

Introducing the Zwicky Transient Facility and the Be star variability program: a progress report at the National Central University

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Abstract. The Zwicky Transient Facility (ZTF) is a modern-day wide-field optical survey to systematically explore the transient and variable sky. The ZTF utilizes the 48-inch Samuel Oschin Schmidt Telescope located at the Palomar Observatory. This telescope is equipped with a mosaic CCD camera that provides a field of view of 47 squared degrees. The allocated observing time of ZTF can be divided into partnership time (40%), public time (40%) and Caltech time (20%). The public time contains two surveys: a 3-day cadence for the Northern Sky Survey and a 1-day cadence for the Galactic Plane Survey. Astronomical communities in South East Asian countries are encouraged to explore the public ZTF data once it is released in March 2019. Taiwan's National Central University (NCU) is one of the partnered institutions, and a major ZTF-related project carried out at NCU is the ZTF Be stars variability (ZTF-BeV) program. The main goal of our program is to study the variability of Be stars in the range of ~ 13.5 to ~ 20.5 magnitudes.

1. Introduction: The Zwicky Transient Facility

The 48-inch Samuel Oschin Telescope or P48 Telescope, located at the Palomar Observatory, has a preeminent history in sky surveys. These imaging surveys ranged from the Palomar Observatory Sky Survey (POSS) in mid-20th century, to the POSS II Survey in late 1980s, and to the Palomar Transient Factory (PTF, [1,2]) which commenced about a decade ago. A full list of the surveys that were carried out using the P48 can be found on the P48 website¹. Since 2017, the P48 has been upgraded to perform one of the largest imaging surveys before the Large Synoptic Survey Telescope (LSST)

1 <http://www.astro.caltech.edu/palomar/about/telescopes/oschin.html>

project – the Zwicky Transient Facility (ZTF), named after the Caltech (California Institution of Technology) astronomer Fritz Zwicky. In brief, ZTF is a dedicated very-wide-field synoptic survey for time domain astronomy, by repeatedly imaging the night sky accessible at the Palomar Observatory in three filters.

By design, the P48 is a wide-field telescope. The curved focal plane of the P48 can accommodate the plates used in POSS II Survey to reach a field of view (FOV) of 43.6 degrees². In the CCD era, the largest FOV achieved on P48 prior to ZTF is ~7.3 degrees² using the PTF mosaic CCD camera that consists of 11 active CCDs. The PTF camera was replaced with a more compact 600-MP (mega pixel) mosaic CCD camera for the ZTF – a camera with sixteen 6.1k x 6.1k CCD in a 4x4 configuration that provides a FOV of 47 degrees², while maintaining the same pixel scale of ~1 arc-second per pixel as the PTF camera. With a much improved readout time of ~8.2 seconds, ZTF can survey ~3750 degree² of the sky in an hour using a nominal exposure time of 30 seconds, reaching to a depth of ~20.5 magnitude. ZTF employs three custom-made filters, the ZTF-g, ZTF-r and ZTF-i filters (hereafter simply referred as g, r and i filters), their transmission curves are similar to the Sloan Digital Sky Survey (SDSS) and the Pan-STARRS1 (PS1) filters as shown in Figure 1.

