center at Stockholm University, the University of Maryland, the University of Washington, Deutsches Elektronen-Synchrotron and Humboldt University, Los Alamos National Laboratories, the TANGO Consortium of Taiwan, the University of Wisconsin at Milwaukee, and Lawrence Berkeley National Laboratories. Operations are conducted by COO, IPAC, and UW. Guoshoujing Telescope (the Large Sky Area Multi-Object Fiber Spectroscopic Telescope LAMOST) is a National Major Scientific Project built by the Chinese Academy of Sciences. Funding for the project has been provided by the National Development and Reform Commission. LAMOST is operated and managed by the National Astronomical Observatories, Chinese Academy of Sciences. This work has made use of data from the European Space Agency (ESA) mission *Gaia* (<https://www.cosmos.esa.int/gaia>), processed by the *Gaia* Data Processing and Analysis Consortium (DPAC, <https://www.cosmos.esa.int/web/gaia/dpac/consortium>). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the *Gaia* Multilateral Agreement. This publication makes use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation.

References

- Andrae, R., Fouesneau, M., Creevey, O., et al. 2018, *A&A*, **616**, A8
- Andrillat, Y., & Jaschek, C. 1998, *A&A*, **337**, 512
- Arenou, F., Luri, X., Babusiaux, C., et al. 2018, *A&A*, **616**, A17
- Asplund, M., Amarsi, A. M., & Grevesse, N. 2021, *A&A*, **653**, A141
- Babcock, H. W. 1949, *The Observatory*, **69**, 191
- Bailer-Jones, C. A. L., Rybizki, J., Fouesneau, M., Demleitner, M., & Andrae, R. 2021, *AJ*, **161**, 147
- Balona, L. A., Catanzaro, G., Abedigamba, O. P., Ripepi, V., & Smalley, B. 2015, *MNRAS*, **448**, 1378
- Bass, G., & Borne, K. 2016, *MNRAS*, **459**, 3721
- Bayo, A., Rodrigo, C., Barrado Y Navascués, D., et al. 2008, *A&A*, **492**, 277
- Bellm, E. C., Kulkarni, S. R., Graham, M. J., et al. 2019, *PASP*, **131**, 018002
- Bernhard, K., Hümmerich, S., & Paunzen, E. 2015a, *Astron. Nachr.*, **336**, 981
- Bernhard, K., Hümmerich, S., Otero, S., & Paunzen, E. 2015b, *A&A*, **581**, A138
- Bernhard, K., Hümmerich, S., & Paunzen, E. 2020, *MNRAS*, **493**, 3293
- Blomme, J., Debosscher, J., De Ridder, J., et al. 2010, *ApJ*, **713**, L204
- Bressan, A., Marigo, P., Girardi, L., et al. 2012, *MNRAS*, **427**, 127
- Buldgen, G. 2019, *Bull. Soc. R. Sci. Liege*, **88**, 50
- Bychkov, V. D., Bychkova, L. V., & Madej, J. 2003, *A&A*, **407**, 631
- Cantat-Gaudin, T., Anders, F., Castro-Ginard, A., et al. 2020, *A&A*, **640**, A1
- Castelli, F., & Kurucz, R. L. 2003, in *Modelling of Stellar Atmospheres*, eds. N. Piskunov, W. W. Weiss, & D. F. Gray, 210, A20
- Castelli, F., Gratton, R. G., & Kurucz, R. L. 1997, *A&A*, **318**, 841
- Catalano, F. A., Leone, F., & Kroll, R. 1998, *A&AS*, **131**, 63
- Chen, Y., Girardi, L., Bressan, A., et al. 2014, *MNRAS*, **444**, 2525
- Chen, X., Wang, S., Deng, L., et al. 2020, *ApJS*, **249**, 18
- Cui, X.-Q., Zhao, Y.-H., Chu, Y.-Q., et al. 2012, *Res. Astron. Astrophys.*, **12**, 1197
- Cunha, M. S., Antoci, V., Holdsworth, D. L., et al. 2019, *MNRAS*, **487**, 3523
- Dias, W. S., Monteiro, H., Moitinho, A., et al. 2021, *MNRAS*, **504**, 356
- Eaton, J. A., Henry, G. W., Bell, C., & Okorogu, A. 1993, *AJ*, **106**, 1181
- Flower, P. J. 1996, *ApJ*, **469**, 355
- Gaia Collaboration (Brown, A. G. A., et al.) 2021, *A&A*, **649**, A1
- Garrison, R. F., & Gray, R. O. 1994, *AJ*, **107**, 1556
- Glushkova, E. V., Koposov, S. E., Zolotukhin, I. Y., et al. 2010, *Astron. Lett.*, **36**, 75
- Gray, R. O., & Corbally, C., Jr. 2009, *Stellar Spectral Classification* (Princeton: Princeton University Press)
