Baade-Wesselink distances to Cepheids (and the metallicity effect on the PL-relation)

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Overview

- Introduction
- A short history of the method
- Baade-Wesselink distances to Galactic Cepheids (Groenewegen 2013)

A closet full of Skeletons....

Overview

- A short history of the method
- Baade-Wesselink distances to Galactic Cepheids (Groenewegen 2013)
- A closet full of skeletons....
  Comparison to Storm et al. (2011)

  essentially same data, same method,
  same calibrators
- Population Synthesis of Classical Cepheids

Introduction

- Cepheids provide the link to the galaxies with SN Ia

- Cepheids with parallaxes

Feast & Catchpole (1997)
$M_{\rm V} = \delta \log P + \rho$
$10^{0.2\rho} = 0.01\,\pi\,10^{0.2\,(V_0 - \delta \log P)}$

220 Cepheids in *Hipparcos*
LMC slope $\delta = -2.81 \Rightarrow \rho = -1.43 \pm 0.10$
LMC DM= 18.70 ± 0.10

Introduction

- Cepheids in clusters

  main-sequence fitting (Feast 1999, Turner 2010)
  Pleiades

- Cepheids in Eclipsing Binaries

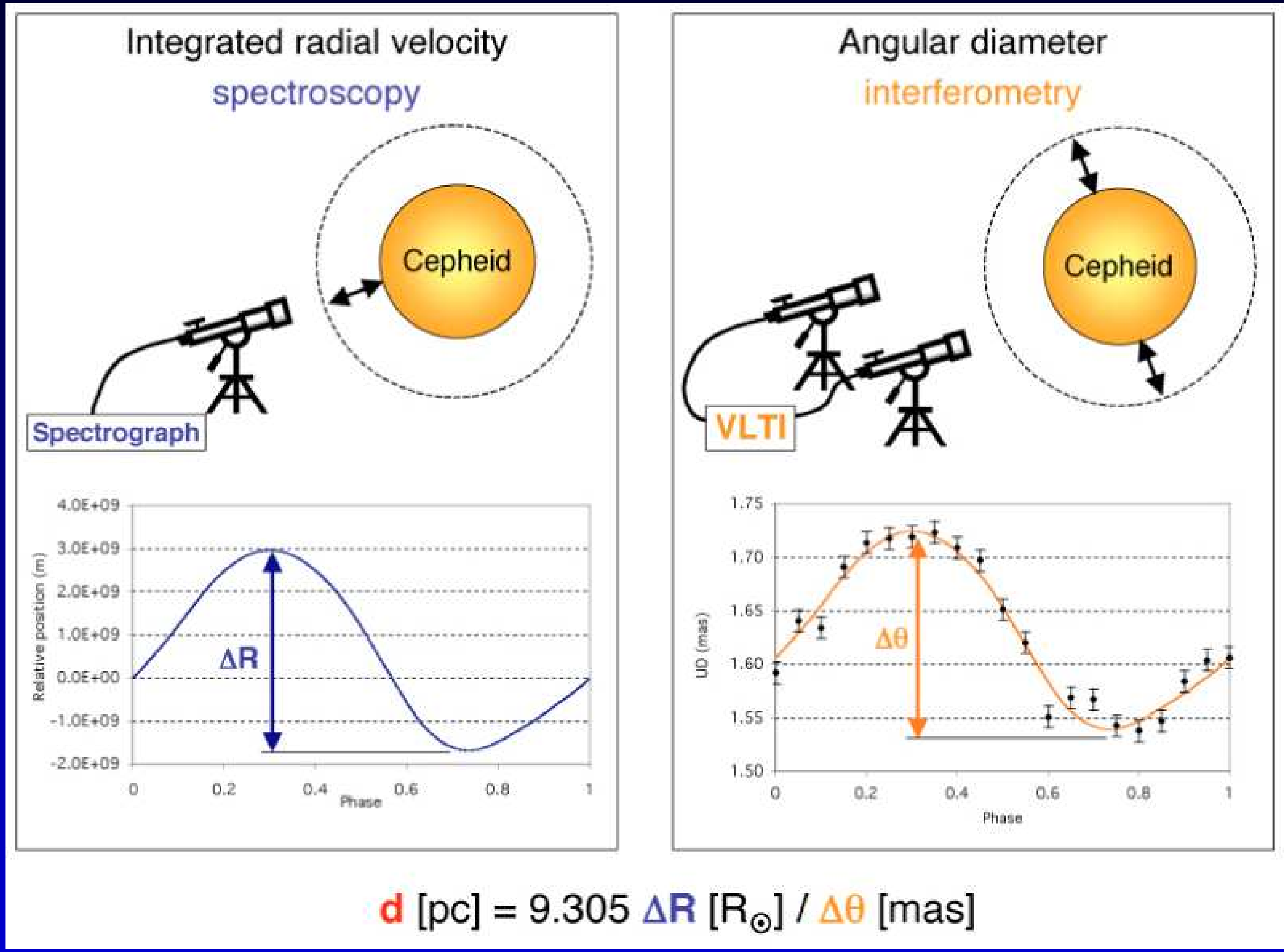
  Pietrzynski et al. (2010), Pilecki et al. (2013), LMC-CEP-227

  Pietrzynski et al. (2011), LMC-CEP-1812

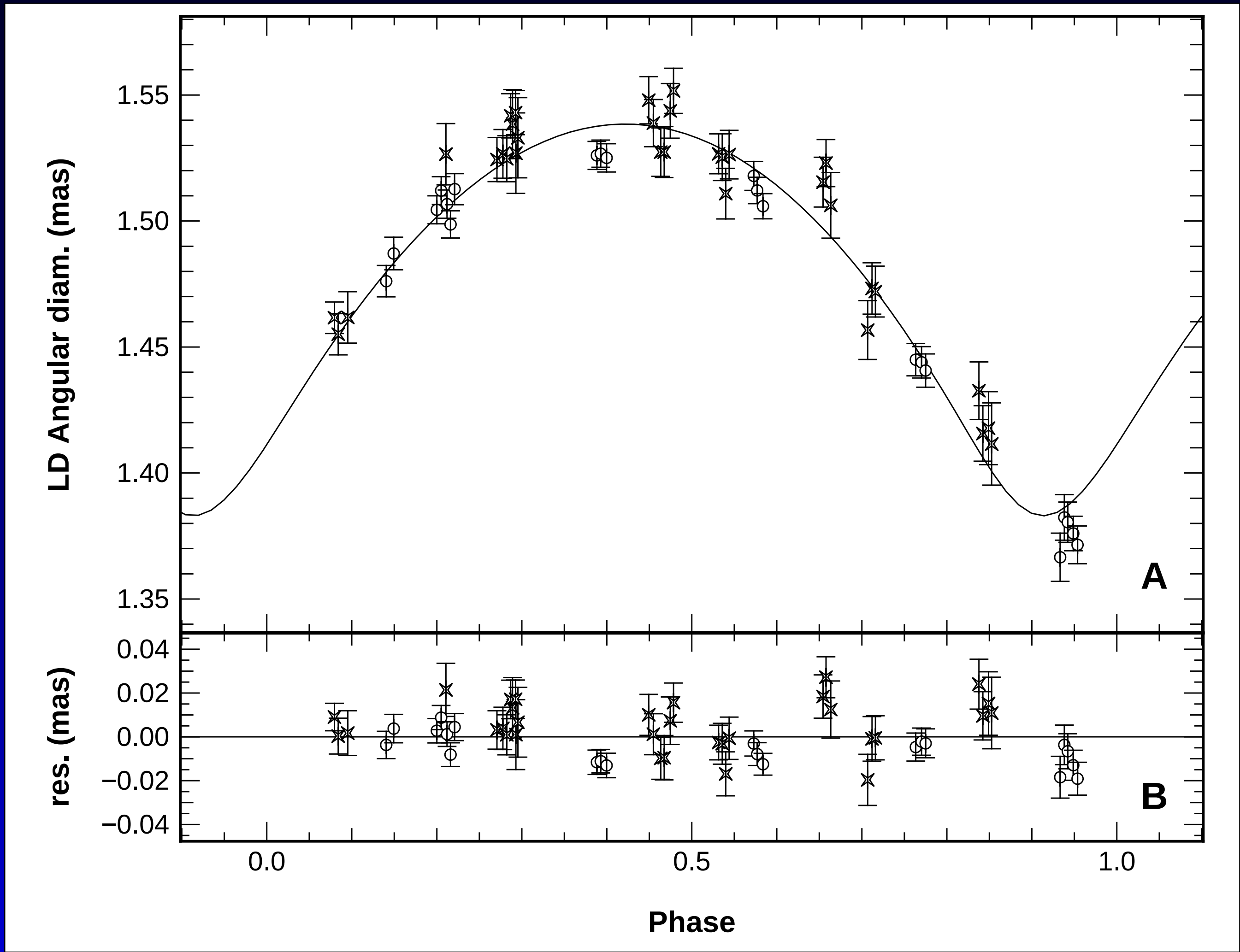
  Gieren et al. (1403.3671), LMC-CEP-1718: Two FO cepheids

