Light Curve Parameters of Cepheid and RR Lyrae Variables at Multiple Wavelengths – Models vs. Observations

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Collaborators

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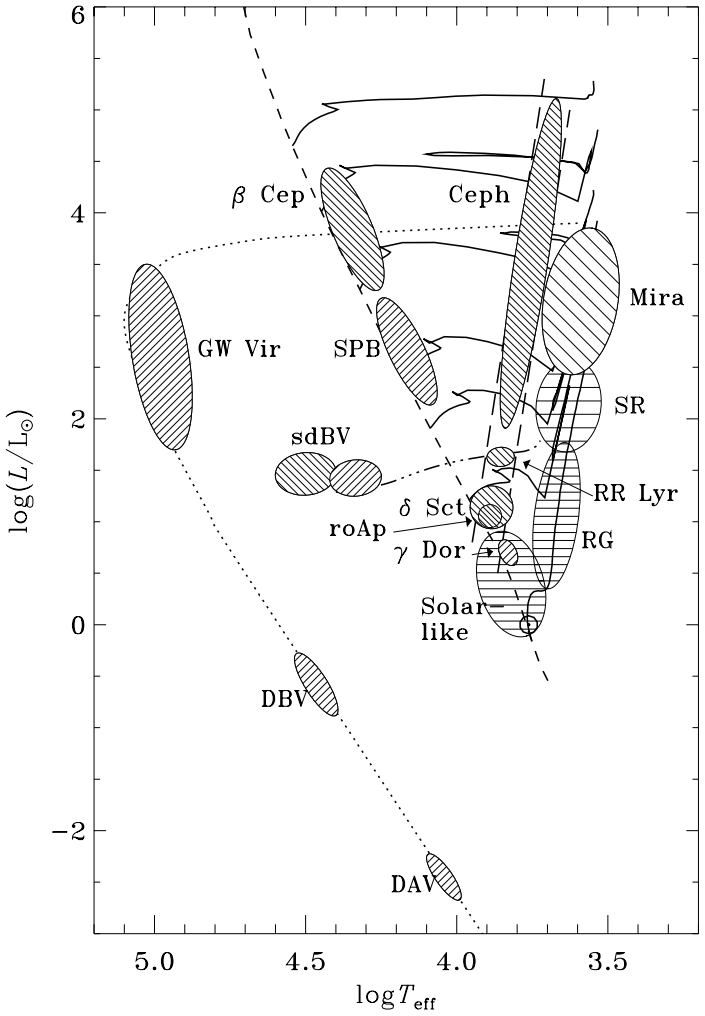
Bhardwaj et al. 2017, MNRAS 466, 2805
Das et al. 2018, MNRAS 481, 2000

Variable Stars

Hertzsprung-Russell Diagram and Pulsating stars



Source: Christensen-Dalsgaard (2016).

Radially pulsating variables:

- RR Lyraes
- Classical or Type I Cepheids
- Type II Cepheids

Importance:

- Primary distance indicators: well-defined PLRs
- Stellar tracers of extinction, metallicity and structure of the host galaxy
- Excellent test beds for theory of stellar structure & evolution
- Provide an opportunity to constrain stellar pulsation models

The Data

model Light Curves from Marconi et al. 2013, 2015, ++

Type I Cepheid models

- 384 fundamental mode models used in the analysis
- Three chemical compositions: Z=0.02 (Galaxy), Z=0.008 (LMC), Z=0.004 (SMC)
- **Canonical M-L relations**: Mass-luminosity (M-L) levels from stellar evolutionary calculations for a given chemical composition (X,Y,Z)
- **Non-canonical M-L relations**: A brighter luminosity level of 0.25 dex to account for possible mild overshooting and/or mass loss efficiency

RR Lyrae models

- 274 RRab models used in the analysis, P > 1 day representing Type II Cep
- Seven chemical compositions ranging from Z=0.02 to Z=0.0001
- Z=0.001 (Bulge), Z=0.0006 (LMC), Z=0.0003 (SMC)

For both Cepheid and RR Lyrae models, bolometric light curves are transformed to optical (UBVRI) and NIR (JKL)

The Data

models

Cepheid models

Z	Y	$\frac{M}{M_\odot}$	$\log \frac{L}{L_\odot}$	$T_{\rm eff}$ (K)	FU
0.02	0.28	5.4	3.18	5200–5900	7
		5.4	3.43	5000–5800	7
		5.6	3.23	5200–5900	7
		5.6	3.48	4700–5600	10
		5.8	3.28	5100–5800	8
		5.8	3.53	4700–5500	10
		6.0	3.33	5000–5600	7
		6.0	3.58	4600–5500	10
		6.2	3.38	4900–5800	10
		6.2	3.63	4600–5700	12
		6.4	3.43	4900–5600	8
		6.4	3.68	4500–5400	10
		6.6	3.47	4900–5600	8
		6.6	3.72	4600–5400	8
		6.8	3.52	4800–5500	8
		6.8	3.77	4400–5300	10
0.008	0.25	5.6	3.30	5200–6200	8
		5.6	3.55	4900–5900	9
		5.8	3.35	5200–6100	8
		5.8	3.60	4800–5900	10
		6.0	3.40	5200–5900	8
		6.0	3.65	4800–5900	11
		6.2	3.45	5200–5900	8
		6.2	3.70	4700–5900	12
		6.4	3.49	5100–5900	9
		6.4	3.74	4700–5750	11
		6.6	3.54	5000–6000	10
		6.6	3.79	4600–5800	11
		6.8	3.58	5000–6000	10
		6.8	3.83	4600–5700	11
0.004	0.25	5.4	3.35	5300–6200	8
		5.4	3.60	5000–5900	8
		5.6	3.40	5300–6200	7
		5.6	3.65	4900–5900	10
		5.8	3.45	5300–6100	7
		5.8	3.70	4900–5900	9
		6.0	3.50	5200–6100	7
		6.0	3.75	4800–5800	8
		6.2	3.55	5100–6200	7
		6.2	3.80	4800–5700	8
		6.6	3.64	5000–5900	6
		6.6	3.89	4900–5800	7
		6.8	3.69	5000–5900	7
		6.8	3.94	4700–5700	9

