The nonlinear Cepheid PL relation: pulsation, evolution and distance scale implications.

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Collaborators

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- Douglas Leonard, Matt Davis, Azalee Bostroem (SDSU), Lucas Macri (NOAO) Nial Tanvir (University of Leicester), Sergei Nikolaev (LLNB), Antonio Kanaan, Paulo Henrique (UFSC), Thomas Barnes (Macdonald Observatory), Robert Szabo (Hungary), Robert Buchler (Florida), Chris Koen (Western Cape). Pascal Fouque (Observatoire de Midi-Pyrenees), A. Nanthakumar (Oswego).
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- 18 papers in leading peer reviewed journals, A+A, MNRAS, APJ, PASP in 3 years.
- 10 conference papers/presentations at international meetings.


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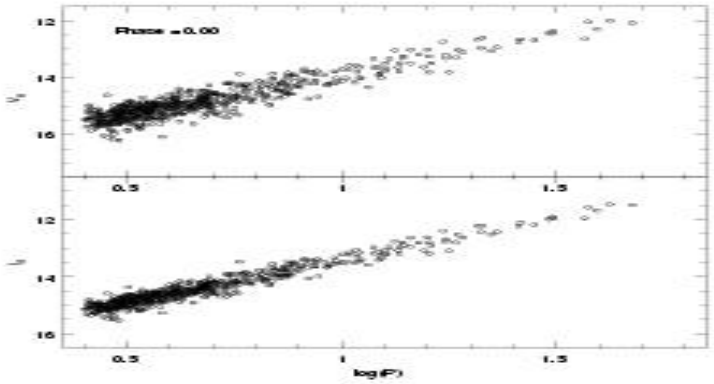
AP


102.03
102.04
A Testimator Based Approach to Investigate the Non-
A Theoretical Investigation into the Properties of RR
Lyraes at Maximum and Minimum Light

The LMC Cepheid PL relation

- Existing paradigm: Linear PL relation:
- Mv = a+blogP.
- Recent evidence strongly suggests that the LMC Cepheid PL relation is non-linear:
- Data are more consistent with two lines of significantly differing slopes separated at a period of 10 days.
- Evidence for B, V, I, J, H and marginally for K.
- Mean light and multiphase relations.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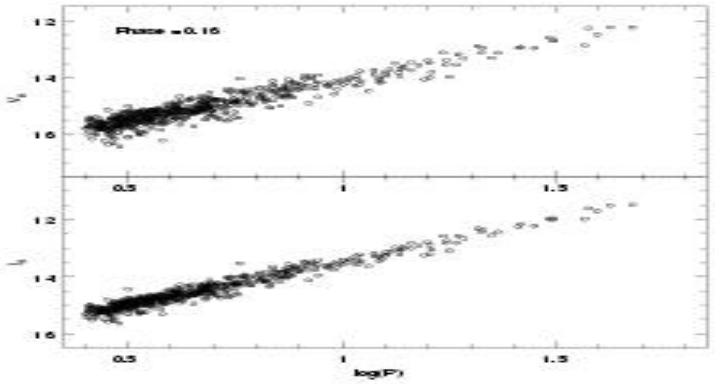
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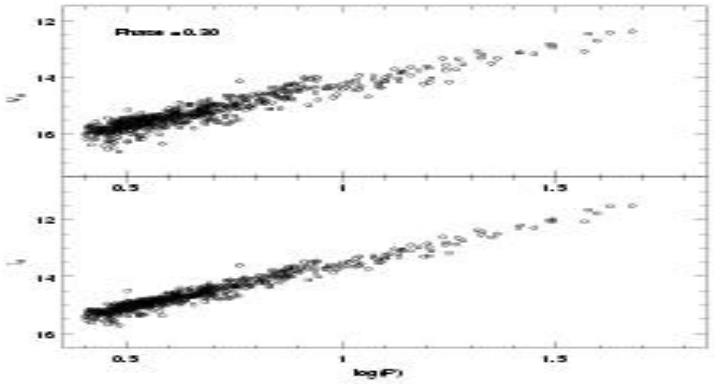
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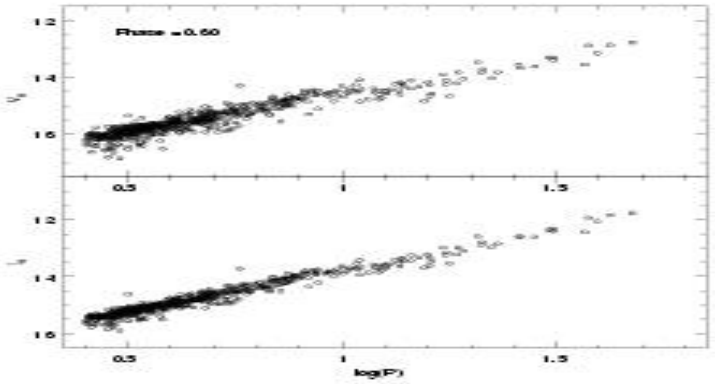
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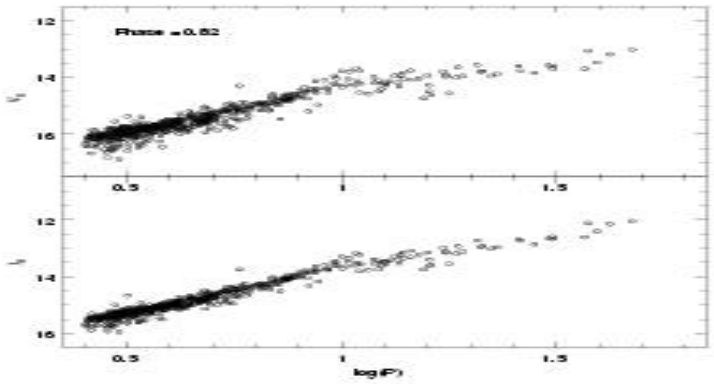
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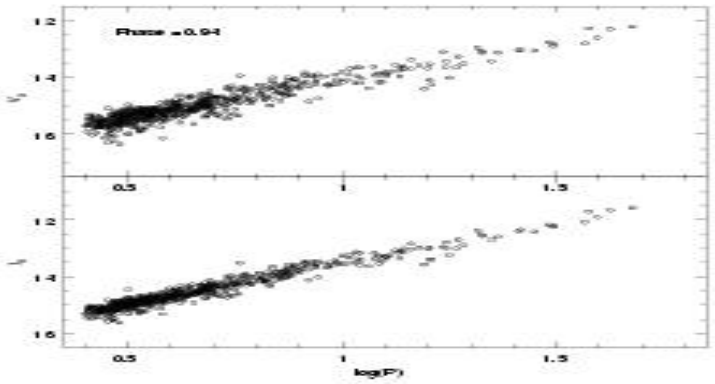
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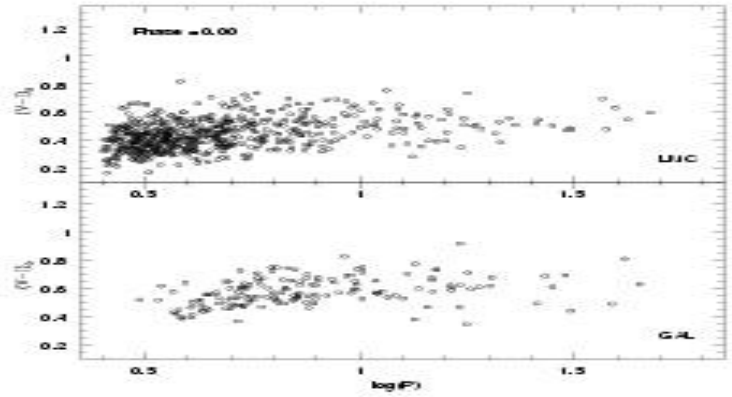
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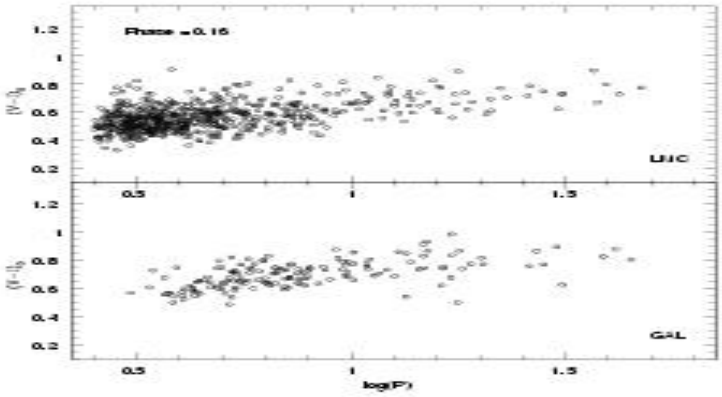
UIC
GAL
log(P)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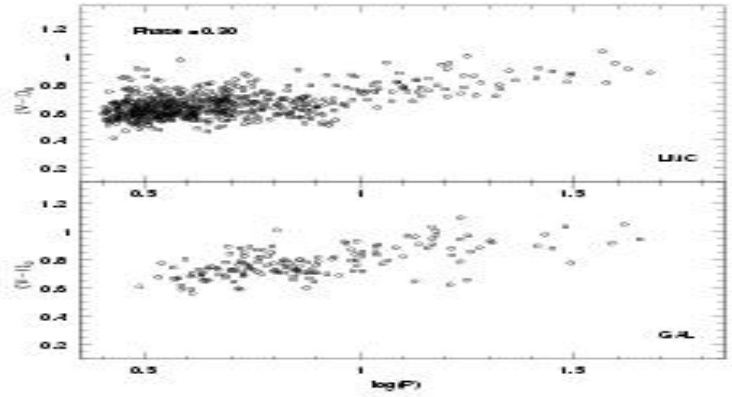
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GAL
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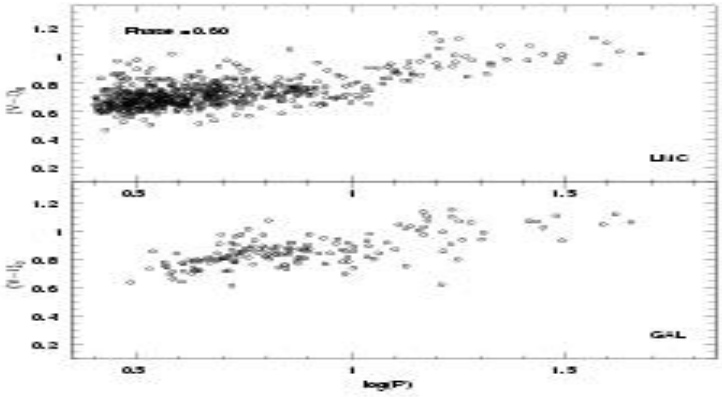
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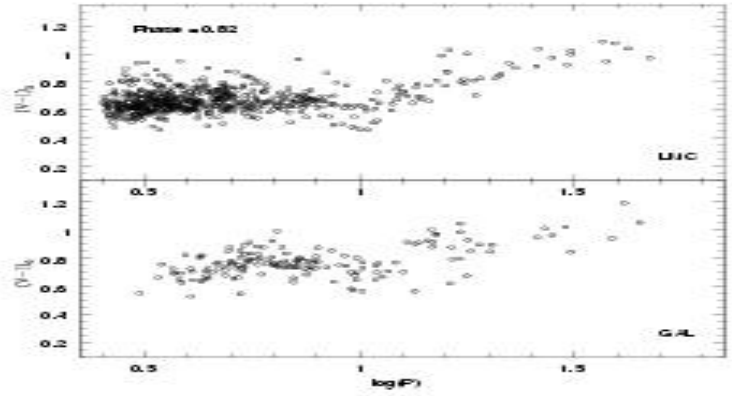
UIC
GAL
log(P)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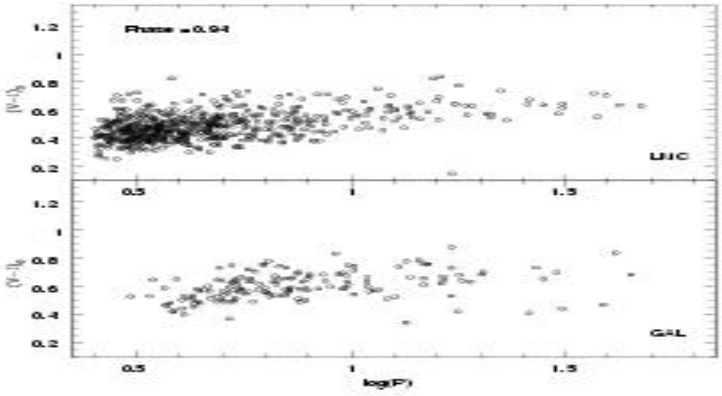
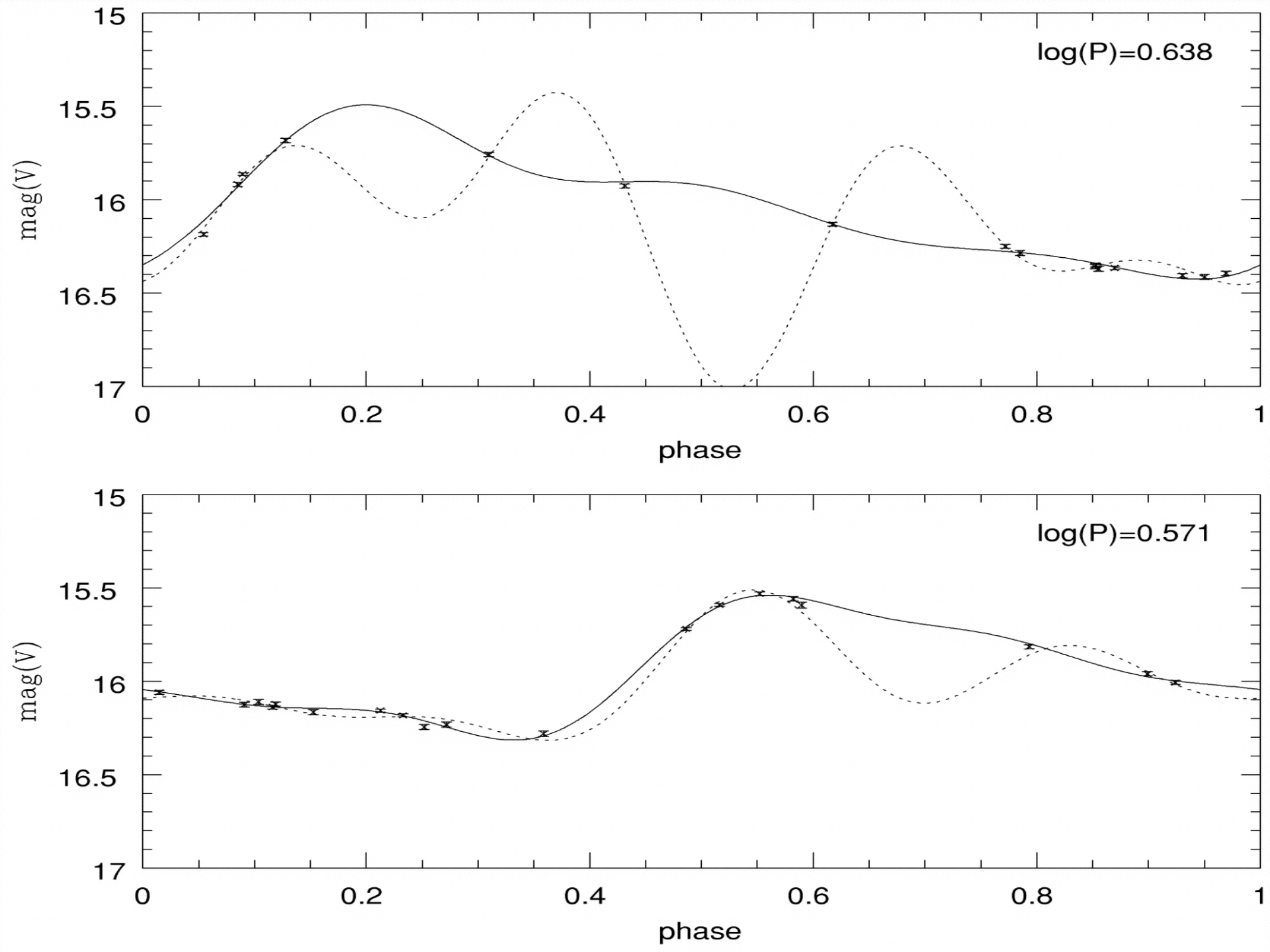
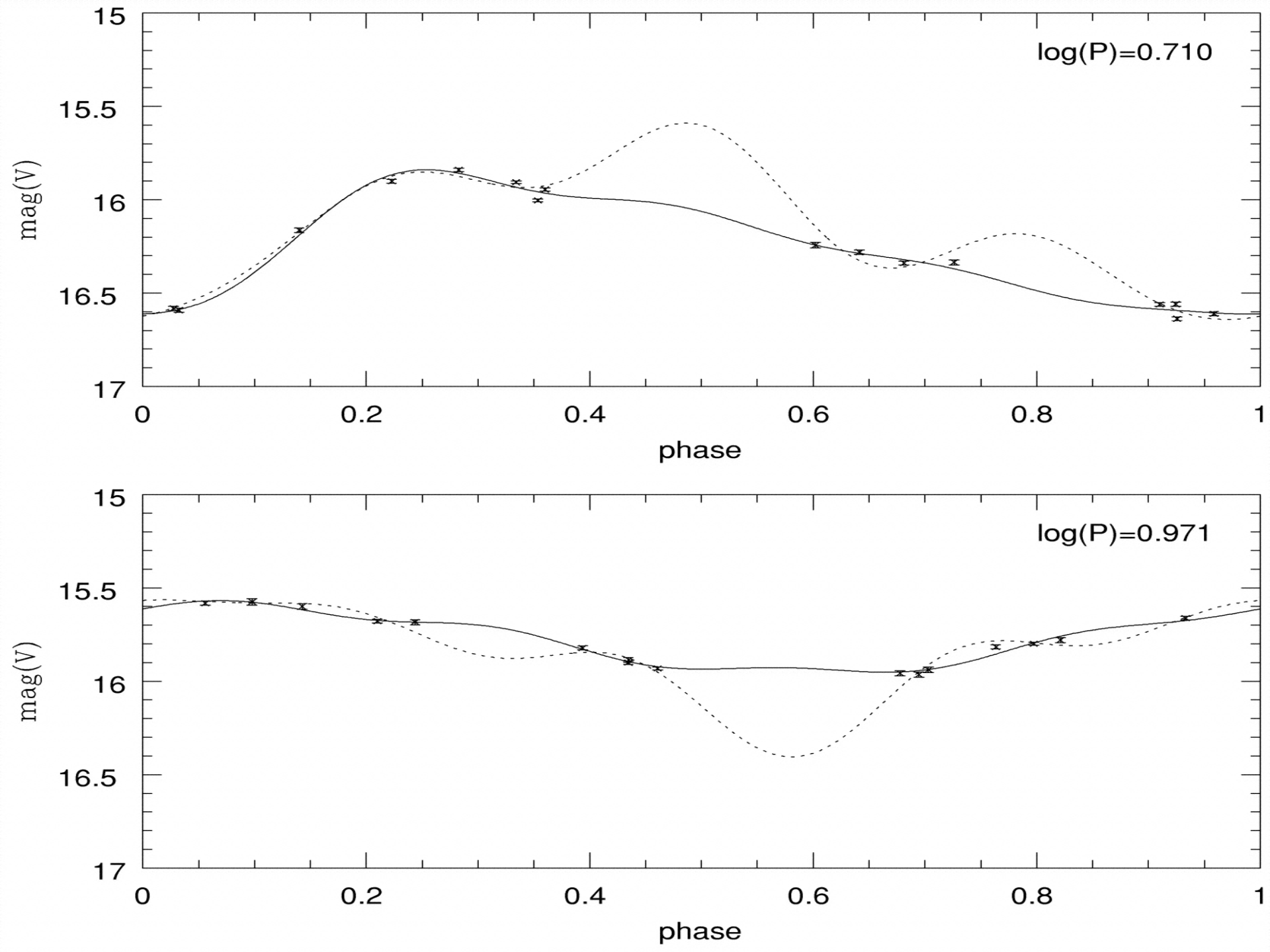
UIC
GAL
log(P)


