On the use of field RR Lyrae as Galactic probes

VII. Light curve templates in the LSST photometric system

V. F. Braga[1,2,⋆], M. Monelli[2,3,1], M. Dall'Ora[4], J. P. Mullen[5], R. Molinaro[4], M. Marconi[4], R. Szabó[6,7], and C. Gallart[2]

A&A, 689, A349 (2024)

Xingzhu Zou (邹星竹)
Yunnan University

2024-12-30

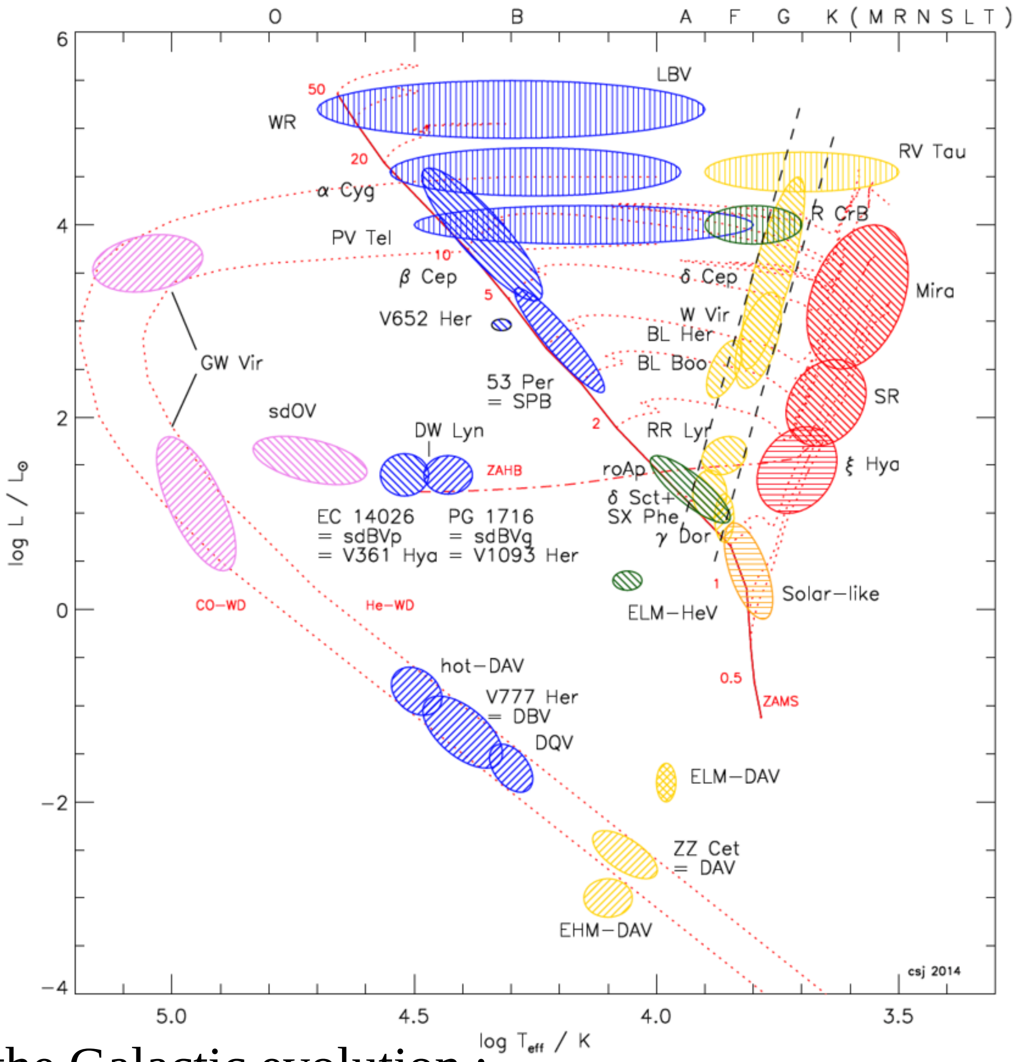
Outline

Introduction

RR Lyrae

- RR Lyrae (RRLs) are old, low-mass, core Helium-burning stars on the Horizontal Branch, pulsating regularly with periods of 0.2 – 1.4 days.
- RRLs are present in every component of the Milky Way: Globular Clusters, Halo, Bulge, Thick Disk and, recently, several Thin Disk RRLs were also found.
- RRLs obey to tight Period-Luminosity (PL) relations at effective wavelengths ranging from ~600 nm to ~4500 nm, makes them reliable old-age standard candles.

Thanks to all these properties, and being strictly old , they can be used as tracers of the earliest stages of Galactic evolution.



The important prerequisites to fully exploit RRLs as probes of the Galactic evolution :

- ➢ Estimating accurate **mean magnitudes (<mag>)**
- ➢ Being variable stars, a <mag> estimate **requires a good sampling of the pulsation cycle** to properly model the light curve.

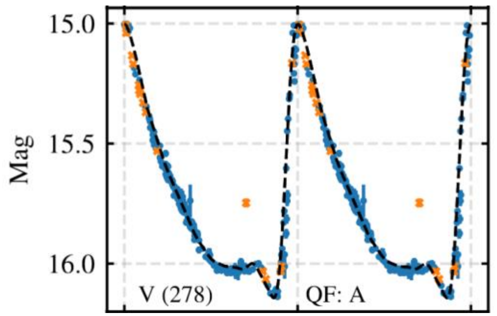
Introduction

Legacy Survey of Space and Time

The Vera C. Rubin Observatory will see the first light at the beginning of 2025 and, for ten years, it will carry on the Legacy Survey of Space and Time (LSST), surveying the entire Southern sky in six passbands (ugrizy).