RR Lyrae models

Z	Y	$\frac{M}{M_\odot}$	$\log \frac{L}{L_\odot}$	T_e (K)	RRab
0.02	0.27	0.51	1.69	5700–6800	7
		0.51	1.78	5600–6800	7
		0.54	1.49	6000–7100	5
		0.54	1.94	5200–6600	8
0.008	0.256	0.55	1.62	5900–7100	12
		0.55	1.72	5800–7000	12
		0.56	1.60	5900–7100	11
		0.56	1.70	5800–7000	10
		0.57	1.58	6000–7100	5
		0.57	2.02	5400–6680	6
0.004	0.25	0.53	1.81	5700–6800	8
		0.55	1.71	6000–7000	10
		0.55	1.81	5700–6900	13
		0.56	1.65	6000–7100	10
		0.56	1.75	5800–7000	10
		0.57	1.63	6000–7100	10
		0.57	1.73	5900–7000	10
		0.59	1.61	6000–7200	10
		0.59	2.02	5700–6700	7
0.001	0.245	0.58	1.87	5900–6900	7
		0.64	1.67	6000–7200	9
		0.64	1.99	5700–6800	10
0.0006	0.245	0.6	1.89	5700–6900	9
		0.67	1.69	6000–7200	9
		0.67	2.01	5800–6800	9
0.0003	0.245	0.65	1.92	5800–6900	6
		0.716	1.72	6000–7200	8
		0.716	1.99	5700–6900	11
0.0001	0.245	0.72	1.96	5800–6900	7
		0.8	1.76	6000–7200	8
		0.8	1.97	5800–6700	10

A range of periods is available for a fixed L because of the width of the instability strip

The Data

observations (Cepheids)

Band	Galaxy		LMC		SMC	
	N_{Cep}	Reference	N_{Cep}	Reference	N_{Cep}	Reference
V	447	Berdnikov (2008)	4368	Soszyński et al. (2015)	4701	Soszyński et al. (2015)
I	351		4647		4922	
J	186	Welch et al. (1984); Laney & Stobie (1992); Barnes et al. (1997); Monson & Pierce (2011)	474	Macri et al. (2014); Persson et al. (2004)	4172	Ripepi et al. (2016)
H	186		532		-	
K_s	186		488		4172	
3.6 μm	37	Monson et al. (2012)	84	Scowcroft et al. (2011)	93	Scowcroft et al. (2016)
4.5 μm	37		84		93	

LMC, SMC Cepheids from OGLE –IV in V and I bands; Bulge V, I and JHK etc. from literature

The Data

observations (RR Lyraes and Type II Cepheids)

	Band	N_{RRab}	Reference	N_{T2C}	Refernce
Bulge	V	11736	Soszyński et al. (2014)	517	Soszyński et al. (2017)
	I	25929		873	
LMC	V	25762	Soszyński et al. (2016)	202	Soszyński et al. (2008)
	I	26209		203	
SMC	V	4769	Soszyński et al. (2016)	42	Soszyński et al. (2010)
	I	4825		43	
M4	3.6 μm	14	Neeley et al. (2015)	-	-
	4.5 μm	14		-	-

Light Curve Structure
Fourier Decomposition Technique

Decompose a periodic signal into periodic components

$$m(t) = A_0 + \sum_{i=1}^{N} a_i \cos(i\omega(t - t_0)) + \sum_{i=1}^{N} b_i \sin(i\omega(t - t_0)),$$

or

$$m(t) = A_0 + \sum_{i=1}^{N} A_i \cos(i\omega(t - t_0) + \phi_i),$$

harmonic amplitude

phase angle

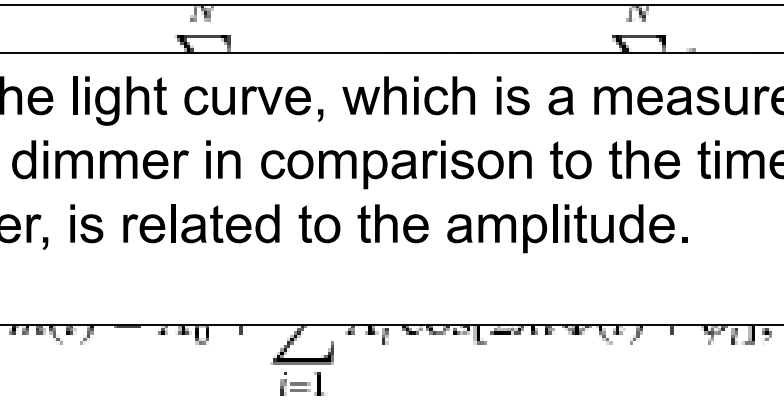
$$A_i = \sqrt{a_i^2 + b_i^2} \qquad \tan\phi_i = -b_i/a_i$$

N is the order of the fit

Fourier Decomposition Technique

The values of the Fourier amplitude and the phase depend on the shape of the decomposed light curve.

The *skewness* of the light curve, which is a measure of the time while the star gets dimmer in comparison to the time while it gets brighter, is related to the amplitude.



