Structural Properties of OGLE Cepheid and RR Lyrae light curves and multiphase PC/PL relations: comparisons between theory and observations

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Celebrating 25 Years of the OGLE project: Warsaw July 2017

Collaborators

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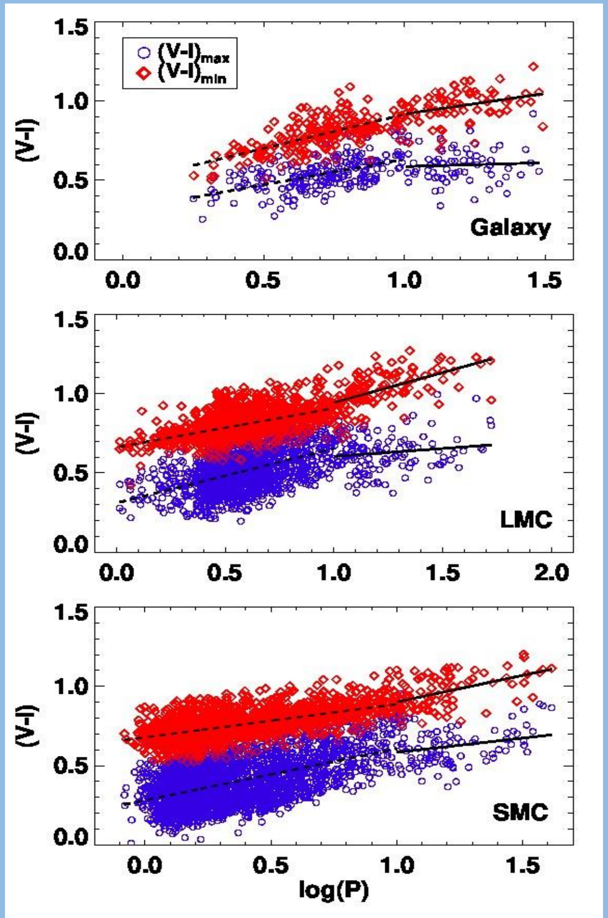
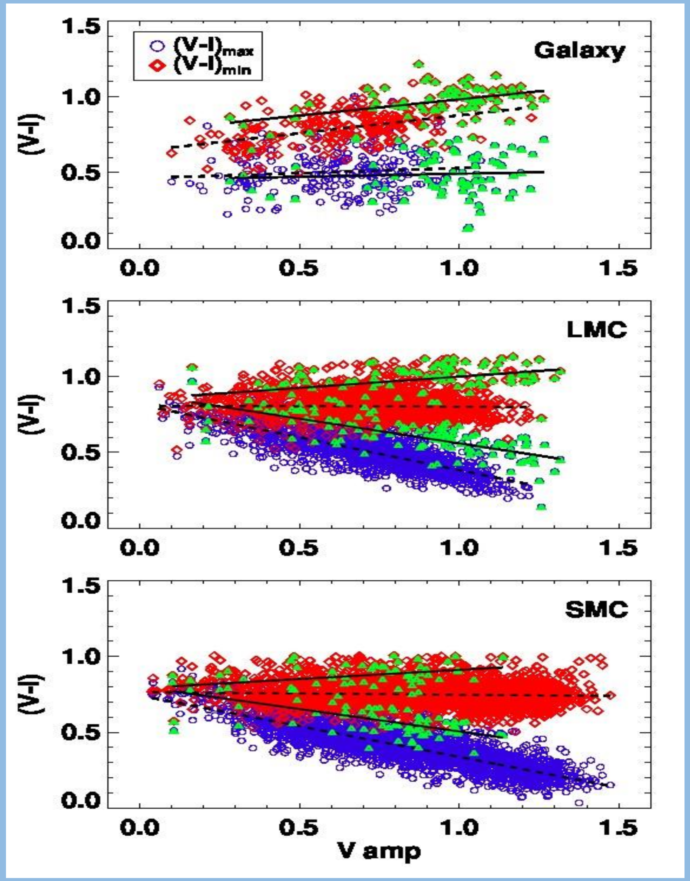
Cepheids at Maximum Light

- Galactic Cepheids at maximum light have a spectral type that is independent of period (Code 1945).
- Simon Kanbur and Mihalas (1993), Kanbur (1995), Kanbur and Phillips (1996)

PC-AC Relations: Bhardwaj et al 2014, MNRAS





Stefan-Bolztmann law at max/min light

$\frac{L_{max}}{L_{min}} \approx \frac{T_{MAX}^4}{T_{MIN}^4}$, assuming radii don't change too much.

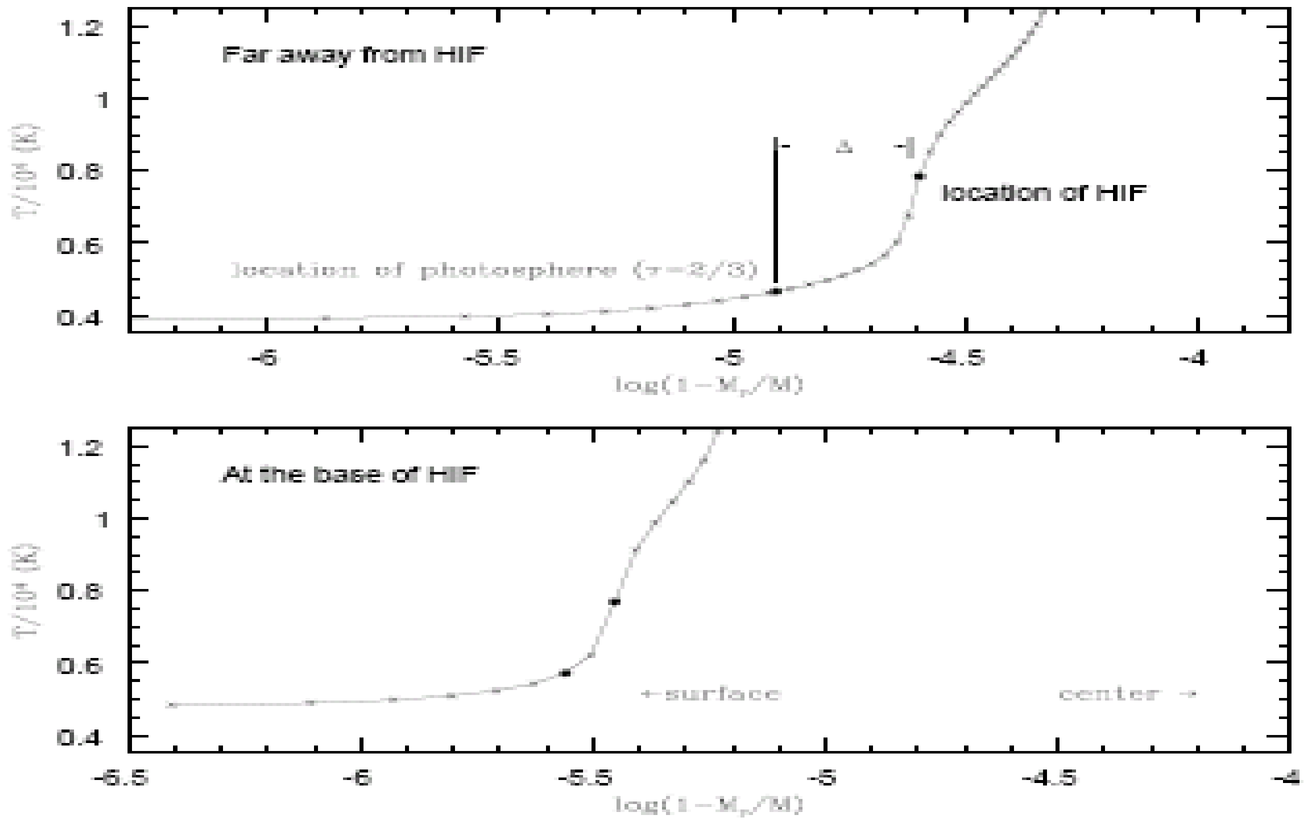
Then

$$logL_{MAX} - \log L_{MIN} = 4logT_{MAX} - 4logT_{MIN}$$

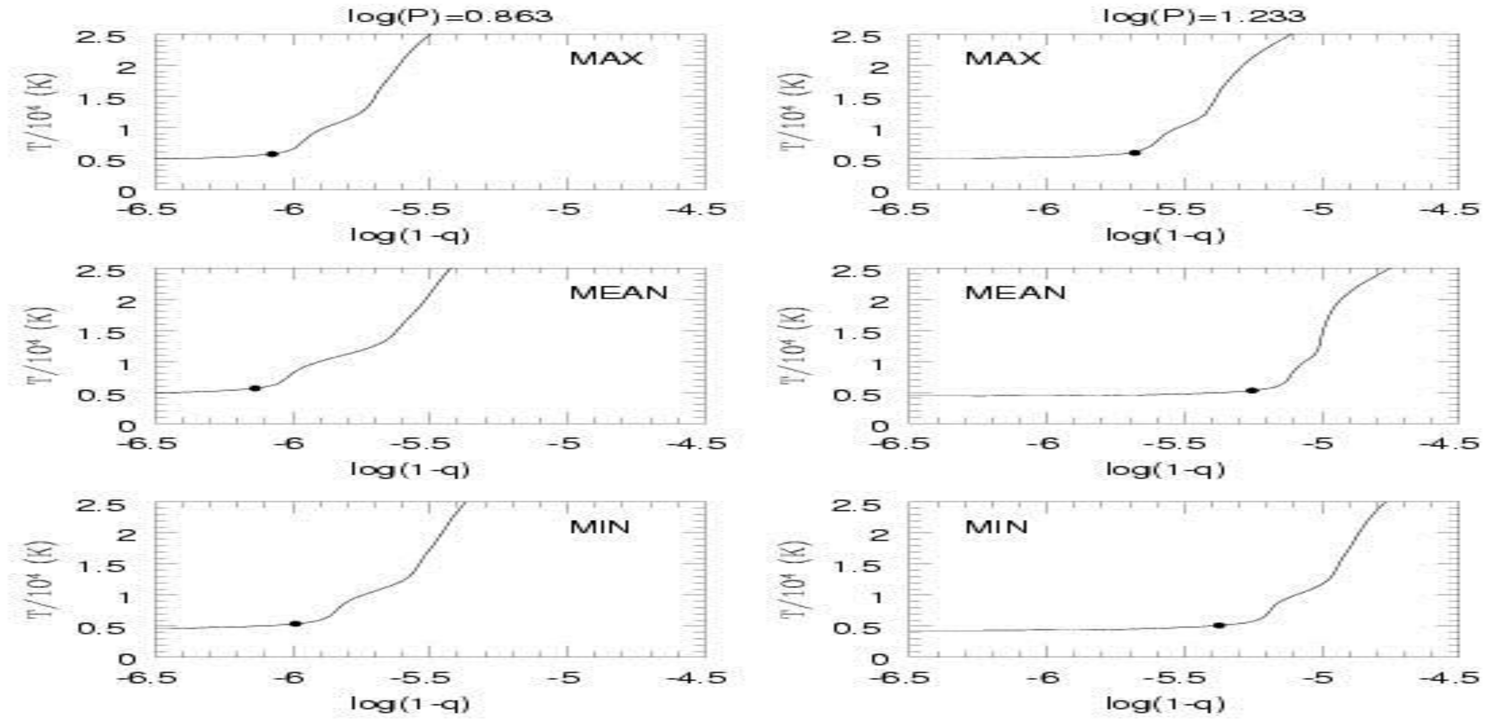
So if the slope of the PC relation is flat at max/min, there is an AC relation at min/max.

If the slope of the PC relation at max/min becomes shallower, then the slope of the AC relation at max/min becomes greater/less.