- Baade-Wesselink distances

Baade-Wesselink distances

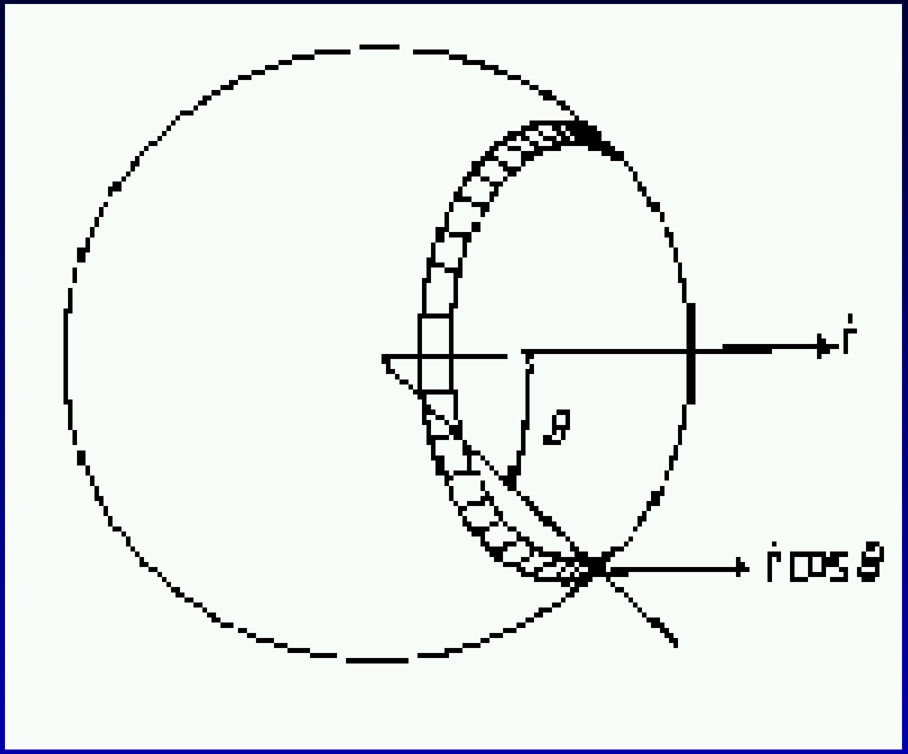


Angular diameter from interferometry, or surface-brightness relation (i.e. lightcurve in colour)



Interferometric observations of δ Cep (Mérand et al. 2005)

p-factor



projection factor

-geometrical effect
-limb-darkening
-$p = 1.4$

$$R(t) - R(t_0) = -p\ P \int_{\phi(t_0)}^{\phi(t)} (v_{\rm R} - \gamma)\, d\phi$$

P = pulsation period, ϕ = phase (t/P),
γ = systemic velocity, $v_{\rm R}$ = radial velocity

Some history

- Mira (o Cet) discovered by Fabricius (1596)
- δ Cephei discovered by Goodricke (1784)
- Thought to be eclipses in a double star
- Schwarzschild (1900): In η Aql there is a continous variation in brightness *and* colour
- Brunt (1913)
  Radial velocity from spectra; only one component observed
- Shapley (1914)
  -The star is bigger than the orbit of the double star
  -radial pulsation
- PL-relation discovered by Leavitt (1912)

The "BW" method

- Walter Baade,
  1926, Astronomische Nachrichten 228, 359
  “Über eine Möglichkeit, die Pulsationstheorie der δ Cephei-Veränderlichen zu prüfen”
- Kurt Felix Bottlinger,
  1928, Astronomische Nachrichten 232, 3
  “Einige Untersuchungen über ζ Geminorum”
- Wilhelm Becker,
  1940, Zeitschrift für Astrophysik 19, 289
  “Spektralphotometrische Untersuchungen an δ Cephei-Sternen. X. Ein Beitrag zur Prüfung der Pulsationstheorie der δ Cephei-Veränderlichen durch die Beobachtung und eine unabhängige Ableitung der Perioden-Helligkeitsbeziehung”

- Armand van Hoof,
  1943, Koninklijke Vlaamsche Academie voor Wetenschappen, Letteren en Schone Kunsten 5, 12
  "Een nieuwe methode ter bepaling van de lineaire diameter en de absolute magnitude van cepheïden"

  1945, Ciel et Terre, Vol. 61, p. 11
  "Une nouvelle méthode pour déterminer le diamètre linéaire et la magnitude absolue des céphéides"
- Adriaan Jan Wesselink,
  1946, Bulletin of the Astronomical Institutes of the Netherlands 10, 91
  "The observations of brightness, colour and radial velocity of δ Cephei and the pulsation hypothesis"

The BW distances

Groenewegen (2008): 68 Galactic Cepheids
$p = 1.33$

Groenewegen (2013): 128 Galactic, 36 LMC, 6 SMC

individual metallicities [Fe/H] for all Galactic and 14 LMC, 1 SMC Cepheid !

(5 SMC, average of -0.68 [from JS])
(4 LMC in NGC 1866, -0.39, average of 3 other cepheids)
(other LMC, average of -0.34 [from JS])

PLZ-relation

Data

Metallicities

RV curve (...binarity...)

V-band lightcurve

K-band lightcurve

$(V - K)_0$ to use with a SB-relation to get θ

(reddening)

Surface-Brightness relation

Wesselink (1969)

$$F_{\rm V} = 4.2207 - 0.1 V_0 - 0.5 \log \theta$$

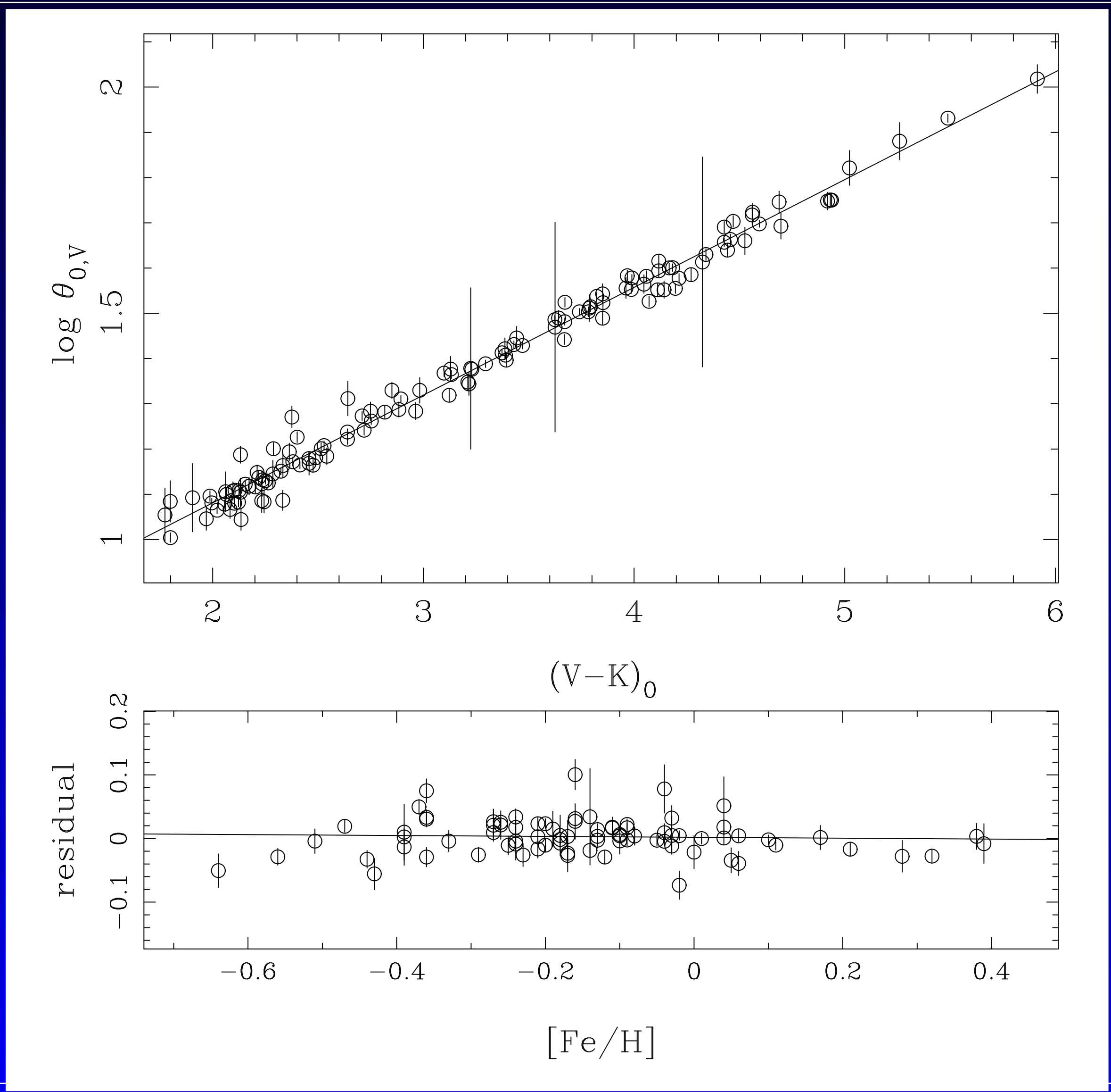
$$\theta_o = \theta \times 10^{(m_1/5)}$$

$$\log \theta_0 = a \times (m_2 - m_3) + b$$

Then:
V versus $(B - V)$, 18 stars, $\sigma = 20\%$

Now:
V versus $(V - K)$, 200 sterren, $\sigma = 5.5\%$

Surface-Brightness relation



Groenewegen (2004)

Fouqué & Gieren (1997)

Kervella et al. (2004)

GP: improving

Method

- Externally:
  Use Period98 to check datasets, remove outliers
  Offsets
  Correct for orbital motion
  Set order of Fourier series ; BIC
- Read in V, K,RV data
  Fit Fourier series; fit period from V-band
  (fix for K and RV)
- Interpolate V-band to the times of the K-band
  data to get $(V - K)$
  De-redden; get θ
- ΔR Analytical; error in Fourier coefficients