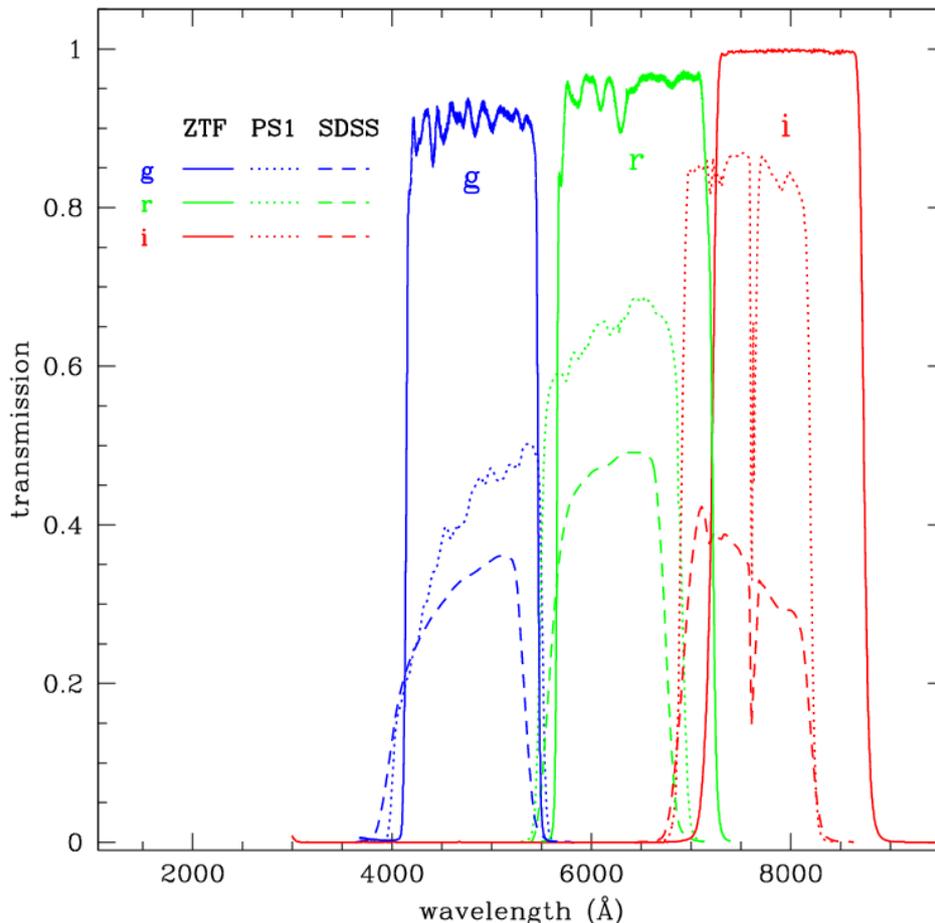


Figure 1. Comparison of the transmission curves for ZTF (solid curves), PS1 (dotted curves) and SDSS (dashed curves) in the g (blue curves), r (green curves) and i (red curves) band. Transmission curves for SDSS and PS1 filters are taken from the “Filter Profile Service” available at the Spanish Virtual Observatory (<http://svo2.cab.inta-csic.es/theory/fps3/index.php?mode=browse>). Note that the transmission curves for SDSS and PS1 include the CCD quantum efficiency, optics and atmospheric effects, while the transmission curves for ZTF are based on filters only.

The ZTF observing time is divided into three portions: partner time, public time and Caltech time. A list of ZTF partnered institutions can be found in the acknowledgment, of which the National Central University (NCU) joined ZTF through the TANGO Consortium of Taiwan. These partnered institutions share 40% of the ZTF observing time, which comprise a variety of observing programs – ranging from the search for various types of supernovae, high cadence observations of Galactic Plane variable stars, to the detection of streaking near-Earth asteroids. Since ZTF is also partly supported by the Mid Scale Innovation Program (MSIP) from the National Science Foundation, an equal amount of the 40% observing time was allocated to carry out two public surveys in g and r filters: (a) The Northern Sky Survey with a 3-day cadence; and (b) The Galactic Plane Survey with a 1-day cadence. The combination of both ZTF public surveys ensures the entire sky north of declination = -31° will be covered. Figure 2 shows the recent sky coverage from the public surveys. The first release of ZTF public-survey data is tentatively scheduled for March of 2019. The remaining 20% of the observing time is reserved for Caltech investigators.

