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INTRODUCING *tlc_s05*: A CODE TO FIT CEPHEID *JHK* BAND LIGHT CURVES USING A TEMPLATE APPROACH

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ABSTRACT

We introduce a code called `tlc_s05`, to fit sparsely sampled JHK band Cepheid light curve data with template light curves to derive the mean magnitude. A brief description of the code is provided here. We tested the performance of the code in deriving the mean JHK band magnitudes using simulations, and we found that it is better to observe more than four evenly spaced data points per light curve, which permits `tlc_s05` to derive accurate mean magnitudes for Cepheid JHK band light curves.

Key words: stars: variables: Cepheids — methods: miscellaneous

1. INTRODUCTION AND MOTIVATION

Cepheids are important pulsating variable stars because they are standard candles that can be used to determine distances to nearby galaxies. Observations based on near infrared JHK bands for Cepheids are becoming more important, as the effects of extinction and the influence of metallicity are smaller in the near infrared when compared to the optical $BVRI$ bands. The smaller amplitudes of Cepheid light curves in the JHK band also suggest that fewer observations can be done in these bands (saving observing time). However, small numbers of data points per light curves may challenge the accuracy of the derived JHK mean magnitudes. Nevertheless, this problem can be remedied with the application of the template light curve (`tlc`) method, with Cepheid JHK band template light curves by Soszyński et al. (2005, hereafter `S05`, see Figure 1). The motivation of this work is to provide the astronomical community with a relatively easy-to-use code that can fit sparsely sampled JHK band light curves with `S05` template light curves. We named our code `tlc_s05`. It is written in `C`, and can be downloaded from `https://code.google.com/p/jhk-template-light-curve-fitting-for-cepheid/`. The code can be altered to use other sets of template light curves.

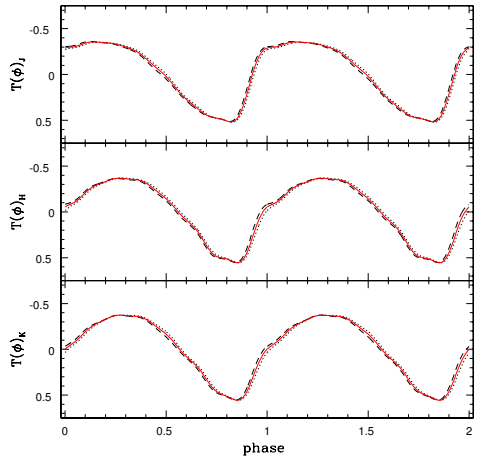

Figure 1. The JHK band template light curves from `S05`. For each JHK band, `S05` derived two sets of template light curves relative to either the V-band light curves (dotted curves) or the I-band light curves (dashed curves). The red curves represent the averaged template light curves of these two, which is used in `tlc_s05`.

2. DESCRIPTION OF THE CODE

Our code can be used to fit sparsely sampled JHK band light curves ($N \geq 3$) with the `S05` template light curves and derive the magnitudes from these observed light curves. The code fits the light curve data by finding three parameters that minimize the χ^2 values between the data points and the template light curves. These three parameters are: (a) the mean magnitude of the observed light curves (i.e. vertical shift); (b) the amplitude of the observed light curves (i.e. the scaling factor); and (c) the phase shift between the observed light curves and the template light curves (i.e. the horizontal shift). To determine the mean magnitude and amplitude, a simplex algorithm implemented in the GNU Scientific Library (GSL) was used to find their best fit values, as this is a non-linear minimization process. For the phase shift, the code simply loops over the phases

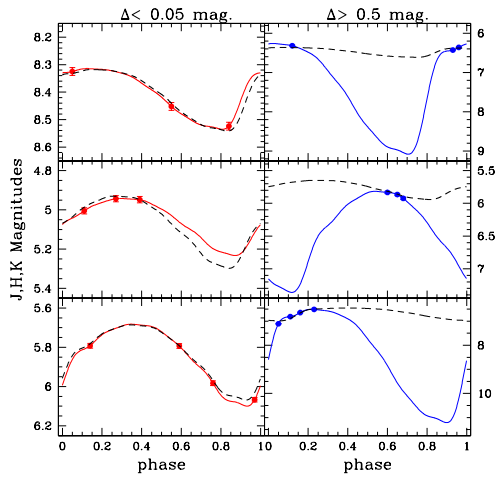

Figure 2. Six examples of the simulated light curves for two cases: (a) good fit with $\Delta < 0.05$ mags on the left panels; (b) bad fit with $\Delta > 0.5$ mags on the right panels. The solid and dashed curves represent the template light curves fitted to these simulated observed data points and the fitted light curves when using all available data points (that is, the full light curves), respectively. The upper two panels display the case of $N = 3$, and the lower panel display the case of $N = 4$.