HIF-Stellar Photosphere Interaction



HIF-Stellar Photosphere Interaction



Saha Ionization Equilibrium

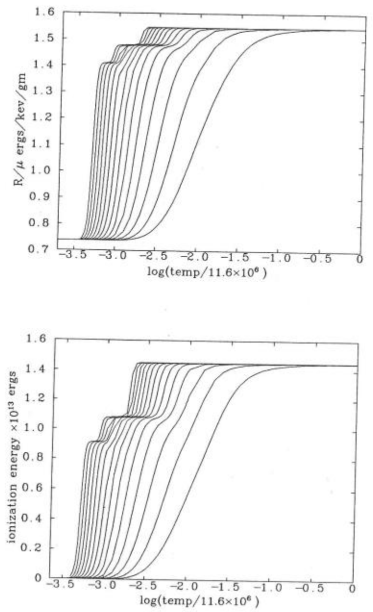


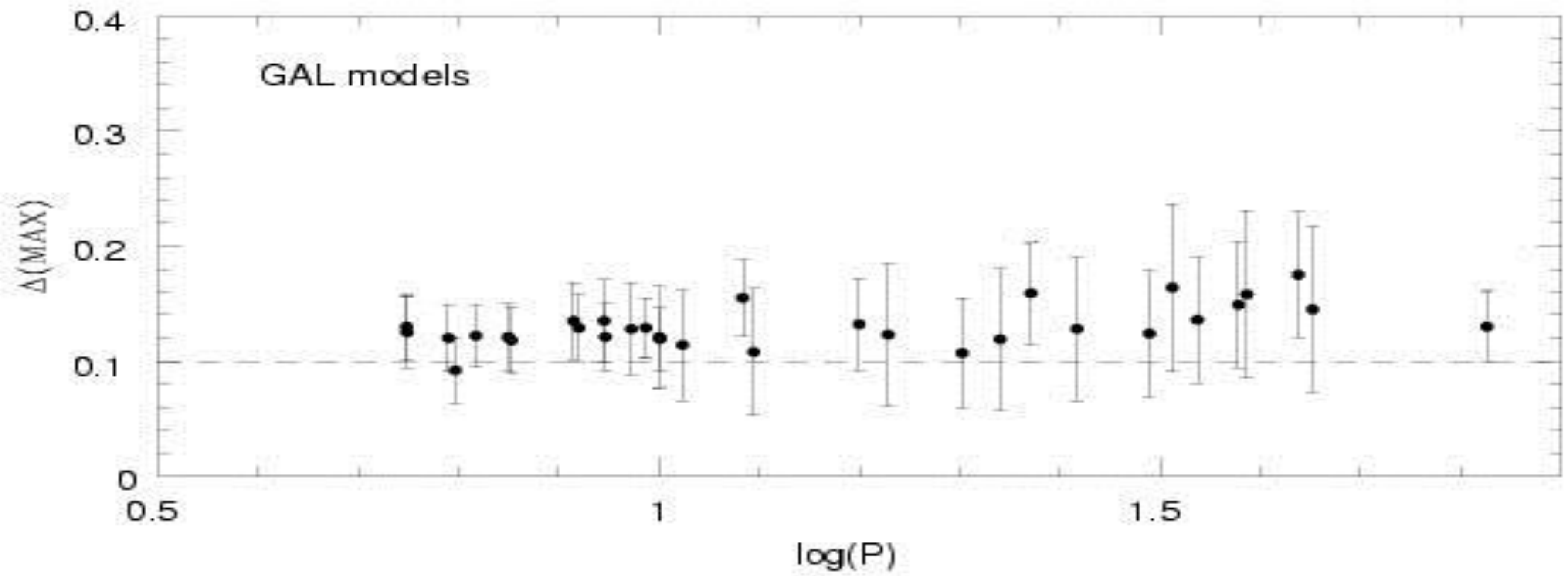
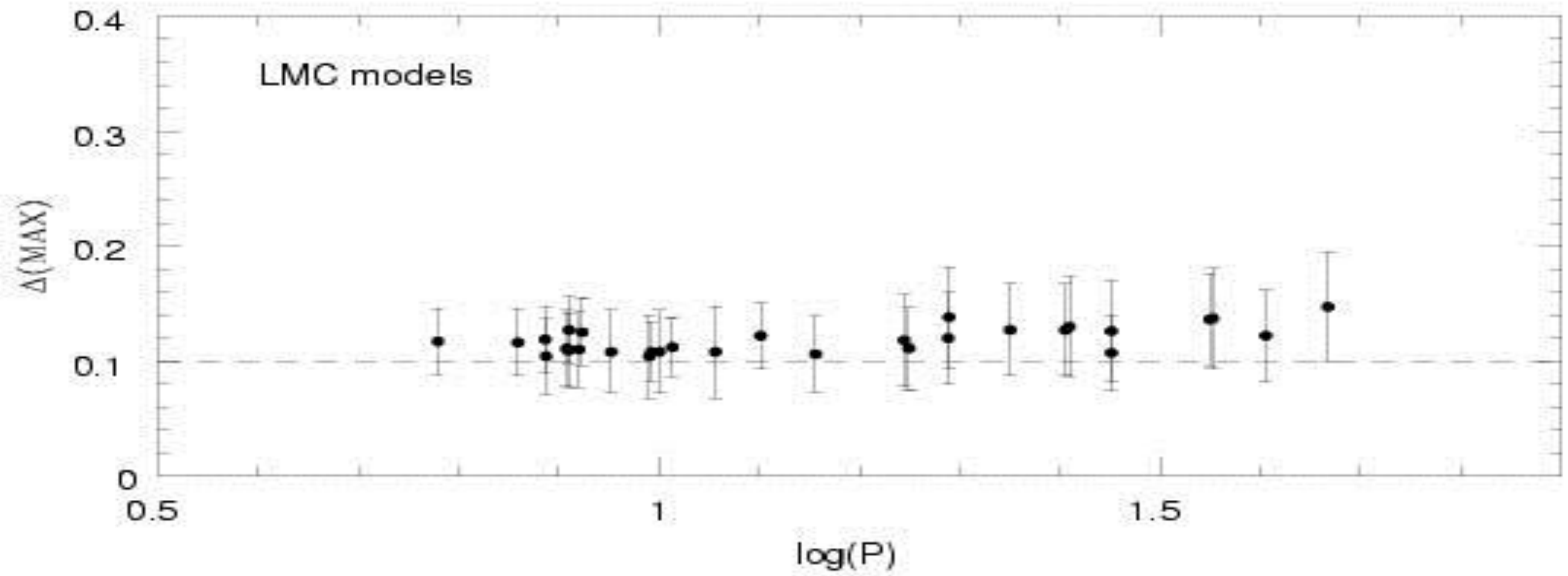
Figure 4.2 : *SAHA results with the Goddard Cepheid composition (see table 4.1). Each curve represents a different density, starting from 10^{-14} gm/cm^3 at the left and going up by a factor of 10 for each subsequent curve.*

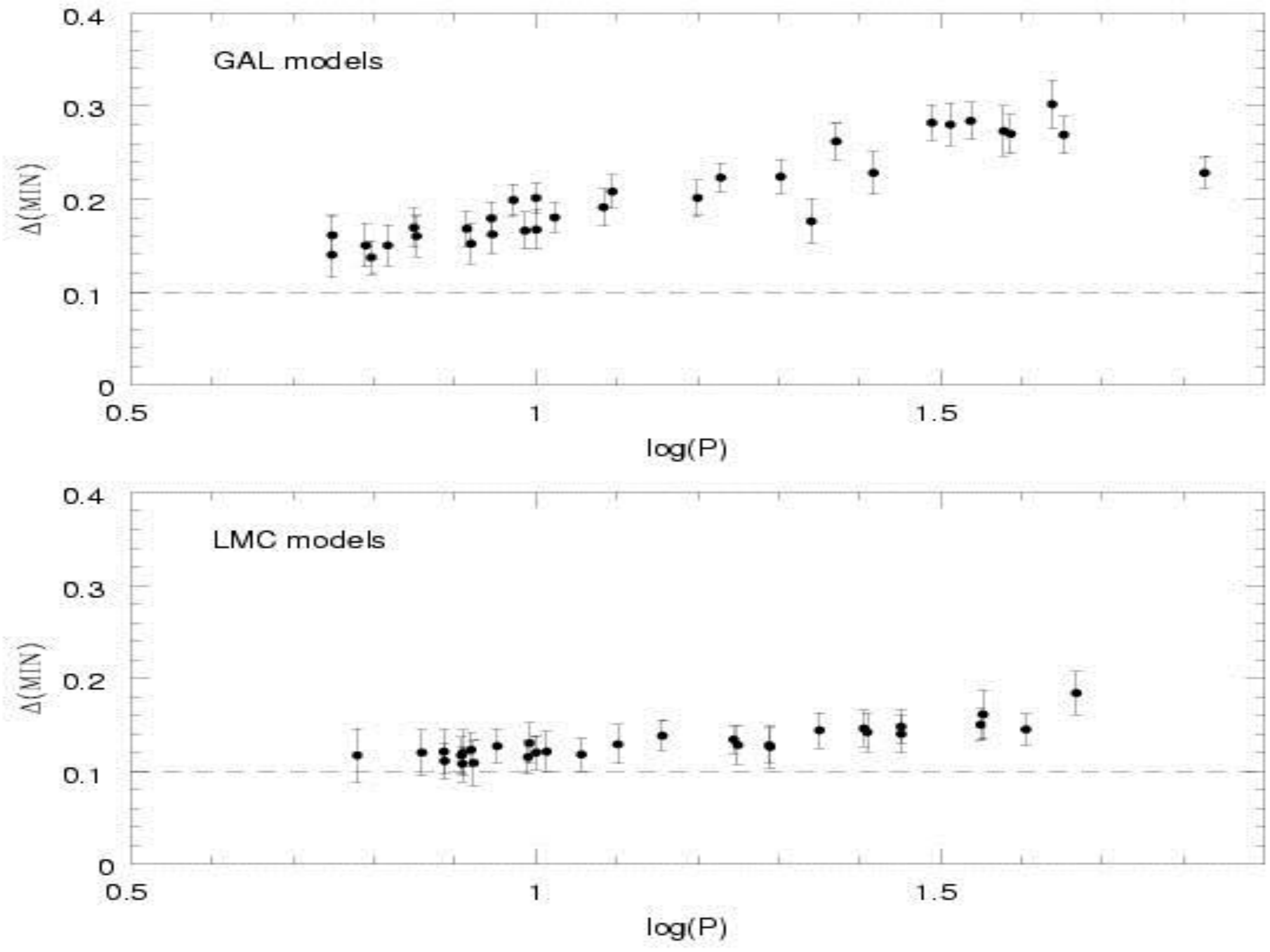
The HIF-photosphere interaction

- In certain situations, the photosphere can lie at the base of the HIF.
- Further movement into the mass distribution very hard due to opacity wall.
- Then the temperature of the photosphere is very close to the temperature at which Hydrogen ionizes.
- In this situation, the color of the star is the temperature at which Hydrogen ionizes.
- In certain situations, this temperature is somewhat independent of global stellar parameters like period
- Distance between stellar photosphere and HIF is important.