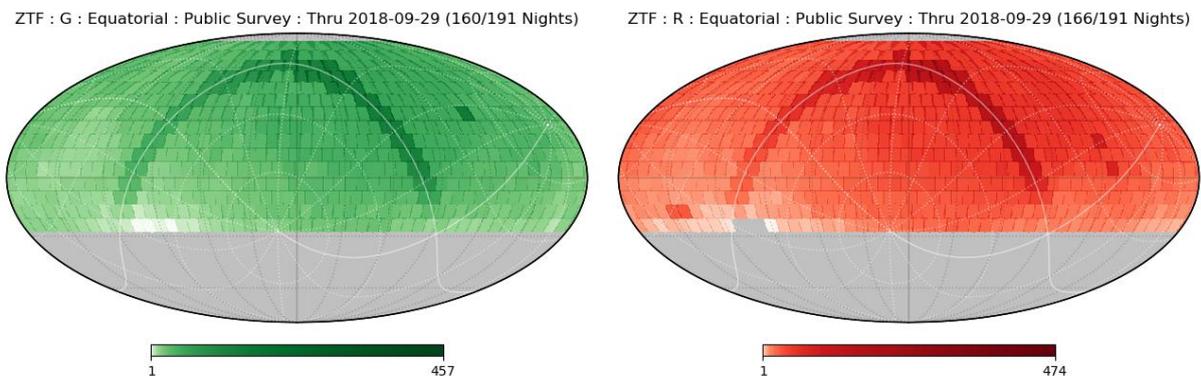


Figure 2. Sky coverage of the ZTF public surveys in g (left panel) and r (right panel) filters. The colour scales represent the number of accumulated observations on each ZTF fields (shown as tiling patterns on the map). These sky coverage maps are represented in equatorial coordinates.

2. The ZTF Be Star Variability Program

Be stars are B-type main-sequence, or near main-sequence, stars that exhibit emission lines, especially the Balmer series, in their spectra at least once. They are also fast rotators as their rotation velocity at equator can be near the critical velocity. Consequently, a “decretion” disk (instead of an accretion disk) was formed around the Be stars, which explains the observed emission lines. Most Be stars also display detectable variability, and sometimes they are referred as Gamma Cassiopeia (GCAS) type or Lambda Eridani (LERI) type variable stars, which exhibit a wide range of photometric variability (from outburst to periodic variation). Some reviews on Be stars, as well as their variability, can be found, for example, in [3,4,5] and references therein.

Based on KELT (kilodegree Extreme Little Telescope) time-series observations, [6] summarized the photometric variability of Be stars into the following classes: outburst variation, semi-regular outbursts (time scales of 10-200 days), long-term variations (time scales of years), non-radial pulsation (time scales of less than 2 days), intermediate periodicity (time scales of 2-200 days) and eclipsing binaries (time scale of 1-200 days). Given that ZTF will frequently visit the same part of the sky (due to its very large FOV and quick readout), time-series ZTF data can be used to probe the majority of the Be stars’ variability, as demonstrated in Figure 3, except for the long-term variations that are longer than three years. We therefore initiated a program to investigate the photometric variability of Be stars using ZTF data at NCU, which we called the ZTF-BeV (ZTF Be stars Variability) program. The main goal of our program is to study the variability of those Be stars with brightness between ~ 13.5 magnitude and ~ 20.5 magnitude covered by the ZTF data. As an illustrative example, we show the

light curves, based on the first 5 months of ZTF commissioning data downloaded to NCU (see Appendix), for a Be star in Figure 4. This Be star is identified in [7] but excluded from the KELT sample ([6]). Light curves from the CoRoT observations ([8]) for this Be star clearly displayed variation, and the ZTF light curves also show a similar variability. The ZTF-BeV program complements the studies from [6] using the KELT data, because KELT can only observe bright Be stars within the range of 7 to 13 magnitudes in V band. Combining both samples from bright to faint, an unbiased sample can be used to reveal the nature of variability seen in the Be stars.