- Gray, R. O., & Garrison, R. F. 1987, *ApJS*, **65**, 581
- Gray, R. O., & Garrison, R. F. 1989a, *ApJS*, **69**, 301
- Gray, R. O., & Garrison, R. F. 1989b, *ApJS*, **70**, 623
- Green, G. M., Schlafly, E., Zucker, C., Speagle, J. S., & Finkbeiner, D. 2019, *ApJ*, **887**, 93
- Gröbel, R., Hümmerich, S., Paunzen, E., & Bernhard, K. 2017, *New Astron.*, **50**, 104
- Guthnik, P., & Prager, R. 1914, *Veröffentlichungen der Königlichen Sternwarte zu Berlin-Babelsberg* (Berlin: Dümmler)
- Henden, A., & Munari, U. 2014, *Contrib. Astron. Obs. Skaln. Pleso*, **43**, 518
- Hubrig, S., Järvinen, S. P., Madej, J., et al. 2018, *MNRAS*, **477**, 3791
- Hümmerich, S., Paunzen, E., & Bernhard, K. 2016, *AJ*, **152**, 104
- Hümmerich, S., Bernhard, K., & Paunzen, E. 2018, *Contrib. Astron. Obs. Skaln. Pleso*, **48**, 277
- Hümmerich, S., Paunzen, E., & Bernhard, K. 2020, *A&A*, **640**, A40
- Jagelka, M., Mikulášek, Z., Hümmerich, S., & Paunzen, E. 2019, *A&A*, **622**, A199
- Janík, J., Mikulášek, Z., Szász, G., et al. 2011, *Magnetic Stars*, 476
- Kochukhov, O., Johnston, C., Alecian, E., Wade, G. A., & BinaMics Collaboration 2018, *MNRAS*, **478**, 1749
- Kochukhov, O., Khalack, V., Kobzar, O., et al. 2021, *MNRAS*, **506**, 5328
- Kozhevnikova, A. V., & Alekseev, I. Y. 2015, *Astron. Rep.*, **59**, 937
- Krtićka, J. 2016, *A&A*, **594**, A75
- Krtićka, J., Mikulášek, Z., Zverko, J., & Žižňovský, J. 2007, in *Physics of Magnetic Stars*, eds. I. I. Romanyuk, D. O. Kudryavtsev, O. M. Neizvestnaya, & V. M. Shapoval, 310
- Krtićka, J., Mikulášek, Z., Henry, G. W., et al. 2009, *A&A*, **499**, 567
- Kügler, S. D., Gianniotis, N., & Polsterer, K. L. 2015, *MNRAS*, **451**, 3385
- Kupka, F., Paunzen, E., & Maitzen, H. M. 2003, *MNRAS*, **341**, 849
- Kupka, F., Paunzen, E., Iliev, I. K., & Maitzen, H. M. 2004, *MNRAS*, **352**, 863
- Lenz, P., & Breger, M. 2005, *Commun. Asteroseismol.*, **146**, 53
- Liu, L., & Pang, X. 2019, *ApJS*, **245**, 32
- Lüftinger, T., Fröhlich, H. E., Weiss, W. W., et al. 2010, *A&A*, **509**, A43
- Malkov, O. Y., Sichevskij, S. G., & Kovaleva, D. A. 2010, *MNRAS*, **401**, 695
- Manfroid, J., & Mathys, G. 1986, *A&AS*, **64**, 9
- Masci, F. J., Laher, R. R., Rusholme, B., et al. 2019, *PASP*, **131**, 018003
- Mathys, G. 2019, in *Southern Horizons in Time-Domain Astronomy*, ed. R. E. Griffin, 339, 106
- Michaud, G., Megessier, C., & Charland, Y. 1981, *A&A*, **103**, 244
- Mikulášek, Z., Zverko, J., Krtićka, J., et al. 2007, in *Physics of Magnetic Stars*, eds. I. I. Romanyuk, D. O. Kudryavtsev, O. M. Neizvestnaya, & V. M. Shapoval, 300
- Molnar, M. R. 1973, *ApJ*, **179**, 527
- Molnar, M. R. 1975, *AJ*, **80**, 137
- Netopil, M., Paunzen, E., Maitzen, H. M., North, P., & Hubrig, S. 2008, *A&A*, **491**, 545
- Netopil, M., Paunzen, E., Hümmerich, S., & Bernhard, K. 2017, *MNRAS*, **468**, 2745
- Ofek, E. O., Soumagnac, M., Nir, G., et al. 2020, *MNRAS*, **499**, 5782
- Paunzen, E. 2015, *A&A*, **580**, A23
- Paunzen, E. 2020, *Contrib. Astron. Obs. Skaln. Pleso*, **50**, 570
- Paunzen, E., & Vanmunster, T. 2016, *Astron. Nachr.*, **337**, 239
- Paunzen, E., Stütz, C., & Maitzen, H. M. 2005, *A&A*, **441**, 631
- Paunzen, E., Schnell, A., & Maitzen, H. M. 2006, *A&A*, **458**, 293
- Paunzen, E., Netopil, M., Rode-Paunzen, M., Handler, G., & Božić, H. 2015a, *A&A*, **575**, A24
- Paunzen, E., Fröhlich, H. E., Netopil, M., Weiss, W. W., & Lüftinger, T. 2015b, *A&A*, **574**, A57
- Paunzen, E., Hensberge, H., Maitzen, H. M., et al. 2011, *A&A*, **525**, A16
- Paunzen, E., Netopil, M., & Herdin, A. 2017, *Bulg. Astron. J.*, **26**, 45