The Fourier phase parameters depend on the *acuteness* of the light curve. The acuteness is a measure of the time the light curve spent below the mean brightness compared to the time spent above the mean brightness.

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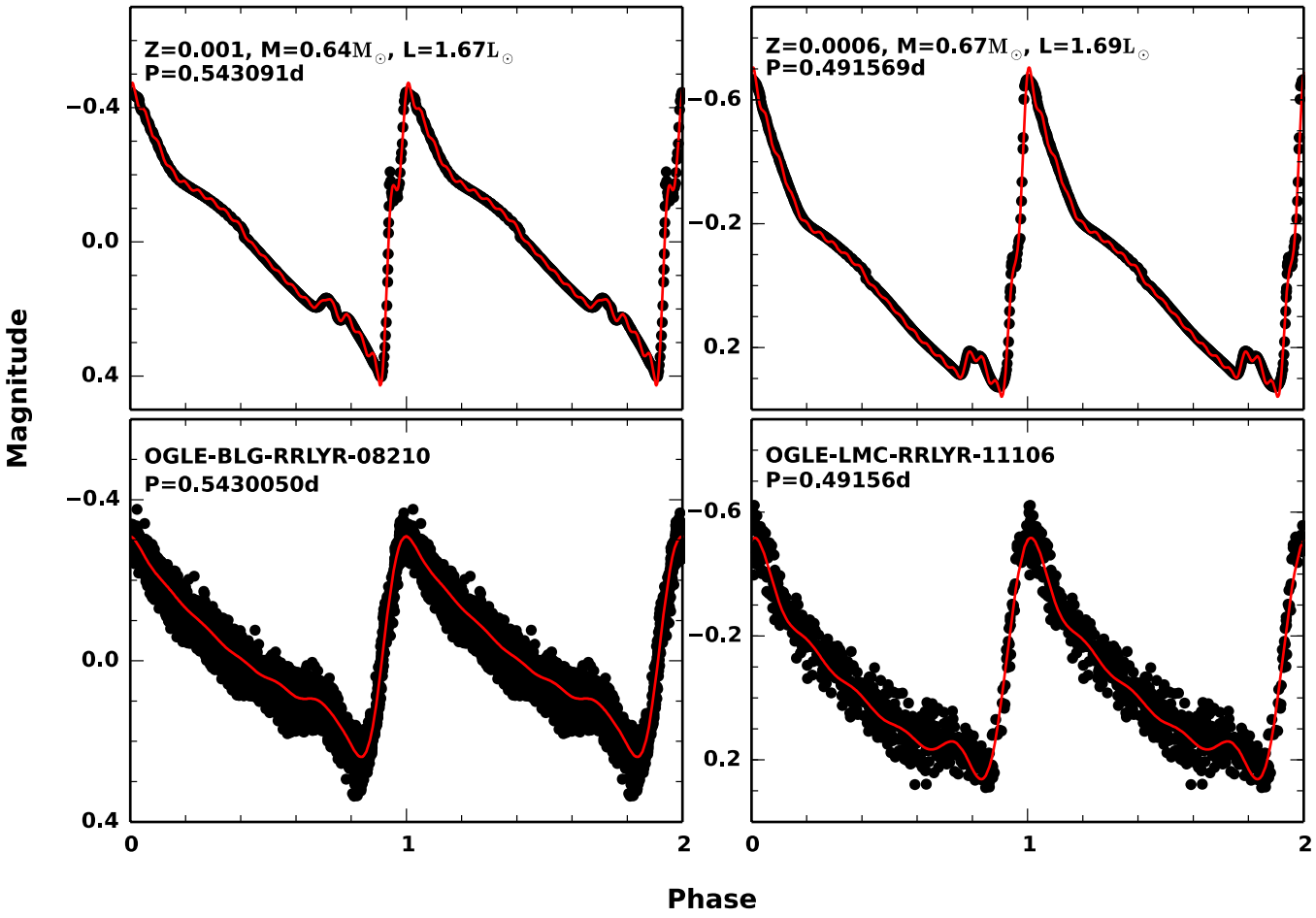
Amplitude ratios

Schaltenbrand & Tammam (1971); Simon & Lee (1981)