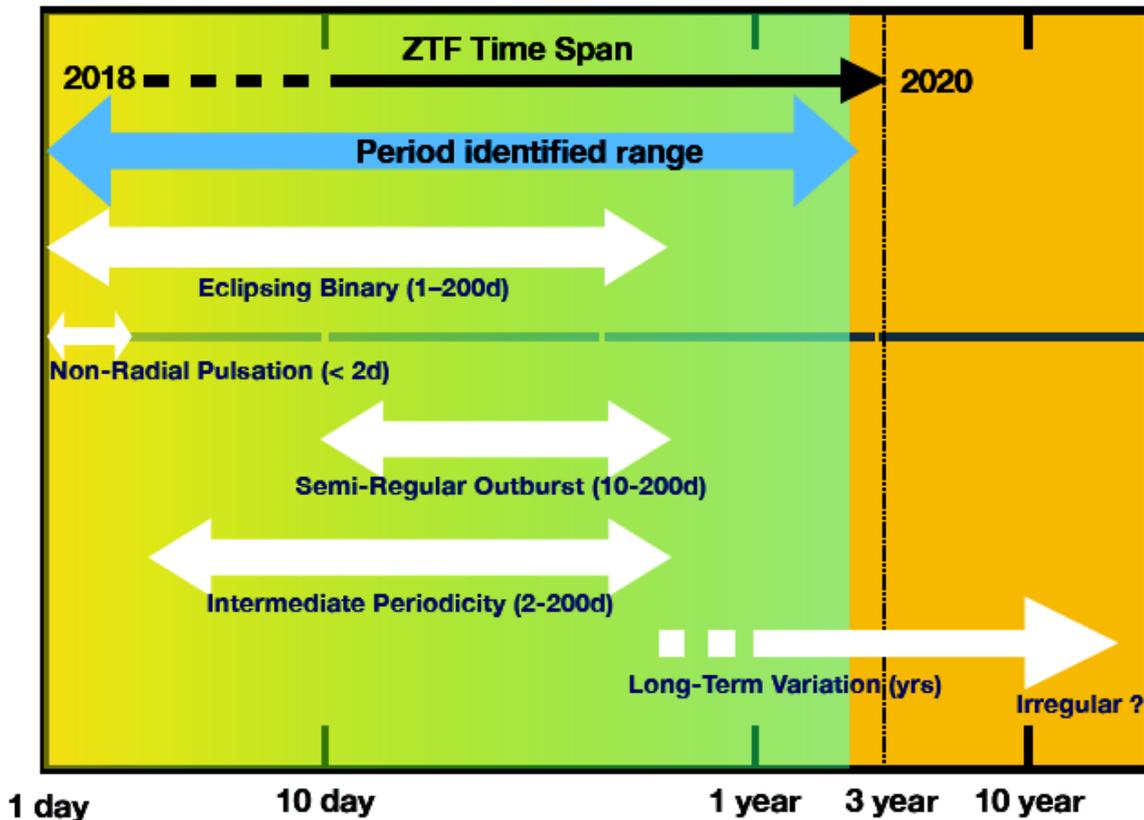


Figure 3. Illustration of time scales for Be stars' variability that can be probed by ZTF within its three years (2018-2020) of operation. The top axis represents the time span of ZTF, while the bottom axis shows the time scale for the different variability exhibited in Be stars. Clearly, ZTF cannot probe variability with time scales longer than three years (shown as the orange area in the right of the plot).

3. Conclusion

In this article, we briefly introduce the ZTF survey with an aim to promote ZTF to the broader astronomical community within South East Asian countries. ZTF contains two public surveys, the Northern Sky Survey and the Galactic Plane Survey, for which the data will be publicly available in March 2019 with sequential annual releases. Further information about ZTF can be found on the ZTF official website, available at <https://www.ztf.caltech.edu/>, and in [9,10]. The time-series imaging data in g and r filters will enable a wide range of scientific investigations, and an example study of the variability of Be stars is presented here. A number of technical papers that describe ZTF in more detail have been submitted to the Publication of the Astronomical Society of the Pacific at the time of this article was written; several noteworthy papers are:

- Graham M *et al.*, "The Zwicky Transient Facility: Science Objectives"
- Bellm E *et al.*, "The Zwicky Transient Facility: System Overview, Performance, and First Results"