- Paunzen, E., Handler, G., Hořková, K., et al. 2018, *Res. Astron. Astrophys.*, **18**, 135
- Paunzen, E., Hümmerich, S., & Bernhard, K. 2021, *A&A*, **645**, A34
- Preston, G. W. 1974, *ARA&A*, **12**, 257
- Prišegen, M., Piecka, M., Faltová, N., Kajan, M., & Paunzen, E. 2021, *A&A*, **645**, A13
- Qin, L., Luo, A. L., Hou, W., et al. 2019, *ApJS*, **242**, 13
- Romanyuk, I. I. 2014, in *Putting A Stars into Context: Evolution, Environment, and Related Stars*, eds. G. Mathys, E. R. Griffin, O. Kochukhov, R. Monier, & G. M. Wahlgren, 371
- Saffe, C., Levato, H., & López-García, Z. 2005, *Rev. Mex. Astron. Astrofis.*, **41**, 415
- Samus', N. N., Kazarovets, E. V., Durlevich, O. V., Kireeva, N. N., & Pastukhova, E. N. 2017, *Astron. Rep.*, **61**, 80
- Sikora, J., David-Uraz, A., Chowdhury, S., et al. 2019, *MNRAS*, **487**, 4695
- Skarka, M., Kabáth, P., Paunzen, E., et al. 2019, *MNRAS*, **487**, 4230
- Skrutskie, M. F., Cutri, R. M., Stiening, R., et al. 2006, *AJ*, **131**, 1163
- Smalley, B., Antoci, V., Holdsworth, D. L., et al. 2017, *MNRAS*, **465**, 2662
- Stibbs, D. W. N. 1950, *MNRAS*, **110**, 395
- Vagnozzi, S. 2019, *Atoms*, **7**, 41
- Weiss, W. W., Fröhlich, H. E., Kallinger, T., et al. 2020, *A&A*, **642**, A64
- Zhao, G., Zhao, Y., Chu, Y., Jing, Y., & Deng, L. 2012, ArXiv e-prints [arXiv:1206.3569]

