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Pulsating star products from the Palomar Transient Factory: Ultra-long period Cepheids in M31 and RR Lyrae in *Kepler* field

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Abstract.
The Palomar Transient Factory (PTF) and its successor, the intermediate PTF (iPTF), are wide-field synoptic sky surveys aimed to detect transients. Even though the main science goal for PTF/iPTF is to detect various types of transients, the synoptic nature of the surveys can also be used for the study of variable stars. In this proceedings contribution, I will first give a brief introduction to PTF/iPTF, followed by the two pulsating stars studies using the PTF/iPTF data: the Ultra-Long Period Cepheids (ULPC) in M31 and the RR Lyrae in the *Kepler* field. For the formal study, we searched the M31's ULPC using PTF imaging data, and follow up the candidates with other telescopes. Our finding revealed that there are only two ULPC in M31. I will give a brief implication of our finding in distance scale studies. For the latter study, I will present our work on the derivation of metallicity-light curve relation in native PTF/iPTF *R*-band using the RRab stars in the *Kepler* field.

1 Introduction

The 48-inch Samuel Oschin Telescope, known as P48, located at the Palomar Observatory, possesses a distinct history in modern observational astronomy. For examples, the P48 Telescope has been used in various surveys in the past, including the Palomar Observatory Sky Survey (POSS), the Near-Earth Asteroid Tracking (NEAT) program, and the Quasar Equatorial Survey Team (QUEST). Today, the fully robotic P48 is used for dedicated wide-field transients surveys, known as the Palomar Transient Factory (PTF, 2009-2012, [1, 2]) and intermediate-PTF (iPTF, 2013-2017). Both PTF and iPTF use the same wide-field mosaic camera, which consists of eleven 2K $\times$ 4K CCDs, equipped on the P48 to produce a field-of-view (FOV) of $\sim$ 7.3 degree-squared with a pixel scale of 1.01$''$/pixel. Nominal time series observations of PTF/iPTF were carried out mainly in Mould R filter; additional but less observed data was taken in the Sloan g filter. With an exposure time of 60 seconds, the PTF/iPTF data can reach to a depth of $R \sim 20.5$ mag. The PTF/iPTF surveys employed a mixed cadence for their time series observations, ranging from few minutes to few days, that depends on various experiments. Besides the studies of transients – the main science goals of PTF/iPTF –, the time series PTF/iPTF data has also been used in the variable stars research with noticeable examples presented in [3–12]. In this proceedings contribution, I present another two examples of using the PTF/iPTF data in pulsating variable stars works: the study of ultra-long period Cepheids (ULPC) and RR Lyrae.

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2 Examples of variable stars studies with PTF/iPTF data

2.1 The search for ULPC in M31

It has been known that Cepheids with very long period appear to be outliers in the period-luminosity (P-L) relation (for example, see [13]), and subsequently they were ignored in distance scale applications. In 2009, [14] (hereafter B09) proposed that Cepheids with periods longer than 80 days follow a different P-L relation and period-Wesenheit (P-W) relation than their shorter period counterparts, hence called them the ULPC. Later, [15] (hereafter F12) compiled a list of 37 ULPC based on literature search, nearby doubling the sample size of ULPC as originally presented in B09. These 37 ULPC are located in 10 nearby galaxies, ranging from dwarf galaxies, such as the Large and Small Magellanic Clouds, to large spiral galaxies like M81. However, the nearest spiral galaxy – the Andromeda Galaxy (M31) – is not included in F12's list. Since M31 holds the promise to be an anchoring galaxy in local distance scale ladder to calibrate a number of secondary distance indicators, it is of great interest to search and identify ULPC in M31. Furthermore, ULPC found in M31 can also be served as test case for applicability of ULPC in distance scale work, because a large number of distance measurements to M31 with various techniques is available in the literature (for a review, see [16]). Therefore, we initiated a program to search for ULPC in M31 using the PTF data, because the FOV of PTF image is large enough to cover the entire M31 (which subtended ~ 3 degrees in the sky) and the multi-year time series PTF data is ideal to search for variable stars with period longer than 80 days.

To search for ULPC in M31, we downloaded the reduced R-band PTF images for M31 that spanned from January 2010 to January 2012, for a total of 172 frames. Cadence of this dataset ranges from 1 day to few days. We applied an image subtraction technique to search for variable sources, and employed various selection criteria to look for the ULPC candidates, including the variable sources have to be periodic with period longer than 80 days. We identified 8 ULPC candidates out of $\sim 10^5$ variable sources. A more detailed description of our selection criteria and results can be found in [17]. To verify the ULPC nature of these candidates, V- and I-band light curves data are needed so that their mean VI-band magnitudes and $(V - I)$ colors can be compared to other known ULPC in the plane of color-magnitude diagram (CMD) and P-W relation as presented in F12, by adopting a recommended distance modulus of M31 ([16]). We used the 60-inch robotic telescope (P60), located at the Palomar Observatory, and the Lulin One-meter Telescope (LOT), located at the Lulin Observatory (in central Taiwan), to perform the VI bands follow-up observations ([18]). Based on their locations in CMD and P-W planes with respect to the known ULPC and other types of long period variables, only two out of the eight candidates were identified as true ULPC.