LSST early data includes the commissioning data, realtime calibrated images and Data Releases 1 and 2 (six and twelve months of data, respectively). there are very few sampling points on the RR Lyrae periods.

RRab



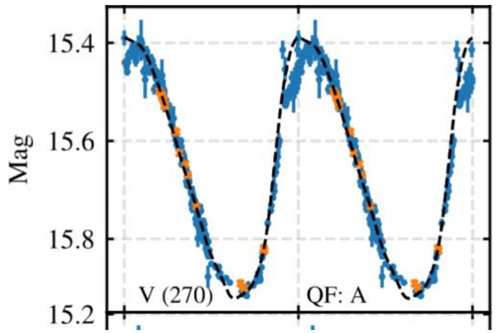
Light curve templates

Light curve templates (LCTs) are, in short, analytical functions (or gridded points) that reproduce the typical shape of the light curve of a variable star within a specific range of periods/Ampl, pulsating in a specific mode.

LCTs can be adopted to estimate accurate <mag> also having only one phase point observed (provided that the period, light amplitude [Ampl] and the reference epoch are well constrained).

The pulsation mode is the most important parameter to consider for LCTs. Based on the pulsation modes, RRLs are classified as RRab for the radial fundamental mode, RRc for the first overtone radial mode, and RRd when both modes are present.

RRc



The main aim for which the LCTs in this work are conceived is to enhance the science performed with LSST early data, particularly for galactic archaeology analysis involving RR Lyrae stars.

Outline

Dataset

There is no existing observed data in the ugrizy photometric system of LSST. They decided to adopt light curves collected by other instruments, with passbands as similar as possible to the $ugrizy_L$ photometric system.:

1) Zwicky Transient Facility light curves of RRLs in the gri bands (gri_Z)

2) The Dark Energy survey of the Galactic Bulge in the ugriz ($ugriz_D$).

ZTF

- Using Gaia DR2+EDR3 and other surveys, They queried the ZTF DR17 database to obtain a catalog of 35,434 RR Lyrae light curves.
- After filtering for high-quality data with fewer than 80 good observations per light curve, the catalog was reduced to 24,925 RRLs, with an average of 303/499/88 phase points in g/r/i bands.

DECam

- ZTF survey not collecting data in passbands redder than i, but the addition of z and y bands is crucial for studying the Bulge, as they are less affected by reddening and offer more precise distance indicators with higher PL relation slopes.
- They complemented DECam time series of RRLs in the Bulge collected by Saha et al. (2019) and detected 474 RRab. Unfortunately, their sample does not include RRc .
- They will not use uband data due to the PL is flat and has a high dispersion at short wavelengths.

Outline

Template building

For the gri LCTs, we adopted only the ZTF data for three reasons.

- the contribution from DECam would be tiny: ZTF provides significantly more phase points and a larger RRL sample than DECam
- Merging datasets from different instruments is avoided to prevent noise from photometric system transformations.
- The ZTF and DECam RRL catalogs represent different populations (Halo vs. Bulge), with distinct metallicities.

To build the LCTs:

1) fold all the light curves by the proper period and adopt the same reference epoch (T0) for the zero phase;
2) normalize the light curves;
3) merge all the normalized light curves in a given band and period bin into a single cumulated and normalized light curve (CNLCV);
4) derive an analytic fit of the CNLCV: this will be the analytic form of the LCT.