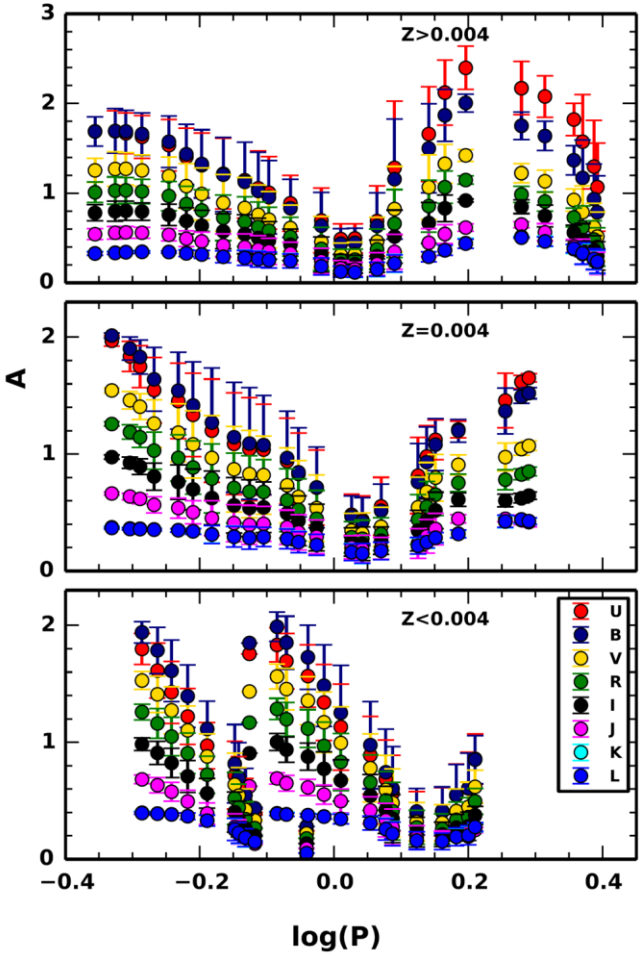
Fourier Fitted Light Curves



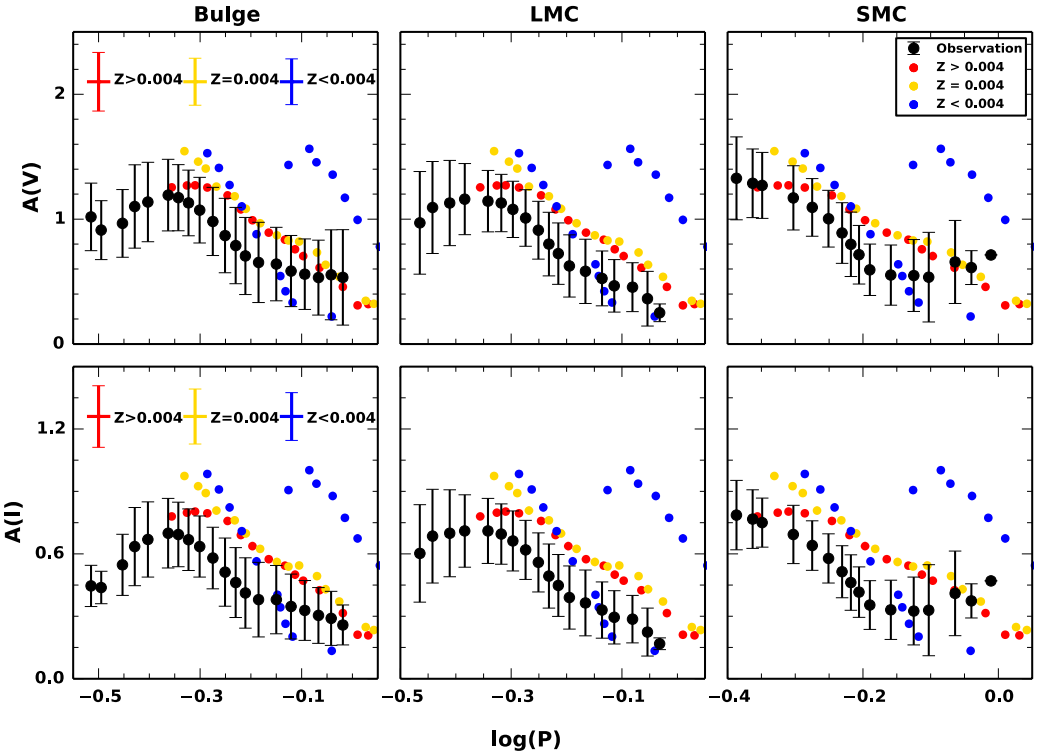
Phased I-band light curves from theoretical models (top panels) and from the OGLE-IV catalog (bottom panels) of RR Lyrae stars in the Galactic Bulge and LMC. Red lines display the Fourier fit to the light curves which are normalized w.r.t the median magnitude.

Amplitude parameters

From models and comparison with observations: RR Lyraes



The variation of the mean amplitudes (A) as a function of period and wavelength for the Model light curves of RRab. The mean amplitudes are obtained by averaging the amplitudes in a bin

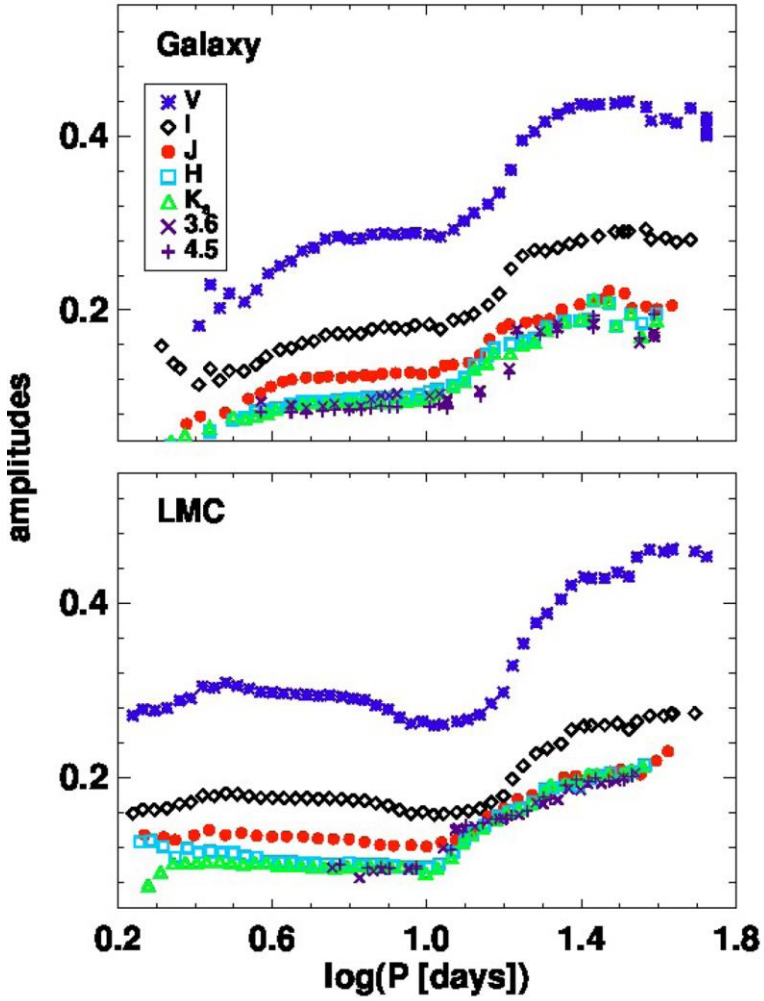


A comparison of the mean amplitudes from RRab models and observations for RRab stars in Bulge, LMC and SMC in *V* and *I*-bands