Appendix A: Essential data and light curves for our sample stars

Table A.1 lists essential data for our sample stars. It is organised as follows:

- Column 1: ZTF ID.
- Column 2: Identifier from Gaia EDR3.
- Column 3: Right ascension (J2000). Positional information was taken from GAIA EDR3 ([Gaia Collaboration 2021](#)).
- Column 4: Declination (J2000).
- Column 5: Period from [Chen et al. \(2020\)](#).
- Column 6: G magnitude (Gaia DR2).
- Column 7: G magnitude error (Gaia DR2).
- Column 8: Parallax (Gaia EDR3).
- Column 9: Parallax error.
- Column 10: Mean effective temperature.
- Column 11: Mean effective temperature error.
- Column 12: Luminosity.
- Column 13: Luminosity error.
- Column 14: Mass.
- Column 15: Evolutionary phase.

Table A.1. Essential data for our sample stars, sorted by increasing right ascension. The columns denote: (1) ZTF ID; (2) Gaia EDR3 ID; (3) Right ascension (J2000; GAIA EDR3); (4) Declination (J2000; GAIA EDR3); (5) Period from [Chen et al. \(2020\)](#); (6) G magnitude (Gaia DR2); (7) G magnitude error (Gaia DR2); (8) Parallax (Gaia DR2); (9) Parallax error; (10) Mean effective temperature; (11) Mean effective temperature error; (12) Luminosity; (13) Luminosity error; (14) Mass; (15) Evolutionary phase.