Phase = 0.94
UIC
GAL
log(P)


log(P)=0.638
mag(V)
phase
15
15.5
16
16.5
17
0
0.2
0.4
0.6
0.8
1
log(P)=0.571
mag(V)
phase
15
15.5
16
16.5
17
0
0.2
0.4
0.6
0.8
1


log(P)=0.710
mag(V)
phase
15
15.5
16
16.5
17
0
0.2
0.4
0.6
0.8
1
log(P)=0.971
mag(V)
phase
15
15.5
16
16.5
17
0
0.2
0.4
0.6
0.8
1

The LMC Cepheid PL relation

- OGLE data using published extinction/reddening values plus simulated annealing which improves Fourier fits.
- Null hypothesis: $M_X = a + b\log P$
- Alternate hypothesis:
- $M_X = a' + b' \log P$, $\log P < 1$
- $M_X = a'' + b'' \log P$, $\log P > 1$

The LMC Cepheid PL Relation

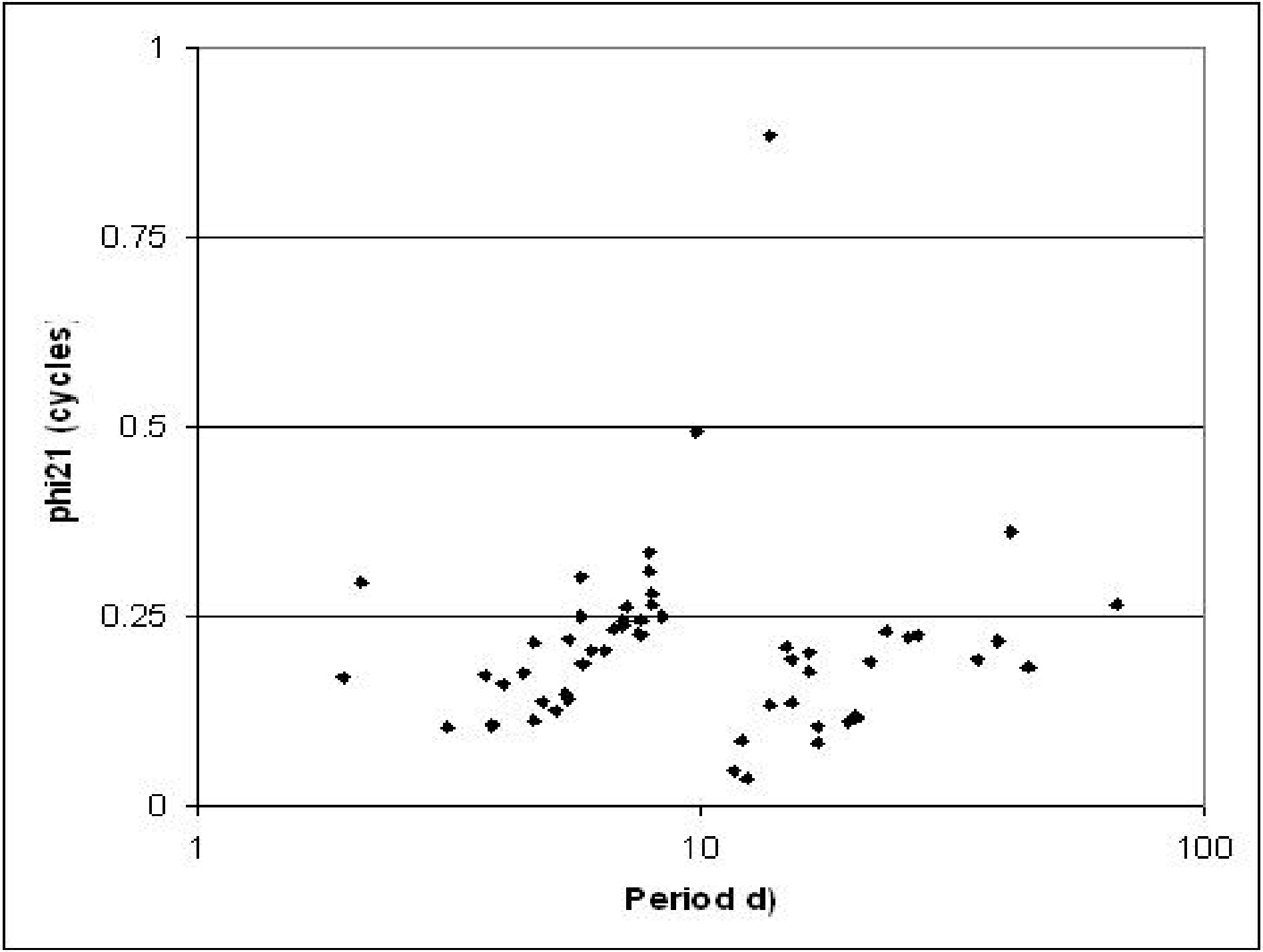
- F test compares residual sum of squares under the two hypotheses.
- OGLE BVI data highly (> 99%) significant (Kanbur and Ngeow 2004).
- MACHO V and R bands highly significant.
- MACHO + 2MASS + random phase correction J, H, significant, marginal for K (Ngeow et al 2005):
- Used reddening maps of Zaritsky.