- Masci F *et al.*, “The Zwicky Transient Facility: Data Processing, Products and Archive”
- Dekany R *et al.*, “The Zwicky Transient Facility: Observing System”
- Mahabal A *et al.*, “Machine Learning for the Zwicky Transient Facility”

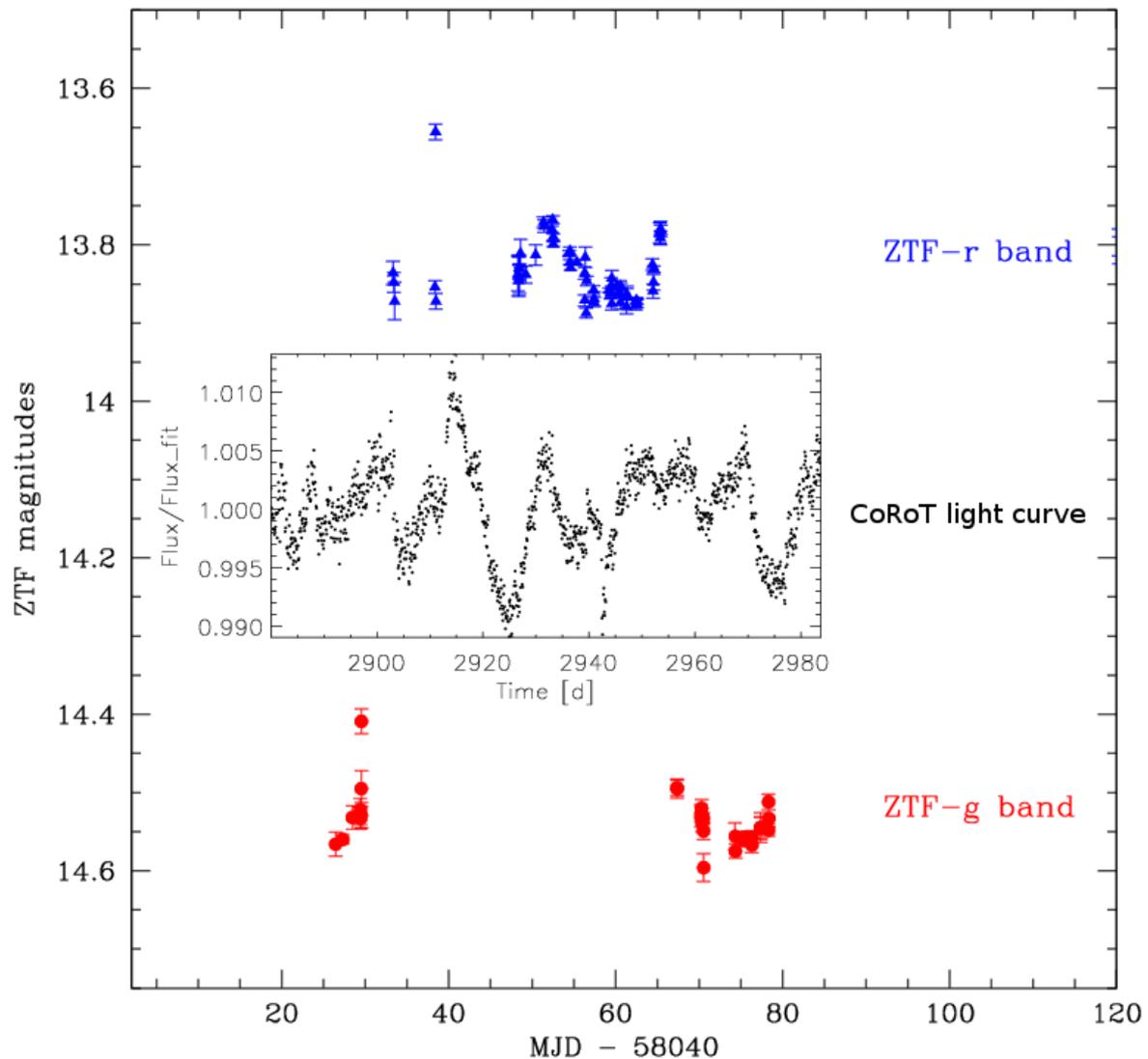


Figure 4. Comparison of the light curves for a Be star, CoRoT 102762536, from ZTF commission data and the CoRoT observations, shown as inserted plot in the middle (this plot is taken from [8]).