(1) ID_ZTF	(2) ID_EDR3	(3) RA(J2000)	(4) Dec(J2000)	(5) Period	(6) G mag	(7) e_G mag	(8) π (EDR3)	(9) e_π (EDR3)	(10) $\log T_{\text{eff}}$	(11) $e_{\log T_{\text{eff}}}$	(12) $\log L/L_\odot$	(13) $e_{\log L/L_\odot}$	(14) Mass	(15) Phase
ZTF0000520.70+604135.4	429317960188135296	1.3362618	60.6931614	5.211591	12.6493	0.0008	0.9322	0.0109	3.923	0.021	1.27	0.01	1.971	5.465
ZTF0001616.48+622426.9	431246572303647872	4.0687157	62.4074779	3.798443	13.5277	0.0017	0.4380	0.0180	4.099	0.034	2.16	0.05	3.354	5.350
ZTF0003646.27+602633.8	427090865026728960	9.1928387	60.4427282	1.978370	14.8742	0.0020	0.3004	0.0196	3.962	0.018	1.42	0.06	2.173	5.377
ZTF0005928.14+603315.8	426494959780476672	14.8672664	60.5543699	1.554077	14.6406	0.0019	0.2667	0.0203	3.966	0.017	1.67	0.07	2.400	5.651
ZTF0012145.50+443625.8	397603921663368704	20.4396315	44.6074171	5.155296	12.5811	0.0004	0.8321	0.0170	3.873	0.006	1.08	0.02	1.748	5.566
ZTF0013330.13+530809.5	407448399025891968	23.3756020	53.1539575	1.414782	15.0926	0.0008	0.2753	0.0276	3.907	0.015	1.24	0.09	1.923	5.535
ZTF0013347.59+532935.7	407478532516336512	23.4483379	53.4932444	3.205112	15.3200	0.0007	0.3245	0.0328	3.898	0.023	0.96	0.09	1.726	5.160
ZTF0014156.09+604451.3	509734591379435648	25.4837795	60.7475760	1.964292	14.6626	0.0015	0.3433	0.0193	3.996	0.040	1.62	0.13	2.430	5.394
ZTF0014923.64+593834.9	506595829275620864	27.3485254	59.6430339	8.084983	13.0248	0.0009	0.8180	0.0173	3.926	0.021	1.26	0.02	1.970	5.428
ZTF0015503.00+542632.7	408366491236405888	28.7625427	54.4424073	3.295617	15.1563	0.0005	0.2460	0.0328	3.872	0.015	1.17	0.12	1.817	5.658
ZTF0040517.81+335007.7	170866138481187712	61.3242246	33.8354789	3.227968	15.6196	0.0005	0.2778	0.0390	3.899	0.023	0.98	0.12	1.736	5.201
ZTF0050455.54+394433.7	200479761891366912	76.2314130	39.7426631	4.382893	14.5562	0.0011	0.4059	0.0233	3.904	0.008	1.26	0.08	1.933	5.577
ZTF0050714.45+405114.0	201061197382735616	76.8102274	40.8538710	2.064551	14.8037	0.0006	0.3951	0.0302	3.897	0.013	1.13	0.07	1.825	5.469
ZTF0050755.19+495727.2	262338771402441728	76.9799733	49.9575289	3.624936	13.3362	0.0033	0.3453	0.0151	3.989	0.007	1.99	0.04	2.803	5.795
ZTF0051331.04+393032.4	188685373675932288	78.3793882	39.5089795	3.312342	14.3473	0.0005	0.4542	0.0221	3.866	0.005	1.19	0.04	1.828	5.702
ZTF0052856.69+475711.7	212446919462212480	82.2362356	47.9532435	3.855257	14.0640	0.0008	0.4955	0.0184	3.887	0.010	1.14	0.03	1.814	5.547
ZTF0053725.01+382012.3	189705617387154560	84.3542173	38.3362781	3.462881	14.1013	0.0036	0.3561	0.0198	4.041	0.022	1.08	0.05	3.034	5.652
ZTF0054009.21+120945.1	3340374156920950144	85.0383933	12.1625140	3.056004	14.0169	0.0012	0.5193	0.0185	3.894	0.011	1.15	0.03	1.834	5.513
ZTF0054550.47+533903.3	264305625903932288	86.4603210	53.6508921	3.491721	14.2157	0.0030	0.2448	0.0188	3.946	0.032	1.64	0.07	2.337	5.712
ZTF0055527.76+152315.3	3347276684763140480	88.8656791	15.3785408	2.827172	12.8498	0.0027	0.7891	0.0181	3.904	0.016	1.13	0.02	1.837	5.417
ZTF0060420.41+265942.2	3430370966070322304	91.0855073	26.9950461	1.472744	13.4932	0.0043	0.4285	0.0153	4.058	0.009	1.85	0.03	2.852	5.206