We then derived the distance modulus of M31 with the two confirmed ULPC in M31. The resulting distance modulus broadly agreed with the recent values based on Cepheids given in the literature (as collected in [16]), however the associated error of the distance modulus is a few times larger than other measurements. The main reason for this large error is the small number statistics that, in the case of M31, relies on only two ULPC. Since ULPC are young and high mass supergiants, we do not expect many of them to be found in a single galaxy, and hence the small number statistics will always be the dominant source of error for the derived distance modulus. Therefore, ULPC may not be a good standard candle to derive the distance to individual galaxies. Other reasons that prevent the application of ULPC in distance scale work include the large dispersion of the ULPC P-W relation (as compared to the shorter period Cepheids) and the fact that the two available P-W relations in B09 and F12 are in discrepancy with each other.

2.2 Metallicity-light curve relation for ab-type RR Lyrae in the *Kepler* field

Besides Cepheids, RR Lyrae are also a type of standard candle that has been widely used in distance scale studies. We have initiated a program to search and characterize RR Lyrae in the PTF/iPTF data. The first step in our program is to derive a metallicity-light curve relation in the native PTF/iPTF *R*-band for ab-type RR Lyrae (i.e. the fundamental mode RR Lyrae; hereafter RRab stars). This is because the absolute *V*-band magnitude, M_V, for RRab stars is correlated with metallicity [Fe/H]. The actual form of the M_V-[Fe/H] relation might be a linear, quadratic, or segmented function, nevertheless a measurement of [Fe/H] is needed. Obtaining spectroscopic [Fe/H] could be expensive in terms of observing time, hence an alternate approach is to estimate the [Fe/H] for RRab stars with a metallicity-light curve relation ([19]). Faint RRab stars found in the PTF/iPTF data could belong to the Galactic halo, at which they are good tracer to map out the sub-structure of Galactic halo (for example, see [20, 21]), however they need to be spectroscopically confirmed. Estimation of photometric [Fe/H] via the metallicity-light curve relation for these faint RRab stars can help in reducing the targets that are needed for spectroscopic follow-up, because their [Fe/H] should be similar to metallicity expected in Galactic halo.

We use a sample of RRab stars in *Kepler* field to derive the PTF *R*-band metallicity-light curve relation, because these RRab stars possess accurate [Fe/H] based on high resolution spectroscopic observations ([22]). Another advantage of using this sample of RRab stars is the fact that their periods have been determined with very high accuracy from the almost continuous *Kepler* light curves. The PTF/iPTF *R*-band light curves are available for the majority of the RRab stars in this sample, some of which have been re-observed with shorter exposure time to ensure the photometry is not saturated. We then derived the following metallicity-light curve relation: $[\mathrm{Fe/H}]_{PTF} = -4.089 - 7.346\,P + 1.280\,\phi_{31}$, where P is the pulsation period in days, and ϕ_{31} is one of the Fourier parameters that describe the light curve shape. We tested our derived relation to RRab stars in the K2-E2 sample ([23]) and a sample of halo RRab stars presented in [21], as both samples contain independent [Fe/H] measurements. The mean difference of our estimated [Fe/H] and the published values are −0.09 dex and −0.15 dex for the K2-E2 sample and the halo sample, respectively, validating our derived PTF *R*-band metallicity-light curve relation.

3 Conclusion and future prospect

The time series data from the PTF/iPTF surveys provides a great opportunity to the variable stars research in addition to transients studies. In this proceedings contribution I provided two examples of using the PTF/iPTF data in the study of pulsating variable stars:

- We searched and identified two ULPC in M31, and found that ULPC in general are not a suitable standard candle. This work has been published in [24].
- We derived the metallicity-light curve relation in native PTF *R*-band with a sample of RRab stars in the *Kepler* field, which can be used to estimate the metallicity for newly found RRab stars in PTF/iPTF. This work has been published in [25].

Part of the PTF/iPTF data has been released to public, details on accessing the data can be found in the following URL: `http://www.ptf.caltech.edu/page/data_access`. The iPTF will cease its operation in early 2017 in preparing and commissioning for the next generation wide-field synoptic survey – the Zwicky Transient Facility (ZTF, late 2017 – ~2020). ZTF will be using the same P48 Telescope with a new ultra wide-field mosaic CCD camera. This camera consists of sixteen 6 K × 6 K e2v CCDs that provide a FOV of ~ 47 degree-squared while still maintaining a pixel scale of 1″/pixel. The filters used in ZTF will be the same as in PTF/iPTF (i.e., the *gR*-band filters). Combining the very large FOV and a typical exposure time of 30 seconds, ZTF can observe $\sim$ 3750 degree-squared of the sky in an hour, and the 3π sky can be surveyed in 8 hours. The ZTF time series data will definitely be a gold mine for variable stars research before the Large Synoptic Survey Telescope (LSST) comes on-line in 2020 or after.

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