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Appendix: ZTF Data Download at NCU

The ZTF imaging data is processed almost in real-time nightly at the Infrared Processing and Analysis Center (IPAC, located in the Caltech campus), hence in the morning data from previous night would be fully processed. At NCU, a Linux server was setup to run the `cronjob` program daily, which in turn executes the `wget` command to automatically download the nightly ZTF data. Due to limit on bandwidth and storage space, we only download the ZTF catalog products. Figure A1 displayed the data volume downloaded in the first 12-months of ZTF observations, with a total data volume of 25.71 terabytes (TB) to our Linux server.

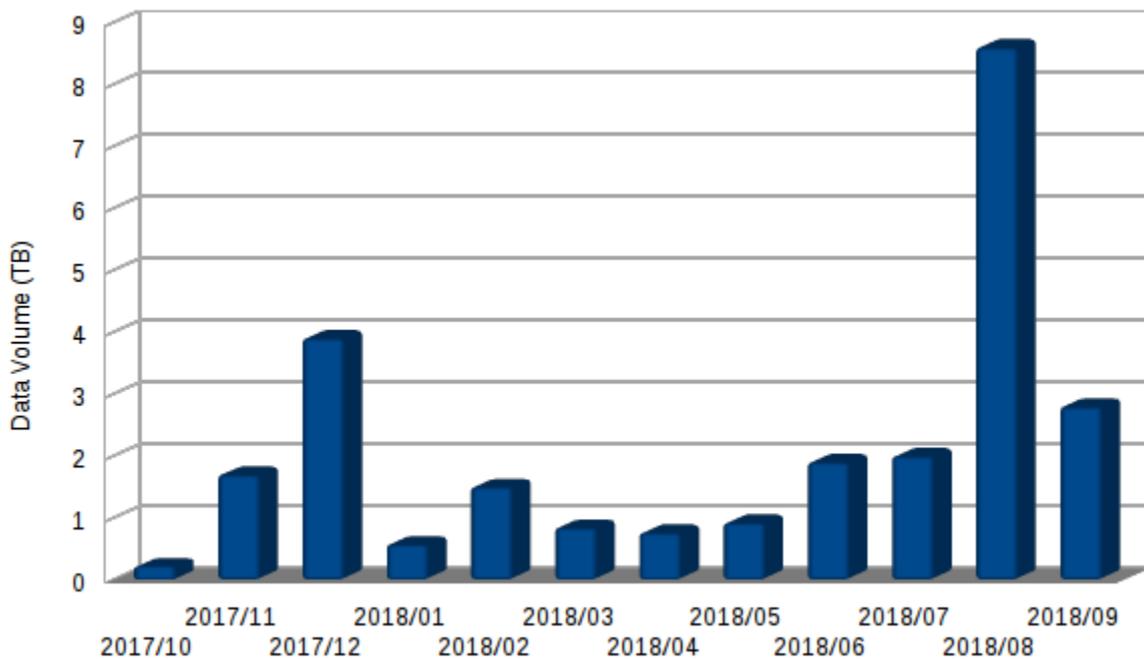


Figure A1. The monthly data volume of the downloaded ZTF catalogue products at NCU, expressed in terabyte (TB). Note that ZTF was under commissioning from October 2017 to 17 March 2018 – the official starting date of ZTF for both partnership and public surveys. We have downloaded the commissioning data as well as the ZTF partnership data after the official starting date. The ZTF public data can only be downloaded after the first data release, tentatively scheduled in March 2019.

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