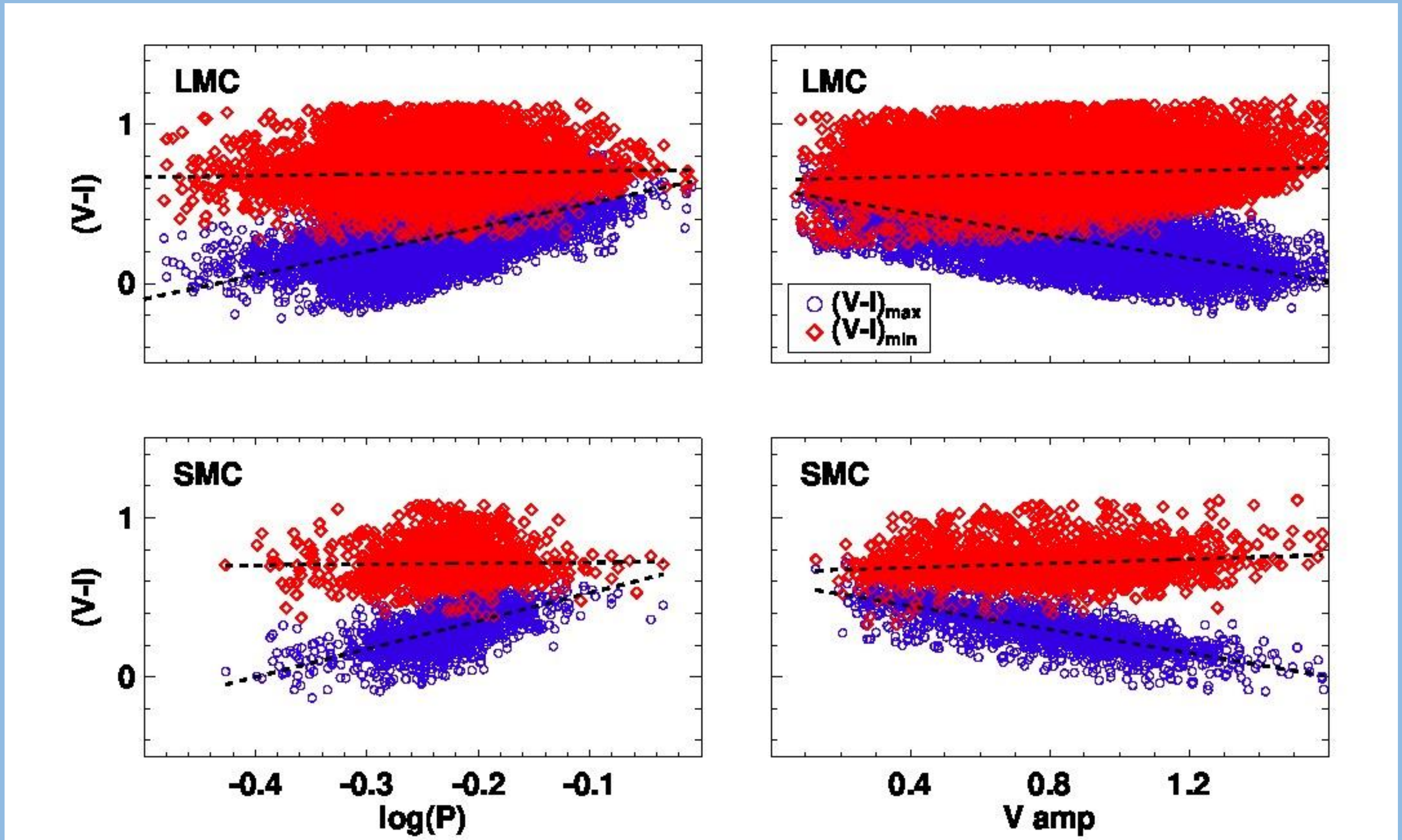
The HIF-photosphere interaction

- Saha ionization equation used in stellar pulsation models.
- Temperature at which Hydrogen ionizes is somewhat independent of density for low densities.
- Thus, when the HIF-photosphere are engaged, temperature of stellar photosphere is somewhat independent of global stellar properties, such as period, at low densities.
- This can lead to changes in the period-color relation, amplitude-color and PL relations.
- This interaction varies with pulsation phase, period and metallicity.
- Mean light relations are averages of relations at different phases.


GAL models
Δ(MAX)
0.4
0.3
0.2
0.1
0
0.5
1
1.5
log(P)

LMC models
Δ(MAX)
0.4
0.3
0.2
0.1
0
0.5
1
1.5
log(P)

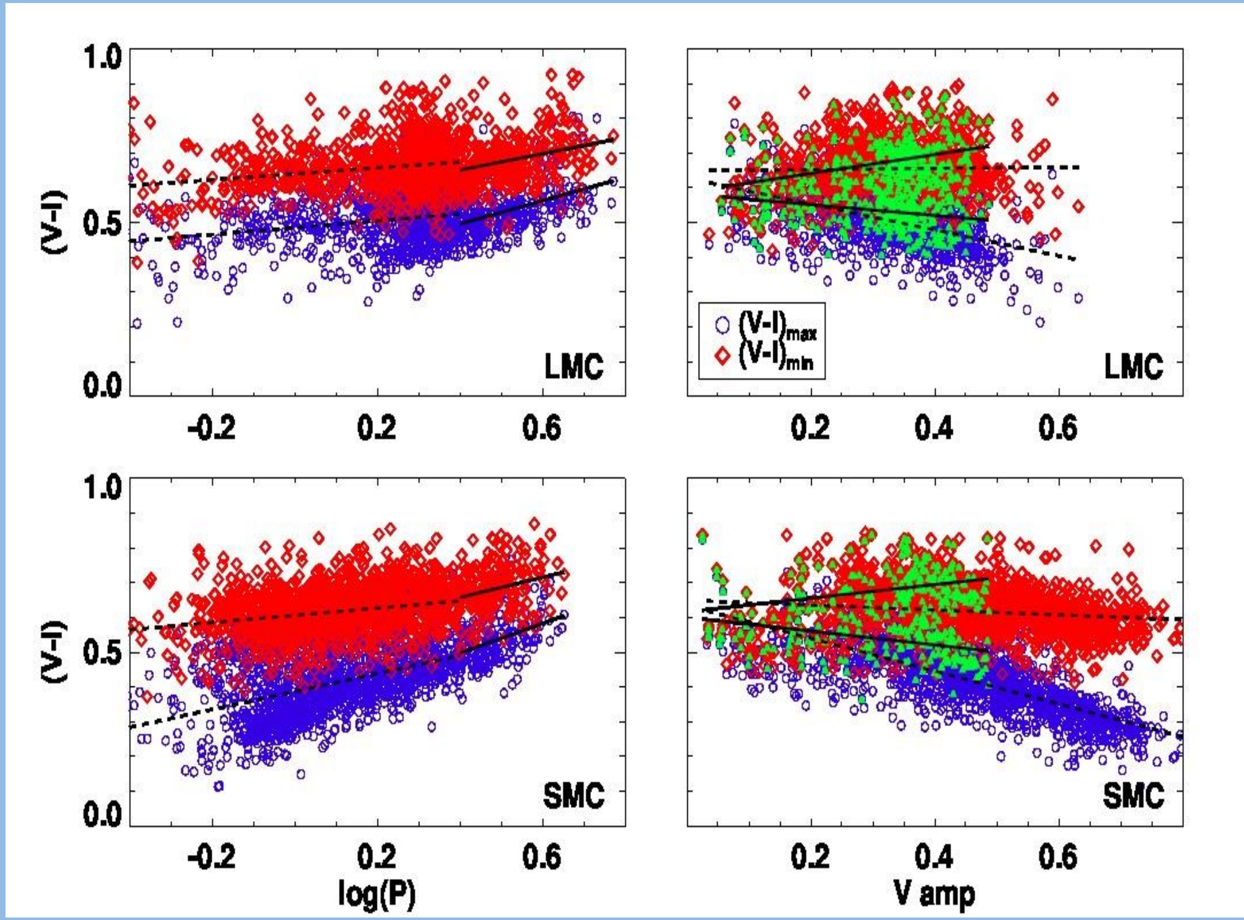

GAL models
0.4
0.3
0.2
0.1
0
Δ(MIN)
0.5
1
1.5
log(P)
LMC models
0.4
0.3
0.2
0.1
0
Δ(MIN)
0.5
1
1.5
log(P)

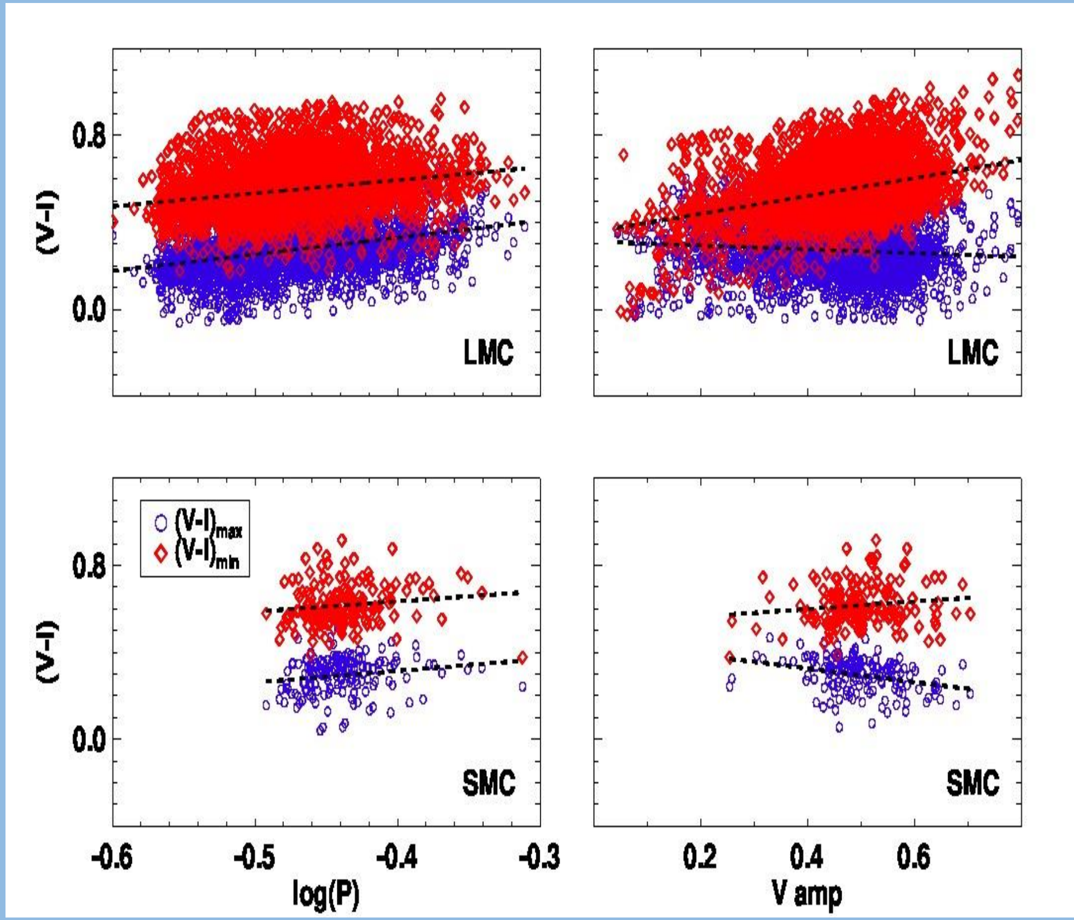
RR Lyraes



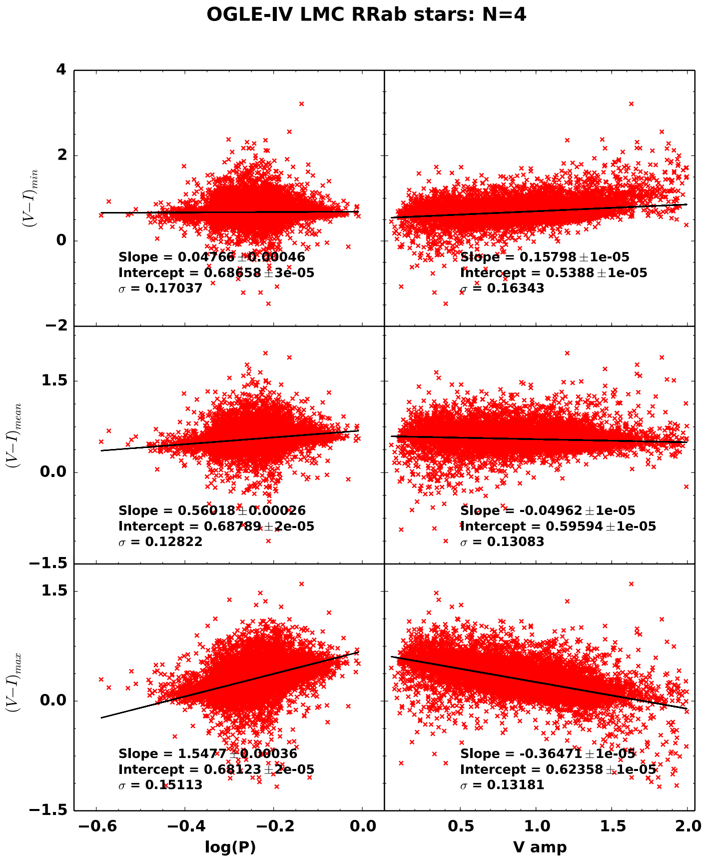
LMC
(V-I)
1
0
LMC
○ $(V\text{-}I)_{max}$
◇ $(V\text{-}I)_{min}$
SMC
(V-I)
1
0
SMC
-0.4
-0.3
-0.2
-0.1
log(P)
0.4
0.8
1.2
V amp