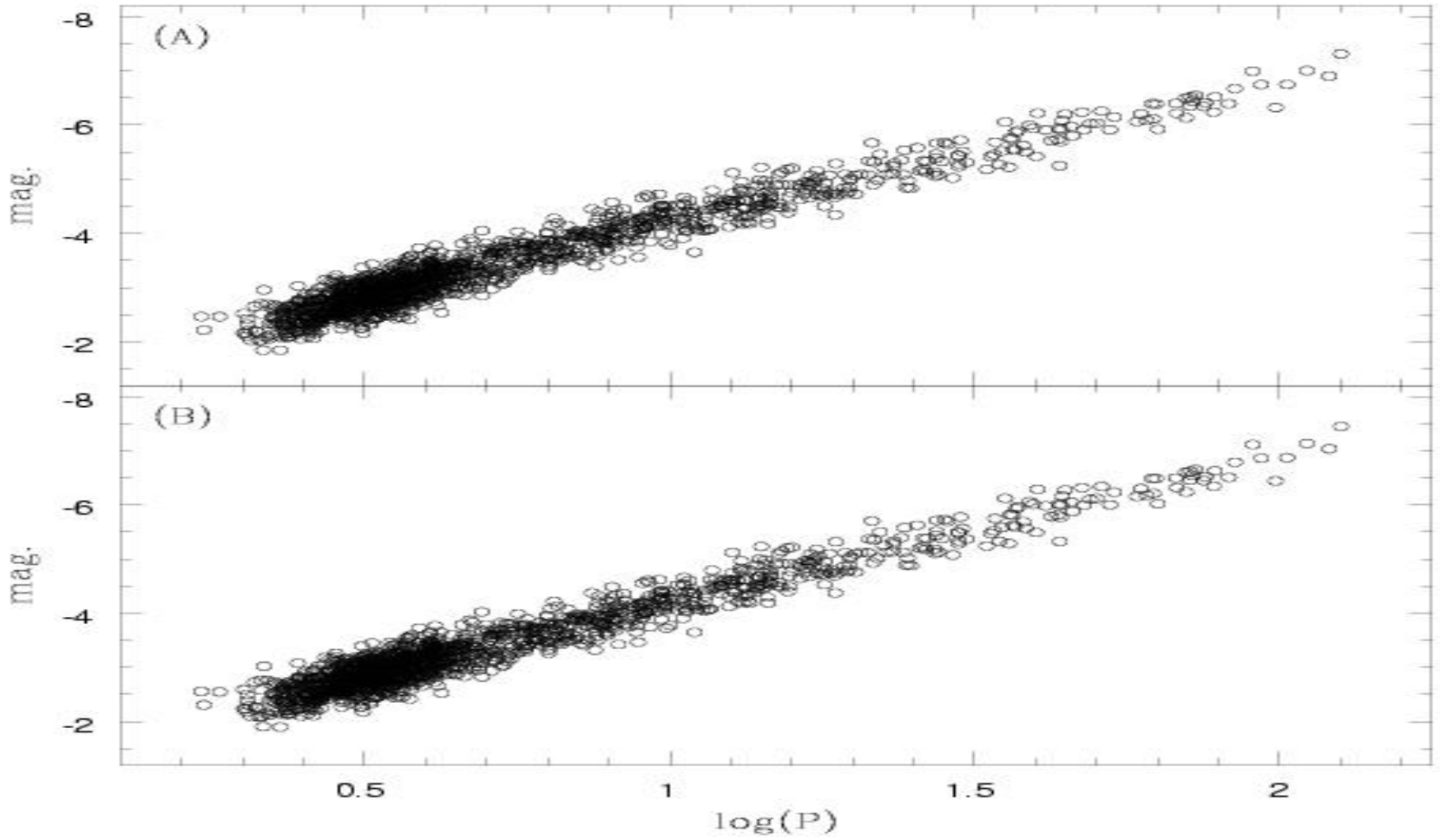
The LMC Cepheid PL Relation

- Check assumptions of F test.
- Check outliers.
- Robust regression (Tukey's bi weight function, M estimation), least absolute deviation, non-parametric regression (LOESS), testimator method, Bayesian likelihood methods (Schwarz Information Criterion).
- PC and PL non-linearities cancel out so PLC linear – reduced effect on the distance scale.
- Tammann et al (2002), Kanbur and Ngeow (2004), Sandage et al (2004),Ngeow et al (2005), Ngeow and Kanbur (2006), Kanbur et al (2007), Koen, Kanbur and Ngeow (2007).
- 2 lines or quadratic?

The LMC Cepheid PL Relation

- Lack of long period data?
- Ngeow et al (2005) added data from Sebo et al (2002), Perrson et al (2004): no change.
- Ngeow and Kanbur (2006) added data from Caldwell and Laney (1991), Gieren et al (1998), Laney and Stobie (1994), Sandage et al (2004) and other sources: no change.
- Perrson et al (2004) find no slope change for JHK: lack of short period Cepheids: F test is sensitive to the numbers of Cepheids.
- Galactic and SMC PL's seem to be linear.
- Statistical tests are important.


1
0.75
0.5
0.25
0
phi21 (cycles)
1
10
100
Period d)


(A)
(B)
mag.
mag.
-8
-6
-4
-2
0.5
1
1.5
2
log(P)

The LMC Cepheid PL relation

- But with some data sets, the short period slope and long period slope are within 1σ of each other?
- Slope is: $\beta \pm \sigma$ means:
- P(slope is in $[\beta-\sigma,\beta+\sigma]$) = $1 - \alpha$, where α is the significance level.
- So A = {short period slope is wrong}, B = {long period slope is wrong}: P(A) = α, P(B) = α.
- P(at least one mistake)=P(AUB) = $2\alpha - \alpha^2$
- But for $1 > \alpha > 0$, $2\alpha - \alpha^2 > \alpha$ = P (F test makes a mistake).
- P(F test makes a mistake) < P(standard comparison of slopes makes a mistake).
- F test compares slopes simultaneously.
- Testimator compares slope of one subset with next subset, independent of the zero point.

The LMC Cepheid PL Relation

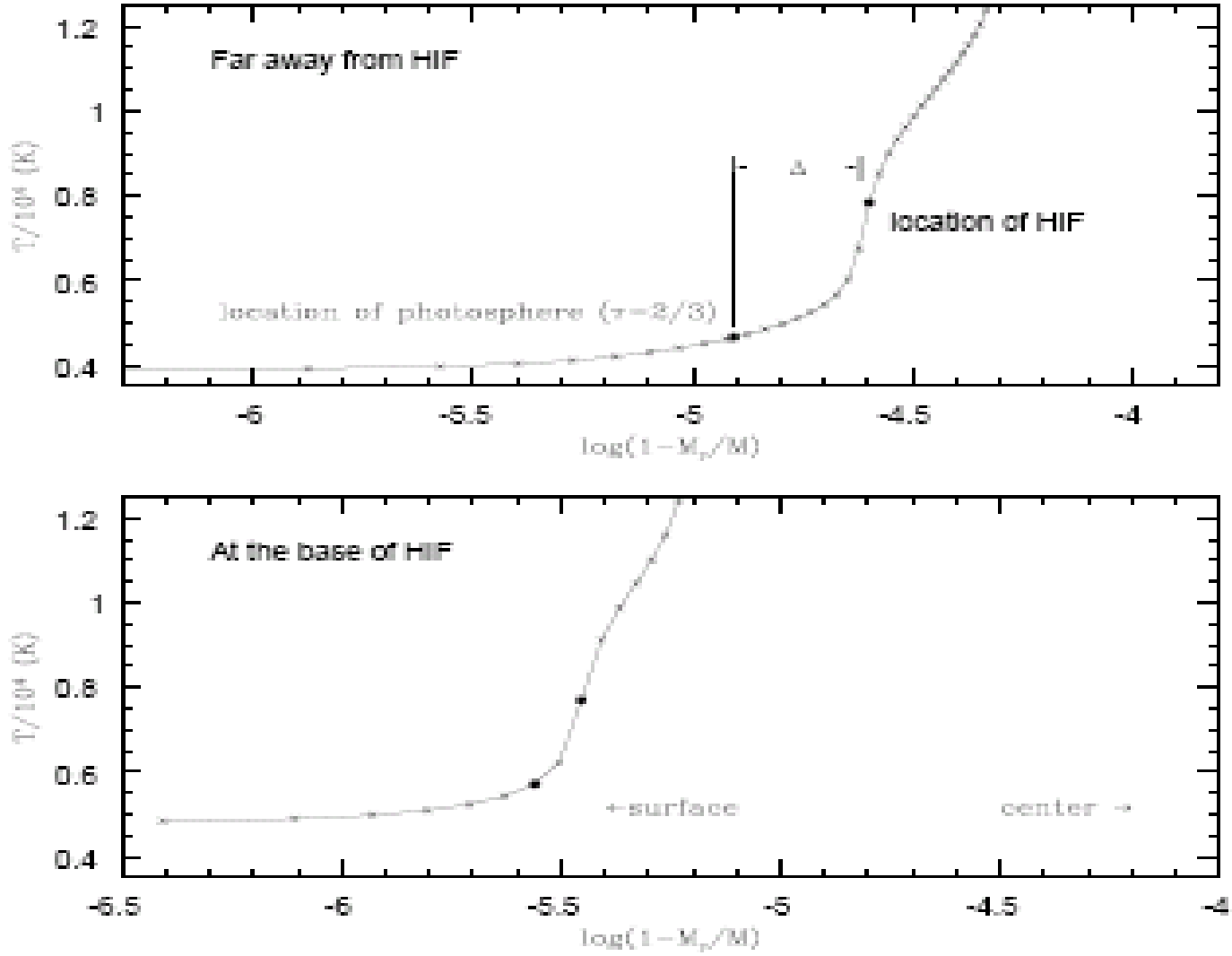
- Are the published reddenings/extinction wrong?
- Multi-phase relations: phase of 0.82.
- Ngeow et al (2005), Ngeow and Kanbur (2006) used two different reddening maps, independent of OGLE reddening map.
- Need reddening errors which are a complicated function of period.
- With such a reddening error, LMC Cepheids get hotter at maximum light as the period increases in contradiction to Galactic Cepheid behavior.
- Cepheid PL relation in the inner field of NGC 4258 is non-linear according to the F test.