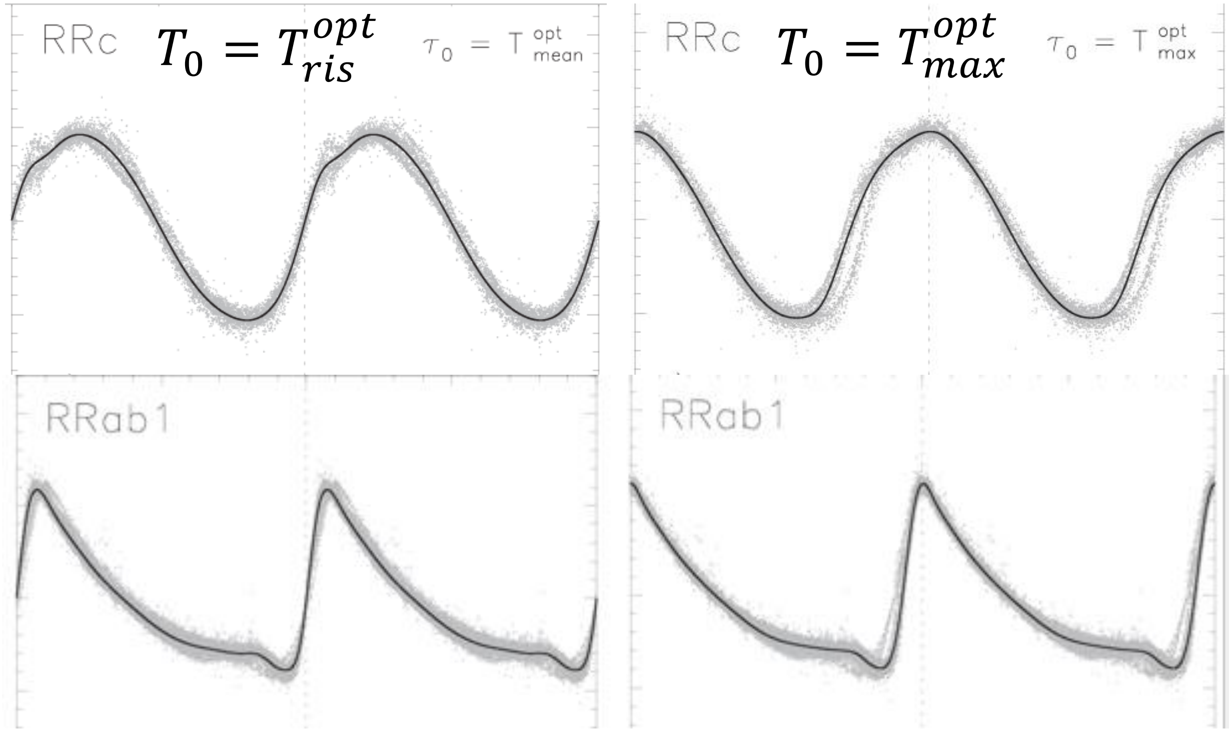
Template building

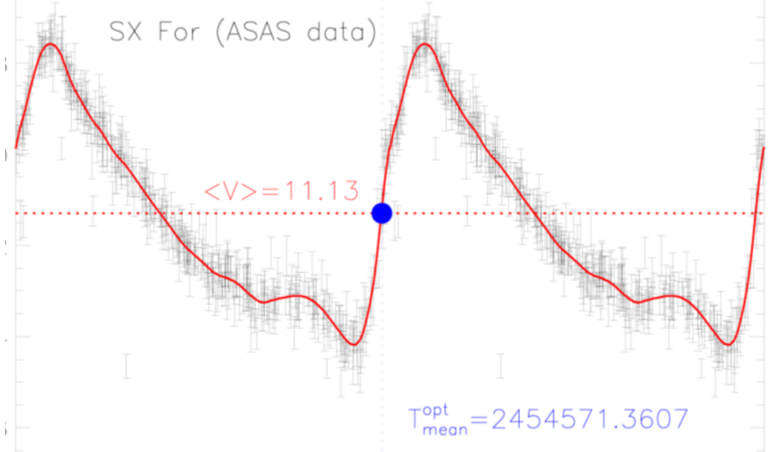
3.1. Phasing of the light curves

Due to the smaller dispersion of the epoch of <mag> on the rising(T_{ris}) compared to the commonly used epoch of maximum light(T_{max}), they adopted T_{ris}^{opt} as the reference epoch for their LCTs.

To estimate T_{ris} for the light curves, they followed a two-step method:

Step 1) After folding the light curves with the proper period and shifting them to a preliminary and arbitrary reference epoch (T_0 =0), they fitted the light curves with Fourier series and derive the <mag> of the star .





Step 2) Searching <mag> intersection with the rising branch fit, they derived T_{ris}. Having an estimate of T_{ris} for each light curve, the time series were re-phased by adopting this new reference epoch and the folded light curves were re-fitted, obtaining the final Fourier series model. The latter provided Ampl and <mag>, integrated over an arbitrary flux scale.

Template building

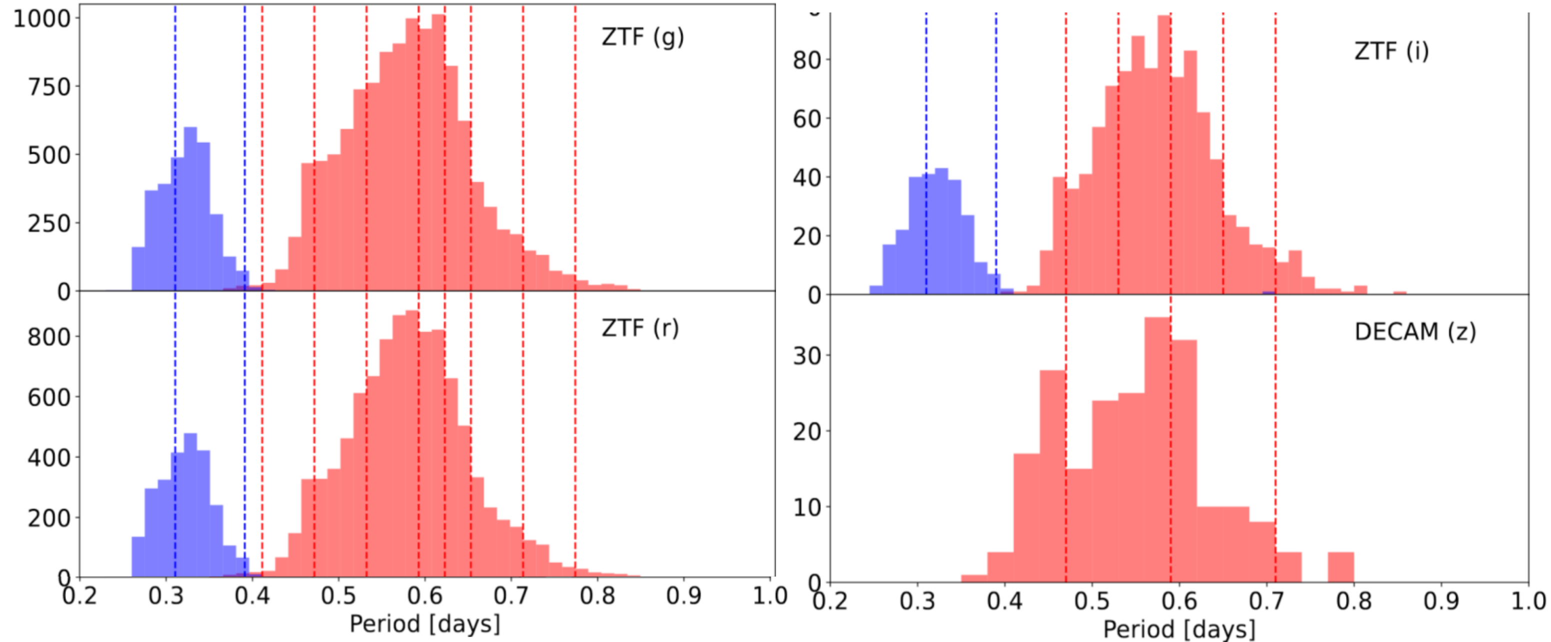
3.2. Selection of the light curves

The ZTF dataset is so large, so they adopted a Neural Networ to perform the selection:

- selected a training sample of 681 gri light curves, visually inspected these light curves and manually flagged [kept/rejected]
- Building a NN, intput:The parameters obtained by fitting; output: a True/False rejection flag for each light curve.