Cepheids/RR Lyraes First Overtone

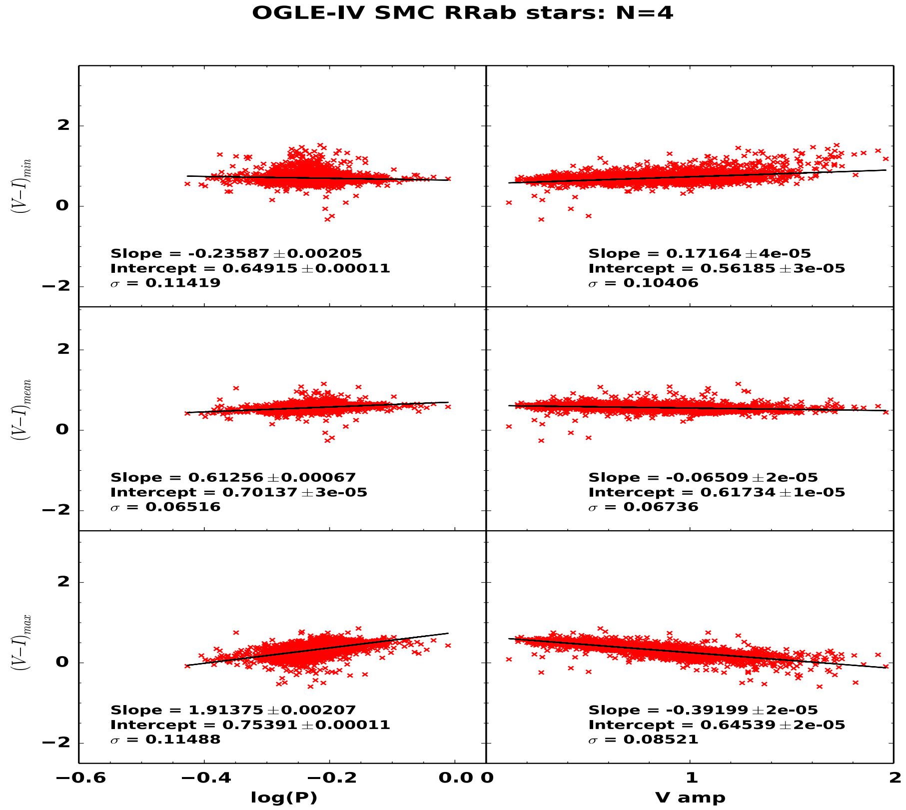




OGLE IV: RRab

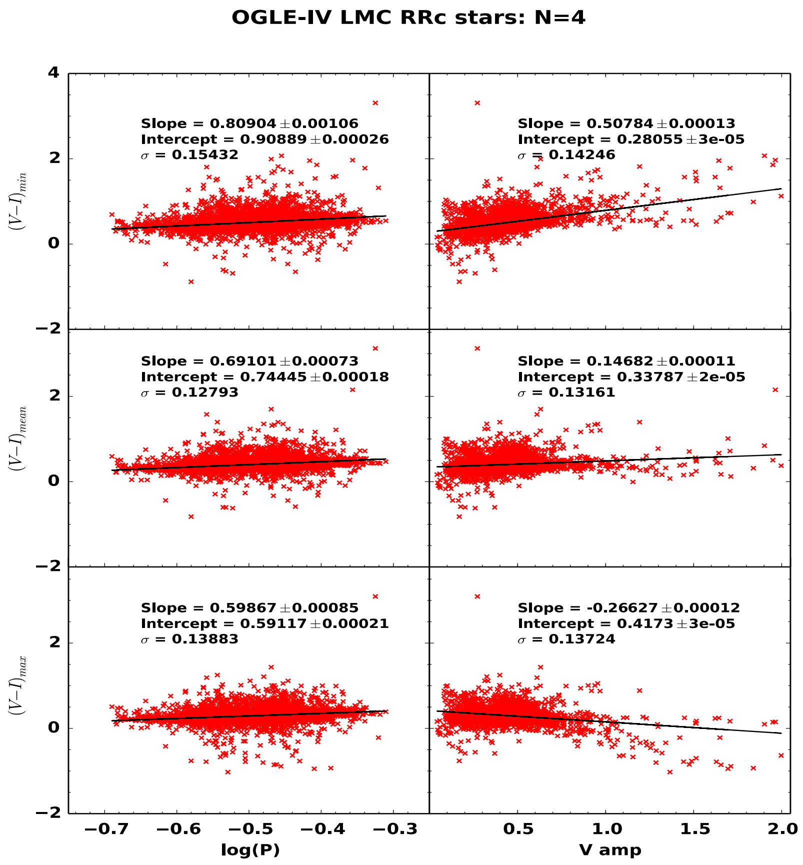


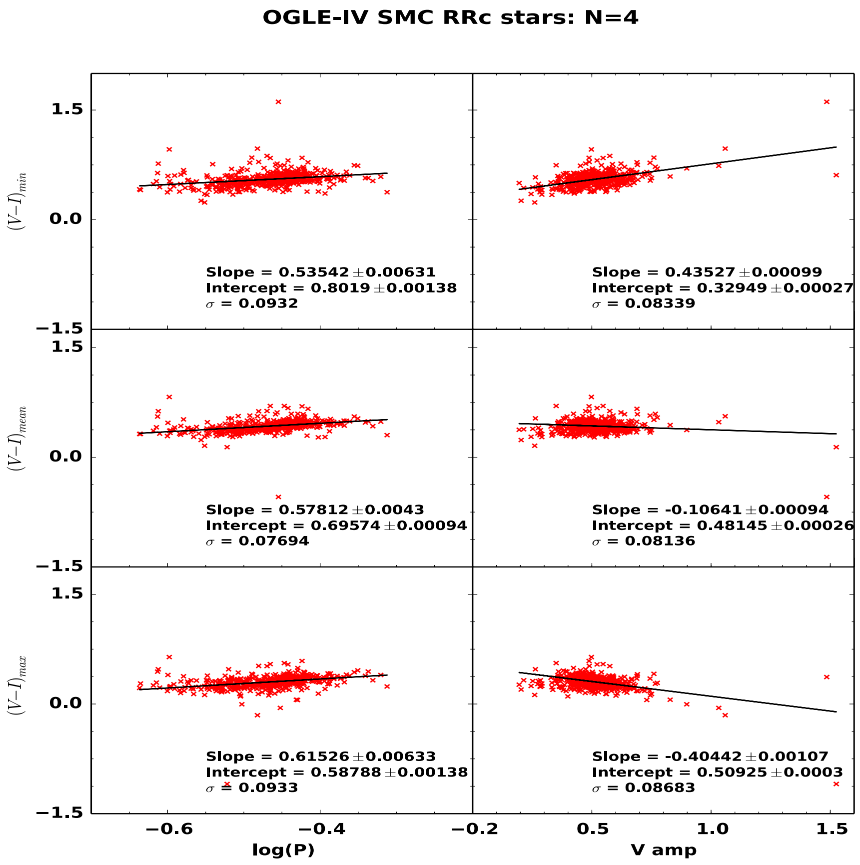
OGLE-IV LMC RRab stars: N=4
Slope = 0.04766 ±0.00046
Intercept = 0.68658 ±3e-05
σ = 0.17037
Slope = 0.15798 ±1e-05
Intercept = 0.5388 ±1e-05
σ = 0.16343
Slope = 0.56018 ±0.00026
Intercept = 0.68789 ±2e-05
σ = 0.12822
Slope = -0.04962 ±1e-05
Intercept = 0.59594 ±1e-05
σ = 0.13083
Slope = 1.5477 ±0.00036
Intercept = 0.68123 ±2e-05
σ = 0.15113
Slope = -0.36471 ±1e-05
Intercept = 0.62358 ±1e-05
σ = 0.13181
(V−I)min
(V−I)mean
(V−I)max
log(P)
V amp



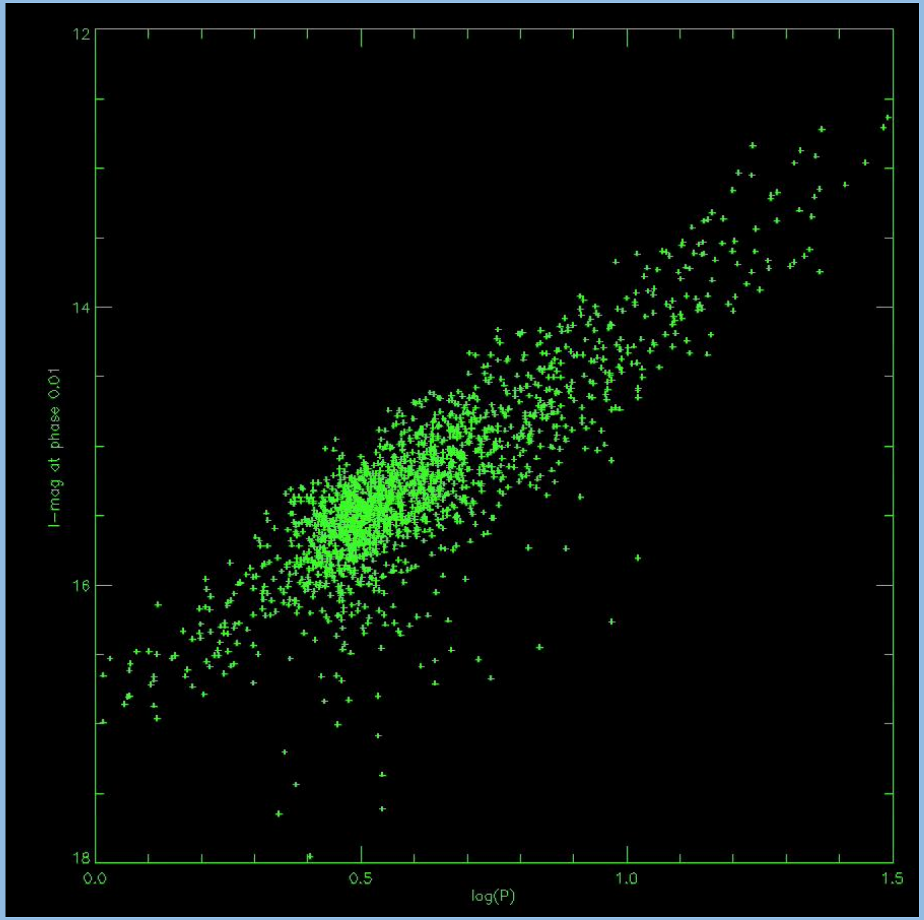
OGLE-IV SMC RRab stars: N=4
Slope = -0.23587 ±0.00205
Intercept = 0.64915 ±0.00011
σ = 0.11419
Slope = 0.17164 ±4e-05
Intercept = 0.56185 ±3e-05
σ = 0.10406
Slope = 0.61256 ±0.00067
Intercept = 0.70137 ±3e-05
σ = 0.06516
Slope = -0.06509 ±2e-05
Intercept = 0.61734 ±1e-05
σ = 0.06736
Slope = 1.91375 ±0.00207
Intercept = 0.75391 ±0.00011
σ = 0.11488
Slope = -0.39199 ±2e-05
Intercept = 0.64539 ±2e-05
σ = 0.08521
(V−I)min
(V−I)mean
(V−I)max
log(P)
V amp