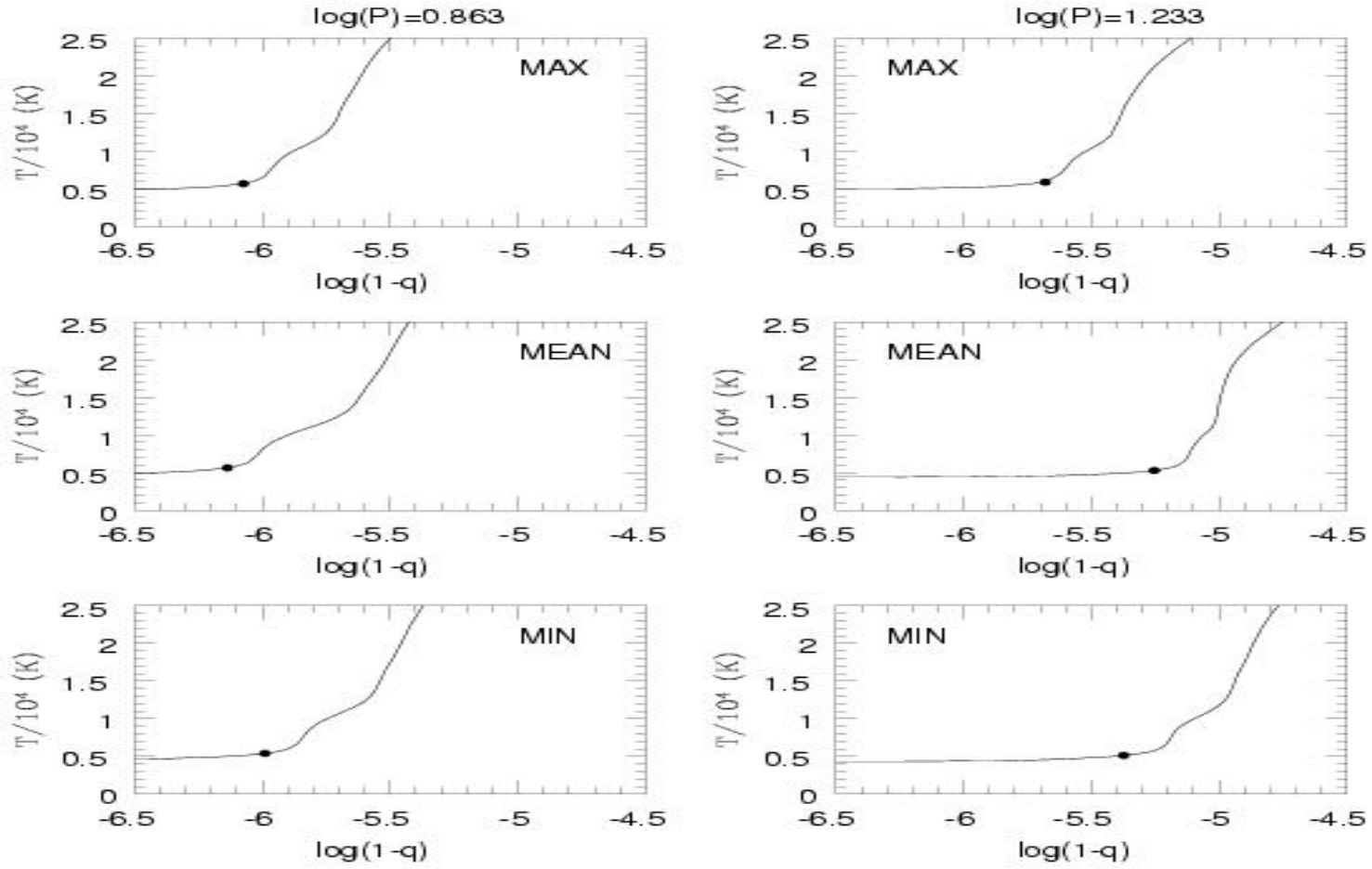
Implications

- Hubble diagram to estimate H_0 using linear PL relations and "non-linear" PL relations.
- 1-2% Ngeow and Kanbur (2006) calibrated the SNIa difference: important if a more accurate Cepheid distance scale (<5%) is required to break degeneracies present from CMB estimates. Best possible template?
- CMB work can only estimate ΩH_0^2.
- 65% reduction in confidence interval on Ω if an independent estimate of H_0 accurate to 1% is available.
- Effort to reduce zero point errors: Macri et al (2006), van Leeuwen et al (2007).
- Cepheid Physics.

The Cepheid Perioc-Color (PC) relation

- The period-mean density theorem, Stefan-Boltzmann law and the presence of an instability strip gives a PLC relation:
- logL = a+blogP +clogT_e
- PC and PL relations related; generally changes in one reflected in the other.
- Relations exist at all phases.
- Understand changes in PL/PC(mean) by studying PL/PC relations at all phases.
- Galactic/SMC relations linear, LMC nonlinear.


Far away from HIF
location of HIF
location of photosphere (τ=2/3)
Δ
T/10⁴ (K)
log(1−M_r/M)
At the base of HIF
←surface
center →

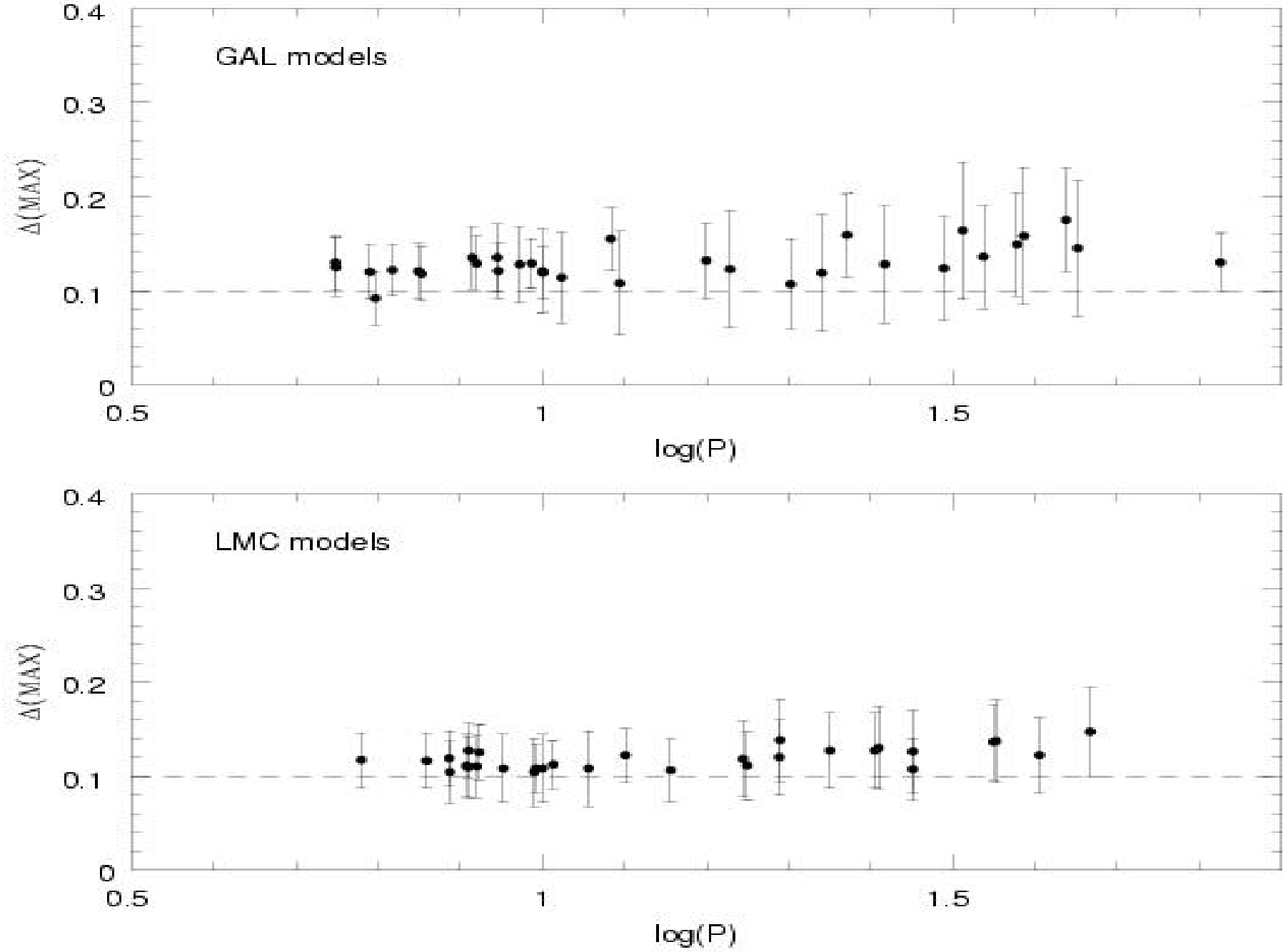

log(P)=0.863
log(P)=1.233
MAX
MEAN
MIN
T/10⁴ (K)
log(1-q)
2.5
2
1.5
1
0.5
0
-6.5
-6
-5.5
-5
-4.5