DECam sample is too small, visually inspected all the light curves and rejected all the light curves that are not suitable to build the LCTs

P	Pulsation period of the variable
mag	Mean magnitude, intensity-averaged over the model fit
$Ampl$	Light amplitude (maximum minus minimum of the model fit)
χ^2	Reduced χ^2 of the model fit with respect to the data
χ^2_A	Reduced χ^2 of the model fit with respect to the data, divided by $Ampl$
U	Uniformity parameter[1]
U_{bin}	Same as U, but calculated on phase points grouped in phase bins of 0.05
n	Number of phase points
$\Delta\phi_{max}$	Largest phase gap between two consecutive phase points
Ku	Kurtosis of the light curve
Sk	Skewness of the light curve
r	Unweighted sum of the residuals divided by the degrees of freedom
r_A	Same as r, divided by $Ampl$
out_1	Phase points at more than$\pm1\sigma$ distance from the model fit
out_3	Phase points at more than$\pm3\sigma$ distance from the model fit
out_5	Phase points at more than$\pm5\sigma$ distance from the model fit
out_{10}	Phase points at more than$\pm10\sigma$ distance from the model fit
A_1	Fourier-fit coefficient: 1^{st}-order amplitude
A_2	Fourier-fit coefficient: 2^{nd}-order amplitude
A_3	Fourier-fit coefficient: 3^{rd}-order amplitude



- ✓ 14829/12239/1243 for the g/r/i bands
- ✓ 217 z-band light curves of RRab with 14-to-86 phase points
- ➢ Three suitable RRLs were excluded from each period bin to serve as independent data for validating the LCTs

Template building

3.3. Period binning

The basic assumption for the LCTs is that different stars of the same variability class, same pulsation mode and with similar physical properties should have similar light-curve shapes.

Since the physical properties are not easily measurable, adoping two easily measurable parameters to group RRLs in template bins inside which all the variables have a similar shape of the light curve:

1. the pulsation mode;
2. the pulsation period.

$$\log P_F = \alpha_F + \beta_F \log L/L_\odot + \gamma_F \log M/M_\odot + \delta_F \log T_{eff} + \eta_F \log Z$$

$$\log P_{FO} = \alpha_{FO} + \beta_{FO} \log L/L_\odot + \gamma_{FO} \log M/M_\odot + \delta_{FO} \log T_{eff} + \eta_{FO} \log Z$$

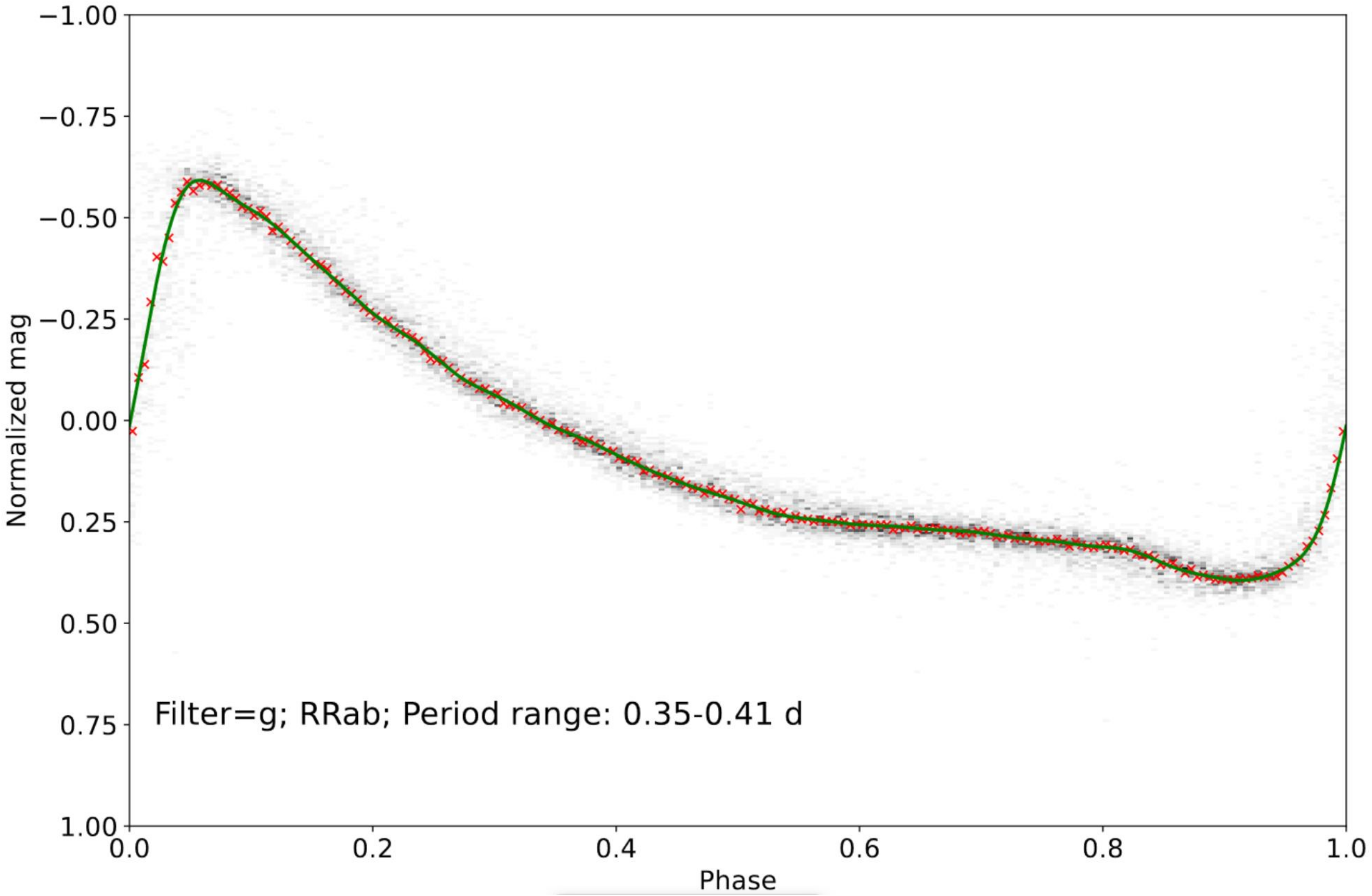
Considering different number of RRLs within the datasets in different passbands, they adopted different criteria to split the bins and merge all the normalized light curves (NLCVs) of RRLs with a period inside a given bin, providing one CNLCV per bin, per band.