ZTF0062241.93+011942.6	3118315482907229952	95.6747684	19.3740622	1.138993	13.0612	0.0009	0.6967	0.0250	3.888	0.010	1.20	0.03	1.860	5.605
ZTF0062701.11+192226.7	3372391213970028544	96.7546478	16.417893	3.614991	14.4531	0.0010	0.3072	0.0235	3.938	0.013	1.48	0.07	2.171	5.611
ZTF0062801.26+162502.0	3369362368672613632	97.0053128	16.417893	3.614991	14.4531	0.0010	0.3072	0.0235	3.938	0.013	1.48	0.07	2.171	5.611
ZTF0063453.43+211828.5	337309864662809216	98.7226575	21.3078995	6.061917	14.2772	0.0005	0.3716	0.0232	3.884	0.018	1.21	0.05	1.863	5.635
ZTF0063557.01+273821.5	3385992378961359104	98.9875744	27.6392864	3.326537	15.0112	0.0020	0.1924	0.0297	3.875	0.003	1.48	0.13	2.099	5.851
ZTF0064847.25+020447.8	3126354802693282176	102.1969031	2.0799216	1.039395	14.4483	0.0019	0.2742	0.0257	4.012	0.014	1.69	0.09	2.540	5.361
ZTF0065551.61+174248.2	3364299358142868736	103.9650861	17.7133839	7.763174	14.3983	0.0012	0.3558	0.0238	3.874	0.024	1.06	0.06	1.738	5.537
ZTF0065621.40+074658.6	3157081922142073216	104.0891923	7.7829449	8.939963	15.5032	0.0008	0.2376	0.0332	3.876	0.014	1.04	0.12	1.729	5.500
ZTF0065821.76+042555.4	310170292736349664	104.5906796	-4.4320896	4.953162	13.0437	0.0027	0.5981	0.0265	3.889	0.015	1.32	0.05	1.958	5.704
ZTF0070329.94+030932.7	3115852576861974784	105.8747822	3.1590828	3.163433	13.0839	0.0010	0.7742	0.0142	3.869	0.012	0.97	0.02	1.671	5.459
ZTF0070334.33+080113.1	3154136815825083392	105.8939111	8.0203100	6.531035	14.1512	0.0019	0.3365	0.0213	3.881	0.021	1.22	0.05	1.868	5.658
ZTF0070618.89+010359.7	3114559551188271744	106.5787204	1.0665777	4.219654	15.6555	0.0012	0.2576	0.0381	3.865	0.012	0.97	0.13	1.664	5.487
ZTF0071633.43+020221.4	3108308758870686976	109.1393315	-2.0392960	3.286375	14.1493	0.0008	0.1306	0.0252	3.948	0.019	1.10	0.07	2.800	7.043
ZTF0072446.47+062829.6	3055096622329654016	111.19136605	-6.4749124	4.890556	14.8763	0.0010	0.3210	0.0244	3.880	0.010	1.00	0.07	1.706	5.417
ZTF0072604.40+062330.9	3055054394210945280	111.5183751	-6.3919508	8.429428	12.1658	0.0009	0.9867	0.0143	3.913	0.022	1.10	0.01	1.836	5.292
ZTF181242.79+264259.6	4585174323482264960	275.4283113	26.7165481	2.826906	14.6153	0.0004	0.3318	0.0185	3.893	0.024	1.13	0.05	1.817	5.496
ZTF182441.88+485404.5	2123491105988632448	276.1745200	48.9012394	4.529918	14.3043	0.0005	0.3527	0.0174	3.903	0.021	1.13	0.04	1.836	5.424
ZTF183551.46+334749.7	209433809969407488	278.9644468	33.7971106	5.251756	13.0377	0.0006	0.6470	0.0178	3.916	0.018	1.12	0.02	1.852	5.299
ZTF1855507.32+323847.6	2090413226384627200	283.7804988	32.6465520	1.927790	13.8901	0.0006	0.4885	0.0126	3.848	0.016	1.04	0.02	1.690	5.663
ZTF185720.49+282654.0	2040346586458802176	284.3354104	28.4482882	4.297991	13.6940	0.0003	0.5476	0.0120	3.909	0.014	1.10	0.02	1.828	5.329
ZTF190408.37+445439.3	210633093656748288	286.0349001	44.9109022	3.544406	13.6395	0.0004	0.5222	0.0113	3.906	0.015	1.05	0.02	1.789	5.270
ZTF190809.13+363121.0	2098738075595710848	287.0380757	36.5224814	7.244690	15.4943	0.0005	0.1511	0.0236	3.869	0.019	1.43	0.14	2.045	5.841
ZTF190831.71+511959.8	2133769375046176768	287.1321686	51.3332604	4.488083	12.8144	0.0009	0.6689	0.0127	3.914	0.022	1.18	0.02	1.890	5.410