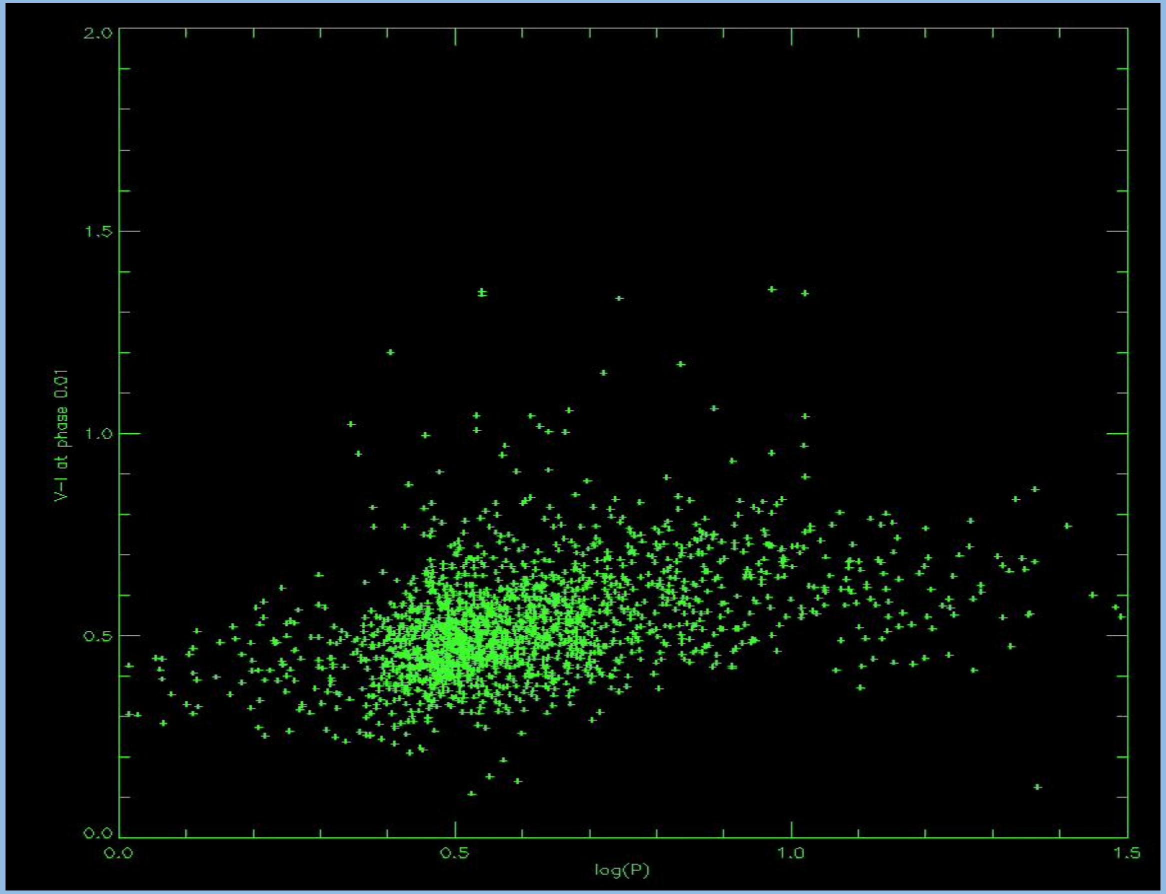
OGLE IV: RRc


OGLE-IV LMC RRc stars: N=4
Slope = 0.80904 ±0.00106
Intercept = 0.90889 ±0.00026
σ = 0.15432
Slope = 0.50784 ±0.00013
Intercept = 0.28055 ±3e-05
σ = 0.14246
Slope = 0.69101 ±0.00073
Intercept = 0.74445 ±0.00018
σ = 0.12793
Slope = 0.14682 ±0.00011
Intercept = 0.33787 ±2e-05
σ = 0.13161
Slope = 0.59867 ±0.00085
Intercept = 0.59117 ±0.00021
σ = 0.13883
Slope = -0.26627 ±0.00012
Intercept = 0.4173 ±3e-05
σ = 0.13724
log(P)
V amp

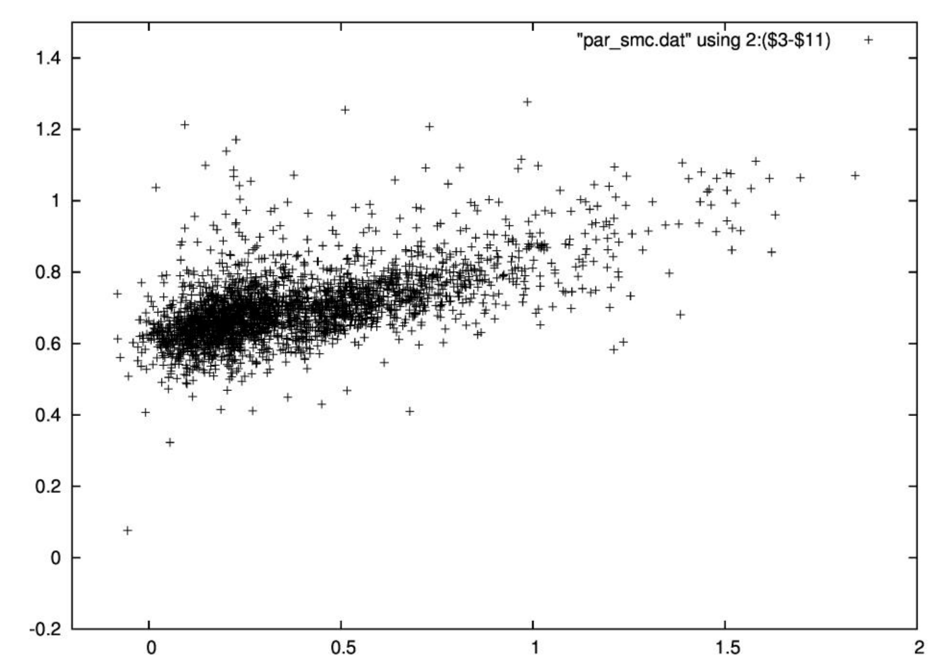

OGLE-IV SMC RRc stars: N=4
Slope = 0.53542 ±0.00631
Intercept = 0.8019 ±0.00138
σ = 0.0932
Slope = 0.43527 ±0.00099
Intercept = 0.32949 ±0.00027
σ = 0.08339
Slope = 0.57812 ±0.0043
Intercept = 0.69574 ±0.00094
σ = 0.07694
Slope = -0.10641 ±0.00094
Intercept = 0.48145 ±0.00026
σ = 0.08136
Slope = 0.61526 ±0.00633
Intercept = 0.58788 ±0.00138
σ = 0.0933
Slope = -0.40442 ±0.00107
Intercept = 0.50925 ±0.0003
σ = 0.08683
log(P)
V amp