Method

- Fit ΔR versus $\Delta\theta$, to find distance and mean radius

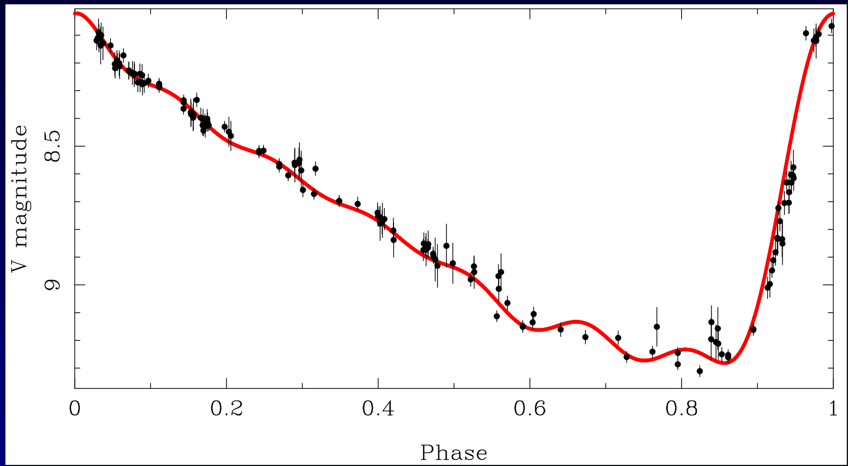
  G08: Bi-sector (JS 2004; SIXLIN from Isobe et al. 1990)

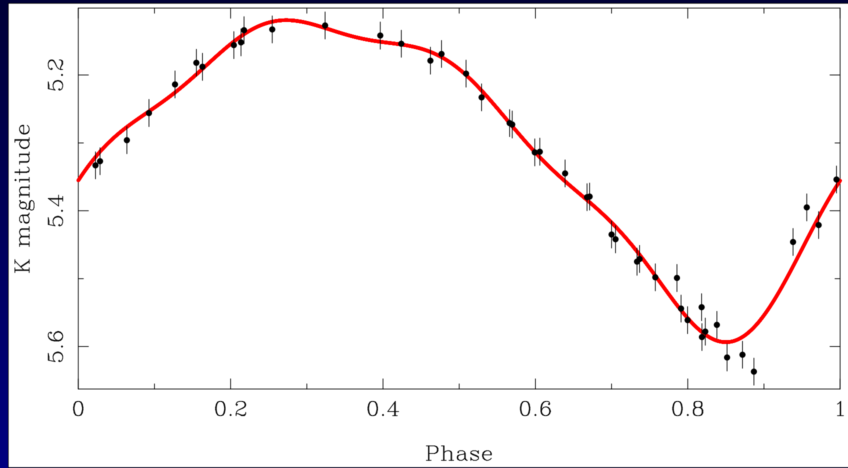
  G13: Bivariate Correlated Errors and intrinsic Scatter (BCES) method (Akritas & Bershady 1996)

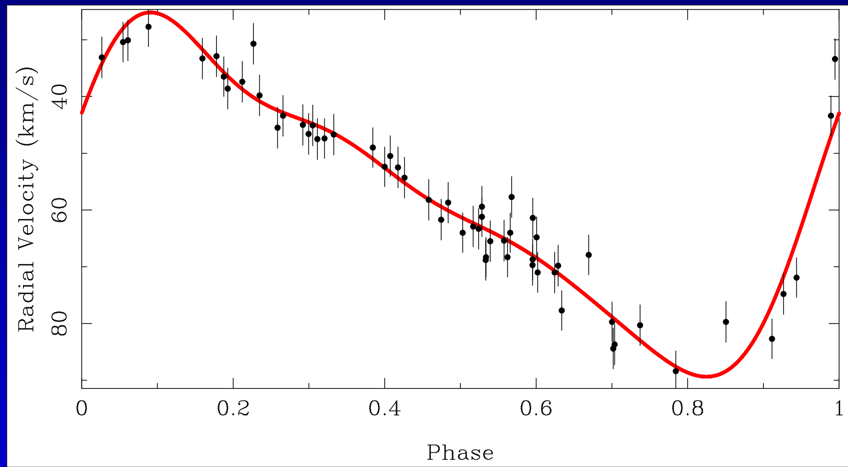
- Formal fit error &

  Monte Carlo simulation:
  -error in every photometry and RV data point
  -error in $E(B-V)$
  -"error" in terms in Fourier series

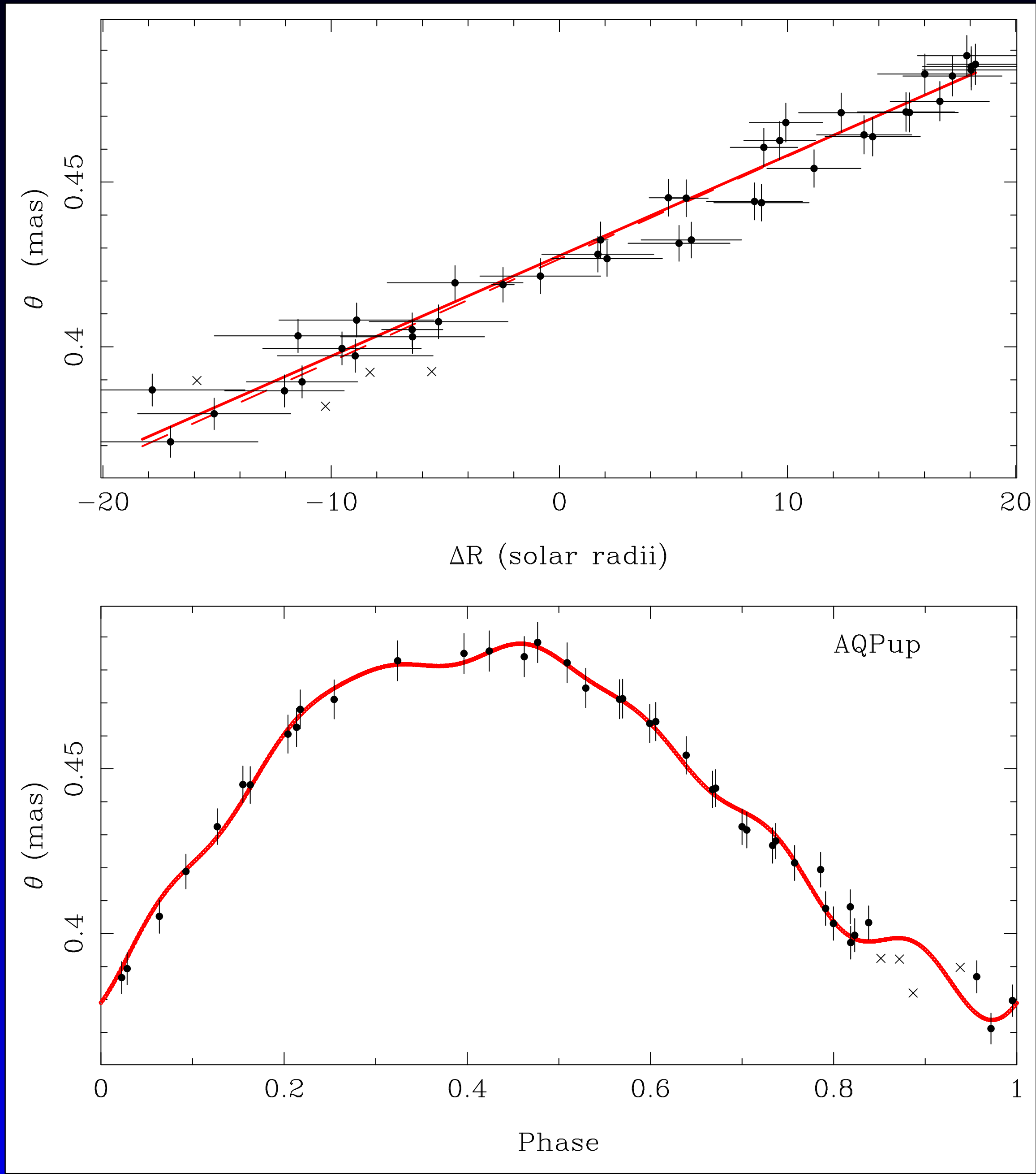
An Example







V, K, RV phased light curves for AQ Pup



θ vs. ΔR gives distance. AQ Pup

Results

- $p = p_0 + a \log P$
- slope:
  distance to LMC should not depend on period
- zeropoint: Cepheids with known distance