Table A.1. continued.

(1) ID_ZTF	(2) ID_EDR3	(3) RA(J2000)	(4) Dec(J2000)	(5) Period	(6) G mag	(7) e_G mag	(8) π (EDR3)	(9) e_ π (EDR3)	(10) log T_{eff}	(11) e_log T_{eff}	(12) log $L/L_{\odot}$	(13) e_log $L/L_{\odot}$	(14) Mass	(15) Phase
ZTF192646.91+345654.2	2049748235512470912	291.6954743	34.9483612	3.353882	14.8057	0.0014	0.2615	0.0186	3.907	0.018	1.34	0.06	1.998	5.639
ZTF192832.09+305205.8	292.1337101	30.862896	30.862896	6.858098	15.3430	0.0008	0.2686	0.0266	3.884	0.016	1.09	0.09	1.775	5.507
ZTF193403.66+632537.7	2241889988402347036	293.5125836	63.4271347	3.040560	13.5126	0.0003	0.5245	0.0180	3.915	0.016	1.09	0.03	1.834	5.257
ZTF193442.59+283840.2	2026247033497540992	293.6774920	28.6444965	1.126965	15.3178	0.0020	0.2534	0.0250	3.833	0.016	1.13	0.09	1.747	5.795
ZTF193501.38+282225.7	2025483800652001152	293.7557111	28.3738018	3.187027	13.3942	0.0014	0.2221	0.0127	3.981	0.020	2.15	0.05	3.000	5.970
ZTF193638.74+262513.5	2024971045912065536	294.1614368	26.4240089	2.040730	13.5042	0.0003	0.6374	0.0140	3.927	0.018	1.26	0.02	1.972	5.421
ZTF194211.28+345344.4	2047363497889823616	295.5470250	34.8956649	8.357030	13.2659	0.0005	0.6911	0.0193	3.873	0.009	1.04	0.02	1.724	5.519
ZTF194314.34+350354.7	2047360371153770240	295.8097744	35.0651743	4.579506	13.2115	0.0003	0.5074	0.0189	3.887	0.017	1.34	0.03	1.974	5.727
ZTF194356.38+470830.9	2080554249216594944	295.9849448	47.1419201	5.374076	13.6845	0.0003	0.4765	0.0144	3.921	0.014	1.14	0.03	1.880	5.288
ZTF194633.68+032219.9	4241823539654694272	296.6403529	3.3721901	7.804066	13.5785	0.0007	0.5930	0.0155	3.899	0.013	1.17	0.02	1.854	5.504
ZTF194708.66+305907.6	2032227616496306048	296.7861319	30.9854390	2.639366	14.0226	0.0003	0.4938	0.0145	3.907	0.011	1.33	0.03	1.990	5.629
ZTF195707.08+172944.9	1820520024151681792	299.2795278	17.4958011	7.053492	13.5815	0.0004	0.4439	0.0145	3.880	0.018	1.37	0.03	1.994	5.773
ZTF195955.94+371754.2	2060214452368626176	299.9831171	37.2983694	8.501441	15.1303	0.0010	0.2645	0.0207	3.892	0.026	1.38	0.07	2.015	5.736
ZTF200107.52+402140.8	2074295725974926208	300.2813808	40.3613362	3.020683	13.8567	0.0011	0.3612	0.0238	3.912	0.013	1.53	0.06	2.181	5.764
ZTF200753.38+541552.6	1809400147648890240	301.9724288	16.3047641	6.998496	14.0547	0.0008	0.4379	0.0183	3.907	0.022	1.22	0.04	1.905	5.511
ZTF201746.62+541552.6	2185170749074136448	304.4442574	54.2645952	2.892516	13.2046	0.0003	0.6501	0.0118	3.921	0.011	1.26	0.02	1.959	5.468
ZTF203527.35+244945.9	1831531491338494080	308.8639635	24.8293879	5.174115	13.4936	0.0003	0.4827	0.0153	3.901	0.004	1.25	0.03	1.920	5.583
ZTF203702.83+520647.9	2180824658793425280	309.2618259	52.1132953	8.610871	13.8723	0.0004	0.6258	0.0172	3.890	0.015	1.43	0.02	1.743	5.380
ZTF203922.63+262122.2	185574939389715328	309.8443026	26.3561266	3.852799	14.5034	0.0003	0.2758	0.0233	3.944	0.018	1.12	0.08	1.850	5.308
ZTF205319.55+313746.4	1859630305566966912	313.3314857	31.6295237	3.594599	15.0831	0.0007	0.2840	0.0265	3.915	0.016	1.12	0.08	1.845	5.389
ZTF211100.94+470048.1	2164472412637485056	317.7539826	47.0133465	2.523780	14.3300	0.0004	0.5850	0.0144	3.874	0.005	0.95	0.02	1.667	5.389