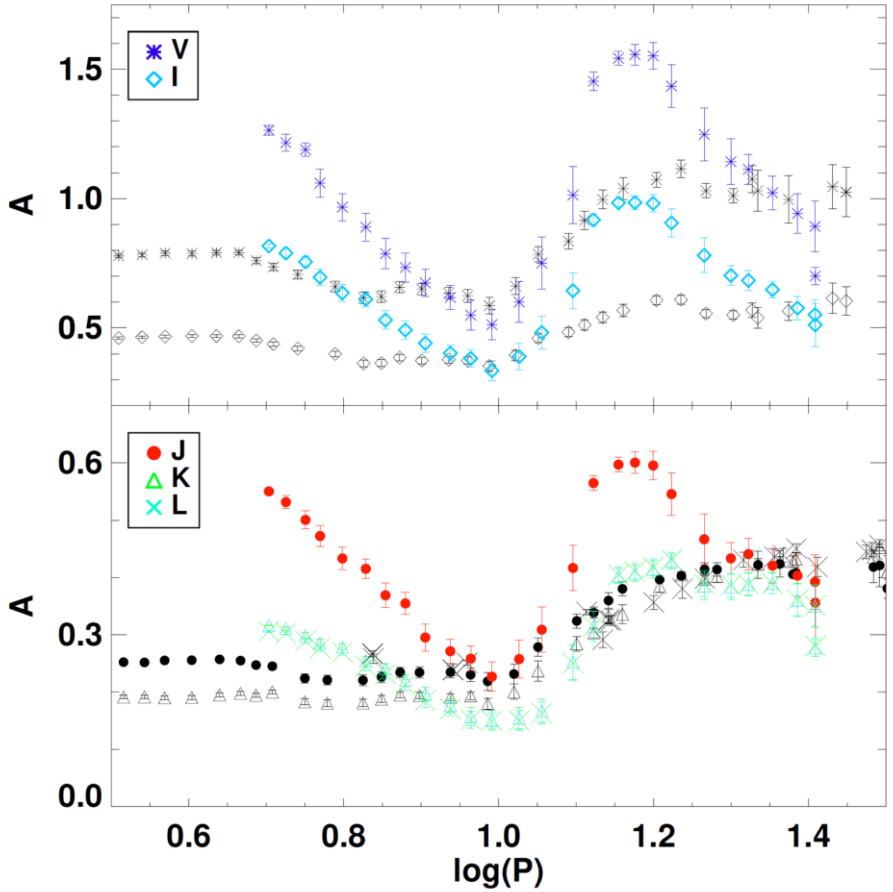
- Amplitude decreases with increase in wavelength
- Amplitudes from models slightly higher than that from observations
- Increase mixing length parameter!

Amplitude parameters

From models and comparison with observations: Cepheids



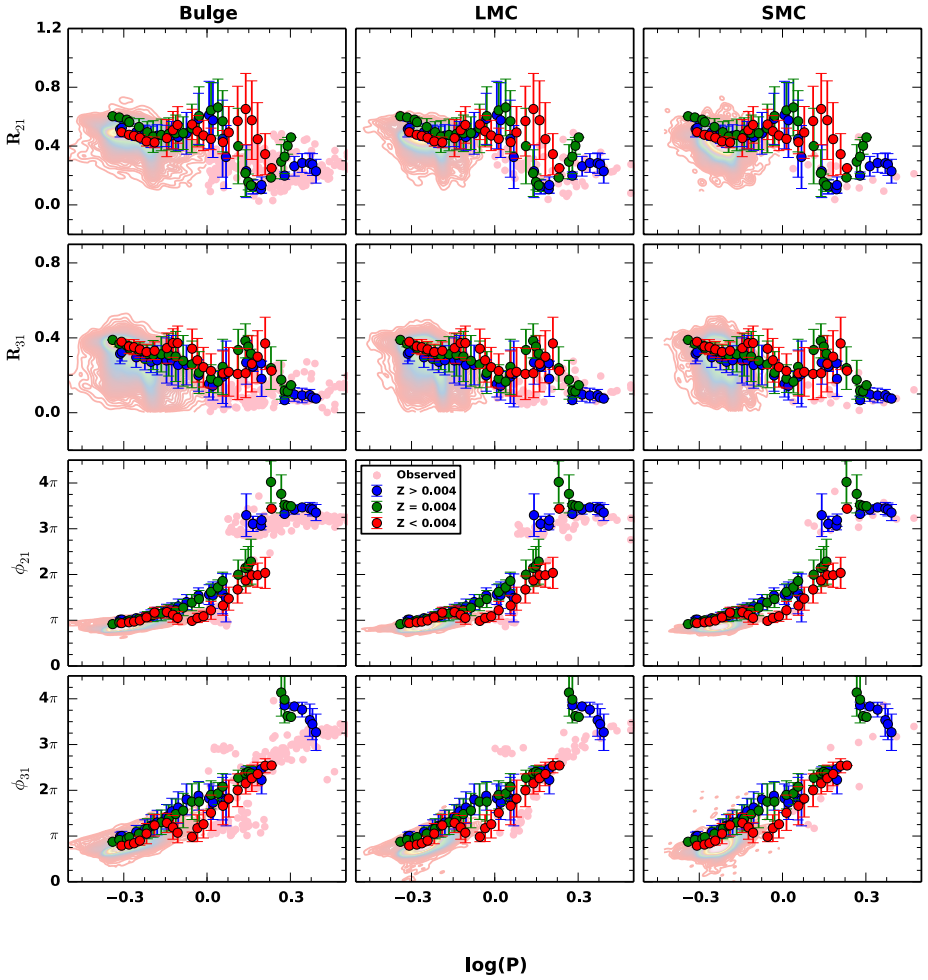
Variation of mean amplitudes with Period and wavelenght