normalized light curves： subtracting <mag> and dividing by the light amplitude.(each phase point)

Template building

3.4. Fitting

Finally, They derived the analytical form of the LCTs by fitting, with a Fourier Series, the CNLCVs.



Template building

3.4. Fitting

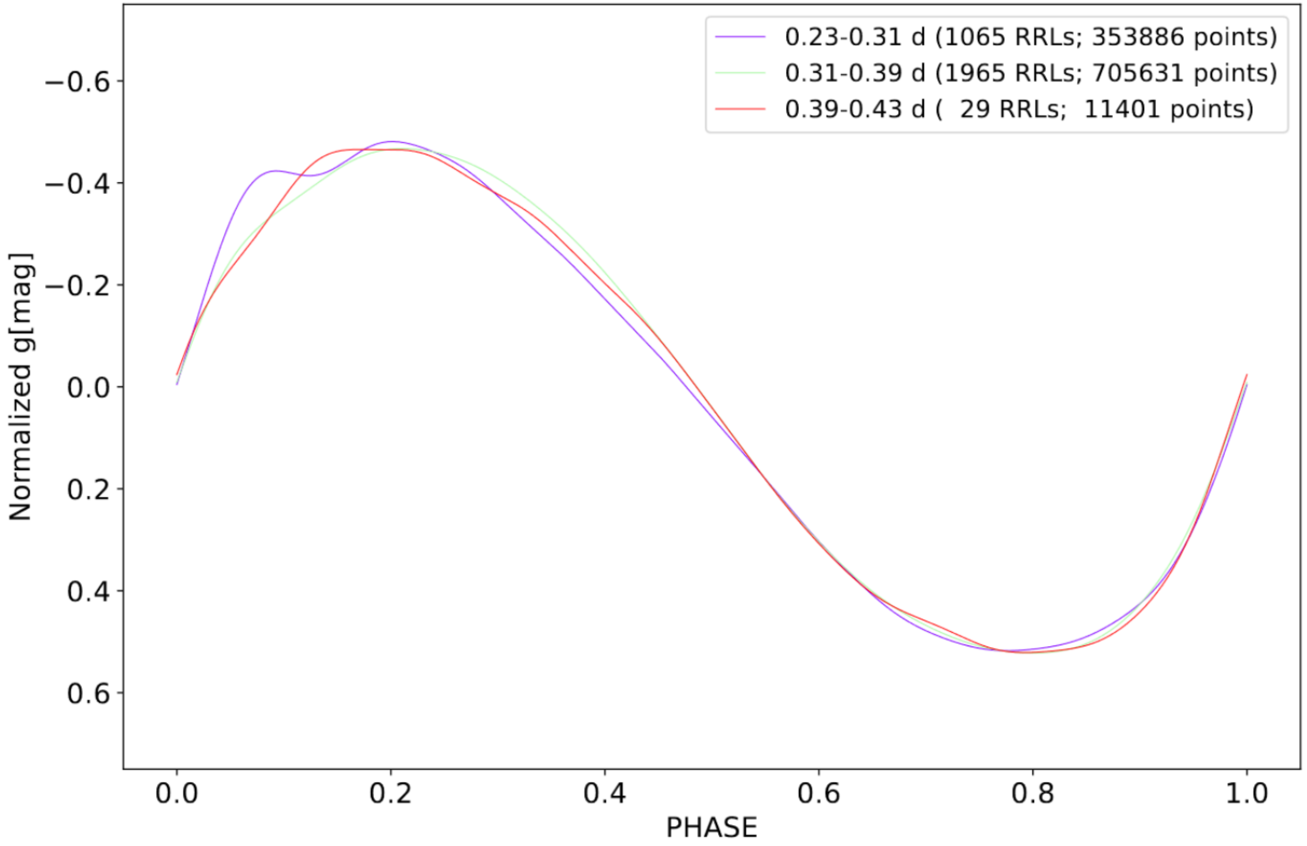


Fig. B.1. LCTs of RRc in the passband g.