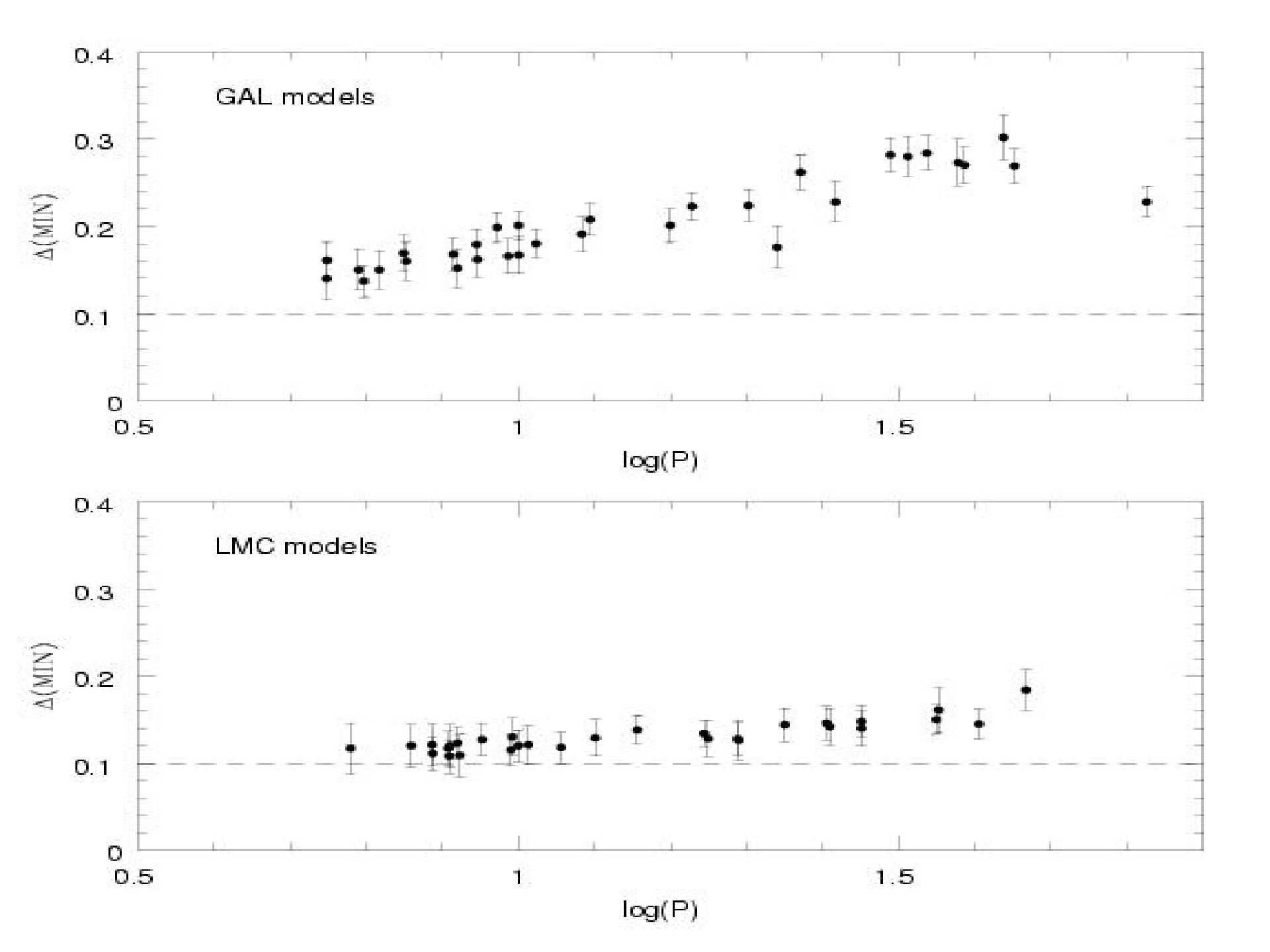
The HIF-photosphere interaction

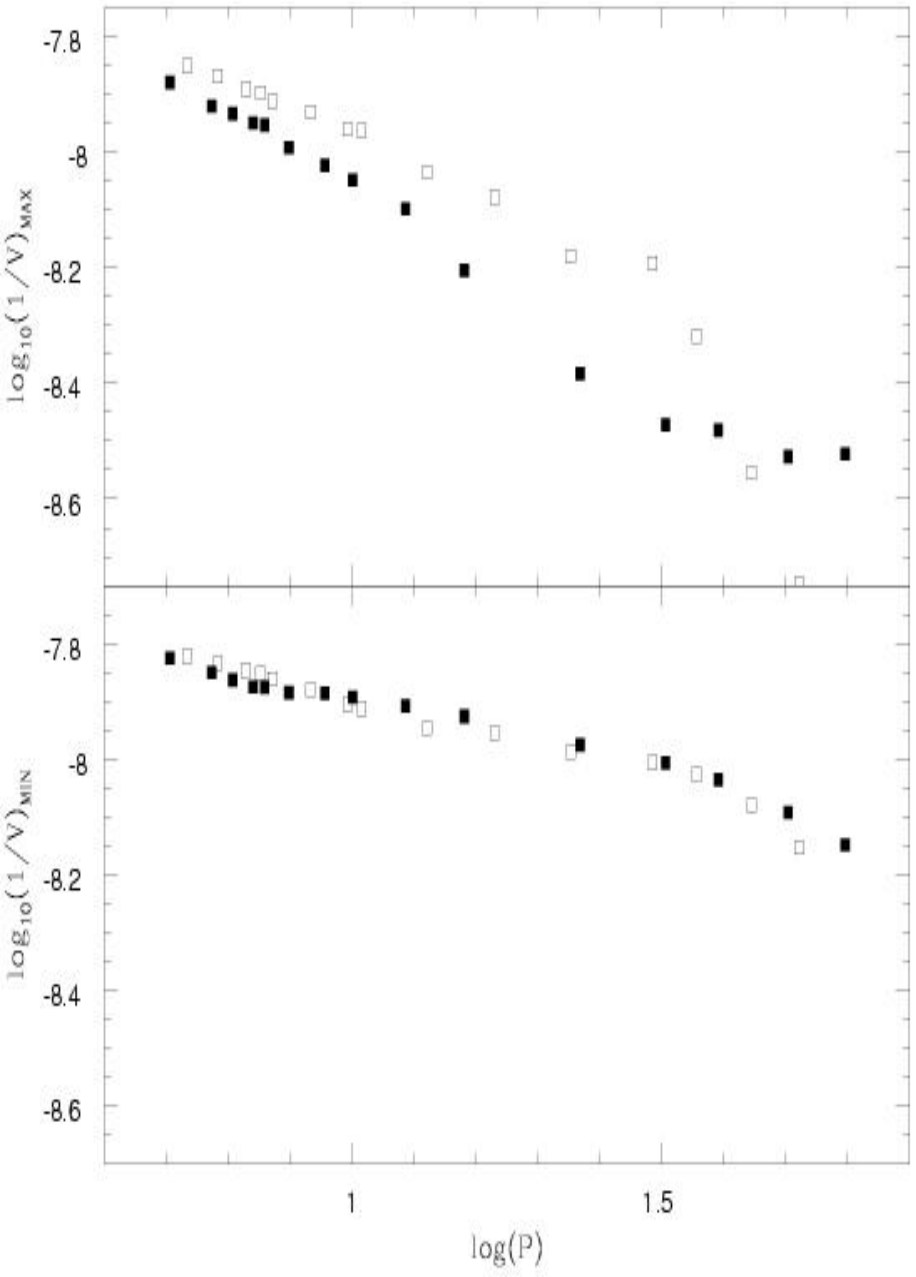
- In certain situations, the photosphere can lie at the base of the HIF.
- Further movement in very hard due to opacity wall.
- Then the temperature of the photosphere is very close to the temperature at which Hydrogen ionizes.
- In this situation, the color of the star is the temperature at which Hydrogen ionizes.
- 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.
- Mean light relations are averages of relations at different phases.


GAL models
Δ(MAX)
log(P)
LMC models
Δ(MAX)
log(P)


GAL models
Δ(MIN)
log(P)
LMC models
Δ(MIN)
log(P)



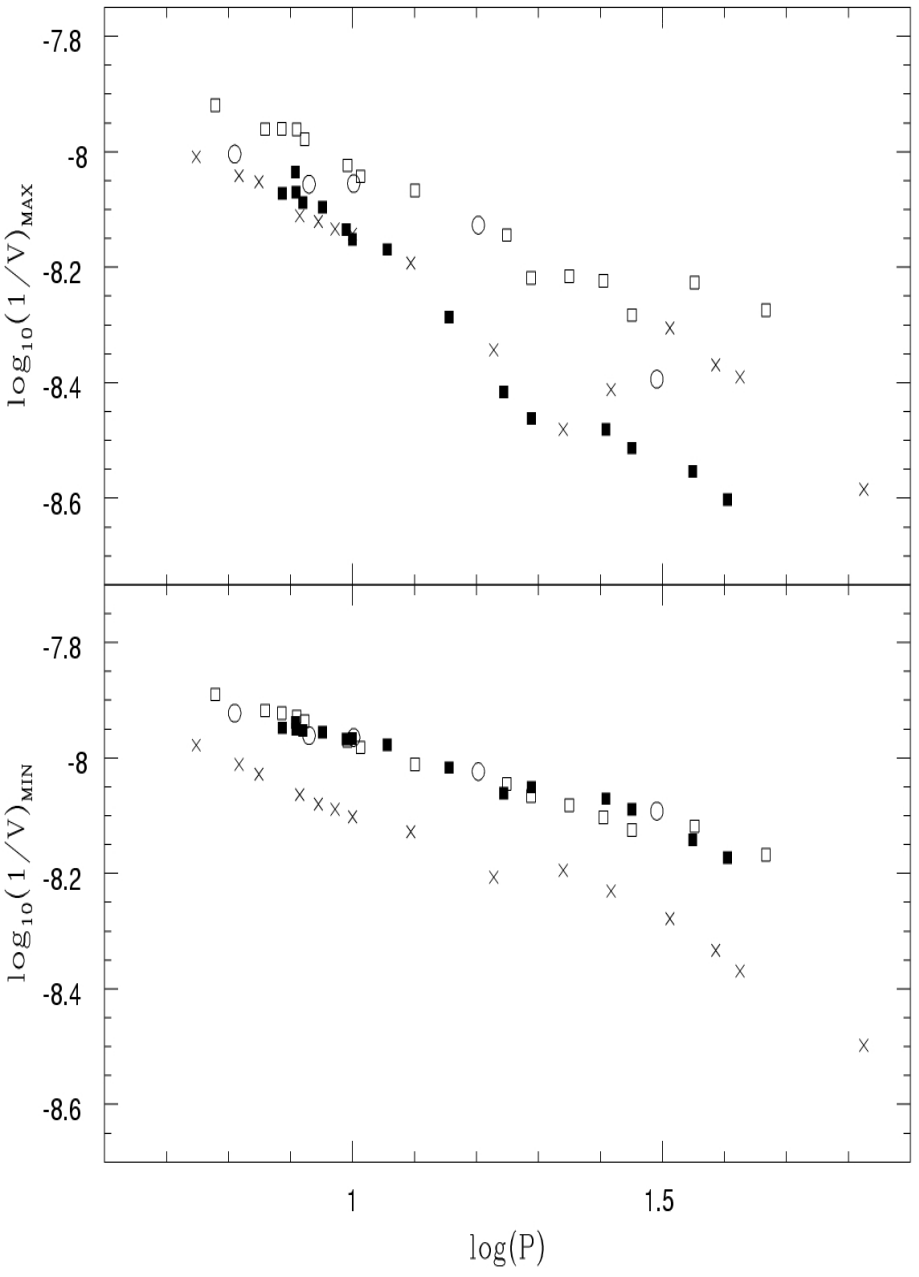


Figure 2: The photospheric density ($1/V$, where V is the specific volume) at maximum (top) and minimum (bottom) light in the theoretical models. The left panel shows the results from the SMC models with two ML relations. The rights panel show the comparison between the LMC models (open and solid squares) and the Galactic models (crosses). The right panel is adopted from KN.

Period-Color Relation in Cepheids

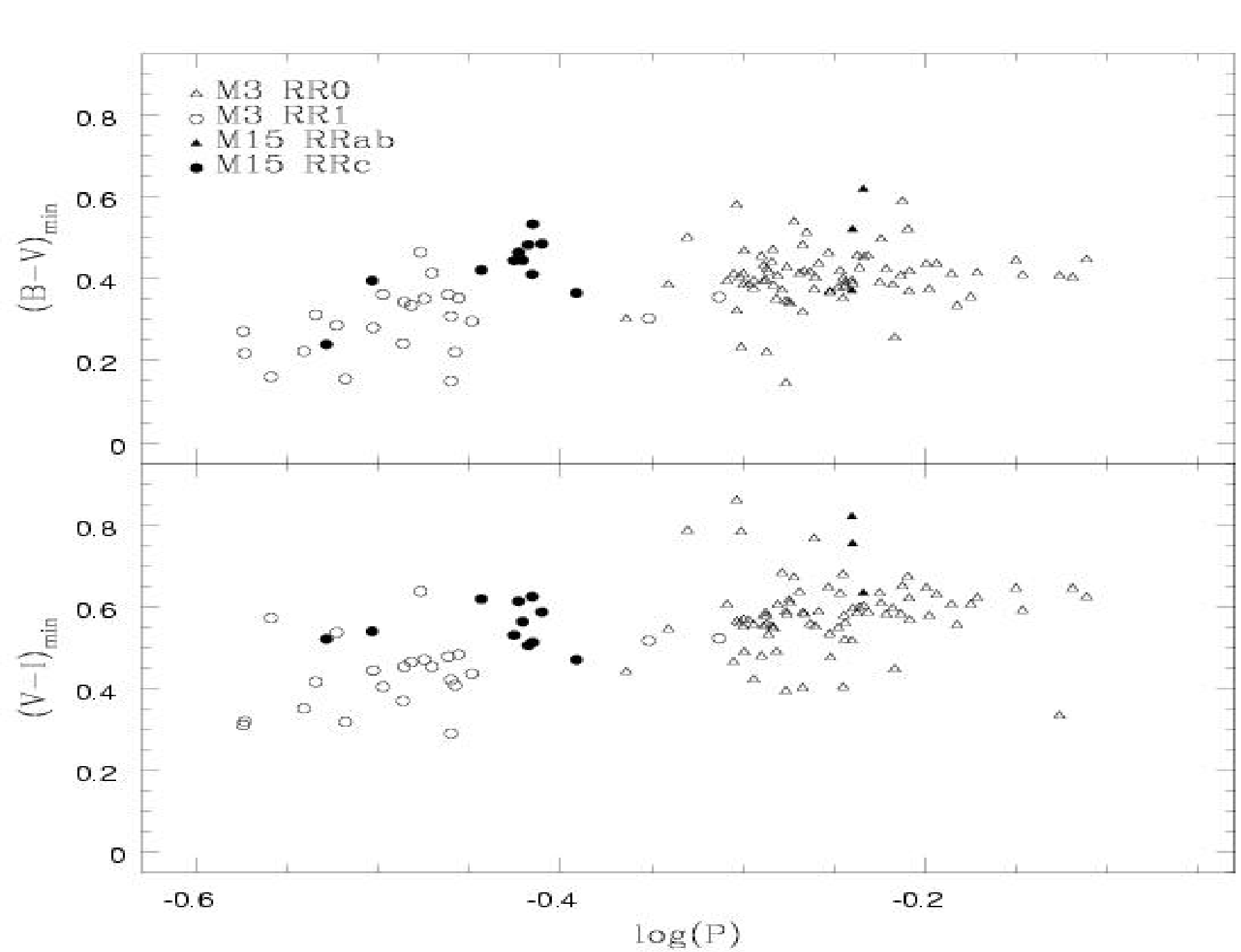
- Because the photosphere and HIF are either engaged or not, such changes can be sudden.
- Only occurs when the interaction is at low densities.
- Because the relative location of the HIF/photosphere changes as the L/M and T_e change, the nature and extent of the HIF/photosphere interaction is a function of period, phase and metallicity.
- PC relation affects PL relation.