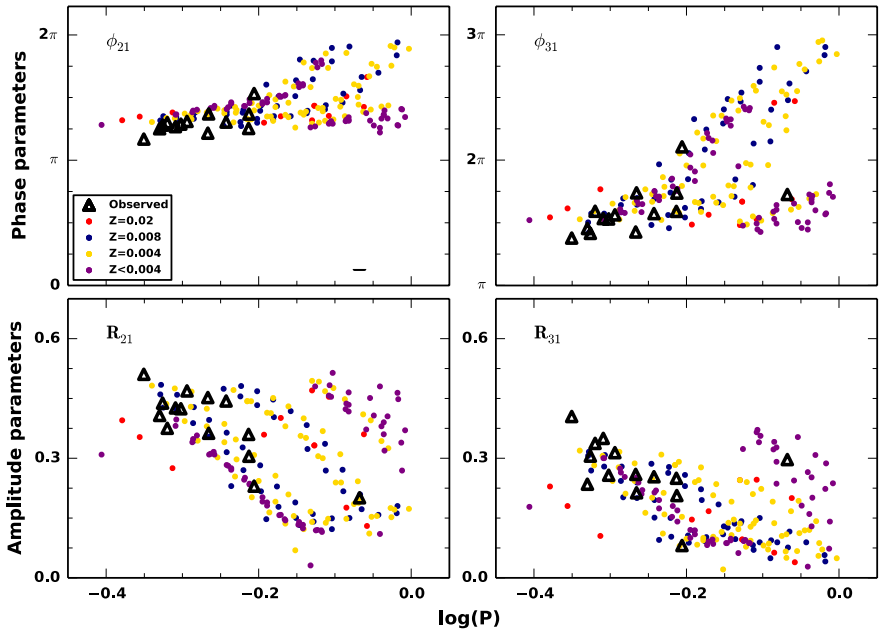
A comparison of observed (black symbols) and model mean amplitudes (colored) for Cepheids in LMC.The K and L amplitudes are consistent in most period bins

Fourier parameters

Comparison of models with observations: RR Lyraes



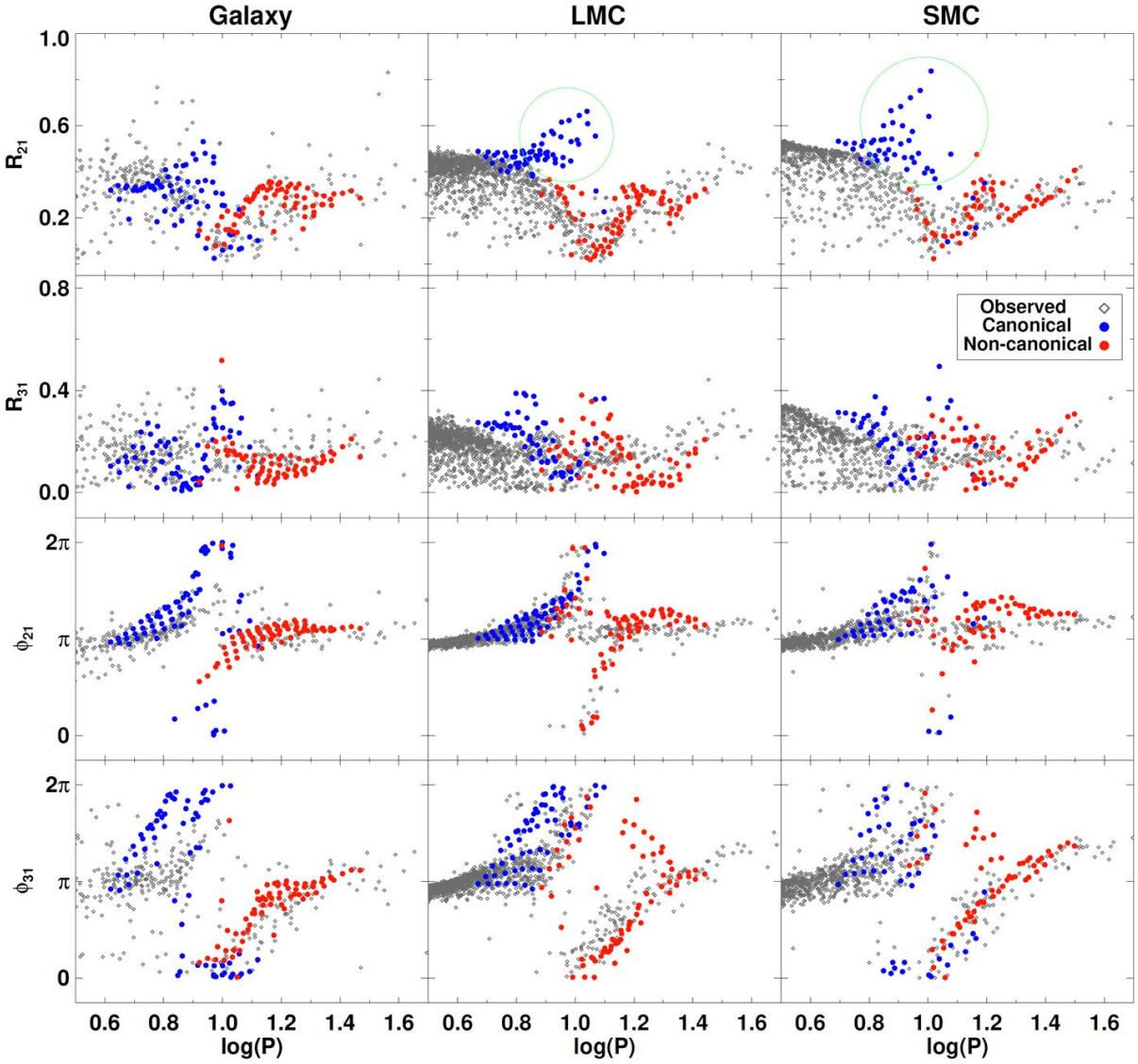
A comparison of theoretical mean Fourier parameters for RRab with observed mean Fourier parameters from OGLE-IV RRab stars and OGLE-III Type II Cepheids in the Bulge, LMC and SMC in I-band.