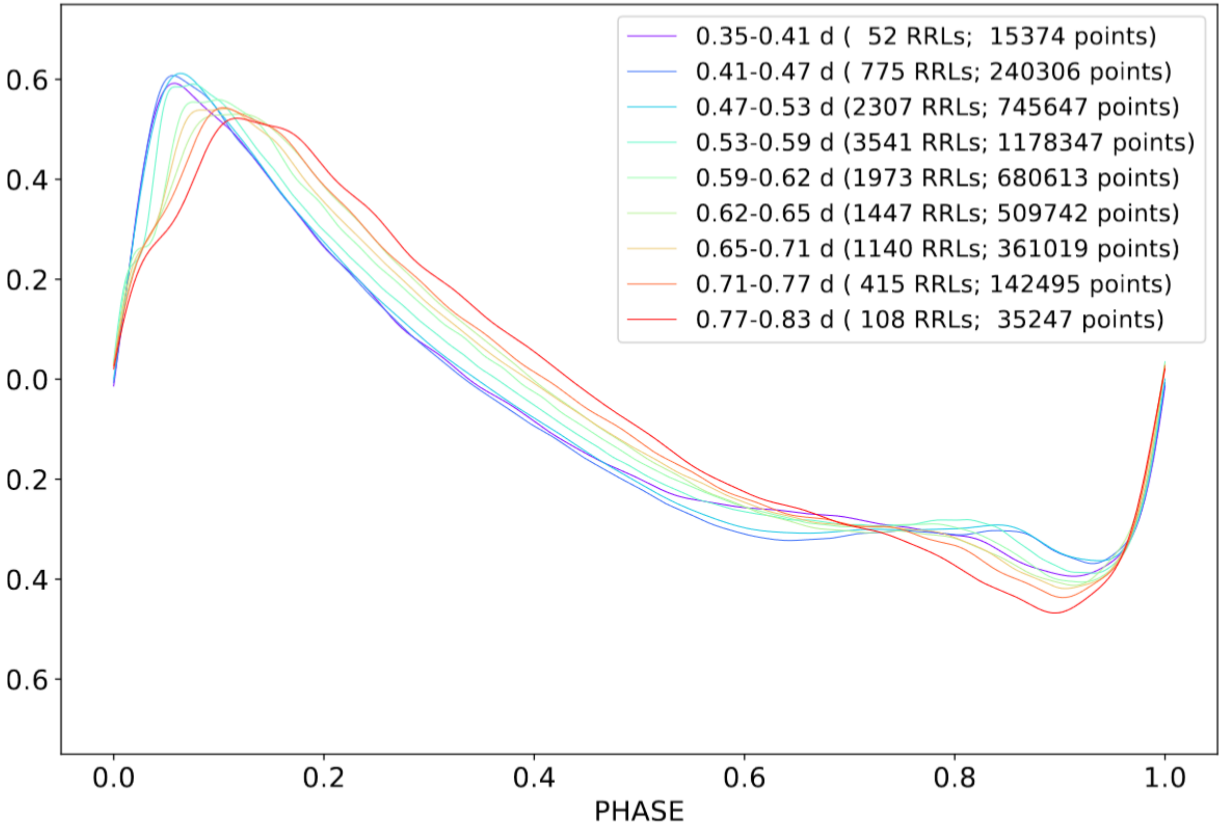


Fig. B.4. LCTs of RRab in the passband g.

Outline

Validation

After deriving the analytical form of the LCTs, they have tested their performance. They used three RRLs for each period bin in every passband that left in Section 3.2 to validate the LCTs with independent data.

LCTs could be used to obtain accurate <mag> estimates and, in turn, distances in several realistic future situations.

4.1. Single point anchoring validation

1 or 2 months from the beginning of the survey, there is only one phase point per band per target will be available. In this case, one can apply the LCTs only to variables for which both the period, reference epoch and Ampl are known

For each variable, thay randomly extracted a single phase, tested = 55,500 re-sampled phase points:

37 LCT × 3 RRLs per LCT × 5 levels of noise × 100 simulations per RRL.

$\sigma = 0.005, 0.01, 0.02, 0.05$ and 0.10

- true <mag> $(<mag>_{true})$
- <mag> derived using the LCT $(<mag>_{LCT(n,\sigma)})$
- magnitude of the re-sampled phase point $(<mag>_{single(n,\sigma)})$

Validation

4.1. Single point anchoring validation

Table 4. Averages and standard deviations of the $\delta_{L(1;\sigma)}$

LCT ID	$<\delta>_{L(1;0.005)}$	$<\delta>_{L(1;0.010)}$	$<\delta>_{L(1;0.020)}$	$<\delta>_{L(1;0.050)}$	$<\delta>_{L(1;0.100)}$
0	0.001±0.016	-0.000±0.019	-0.000±0.025	-0.002±0.052	0.011±0.103
1	0.000±0.014	0.000±0.019	0.001±0.022	-0.003±0.053	-0.004±0.099
2	0.001±0.014	0.003±0.016	-0.002±0.023	0.004±0.056	-0.011±0.093
3	0.001±0.012	-0.000±0.015	0.001±0.021	0.001±0.052	0.004±0.099
4	-0.000±0.010	0.000±0.013	0.002±0.021	0.003±0.048	-0.002±0.096
5	0.000±0.015	-0.002±0.019	-0.001±0.027	-0.003±0.054	0.002±0.094
6	0.000±0.010	0.001±0.014	0.001±0.021	0.000±0.051	0.005±0.102
7	0.000±0.014	-0.001±0.018	-0.001±0.021	-0.003±0.053	0.007±0.103
8	0.001±0.008	0.000±0.012	-0.000±0.022	-0.002±0.052	-0.004±0.097
9	0.001±0.027	0.003±0.028	-0.002±0.033	0.001±0.062	-0.009±0.106

Table 5. Averages and standard deviations of the $\delta_{S(1;\sigma)}$

LCT ID	$<\delta>_{S(1;0.005)}$	$<\delta>_{S(1;0.010)}$	$<\delta>_{S(1;0.020)}$	$<\delta>_{S(1;0.050)}$	$<\delta>_{S(1;0.100)}$
0	0.005±0.184	0.024±0.195	0.018±0.193	0.016±0.200	0.041±0.222
1	0.015±0.183	0.014±0.173	0.012±0.179	0.015±0.182	0.002±0.191
2	0.010±0.202	0.009±0.209	0.003±0.209	0.012±0.214	0.008±0.227
3	0.005±0.139	0.018±0.133	0.000±0.134	0.017±0.152	0.015±0.169
4	0.001±0.127	0.016±0.131	0.020±0.131	0.006±0.139	-0.004±0.152
5	0.009±0.128	-0.001±0.130	0.015±0.132	0.008±0.145	0.014±0.156
6	0.002±0.107	-0.008±0.108	0.009±0.110	0.005±0.120	0.007±0.144
7	0.012±0.110	-0.003±0.108	-0.001±0.112	-0.004±0.124	0.012±0.157
8	0.017±0.107	0.009±0.104	-0.003±0.110	0.006±0.112	0.005±0.142
9	0.111±0.447	0.112±0.452	0.127±0.452	0.150±0.467	0.138±0.455