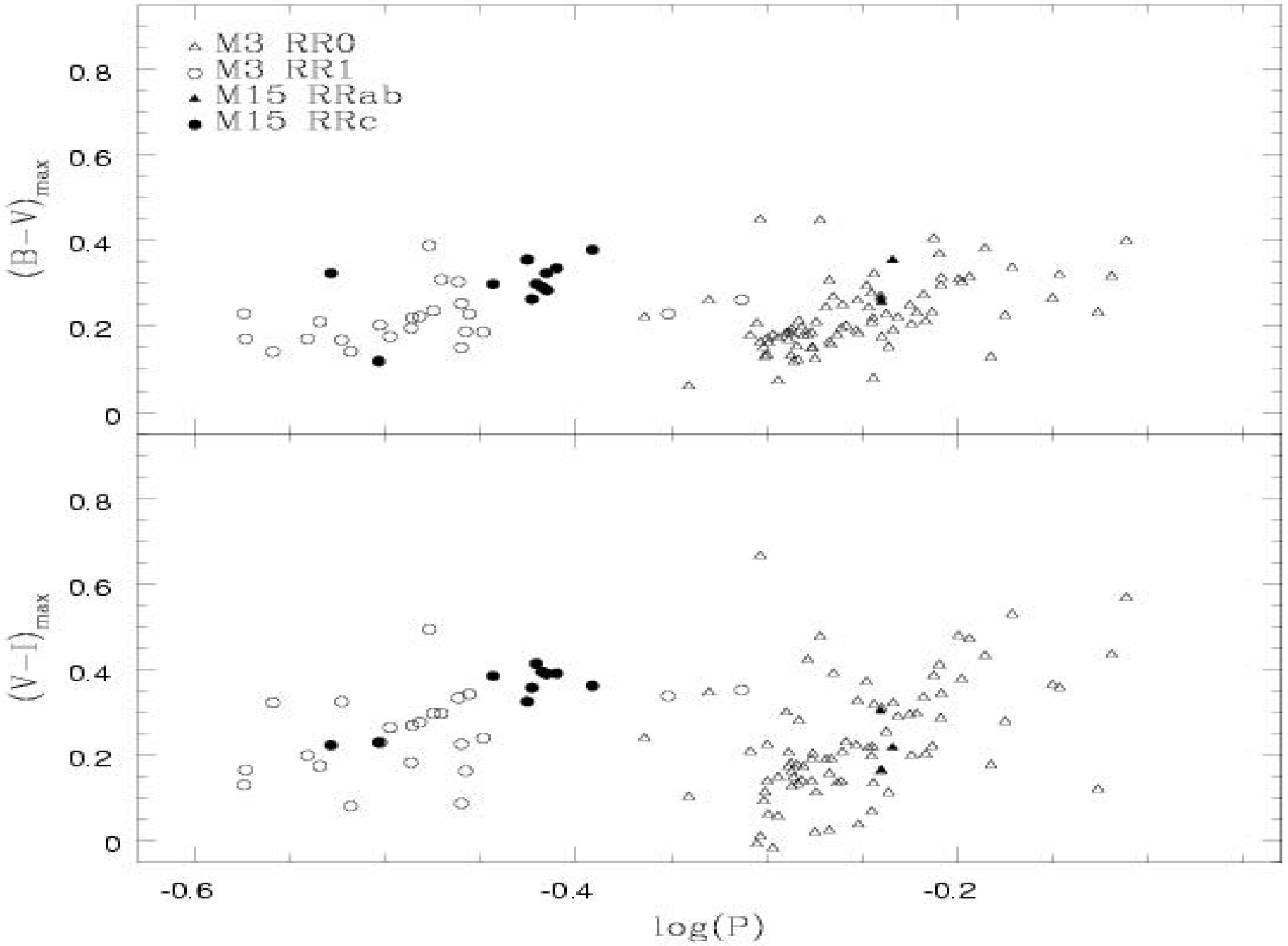
RR Lyraes

- PC relation at minimum light is flat
- Sturch, Clementini et al (1996), Kanbur and Phillips (1996), Kanbur and Fernando (2005), Guldenshue et al (2005), Kunder et al (2006).
- AC relation at maximum light such that higher amplitude stars are driven to bluer colors at maximum light.
- PC relation at minimum light used to estimate reddening.
- Could also use AC relations.

RR Lyraes

- PC relation at minimum light is flat because HIF is further out in the mass distribution.
- HIF-photosphere interaction only occurs at a low range of densities at minimum light.
- At other phases interaction is at a larger range of density and so more sensitive to temperature i.e.. There is PC(max) relation.
- Working on the situation at maximum light or as the star brightens from minimum.


M3 RR0
M3 RR1
M15 RRab
M15 RRc
$(B-V)_{min}$
$(V-I)_{min}$
0
0.2
0.4
0.6
0.8
-0.6
-0.4
-0.2
log(P)


M3 RR0
M3 RR1
M15 RRab
M15 RRc
$(B-V)_{max}$
$(V-I)_{max}$
0
0.2
0.4
0.6
0.8
-0.6
-0.4
-0.2
log(P)

Future

- 2 weeks of time on SMARTS facilities in Cerro-Tololo, Chile using CPAPIR CCD from Montreal. 20 nights in November 2007/January 2008. 3 nights with 2.5m Las Campanas telescope (6.5x6.5 minute FOV) in August 2007).
- Same pointings as OGLE/MACHO LMC: develop infra-red light curves for OGLE/MACHO LMC Cepheids: data currently being reduced in SUNY Oswego and NOAO (Lucas Macri).
- Check non-linearity in infra-red. Spitzer PL relation.
- PCA templates for IR light curves.
- Definitive test of non-linearity with results from HST Legacy survey plus LMC Shallow Survey.
- Further IR LMC/SMC observations with 1.5m LNA Brazil (4 nights September 2007) plus Antonio Kanaan of UFSC: robotic telescope.
- DIRECT data for M31/M33 CFHT data for M31 in Sloan filters, NGC 4258 (water maser galaxy).
- More modeling, PCA analysis.
- RR Lyraes: M15 observations, M31 data, modeling, PCA –light curve structure relations.
- New Statistical tests (Nanthakumar and Koen and Daphne Zhang).