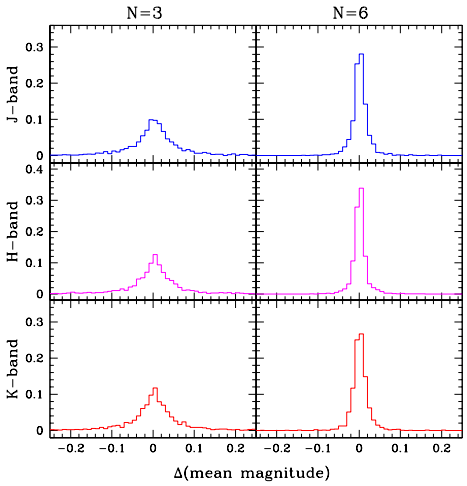

Figure 3. Distributions of Δ in J (upper panel), H (middle panel) and K (lower panel) bands based on 2000 simulations. The left & right panels show the cases with $N = 3$ and 6, respectively. As expected, the distributions become narrower and centered around $\Delta \sim 0.0$ mags when the number of data points per light curves increases from 3.

from 0 to 1 to find the minimum χ^2 value. Outputs of the code include the intensity, mean magnitude and amplitude of the light curve, as well as two ASCII files that record the data points and the fitted template light curve. The latter two output files can be used for plotting the results with the plotting package preferred by the user.

3. TESTING WITH SIMULATIONS

To test the performance of `tlc_s05`, we ran a series of simulations using JHK band light curve data taken from Monson & Pierce (2011, hereafter MP). MP's data contains $\sim$ 130 Galactic Cepheids observed in JHK bands, with an average of 22 data points per light curve. The method of our simulations is as follows:

1. We randomly picked one Cepheid from the MP sample, and ran the `tlc_s05` code on this Cepheid to derive the "true" mean JHK band magnitudes ($m_{\rm full}$) from the full light curve.
2. We then randomly selected N data points for this Cepheid in JHK bands separately and derived the fitted mean JHK magnitudes ($m_{\rm fit}$) using `tlc_s05`, and calculated the difference in JHK bands: $\Delta = m_{\rm full} - m_{\rm fit}$. Figure 2 shows a few examples of the good and bad fitted light curves based on our simulations.

To built up statistics, the above procedure was repeated 2000 times for the cases of $N = 3$ to 10. Distributions of Δ for the cases of $N = 3$ and $N = 6$ are displayed in Figure 3. We further calculated the means and standard deviations of Δ in our simulations as a function of N data points in each light curves, and the results are presented in Figure 4. Based on the results from our simulations, for `tlc_s05` to derive accurate mean

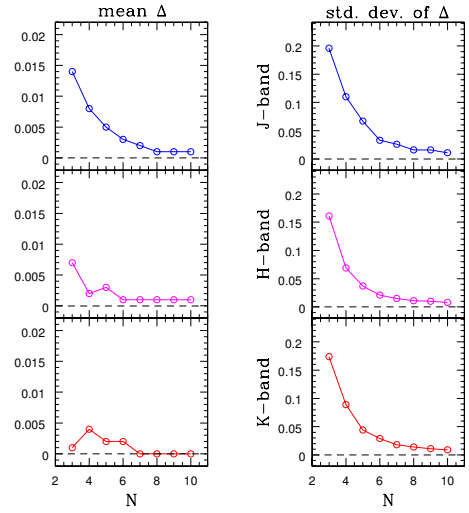

Figure 4. Means and standard deviations of Δ (after removing $|\Delta| > 2.0$) in J (upper panel), H (middle panel) and K (lower panel) band as a function of N. Our results indicate that when $N > 4$, the means of Δ drop to below 0.005 mags, at the same time the standard deviations for Δ reduce to 0.05 mags & lower. This implies that the errors on the fitted mean magnitudes will be $\sim$ 0.05 mags or smaller for the case of $N > 4$.

JHK band magnitudes we suggest four or more more data points for the Cepheid JHK band light curves. Furthermore, it is better to evenly spaced the observed data points in the JHK band light curves, as the periods and epochs of the Cepheids can be found from the V-band data.

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