The use of templates significantly improves the fitting, with standard deviations of δL(1,σ) smaller than δS(1,σ) by a factor of 215, and the improvement being more evident for brighter stars, with ratios increasing as σ decreases.

Validation

4.2. Template fit

The LCTs can be used as fitting functions by minimizing the χ2 on two/three free parameters:

1. [mandatory] an offset in phase (Δφ);
2. [mandatory] an offset in magnitude (Δmag);
3. [optional] the light amplitude (Ampl).

Fixed-amplitude template fit

If the LSST source is associated to a variable with known Ampl from another survey, in principle, one can fix the value of Ampl in the LCT fitting procedure, The advantage of this approach is that one can apply it also when only three phase points are available. 166,500 resampled light curves for this test:

37 LCT × 3 RRLs per LCT × 5 levels of noise × 3 sets of four, eight and twelve phase points × 100 simulations

- true <mag> $(<mag>_{true})$
- <mag> derived using the LCT fit $(<mag>_{LCT(n,\sigma)})$
- simply averaging the resampled points $(<mag>_{avg(n,\sigma)})$

The LCT fitting improves the robustness of the <mag> estimate, showing the most significant improvement for resampled light curves with fewer phase points or smaller photometric errors, particularly in cases with 8 or 12 phase points and errors smaller than 0.100 mag.

Validation

4.2. Template fit

Free-amplitude template fit

The fitting technique that will be adopted the most is likely the LCT fit by leaving the amplitude as a free parameter. In fact, in this case, it is not required any previous knowledge of Ampl. Moreover, four phase points per target per band will already be available around five months from the start of the survey.

The fixed amplitude LCT fitting improves the robustness of the mean magnitude estimate, with the ratio $\frac{\sigma\delta_{A(n,\sigma)}}{\sigma\delta_{L(n,\sigma)}}$ ranging from ∼1 to 12, showing the most significant improvement in cases with 8 or 12 phase points or photometric errors smaller than 0.100 mag, and a positive $\Delta(\sigma\delta)S(n,\sigma)$ in 438 out of 555 cases.

Validation

4.3. Improvement on distance estimates

$$W(X, Y) = M_X - \xi(M_X - M_Y),$$

The main scientific outcome is, in turn, an improvement on the distance estimates when adopting the relations to derive them.

They adopted the PLs(i), PL(z) and the PW(r,g−r) and selected the coefficients provided by Marconi et al. (2022),

Mode	N	$\text{Band}_{\text{LSST}}$	R^2	σ	α	β	γ
				$\boxed{Mag = \alpha + \beta \log P + \gamma[Fe/H]}$		$\boxed{W = \alpha + \beta \log P + \gamma[Fe/H]}$	
F	155	r	0.750	0.128	0.25 ± 0.02	-1.35 ± 0.08	0.163 ± 0.014
FO	93	r	0.916	0.075	-0.19 ± 0.03	-1.66 ± 0.06	0.149 ± 0.011
FO (F slope)	93	r	0.650	0.084	-0.07 ± 0.02	-1.35 ± 0.09	0.156 ± 0.012
F+FO	248	r	0.733	0.132	0.22 ± 0.02	-1.25 ± 0.06	0.168 ± 0.012
F	155	i	0.863	0.099	0.21 ± 0.02	-1.6 ± 0.07	0.163 ± 0.011
FO	93	i	0.955	0.059	-0.22 ± 0.02	-1.87 ± 0.05	0.149 ± 0.008
FO (F slope)	93	i	0.738	0.067	-0.12 ± 0.014	-1.6 ± 0.07	0.154 ± 0.01
F+FO	248	i	0.850	0.105	0.18 ± 0.02	-1.52 ± 0.05	0.166 ± 0.009
F	155	z	0.903	0.087	0.23 ± 0.02	-1.73 ± 0.06	0.168 ± 0.01
FO	93	z	0.968	0.052	-0.21 ± 0.02	-1.99 ± 0.04	0.152 ± 0.008
FO (F slope)	93	z	0.780	0.061	-0.104 ± 0.013	-1.73 ± 0.06	0.158 ± 0.009
F+FO	248	z	0.893	0.092	0.205 ± 0.014	-1.67 ± 0.04	0.17 ± 0.008
F	155	$r, g - r$	0.961	0.068	-0.489 ± 0.013	-2.63 ± 0.04	0.047 ± 0.008
FO	93	$r, g - r$	0.980	0.048	-0.85 ± 0.02	-2.58 ± 0.04	0.054 ± 0.007

Validation

4.3. Improvement on distance estimates

Objective: The goal is not to provide absolute distances, but to compare distance estimates using three different magnitudes:

- **dtrue**: Distance using true magnitude (<mag>true)
- **davg(n,σ)**: Distance using the simple mean magnitude (<mag>avg(n,σ))
- **dLCT(n,σ)**: Distance using the mean magnitude from the LCT (<mag>LCT(n,σ))

Single Phase Point: For a single phase point, **davg(n,σ)** is directly derived from that phase point's magnitude without averaging.