The Robotic Telescope Project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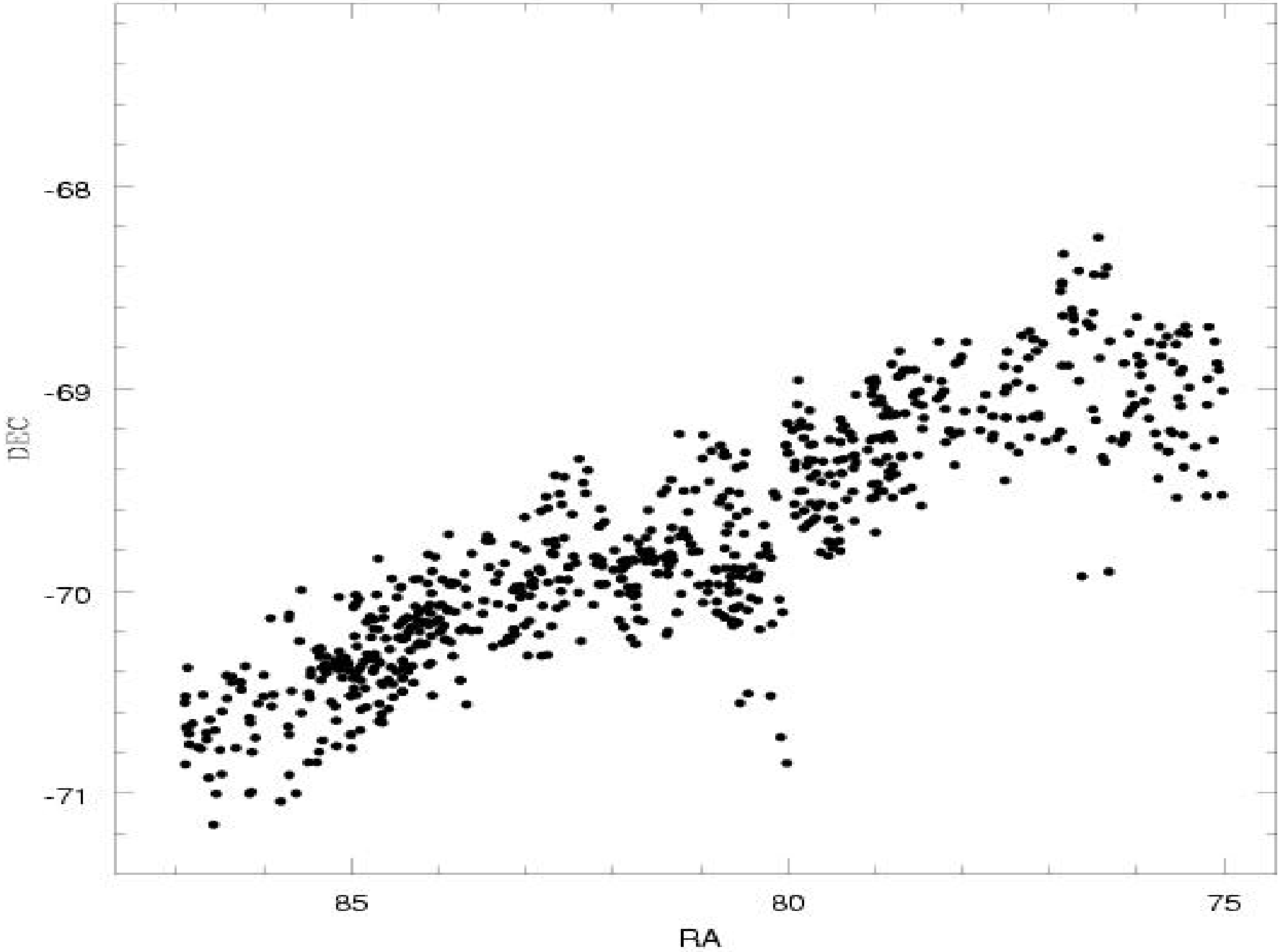
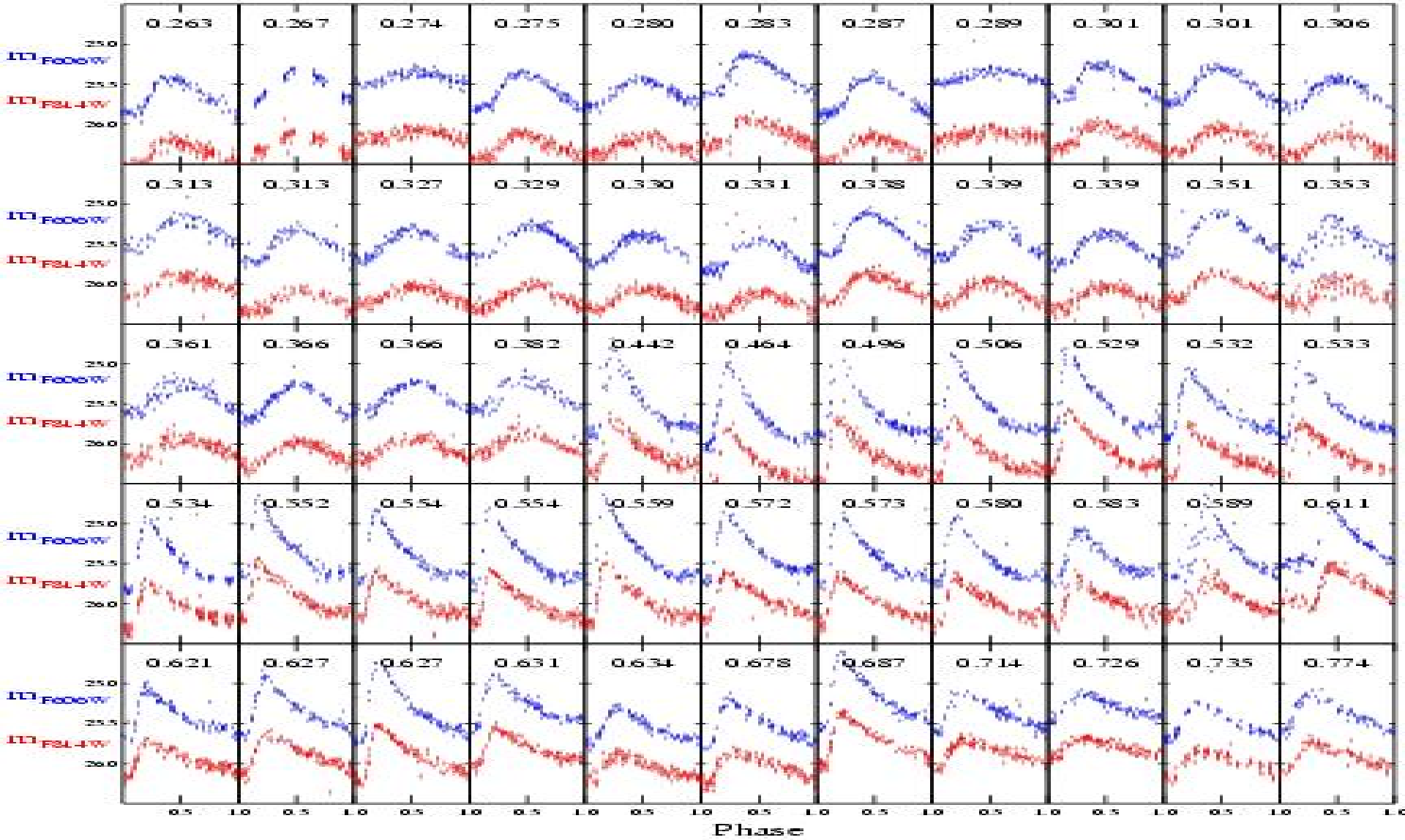
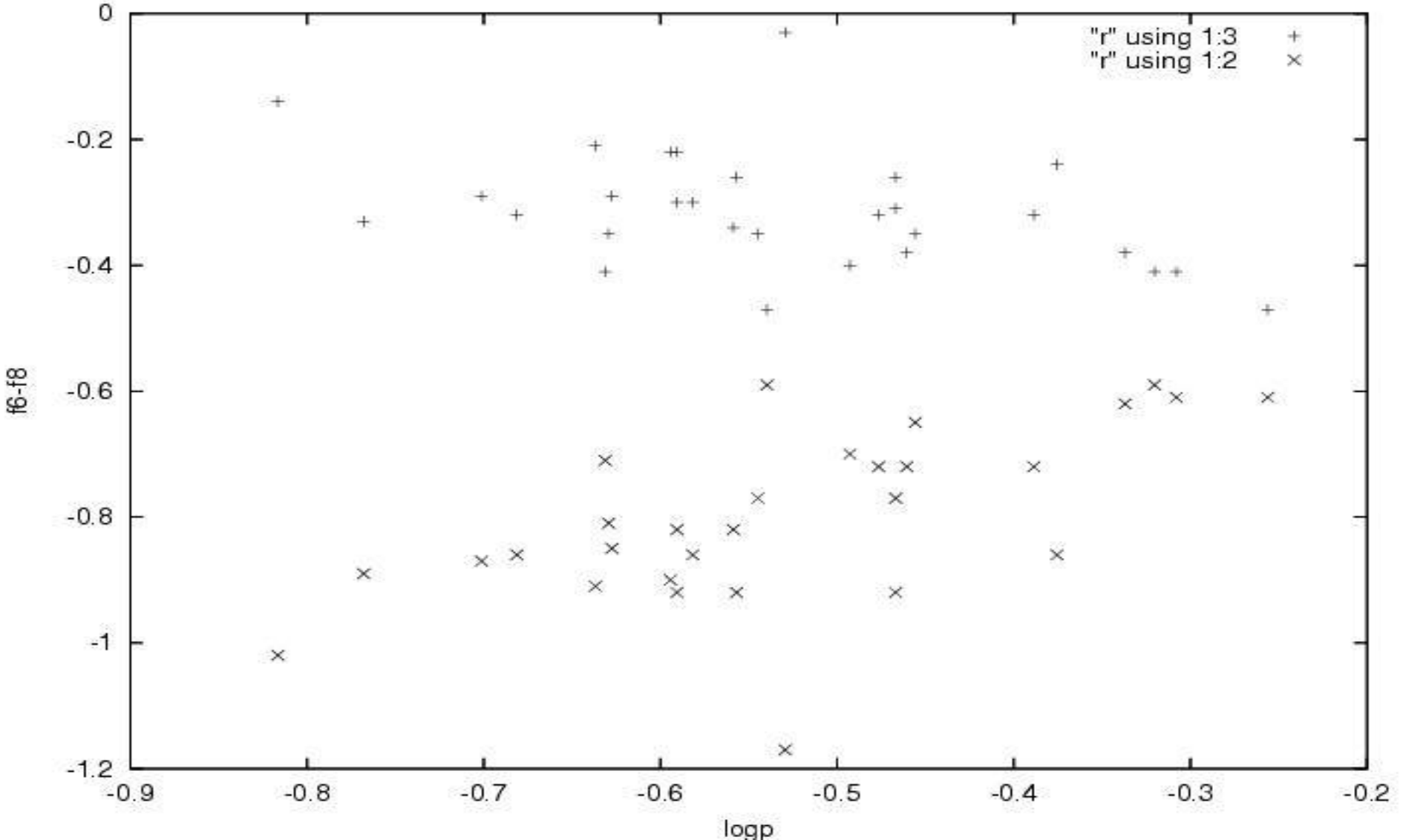
The SUNY Oswego LMC Cepheid IR Survey