A comparison of the theoretical Fourier parameters for RRab with different compositions in *K*-band with observed Fourier parameters from the globular cluster M4 RRab stars in 3.6 μm band.

Fourier parameters

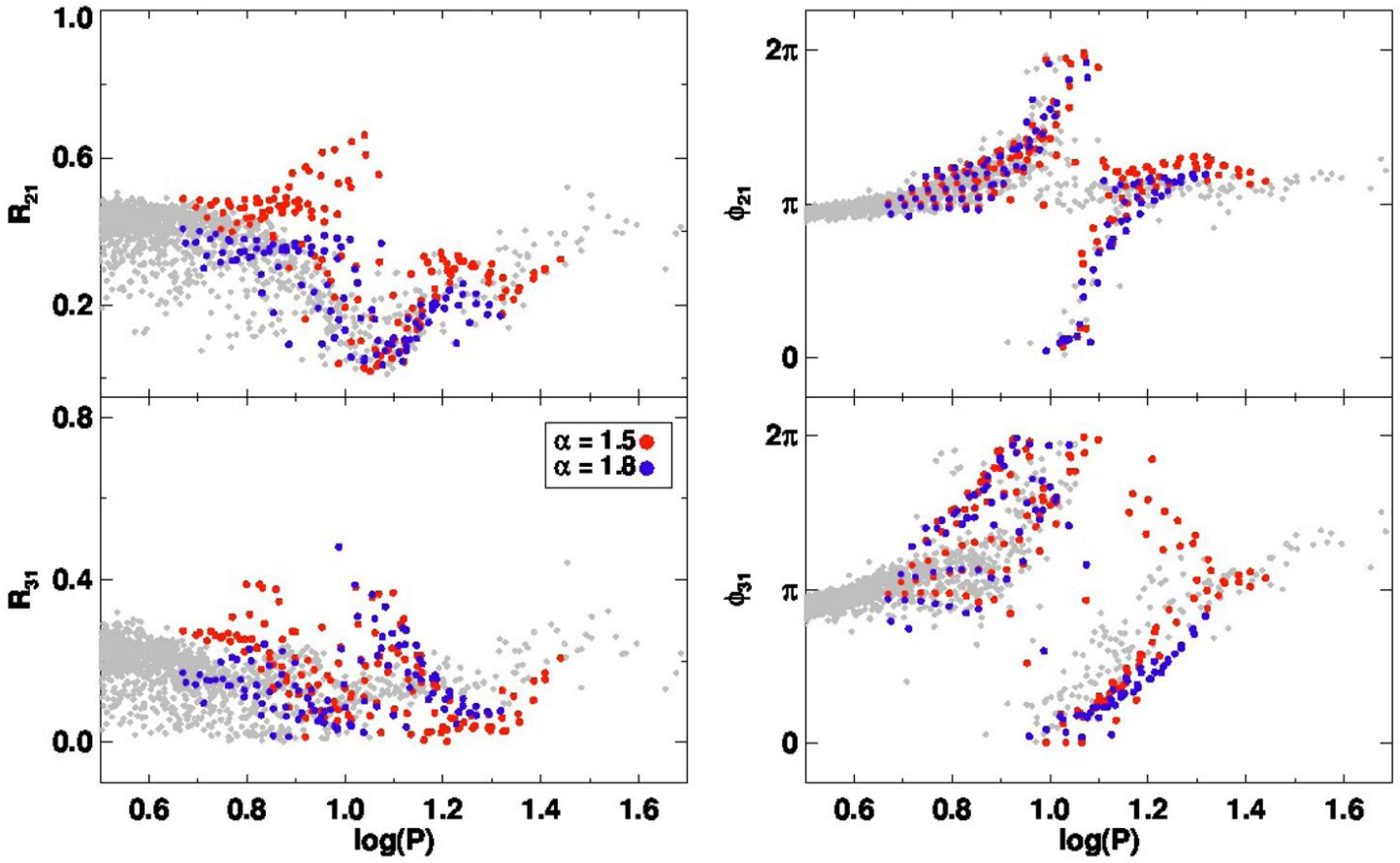
Comparison of models with observations (I band): Cepheids