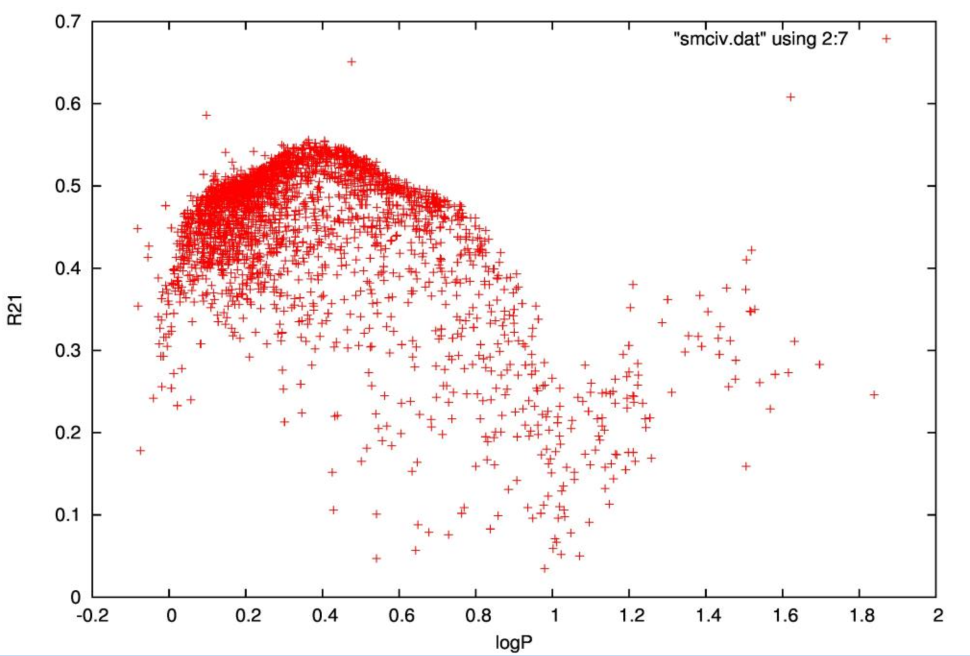
Multiphase and NonLinearity





SMC FU PC relation using OGLE IV V-I data





FO MC Possible Non-Linearity at short periods

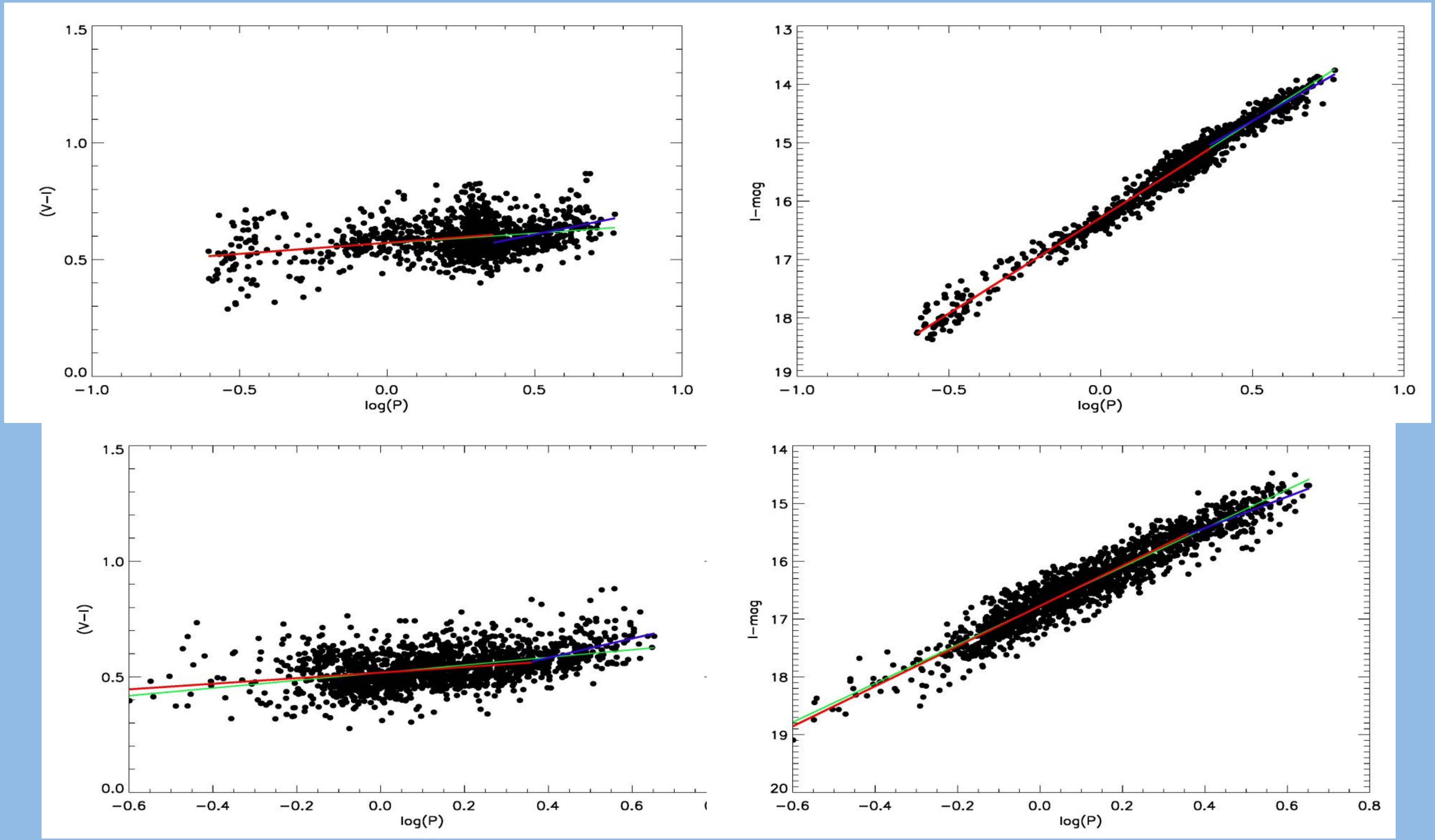


Table 10. Results of non-linearities in PL, PW and PC relations for FU and FO mode Cepheids in LMC at multiple wavelengths.

	OGLE-III + CPAPIR									
	FU					FO				
	FT	RW	TM	DT	AD	FT	RW	TM	DT	AD
$V_{\rm L}$	✗	✗	✗	✗	✗	–	–	–	–	–
$V_{\rm NL}$	✓	✓	✓	✓	✓	–	–	–	–	–
V	✓	✗	✓	✓	✓	✓	✓	✓	✓	✓
I	✓	✗	✓	✓	✓	✓	✓	✓	✓	✓
J	✓	✓	✓	✓	✓	✓	✗	✓	✗	✓
H	✓	✓	✓	✓	✓	✗	✗	✓	✗	✗
K_s	✓	✓	✓	✓	✓	✗	✗	✓	✗	✗
$W_{V,\,I}$	✓	✗	✓	✗	✓	✓	✓	✓	✓	✓
$W_{J,\,H}$	✓	✓	✓	✓	✓	✗	✗	✓	✗	✗
$W_{J,\,K_s}$	✓	✗	✓	✓	✓	✗	✗	✗	✗	✗
$W_{H,\,K_s}$	✗	✗	✓	✗	✗	✗	✓	✗	✗	✗
$W_{V,\,J}$	✓	✗	✗	✓	✓	✓	✗	✓	✗	✓
$W_{V,\,H}$	✓	✗	✗	✓	✓	✗	✗	✓	✗	✗
$W_{V,\,K_s}$	✓	✗	✓	✓	✓	✗	✗	✗	✗	✗
$W_{I,\,J}$	✓	✗	✗	✓	✓	✗	✗	✗	✗	✗
$W_{I,\,H}$	✓	✓	✗	✓	✓	✗	✗	✗	✗	✗
$W_{I,\,K_s}$	✓	✗	✓	✓	✓	✗	✗	✗	✗	✗
$W^H_{V,\,I}$	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
$V-I$	✓	✗	✗	✓	✓	✓	✓	✓	✓	✓
$J-H$	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
$J-K_s$	✗	✗	✗	✗	✗	✓	✗	✓	✓	✓
$H-K_s$	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗
$V-J$	✗	✗	✓	✗	✗	✗	✗	✓	✗	✗
$V-H$	✗	✗	✗	✗	✗	✓	✓	✓	✗	✓
$V-K_s$	✗	✗	✗	✗	✗	✓	✗	✓	✓	✓
$I-J$	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗
$I-H$	✗	✗	✗	✗	✗	✓	✓	✓	✗	✓
$I-K_s$	✗	✗	✗	✗	✗	✓	✓	✓	✓	✓
	OGLE-III-SS									
V	✗	✗	✗	✗	✗	–	–	–	–	–
I	✗	✗	✗	✗	✗	–	–	–	–	–
$W_{V,\,I}$	✗	✗	✓	✗	✗	–	–	–	–	–
$V-I$	✗	✗	✗	✗	✗	–	–	–	–	–

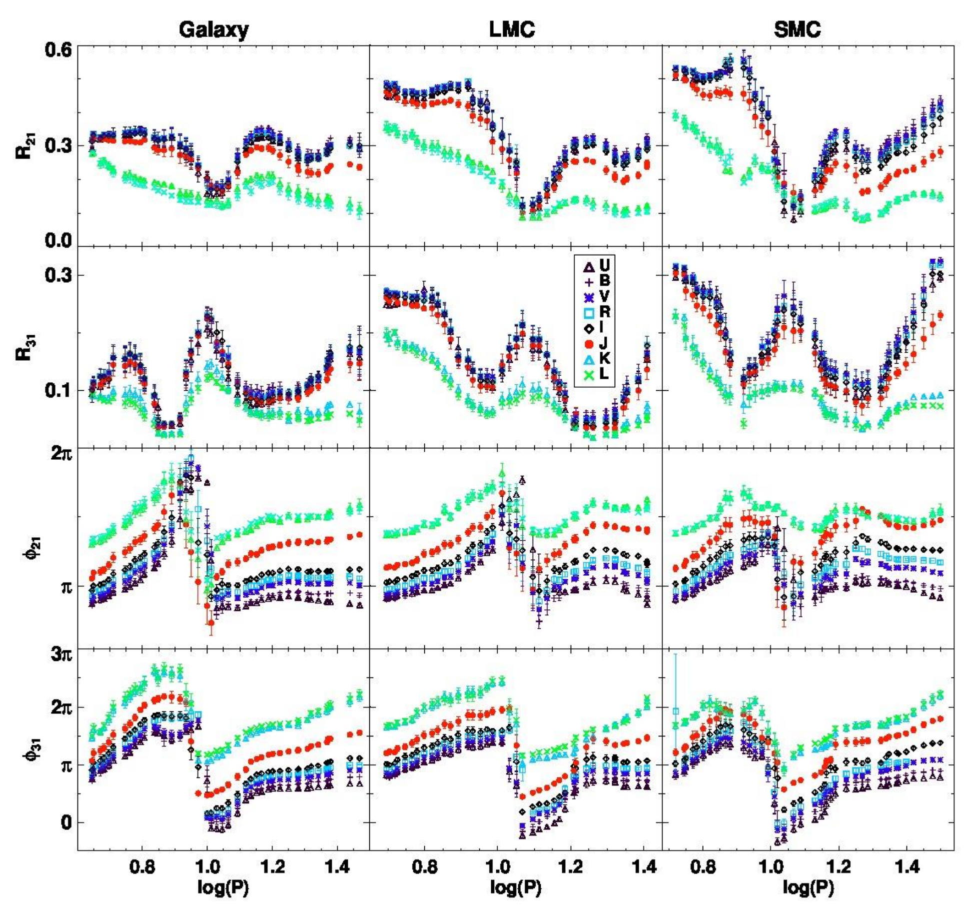
Notes. (i) For each band PL, PW or PC relations, ✓/✗ represents the break/no break under each test statistics.
(ii) For the F-test, the break is accepted if F-value > 3.
(iii) For the random-walk, it is accepted if $p(R) < 0.10$.
(iv) For the testimator, we accept a break if null hypothesis is rejected for the subset which includes break period.
(v) For the Davies test, we accept a break if $p(D) < 0.05$ (equation 11).
(vi) The adopted result is listed under 'AD' column. The break is accepted if at least two tests result in a '✓'.

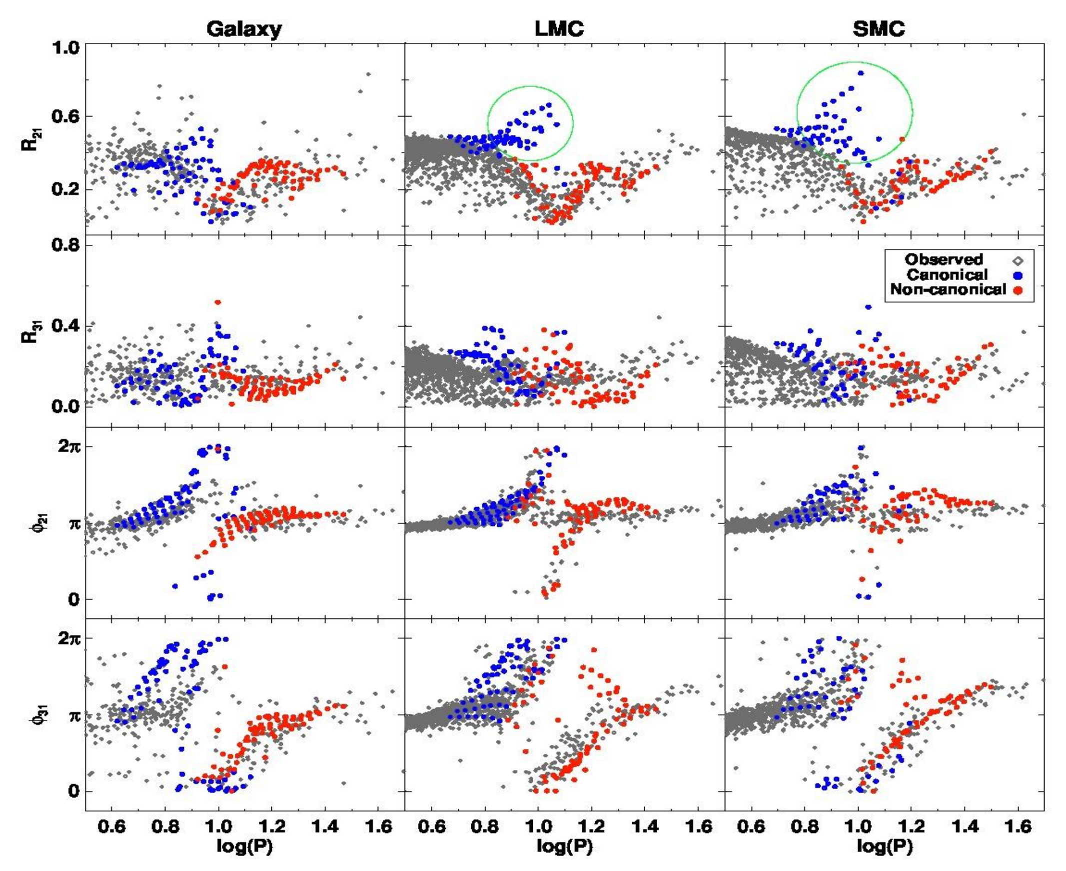
In order to address a particular case, we will refer to the calibrator choice followed by the variant (e.g. a1 refers to the three-calibrator case with variant '1'). Our slopes are shallower for cases a1 & b1 and steeper for c1 relative to R11 (who obtained −3.21, −3.19 and −3.02, respectively), perhaps because we did not adopt a prior on the slope of the Milky Way or the LMC PL relations. Cases a2, b2 and c2 show that the adoption of the new LMC sample results in a significant improvement of the constraint in the global slope, and the resulting value is in fact identical to the three-calibrator case of R11. It also provides a better constraint on the value of the metallicity coefficient. Lastly, cases a3, b3 and c3 show that restricting the LMC sample to long-period Cepheids only does not make any significant difference to the slope.

