

# Light Curve Template for First-Overtone Cepheid Variable Stars

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## Background

Cepheid variable stars are an essential tool in measuring cosmic distances.

Their distance is calculated using the Cepheid Period-Luminosity relationship. Because they are variable stars, the luminosity varies over time, so the luminosity used in the calculation is the mean luminosity.

In order to find an accurate mean luminosity, a curve must be fitted to the data, as taking the sample mean of the observed points would be inaccurate.

To fit a meaningful curve to data, a large number of data points is needed. In order to reduce the number of data points needed for a good curve, a template curve must be found.

A template curve is simply a curve which best fits the data from many well sampled cepheids, which have all been scaled so that their data points overlap. The curve is then re-scaled according to individual stars, in order to obtain their respective curves.

## Data

Data were taken of the apparent brightness over time of first overtone cepheid variable stars in the Large Magellanic Cloud (LMC).

J, H, and K band data were taken from CPAPIR in Chile.

- These data were already adjusted for reddening.

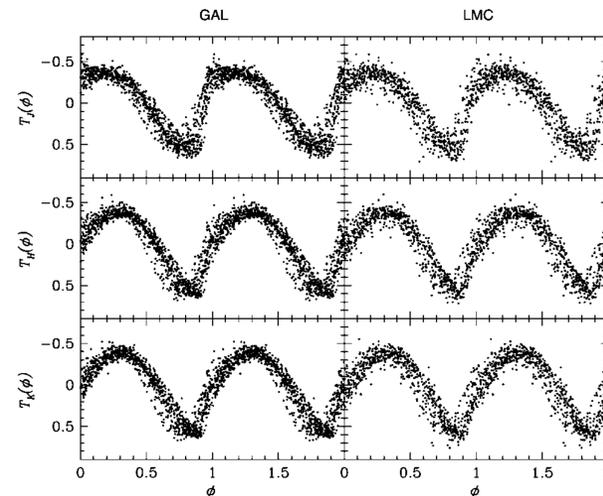
V and I band data were taken from the results of the Optical Gravitational Lensing Experiment (OGLE) in Chile.

- Only the periods of oscillation and the mean magnitudes were used, which were already adjusted for reddening.

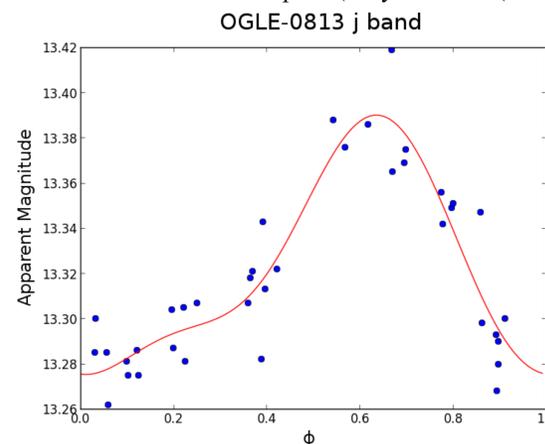
## Template

The template for this project is for first overtone cepheid variable stars only. The methods used were taken from Soszynski et al. (2005), which dealt with fundamental mode cepheids. The important difference between the two types of cepheids is that their light curves are shaped differently, and therefore they require different templates.

The most important scaling step is converting time data into phase data. Using phase creates a curve with a single oscillation, which not only causes that oscillation to be better sampled, but it also makes the Fourier curve much more simple and accurate.



Fundamental Mode Template (Soszynski et al. (2005))



An example of a fourier fit of a fairly well-sampled star.

Scaling by phase (x-axis) must be done prior to scaling the y-axis, because the mean magnitude is needed for that. In order to obtain the mean magnitude, a Fourier curve is fit to the data, which takes the form

$$T(\phi) = A_0 + \sum_{k=1}^N A_k \sin(2\pi\phi + \Phi_k),$$

where  $T(\phi)$  is magnitude for a given  $\phi$ ,  $\phi$  is the phase of observation,  $N$  is the order of the fit,  $A_0$  is the mean magnitude,  $A_k$  is the magnitude coefficient for the  $k$ th curve, and  $\Phi_k$  is the phase shift coefficient for the  $k$ th curve.

Cepheids with enough data points to be considered well sampled are fitted using Fourier Analysis with this equation. Only the ones which have well fitted curves (low RMS value) are kept. Their mean magnitudes,  $A_0$ , are the only values needed from this step. Next, their amplitudes are found, which, for X-band data, is given by the function

$$A(X) = X_{max} - X_{min}.$$

This is used to find the value  $T$  for each data point, which is the scaled version of the y-axis. For the resulting  $T$  values, the amplitude of the curve is equal to 1. For X-band data,  $T$  is given by the function

$$T = \frac{(K - \langle K \rangle)}{A(K)}$$

A large number of well-sampled stars are all scaled, so that their axes are  $\phi, T$ . A Fourier curve is then fit to this well sampled data. This curve is the template.

To apply the template to a star, three steps must be taken:

1. Using the visible-band amplitudes from OGLE, estimate the amplitude of the star using the visible:infrared amplitude ratios from Soszynski et al.
2. Using the epoch of maximum brightness from OGLE, convert time to phase data.
3. Find the fitted magnitude  $T(\phi)$  for that phase, using the template. Then use that magnitude in the following function to find the mean magnitude of the star in the X-band

$$\langle X \rangle = X - A(X) \times T_X(\phi)$$

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## Conclusions

The use of templates can significantly increase the number of cepheids whose mean luminosities we know in multiple light bands. They allow us to spend time observing many different cepheids, in various bands, instead of having to observe a single cepheid for a long period of time. Doing this means increasing the number of stars we know the distance to, which is an essential asset in mapping out the Universe.