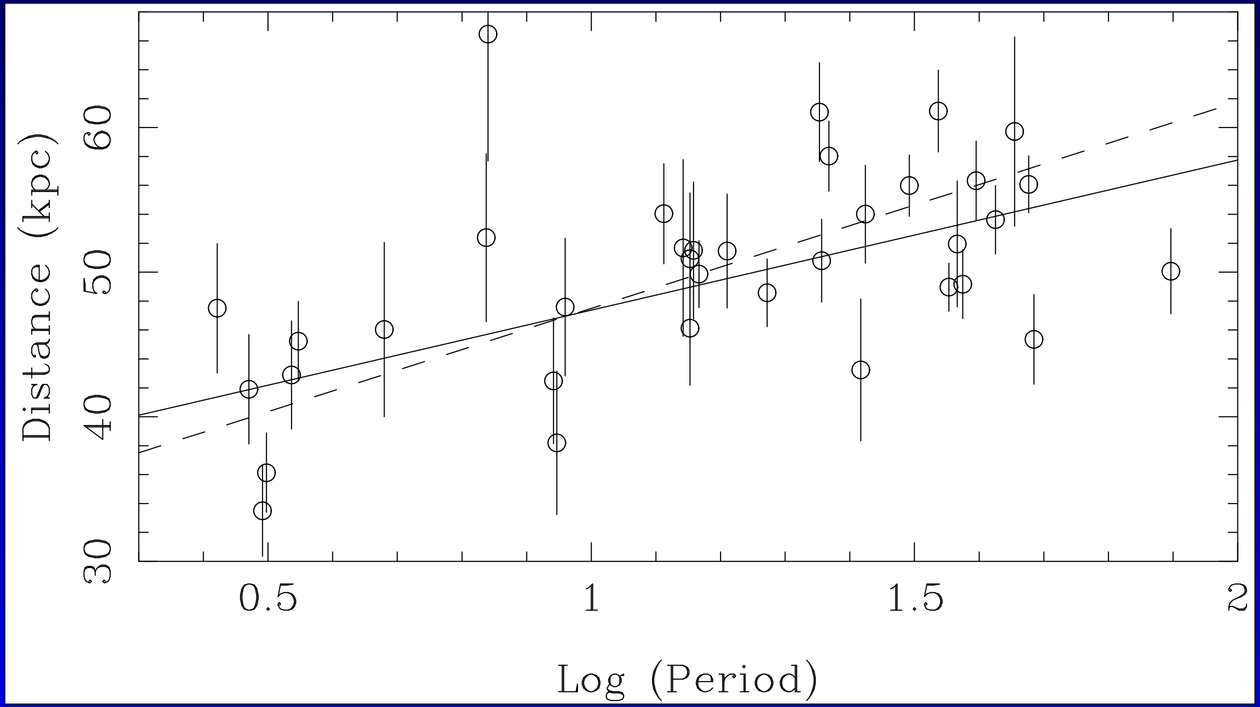
  Gieren et al. (2005), S11:
  $p = (1.58 \pm 0.02) - (0.150 \pm 0.05) \log P$
  $p = (1.55 \pm 0.04) - (0.186 \pm 0.06) \log P$

G13:

Distance to the LMC should be independent of Period

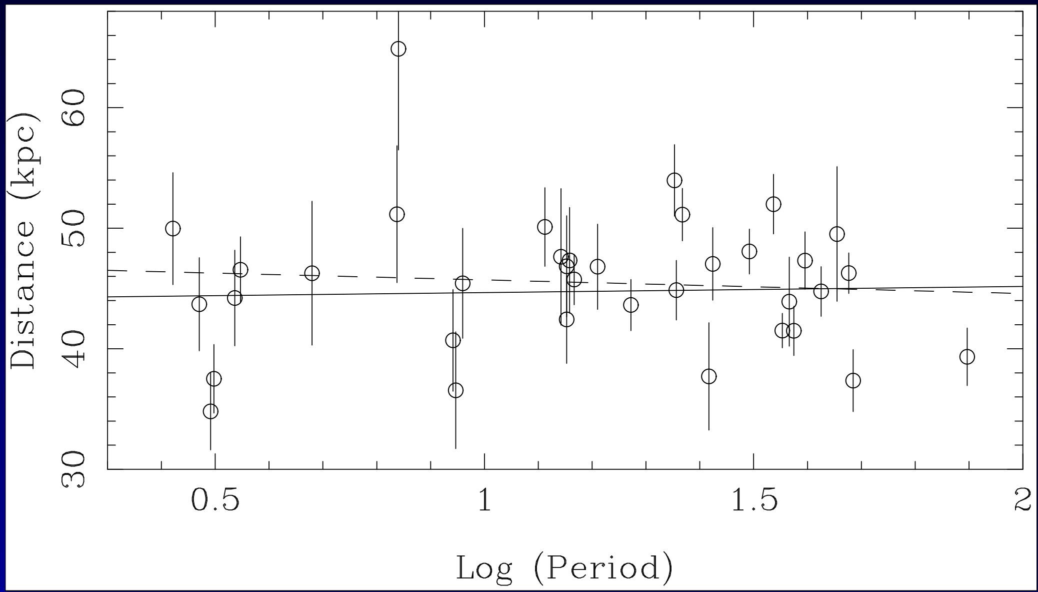
Distance to the LMC should be independent of (mean) $(V-K)$ colour

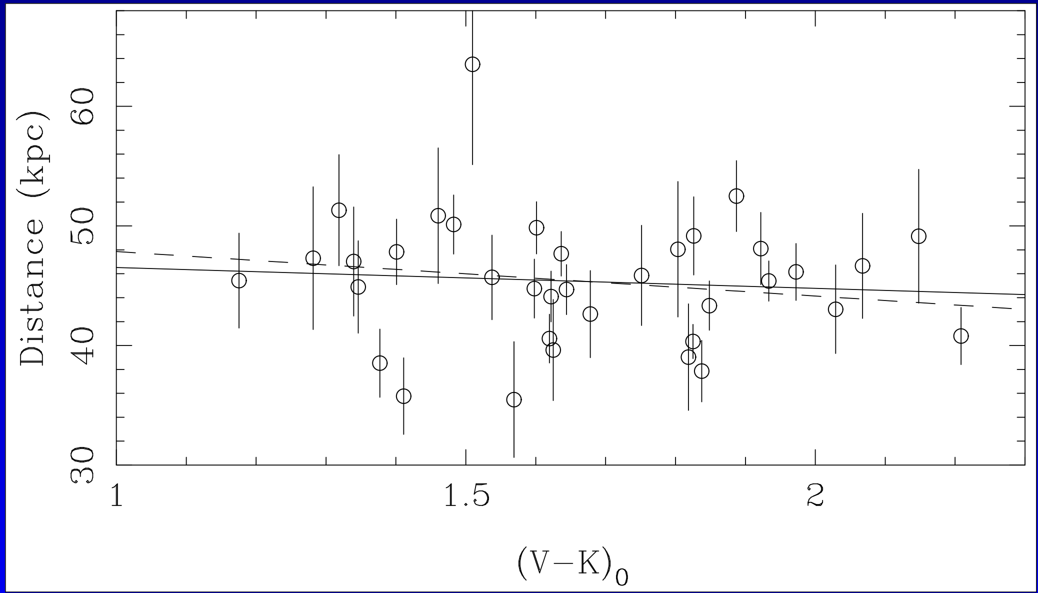
Slope of the $M_{\rm V\ or\ K} - P$ relation should be the same as the $m_{\rm V\ or\ K} - P$ one



LMC distance (corrected for "plane") versus Period for $p = 1.33$

$p(P)$ dependence





$$1.50 - 0.24 \log P$$

$p(P)$ zeropoint

- HST and revised *Hipparcos* parallax
  8 stars (10 - 2 outliers)
- Clusters
  18 clusters (21 - 3 outliers)

$$p = 1.50 - 0.24 \log P$$

PL(Z)-relations

$M_{\rm K} = (-2.49 \pm 0.08) + (-3.07 \pm 0.07) \log P$
+ $(-0.05 \pm$ 0.10) [Fe/H]   (all 162)

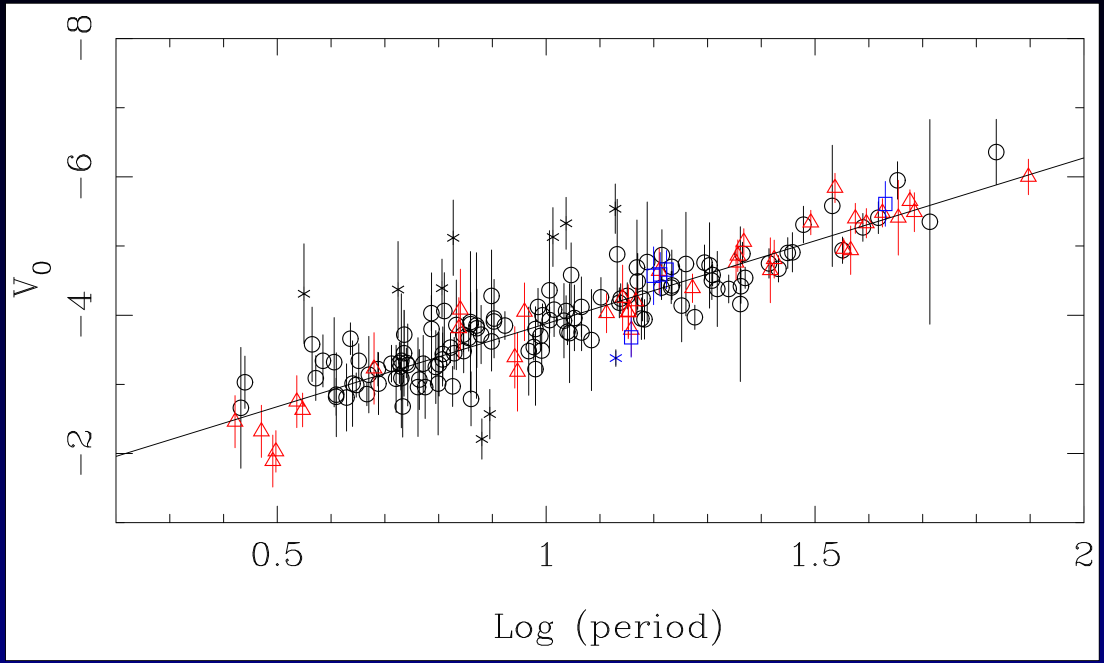
(121 GAL: $\gamma = +0.07 \pm 0.20$)