We recall from Table 4 that the slopes of the $W^H_{V,I}$ relations for all periods, short periods, and long periods are $b_{\rm all} = -3.247 \pm 0.010$, $b_{\rm S} = -3.220 \pm 0.020$ and $b_{\rm L} = -3.369 \pm 0.047$, respectively. From Table 12, we note that the slopes of the global-fit solutions for the linear and non-linear versions (variants '2' and '3') are very consistent with the LMC-based values for $b_{\rm all}$ and $b_{\rm S}$, but significantly different from $b_{\rm L}$. In fact, the slope of the global-fit solution with LMC calibration is identical to short-period version of the solution based exclusively on LMC data.

The slopes obtained from a global fit to Cepheids in SH0ES galaxies using the linear and non-linear versions of the LMC PL relations are very similar, independent of the choice of the calibrator galaxy. Therefore, we do not expect any significant impact of this parameter on the distance scale or the value of H_0, considering that the dispersion of the *HST*-based PL relations (∼0.3–0.4 mag) is more than three times the dispersion of the LMC PL relation. Therefore, even a significant change in slope for the long-period PW relation will be masked by the dispersion of the global fit and will not have any impact on distance parameters until more precise relations

Light Curve Structure: Cepheids
Bhardwaj et al (2015, 2017, MNRAS)

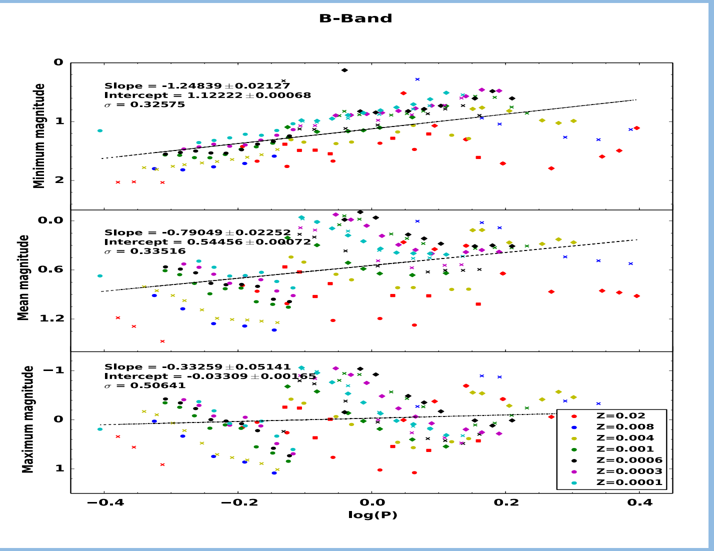


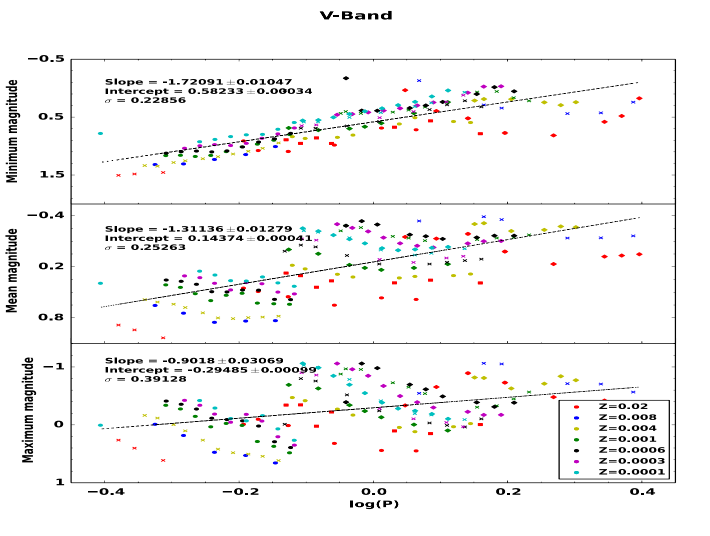


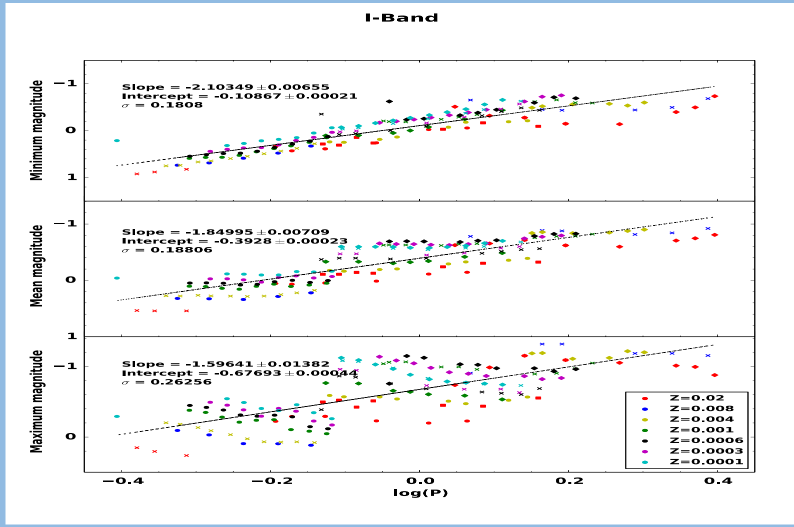
Preliminary Results

- Large offset between theory and observations for periods between 7 and 11 days with non-canonical mass-luminosity levels
- Can be reduced by changing the mixing length parameter from 1.5 to 1.8
- More models, especially at shorter periods

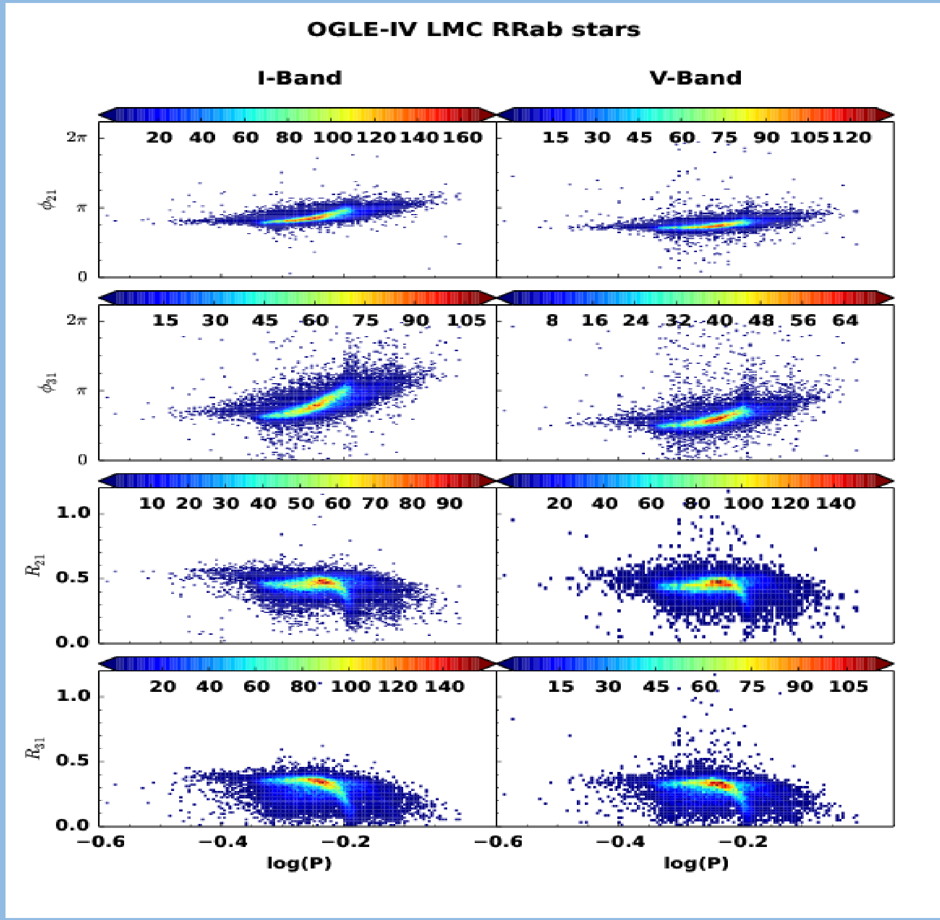
RR Lyrae PL Relations as a function of phase