Mixing length parameter

Increase in ML reduces offset between models and observations

- Accounting for variation in the convective efficiency by increasing mixing length parameter
- While the Fourier phase parameters remain the same, there is a decrease in Fourier amplitude parameters for a higher mixing length of 1.8

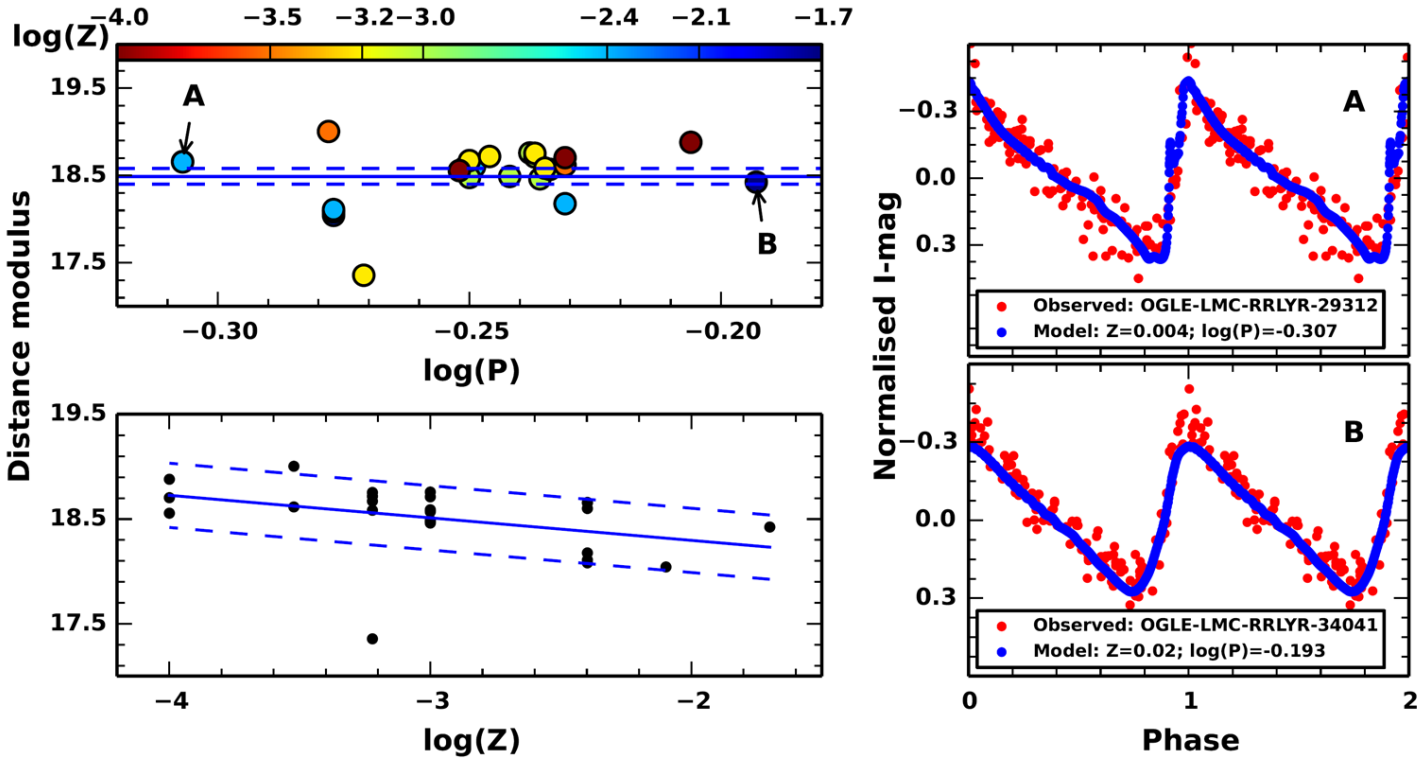


LMC Cepheids, I band

Comparison of RRL models (274) with LMC I-band observations (26209) to obtain LMC distance

25 cases with (i) $|\log(P)_{model} - \log(P)_{observed}| \leq 0.01$
(ii) $|A_{i,model} - A_{i,observed}| \leq 3\sigma_{A_{i,observed}}$
(iii) $|\varphi_{i,model} - \varphi_{i,observed}| \leq 3\sigma_{\varphi_{i,observed}}$

m-M(LMC)=18.51 mag ± 0.07 (statistical)



The left panels display the variation of distance modulus as a function of period (top) and metal-abundance (bottom). Solid lines represent LMC = 18.49 ± 0.09 (de Grijs et al. 2014) in the top panel and best fit linear regression in the bottom panel while the dashed lines represent 1σ error. On the right panels, we show the light curves of 2 of the 25 matches.

Summary of Results

1. A decrease in the mean amplitudes with increase in the wavelength
2. The mean amplitudes from the models are slightly higher than that from the observations.
3. We found that the Fourier parameters from the models are consistent with the observations in the observed RR Lyrae range ($\log(P) < 0$) but we find better agreement in the NIR-bands as compared to that in the optical bands.
4. An increase in the mixing length parameter might result in a decrease of the pulsation amplitude, while maintaining the light curve structure (Di Criscienzo et al. 2004; Fiorentino et al. 2007; Bhardwaj et al. 2017).
5. We used a subset of 25 RR Lyrae models/observations from LMC to obtain an average distance modulus to LMC of 18.51± 0.07 mag, which is in good agreement with latest published results.

Thank You