ZTF212905.49+142755.5	1771272692152137088	322.2728965	14.4654079	4.655821	14.7020	0.0007	0.3010	0.0222	3.898	0.015	1.16	0.06	1.845	5.499
ZTF213347.82+451647.7	1971144076219123584	323.4492766	45.2798944	8.467327	15.2336	0.0007	0.2678	0.0222	3.894	0.006	1.39	0.07	2.027	5.736
ZTF213829.74+332758.7	1947187268337795328	324.6239446	33.4662933	5.704374	12.7055	0.0011	0.6050	0.0142	3.931	0.023	1.40	0.02	2.089	5.568
ZTF214304.40+541759.0	2174297304939557888	325.7683695	54.2997118	2.204300	13.4431	0.0004	0.7522	0.0109	4.036	0.011	1.58	0.02	2.506	5.000
ZTF215054.23+480704.0	1977830588687388160	327.7259888	48.1177538	6.024571	14.6211	0.0007	0.3914	0.0184	3.892	0.003	1.25	0.04	1.904	5.632
ZTF215213.06+350116.1	1948994899811877504	328.0544517	35.0211370	6.551755	13.6075	0.0013	0.5333	0.0138	3.895	0.023	1.20	0.02	1.872	5.565
ZTF215440.11+451202.7	1973564895885865728	328.6671634	45.2007511	2.237877	15.5960	0.0007	0.3017	0.0405	3.892	0.008	0.96	0.12	1.707	5.235
ZTF220333.87+481129.9	1976145862000260736	330.8911355	48.1916256	3.319605	14.4741	0.0006	0.4437	0.0170	3.888	0.018	0.96	0.03	1.697	5.277
ZTF220412.94+485912.5	1976602880880596480	331.0539267	48.9868040	3.797498	15.0597	0.0006	0.2436	0.0206	3.884	0.014	1.37	0.07	1.998	5.760
ZTF221032.85+542437.5	2005454684479351680	332.6369071	54.4104017	4.285011	15.9310	0.0007	0.2432	0.0338	3.866	0.012	1.01	0.12	1.691	5.529
ZTF221304.21+533624.2	2004607162854210304	333.2675925	53.6067245	5.554406	15.4930	0.0021	0.1400	0.0302	3.949	0.019	1.95	0.19	2.704	5.882
ZTF222357.65+474904.5	1987334835917530752	335.9902188	47.8178843	5.097425	16.0132	0.0007	0.1216	0.0327	3.902	0.010	1.45	0.23	2.092	5.748
ZTF225444.54+522009.4	2010105446854516096	343.6854340	57.3359641	2.682164	13.0778	0.0013	0.5345	0.0543	3.958	0.007	1.57	0.09	2.290	5.592
ZTF225454.64+542804.4	2002652269845315328	343.7276850	54.467860	2.199670	13.2038	0.0003	0.4061	0.0129	4.055	0.023	2.06	0.03	3.057	5.547
ZTF230203.90+535218.1	1996509951213474688	345.5162916	53.8716968	5.797225	14.7657	0.0014	0.3245	0.0215	3.919	0.024	1.29	0.06	1.978	5.517
ZTF232236.78+512549.1	1991543109289628672	350.6532833	51.4303083	4.658976	12.5543	0.0029	0.4921	0.0131	4.016	0.017	1.87	0.02	2.728	5.569
ZTF232952.58+501457.3	1943202500757860736	352.4691048	50.2492446	8.603556	16.5588	0.0016	0.0136	0.0543	3.880	0.037	3.14	3.47	5.087	7.712
ZTF234424.36+583531.0	1999341159296500096	356.1015203	58.5919399	1.813400	14.0961	0.0007	0.3517	0.0176	3.941	0.012	1.71	0.04	2.402	5.782
ZTF234442.88+512735.0	1944637191635780736	356.1786717	51.4597100	5.498045	16.2571	0.0012	0.1365	0.0378	3.913	0.043	1.33	0.24	1.999	5.599
ZTF235154.72+621521.9	2012988125824883200	357.9780206	62.2560817	7.425652	14.1324	0.0006	0.3240	0.0150	4.057	0.048	2.11	0.04	3.123	5.589

Fig. A.1. Phased light curves of our target stars in all available passbands. Orange, red, and green symbols correspond to *i*, *r*, and *g* band data, respectively.

Fig. A.1. continued.

Fig. A.1. continued.

Fig. A.1. continued.

Fig. A.1. continued.