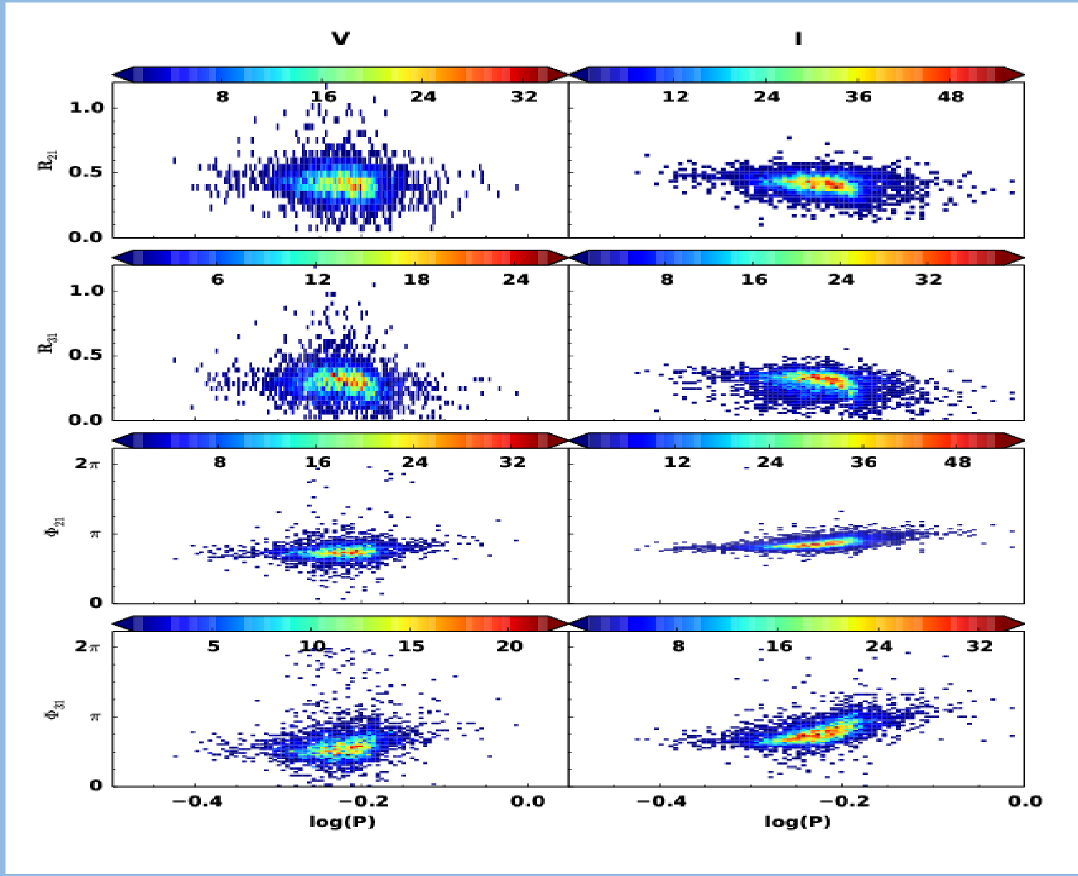






Light Curve Structure: RR Lyraes

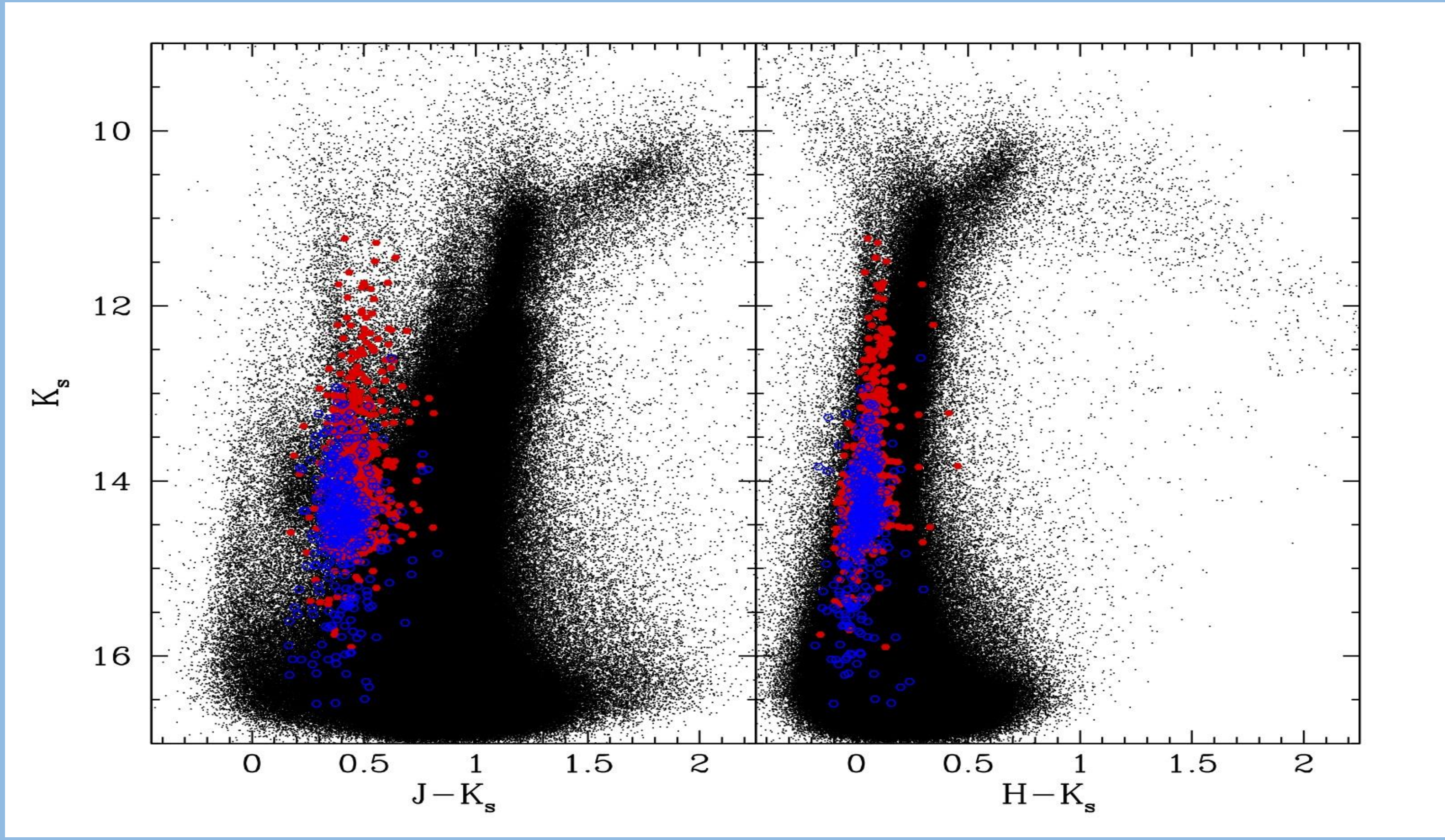




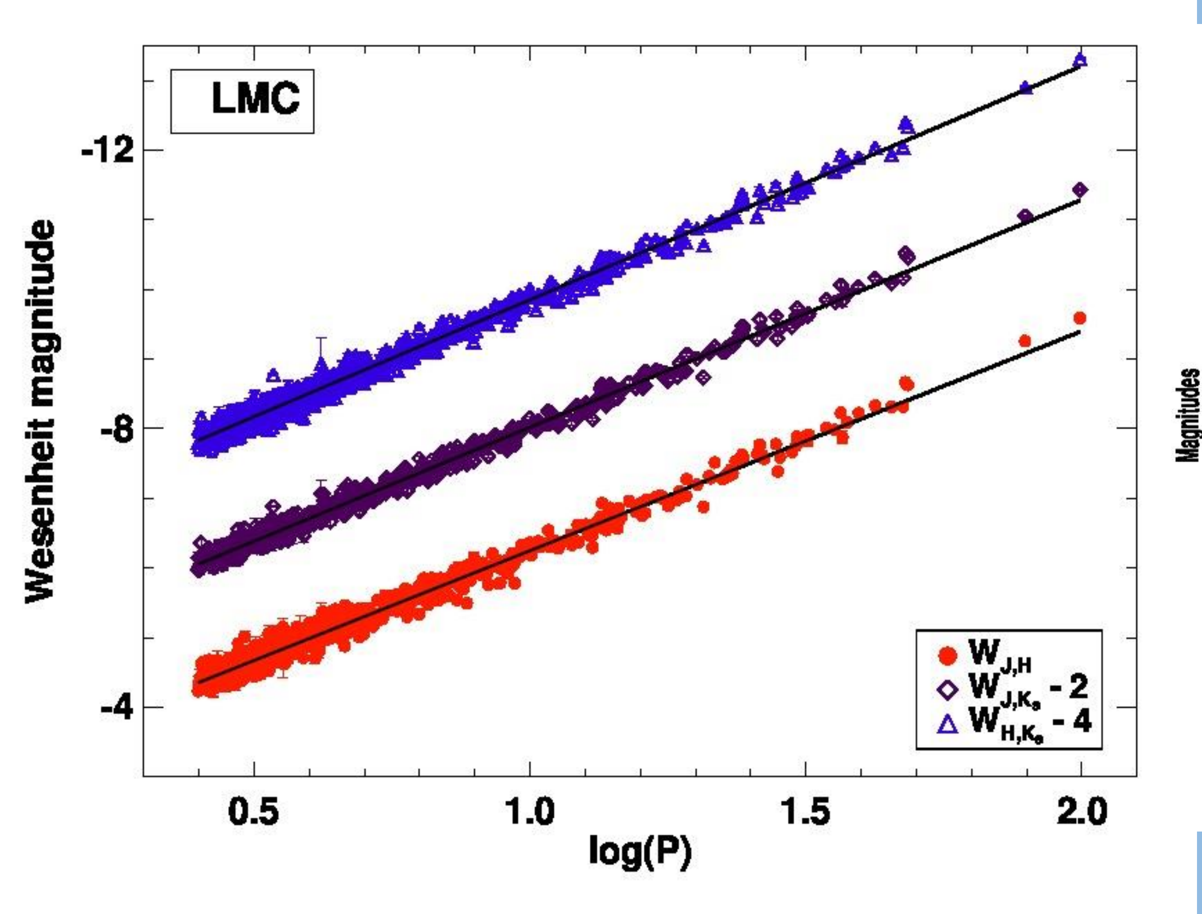
Non-Linear Optimization

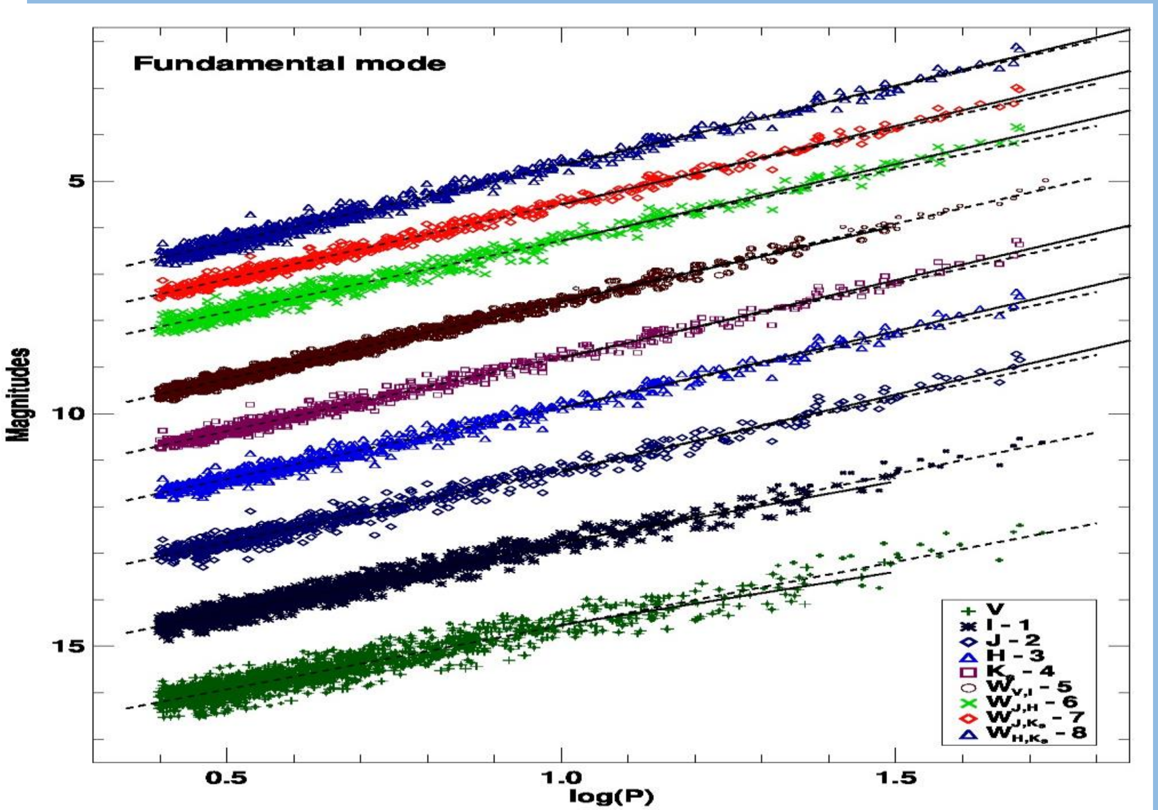
- Fourier Parameters = f(M,L,T,X,Z)
- For a fit of order 8, have 17 parameters, or 6 if we use Rk1 etc.)
- Non-linear optimization problem to get the best M,L,T,X,Z.
- Multiwavelength data
- Approx. a million models….
- Use machine learning techniques developed by Bellinger et al (2017).
- Use MESA to produce full amplitude pulsation models that are completely consistent with stellar evolution

CPAPIR LMC JHK data



Cepheid Multiwavelength PL Relations





Conclusion

- OGLE has dramatically changed variable star Astrophysics.
- Many questions answered, but also many new questions.
- SMC FU Cepheids have a positive slope in the PC minimum light relation with OGLE IV.
- Physical cause for dispersion at minimum light
- Stellar-Photosphere-HIF interaction: Saha Ionization equilibrium, optical depth=2/3 – f parameter (Dasznyska-Daskiewicz et al 2003)
- NonLinear Optimization
- Thank You to the entire OGLE team.