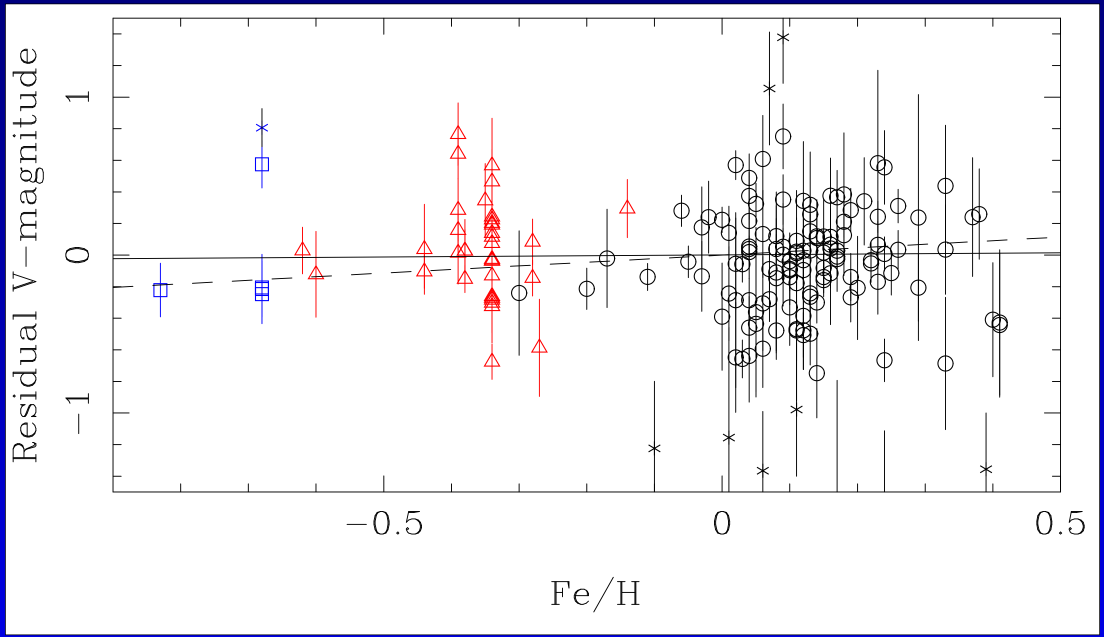
$M_{\rm V} = (-1.55 \pm 0.09) + (-2.33 \pm 0.07) \log P$
+ $(+0.23 \pm$ 0.11) [Fe/H]

(121 GAL: $\gamma = +0.17 \pm 0.25$)

$M_{\rm VK} = (-2.68 \pm 0.08) + (-3.11 \pm 0.07) \log P$
+ $(+0.04 \pm$ 0.10) [Fe/H]

(120 GAL: $\gamma = +0.34 \pm 0.20$)





V-band PL-relation

Summary

- steep P-dependence of p-factor
- marginal to no metallicity dependence (2σ in V)
  $\gamma_{\rm WVK} \sim 0$
  $\gamma_{\rm K} < \gamma_{\rm V}$
  $\gamma_{\rm V} - \gamma_{\rm K} \sim 0.3$
- Current distance scale is shorter than S11
  At a typical period of 10 days,
  $1.364/1.260 = 1.08$.

  LMC 45.5 ± 0.47 kpc (18.29 ± 0.02)
  SMC 55.7 ± 1.4 kpc (18.73 ± 0.06)
  (S11: 18.45 ± 0.04)

Differences

- SB-relation, reddening, data sets
- Technical issues
  fitting or fixing a period
  number of harmonics
  interpolating
  actual fitting of $\Delta\theta$ and ΔR
  excluding a phase range in the fit
- HST parallax versus HST & Hipparcos parallax (Lutz-Kelker bias plus some cluster data)
- Compare ratios, cf. $d_{\rm BW}/d_{\rm calib}$ (weighted mean), or relative differences $(d_{\rm BW} - d_{\rm calib})/(0.5 \cdot (d_{\rm BW} + d_{\rm calib}))$ (unweighted mean), to calibrate the zeropoint of the p-factor relation.

Differences

- SB-relation:
  θ (S+11/G13) is 1.0055, respectively, 1.0048, at $(V - K)$ = 1 and 2.5, respectively.
- Reddening:
  $E(B - V)$ taken from Fouqué et al. in both studies for GAL; took JS for MCs
  S+11: $R_{\rm V} = 3.23$, $A_{\rm K}/A_{\rm V} = 0.119$;
  G13: $R_{\rm V} = 3.3$, $A_{\rm K}/A_{\rm V} = 0.115$
- Data:
  -tranformations
  -offset (in RV)
  -RV determination itself
  -binary
  -limit in JD ($\dot{P}$)

Differences

	unweighted mean	weighted mean	median
<u>1: method: S+11</u>			
<u>1: BW: S+11, Calib: S+11</u>			
$1.54 - 0.186 \cdot \log P$	0.0070	0.0088 ± 0.029	-0.032 ± 0.021
$1.55 - 0.186 \cdot \log P$	**-0.0002**	0.0015 ± 0.029	-0.039 ± 0.021
$1.56 - 0.186 \cdot \log P$	-0.0074	-0.0057 ± 0.029	-0.048 ± 0.022
<u>2: method: G13</u>			
<u>2: BW: G13, Calib: G13</u>			
$1.49 - 0.24 \cdot \log P$	1.049	1.009 ± 0.027	1.011 ± 0.094
$1.50 - 0.24 \cdot \log P$	1.041	$\mathbf{1.001} \pm \mathbf{0.027}$	1.003 ± 0.093
$1.51 - 0.24 \cdot \log P$	1.033	0.993 ± 0.026	0.996 ± 0.093
$1.55 - 0.24 \cdot \log P$	1.002	0.962 ± 0.026	0.966 ± 0.089

Differences

	JS		My code on JS data JS p-factor		MG	
	d	σ	d	σ	d	σ
beta Dor	326.9	4.7	303.1	5.6	329.5	6.0
del Ceph	267.1	4.6	260.7	8.5	249.8	10.5
FF Aql	360.3	11.5	606.0	239.0	666.2	80.2
l Car	598.9	7.3	475.8	22.9	436.8	7.2
RT Aur	389.4	6.1	461.4	16.9	475.7	15.0
T Vul	543.1	4.9	540.2	24.5	512.8	12.8
Y Sgr	445.7	14.4	474.5	48.7	415.2	57.8
X Sgr	320.3	5.3	327.2	13.0	317.4	8.1
zeta Gem	384.8	8.6	392.4	11.1	359.3	9.2
W Sgr	217.0	15.7	135.1	17.4	201.7	22.6

Still unclear!! Work in progress

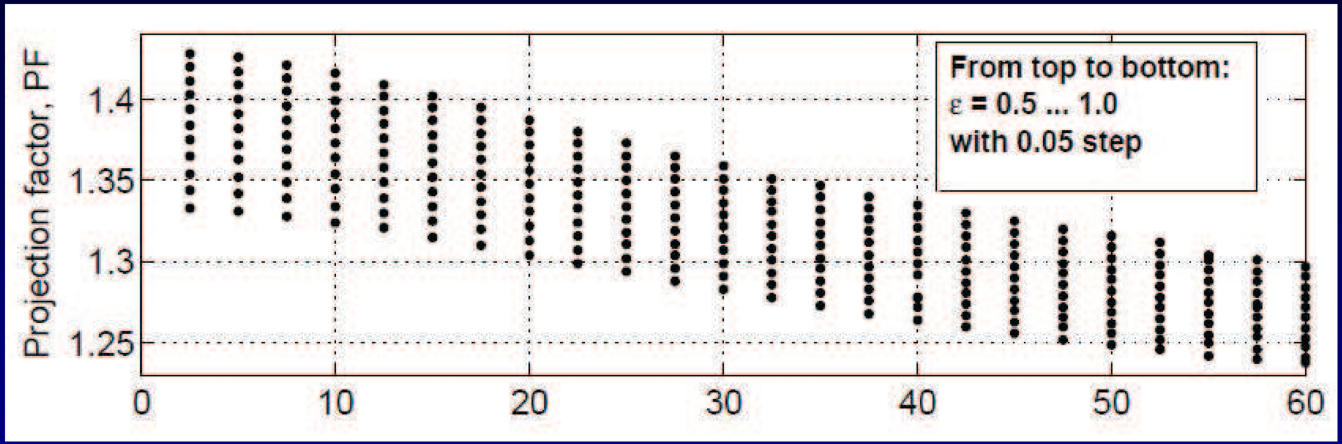
p-factor

Reference	a	b
Getting (1934)	$\cdots$	$24/17 = 1.41$
Sabbey et al. (1995)	$\cdots$	1.43 (actually $p(\phi)$)
Gieren et al. (1993)	-0.03	1.39
Gieren et al. (2005)	-0.15 ± 0.02	1.58 ± 0.02
Mérand et al. (2005)		1.27 ± 0.06 (δ Cep P=5.36)
Nardetto et al. (2007)	-0.075 ± 0.031	1.366 ± 0.036
Nardetto et al. (2009)	-0.08 ± 0.05	1.31 ± 0.06
Neilson et al. (2012)	-0.053 ± 0.002	1.471 ± 0.002 (K-band)
Storm et al. (2011)	-0.186 ± 0.06	1.550 ± 0.04
Groenewegen et al. (2013)	-0.24 ± 0.03	1.50 ± 0.03
Pilecki et al. (2013)		$1.21 \pm 0.03 \pm 0.04$ (P=3.80)