Validation Method: The differences between distances derived from LCTs and true distances are calculated

Metrics: For each case, and standard are calculated relative values are also derived by normalizing by dtrue

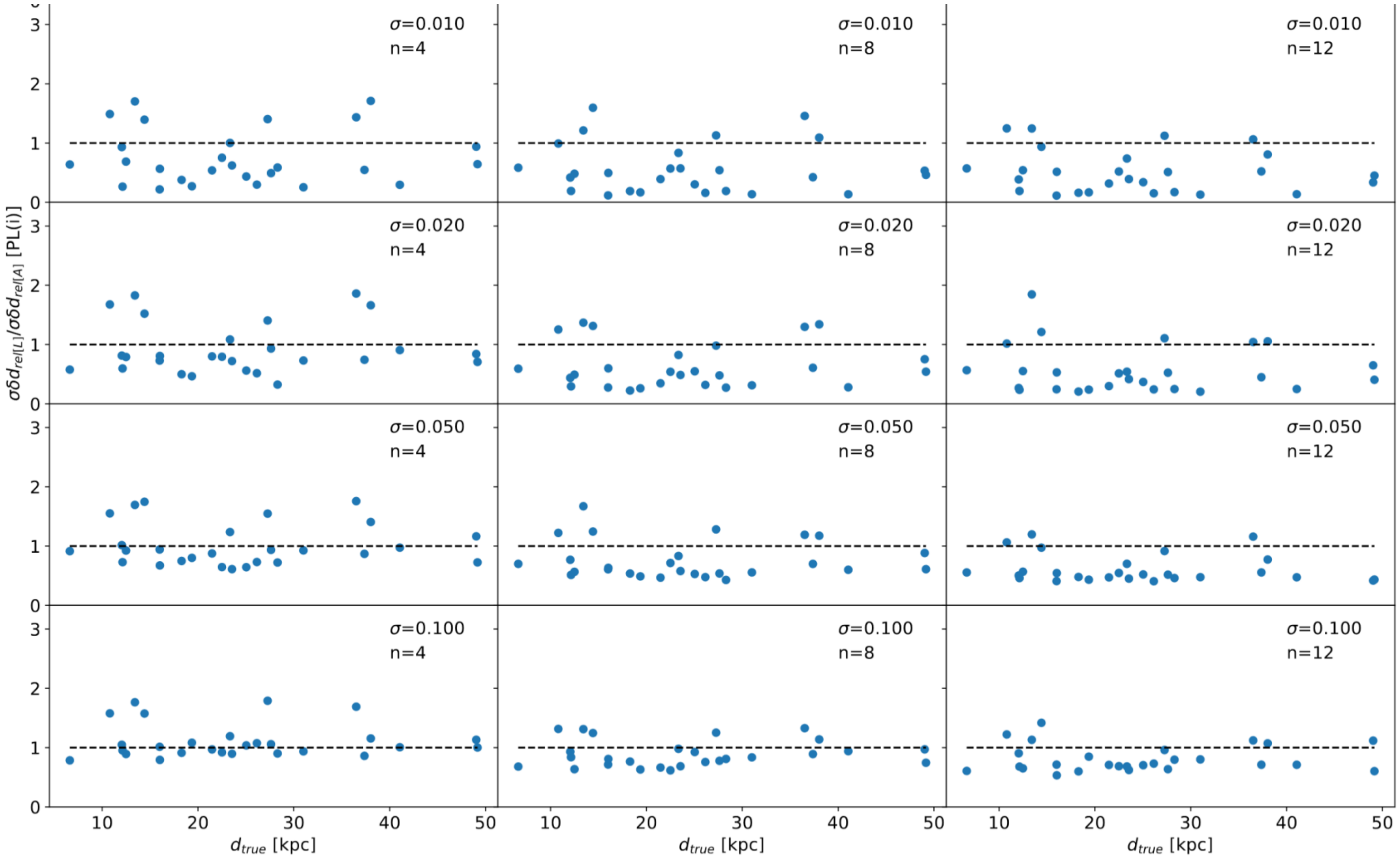
- $\delta d_L(n,\sigma) = d_{LCT}(n,\sigma) - d_{true}$
- $\delta d_S(n,\sigma) = d_{avg}(n,\sigma) - d_{true}.$
- $< \delta d_{rel[L/S]}(n,\sigma) >= \frac{<\delta d[L/S](n,\sigma)>}{d_{true}}$
- $\sigma_{\delta d_{rel[L/S]}(n,\sigma)} = \frac{\sigma_{\delta d[L/S](n,\sigma)}}{d_{true}}.$

Validation

4.3. Improvement on distance estimates

The authors plotted the ratio of distance estimation offsets under different methods, sampling points, and random noise levels.

Advantage of LCTs:
it demonstrates the effectiveness of this method in reducing errors and improving estimation accuracy. reflecting a more robust.



mean magnitudes were obtained by fitting the simulated time series with the LCT with fixed amplitude.

Outline

Summary

- This study developed Light Curve Templates (LCTs) for RR Lyrae stars (RRLs) in the gri LSST bands and the z band for RRab, aimed at enhancing early science with Rubin Observatory data, particularly in improving mean magnitude and distance estimations for Galactic structure studies.
- A total of 37 LCTs were delivered in analytical form using high-order Fourier series, capturing the characteristic pulsation behaviors of RRab and RRc stars.
- Validation using three methods demonstrated that LCTs significantly improve mean magnitude and distance estimates in most cases, with the new "free amplitude" fitting method being especially beneficial for early LSST science.
- For limited observations or high photometric errors (e.g., >0.05 mag), a simple mean magnitude calculation is recommended.
- The study confirmed the consistency of amplitudes between ZTF, DECam, and LSST systems and provided amplitude ratios, enabling cross-survey conversions and facilitating Galactic archaeology studies.

Thank you!