-68
-69
-70
-71
DEC
85
80
75
RA

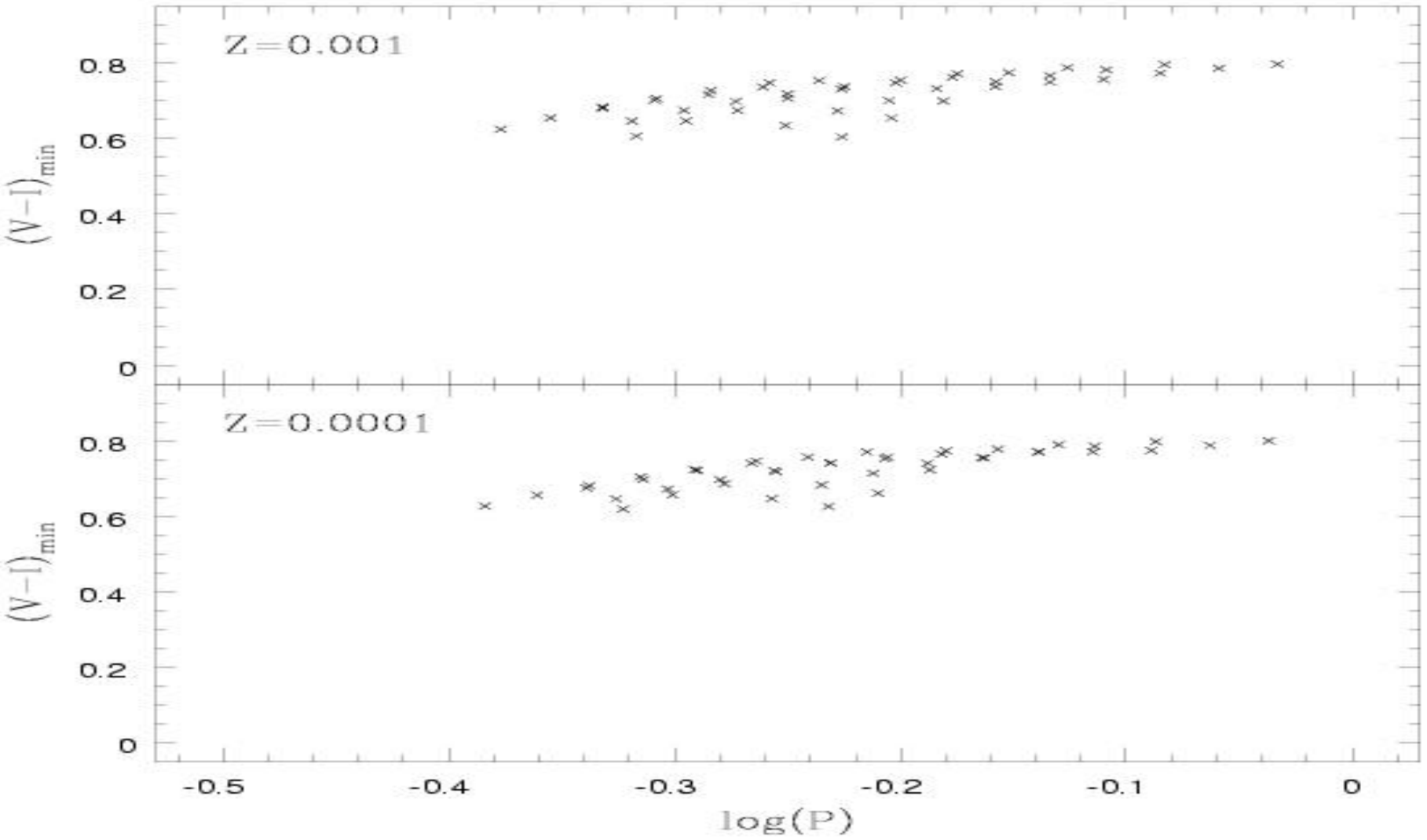
RR Lyraes in M31



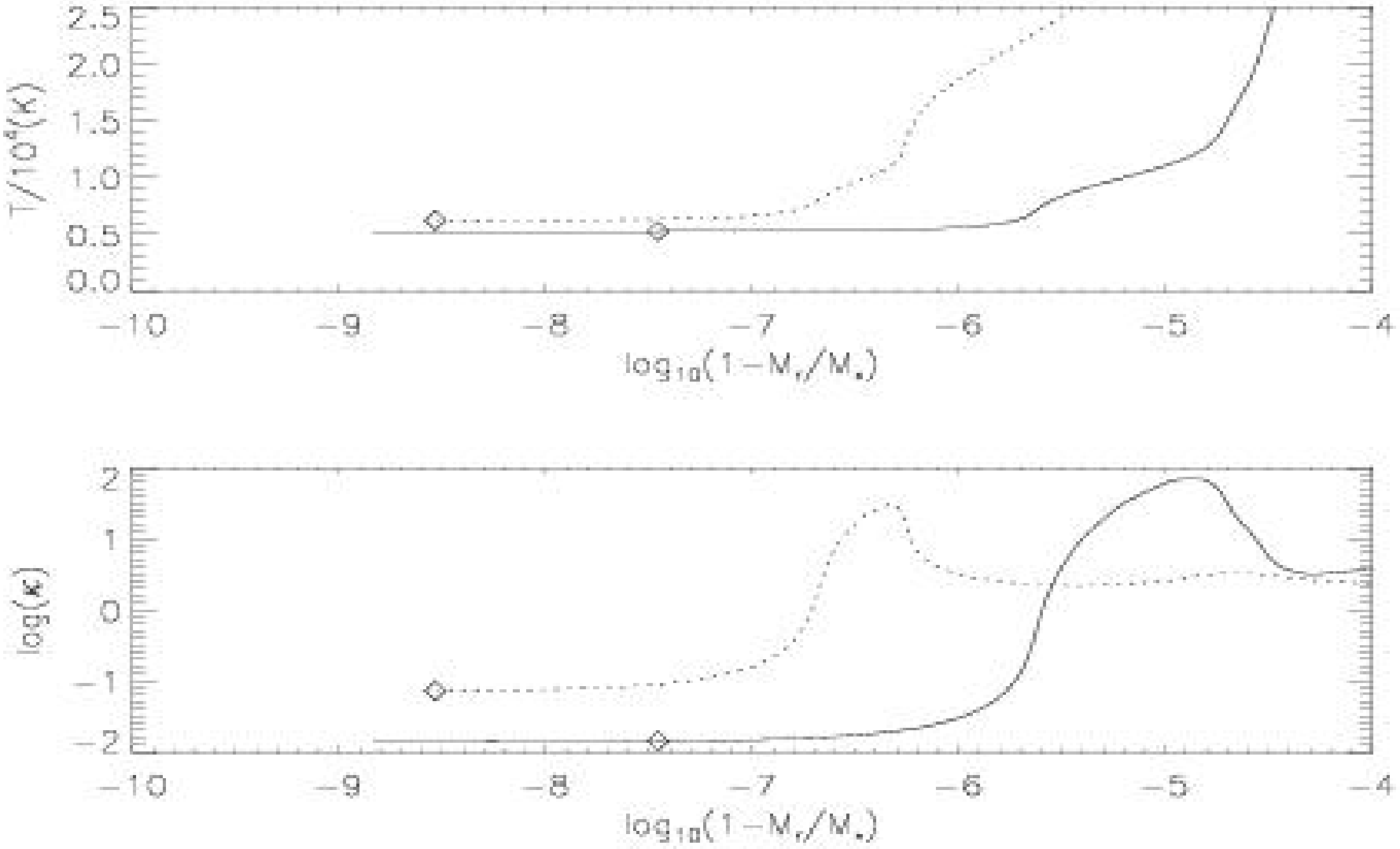
Period-Color Relations in M33



Theoretical RR Lyrae models



Cepheid Evolution



M33 © IAC/RGO/Malin
Photo from Isaac Newton Telescope Plates
by David Malin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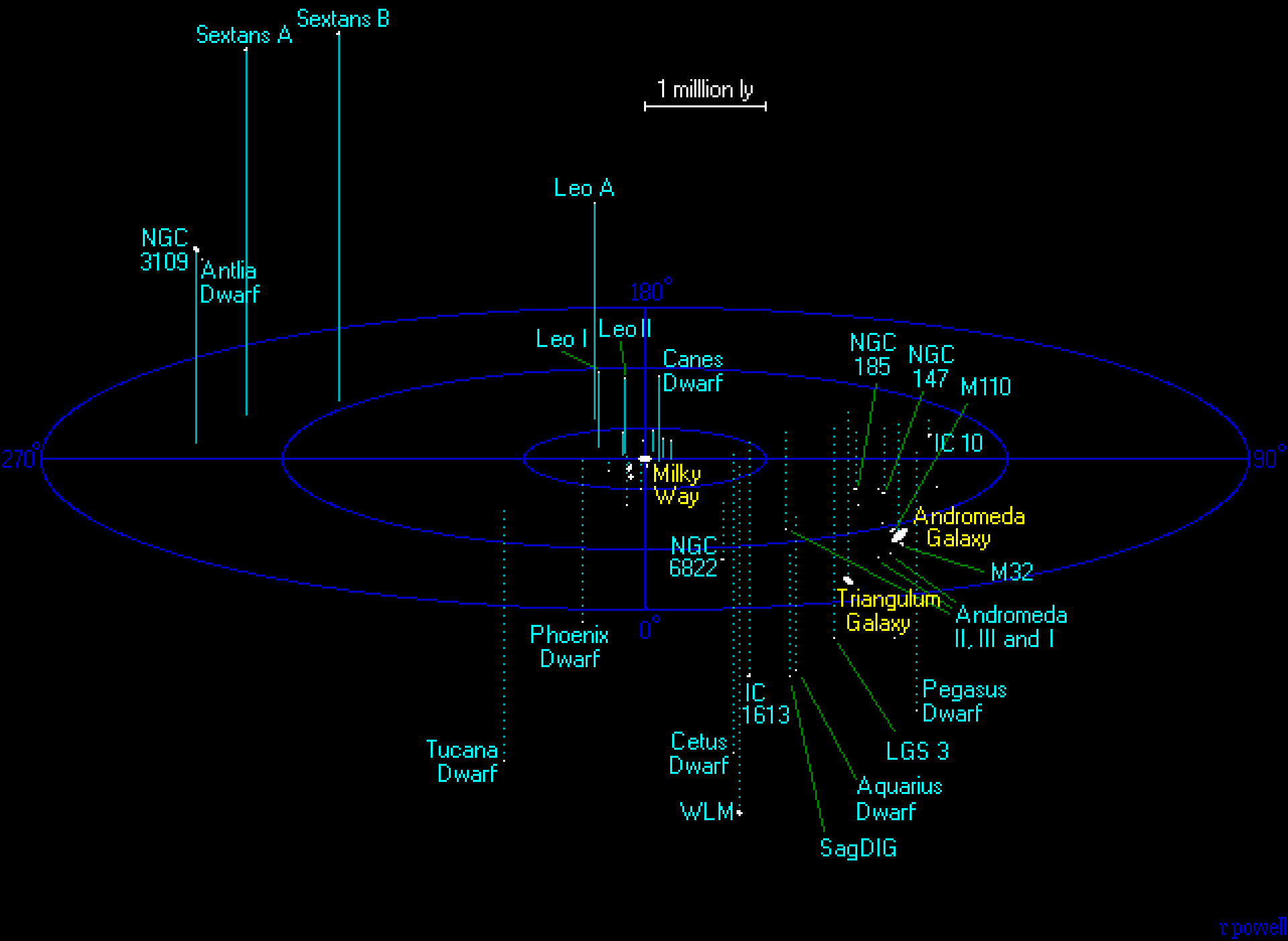
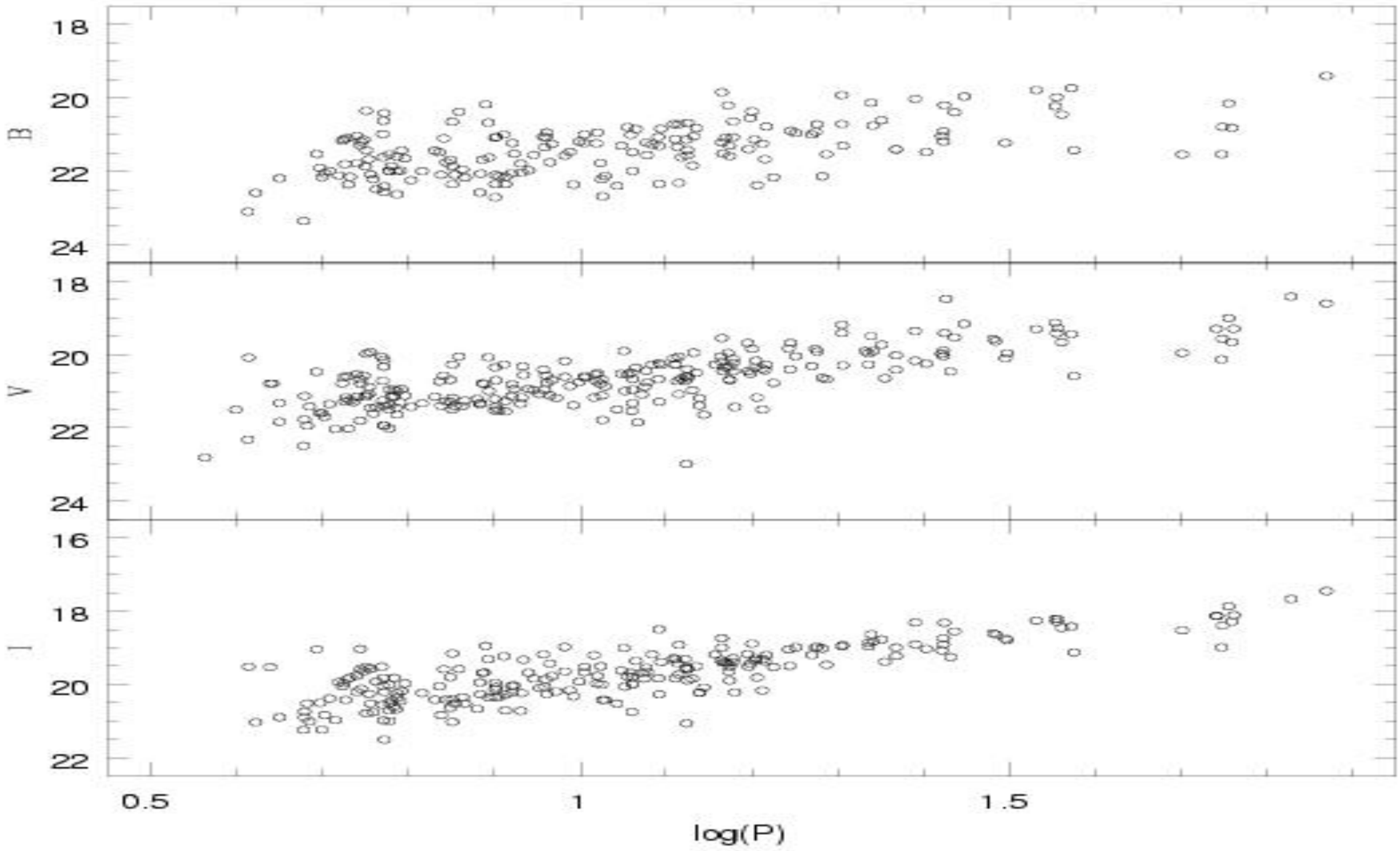

Sextans A
Sextans B
1 milllion ly
Leo A
NGC
3109
Antlia
Dwarf
180°
Leo I
Leo II
Canes
Dwarf
NGC
185
NGC
147
M110
IC 10
270°
90°
Milky
Way
Andromeda
Galaxy
NGC
6822
M32
Triangulum
Galaxy
Andromeda
II, III and I
0°
Phoenix
Dwarf
IC
1613
Pegasus
Dwarf
Tucana
Dwarf
Cetus
Dwarf
LGS 3
Aquarius
Dwarf
WLM
SagDIG
rpowell

The PL Relation in M33



PCA and Light Curve Structure