Nardetto et al. (2011): model for δ Cep at Z=0.008: slightly smaller (1.305 vs. 1.325)

Neilson et al. (2012): at lower metallicity marginally larger, 3% at P=100 days.

p-factor



Projection factor as a function of $|dr/dt|$ for an instrumental width of $S_0 = 6\ km/s$ and for different values of limb-darkening coefficient $0.5 < \epsilon < 1$.
Nominal value is 1.31.
Rastorguev (IAUS 289)

Binaries

László Szabados:
http://www.konkoly.hu/CEP/intro.html

16 spectroscopic binaries

Recompute the orbit to subtract orbital motion

Binaries

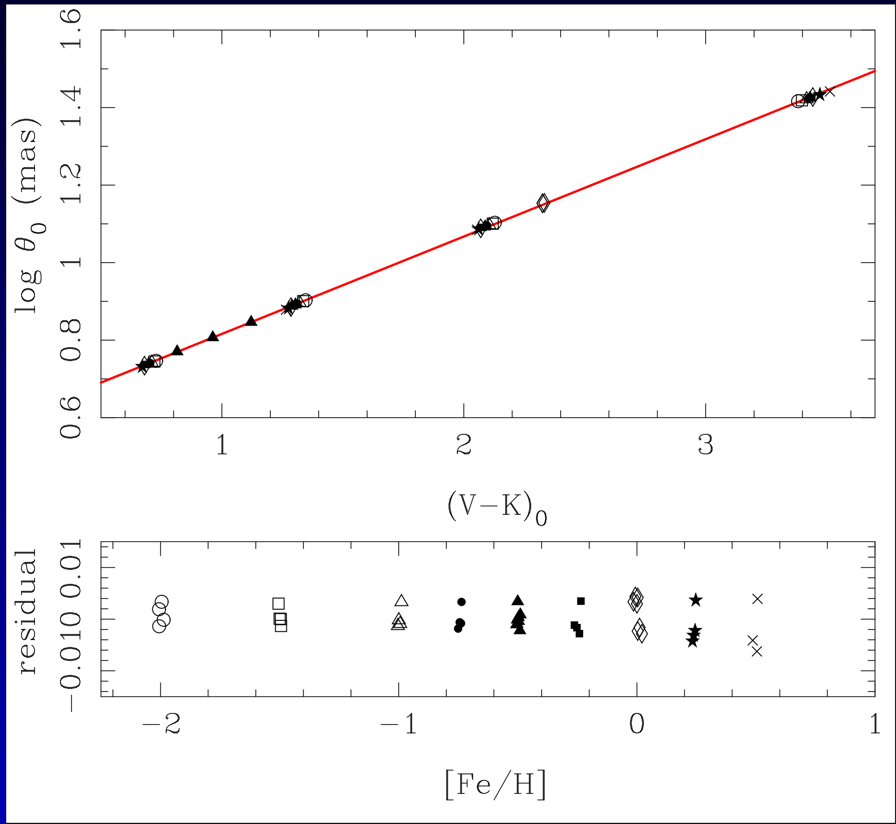
Gallenne et al. (1406.0493)

NAOS-CONICA to look for companions around
Y Oph, FF Aql, X Sgr, W Sgr, η Aql

W Sgr $\Delta K > 4.7$ A1

K= 2.80 V= 4.31 K= 7.50 V= 7.50
K= 2.81 V= 4.37
$(V - K)$ from 1.51 to 1.56 $\Rightarrow$ 3.1% increase in θ

SB-relation



44 MARCS models, $T_{\rm eff}$= 4000 - 7000 K, *mostly* log g= 2, M= 5M$_\odot$

$\log \theta_0 = 0.5648 + 0.2513\,(V-K)$

$\log \theta_0 = 0.5327 + 0.2675\,(V-K)$ (G13)

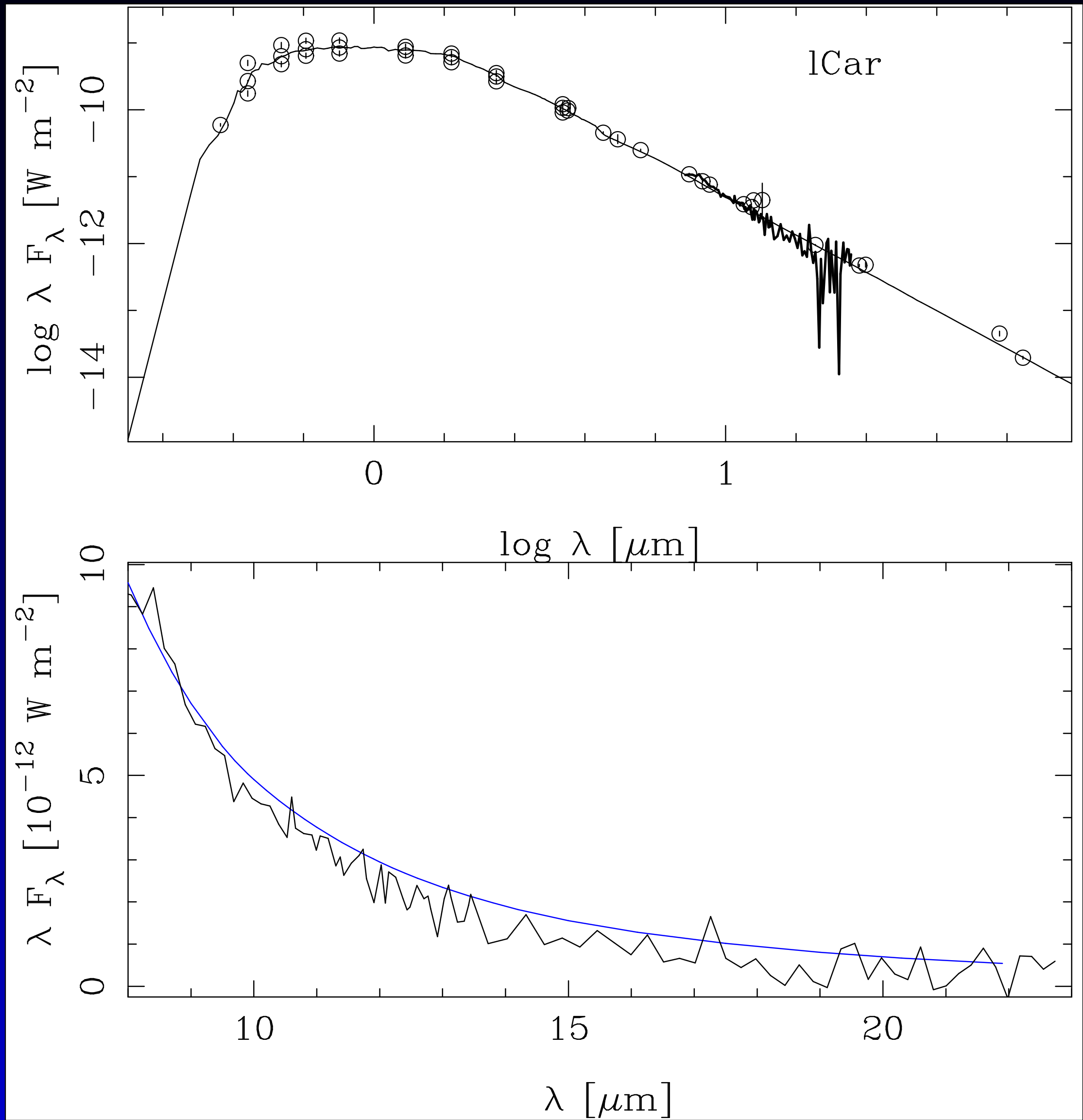
(ratio 1.037 - 0.981 $(V-K)$= 1, 2.5)

Mass loss

Cepheid mass discrepancy:
theoretical mass estimates using stellar evolution and stellar pulsation calculations differ

Cepheids in EBs

Observational:
IR excess emission, interferometry
l Car, Kervella, Mérand, Gallenne (2009)
CSE emission: 4.2% @ K-band, 10% @ 8 micron, 50% @ 70 micron



$\tau_V = 0.049$, $\dot{M} = 3.9 \cdot 10^{-9}$ M$_\odot$ yr^{-1}
($\Psi = 0.005$, $v =$10 km/s, dust species)
$(V - K)$ = 0.062 bluer

Conclusions

- No metallicity effect on PLZ in K, and WVK
- Emperically quite steep dependence of p on P

  Contradiction to atmosphere model predictions (no or moderate)
  More complicated dependencies (velocity, phase)
- Influence and nature of mass loss ?
  Mimic $p(P)$ dependence ?
- Influence of data and analysis on the distances
  Work in progress
- Riess et al. (2014) WFC3 ; *Gaia* DR1

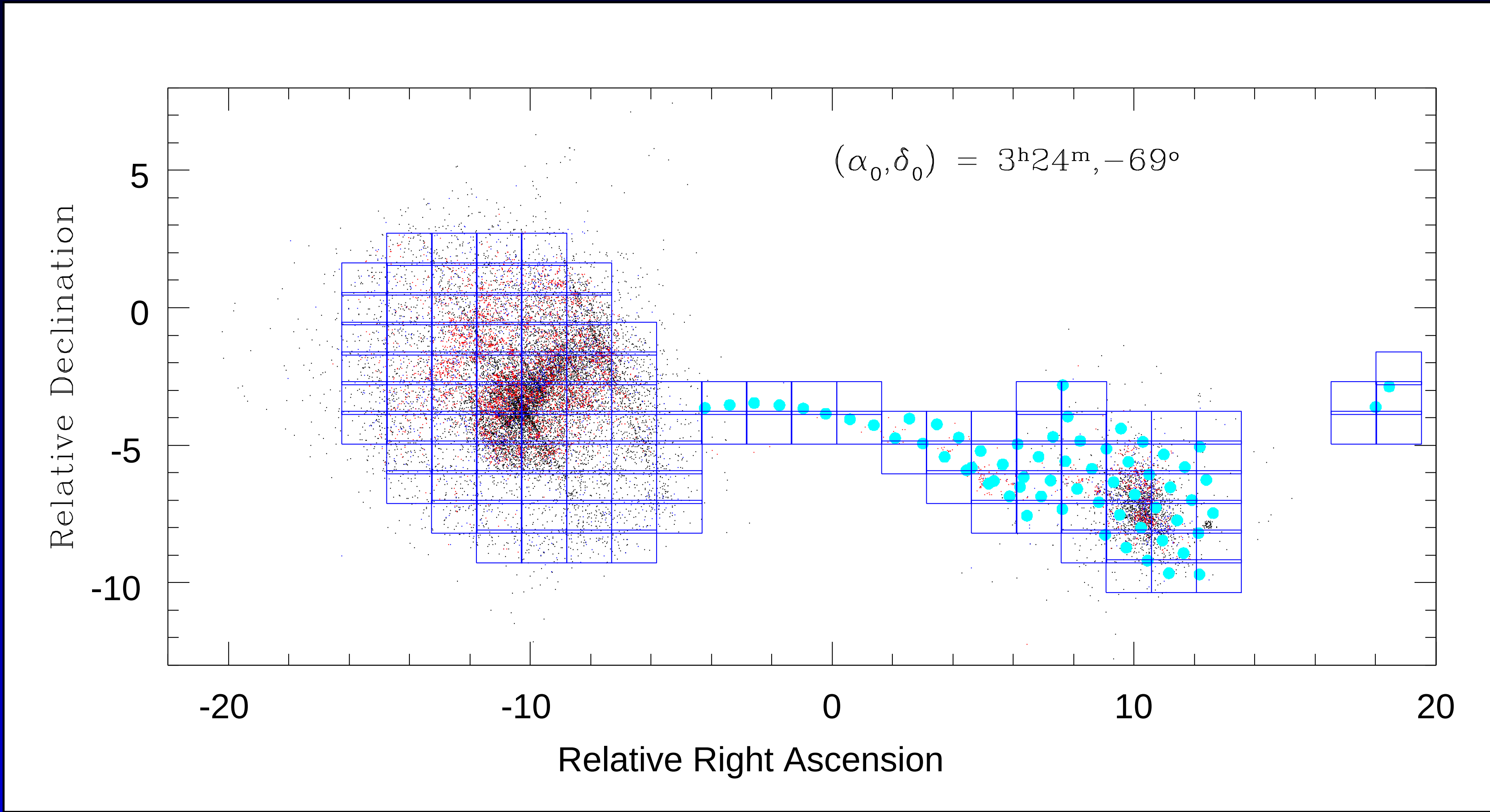
VMC

VMC = VISTA Magellanic Cloud Survey

PI. Maria-Rosa Cioni (University of Hertfordshire)

- One of 6 Public Surveys selected by ESO
- Survey in YJK of LMC, SMC, Bridge & Stream
- Total area 184 sq.degrees = 110 "tiles"
- 200 nights allocated
- Started in January 2009, projected end early-2018 51% complete

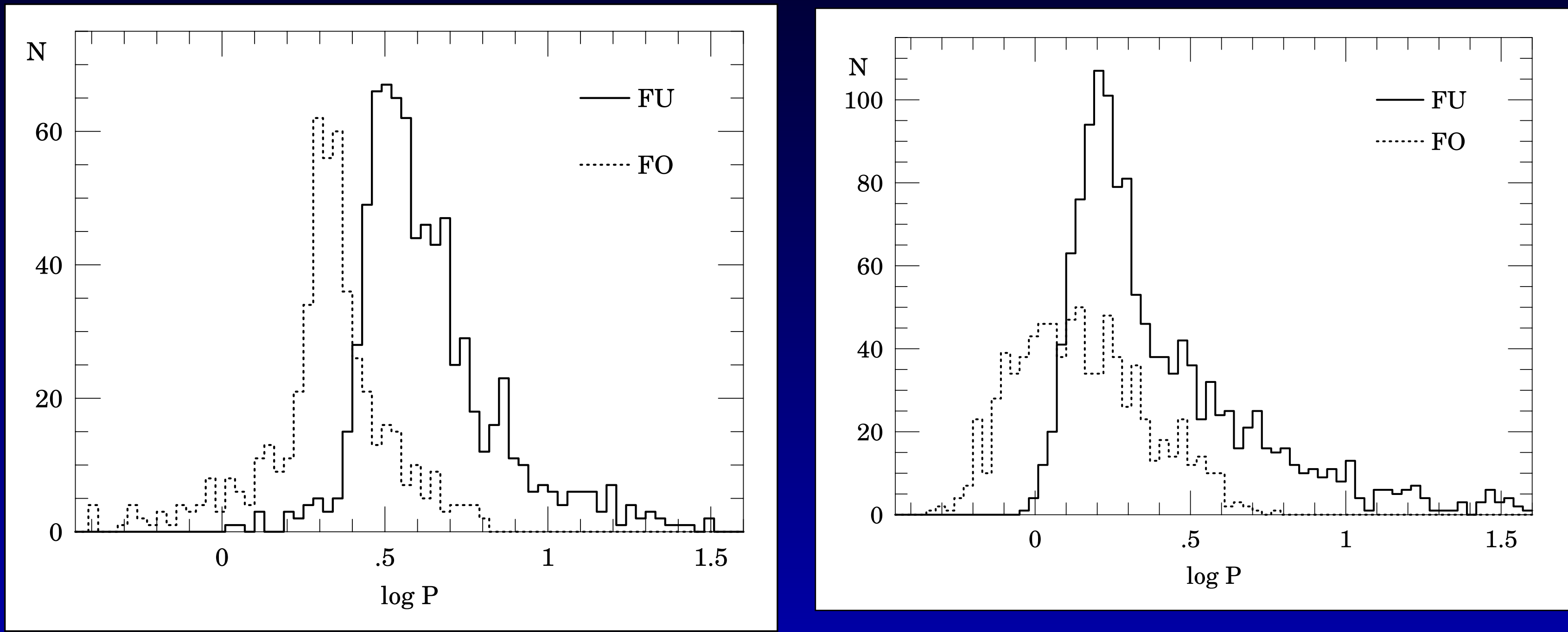
VMC pointings



VMC: science goals

- Determine spatially resolved SFH (star formation history) and AMR (age metallicity relation)
- Interaction of MCs (and our Galaxy)
- 3D picture of MCs: red clump, RR Lyrae and Cepheids (12 epochs in K)

Cepheid Period Distribution



Period distribution of LMC (left) and SMC Cepheids

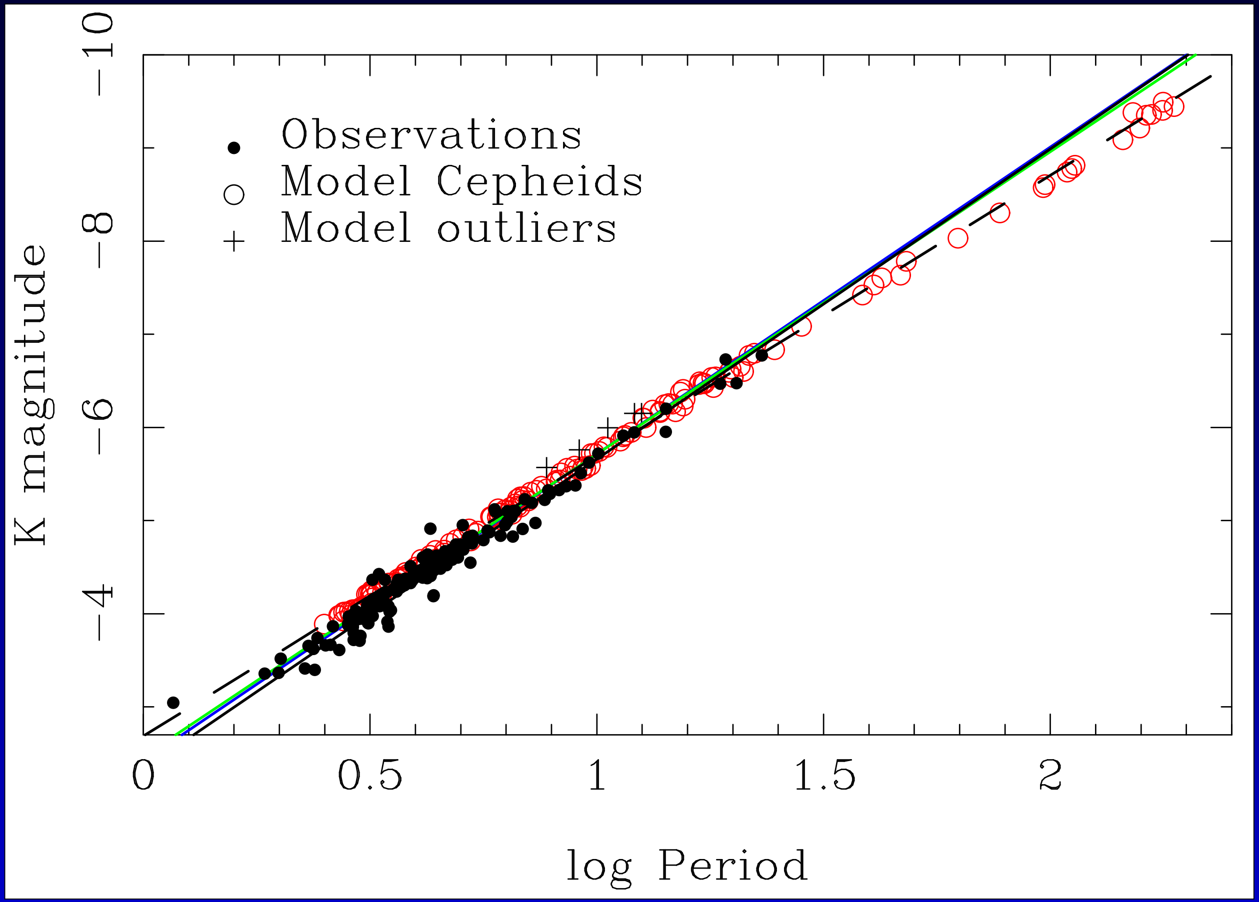
SFH, metallicity

Modelling

- SFH determined at a spatial resolution of 1 sq.deg. (Rubele et al. 2012)
  DM derived: 18.470 ± 0.006
  DM 8_8: 18.40
- Cepheid period distribution from OGLE/EROS (Ripepi et al. 2012)
  K-band PL-relation
- TRILEGAL Population synthesis code (Girardi et al. 2005) &

  Instability Strip, $P(L, M, T_{\rm eff}, Z)$
  (Bono et al. 2000)

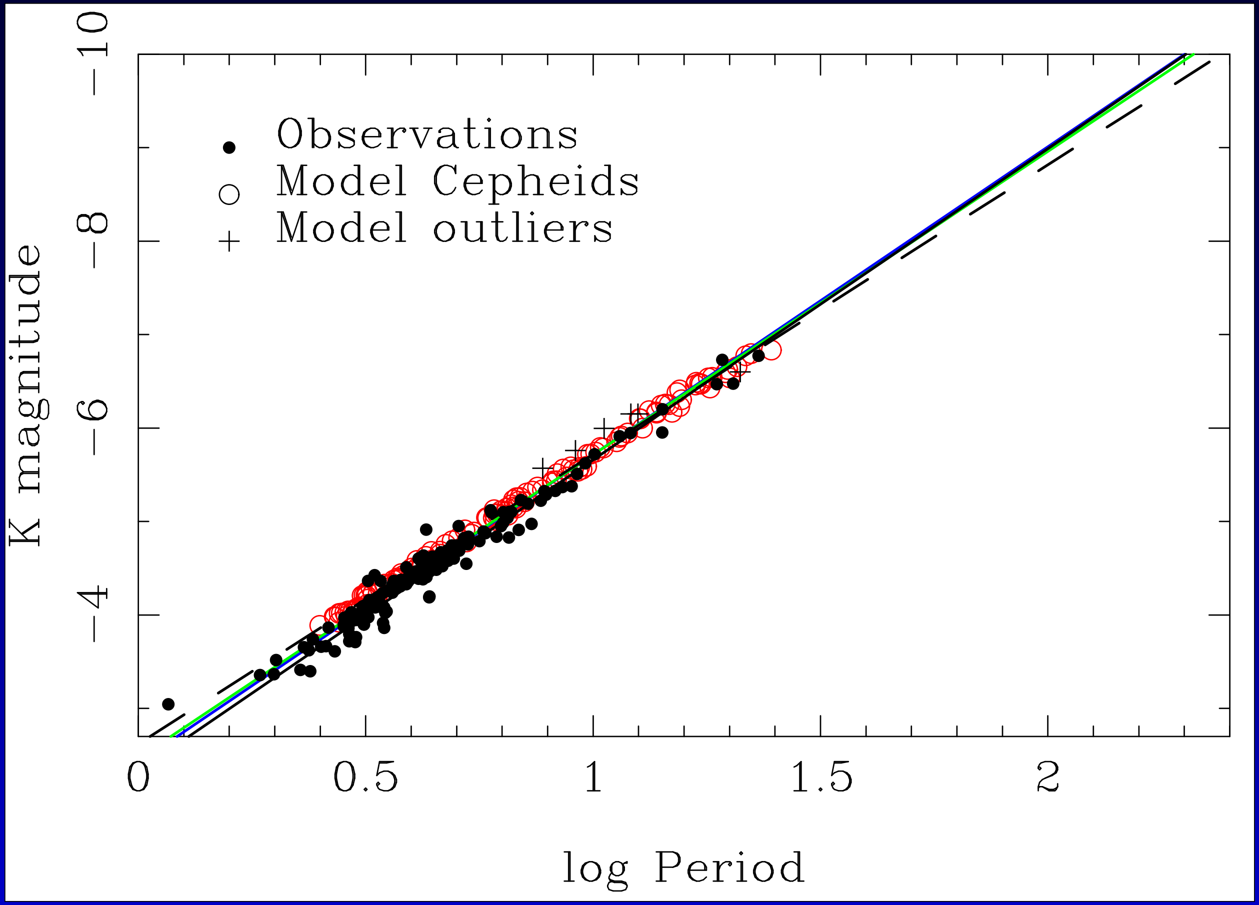
First Results



Saturation in VMC ($K \sim 11.5$), or OGLE

"Shallow survey" not taken into account yet

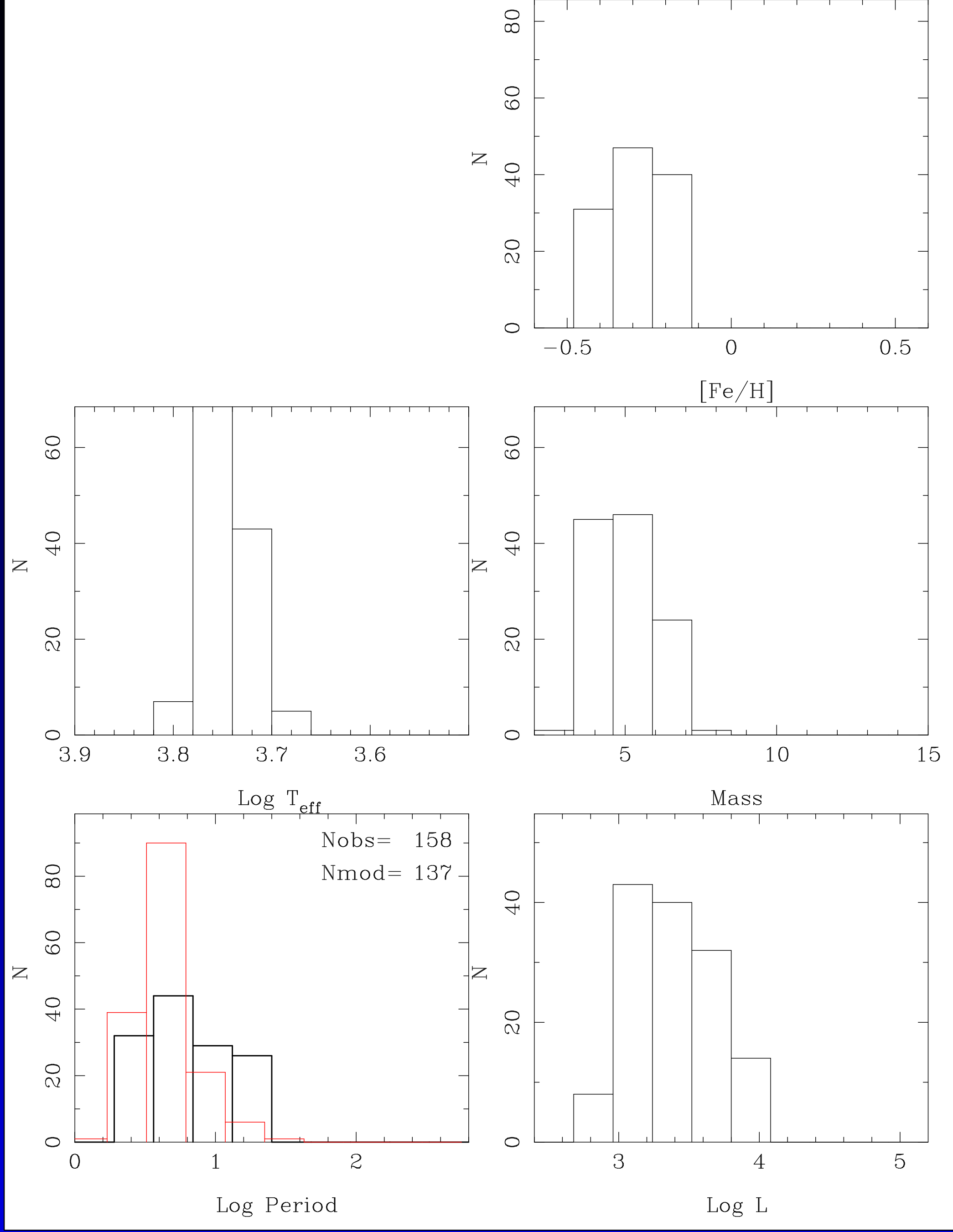
First Results



Limit at $M_{\mathrm{K}} = -7.0$

$M_{\mathrm{K}} = -2.62 - 3.10 \log P$

$M_{\mathrm{K}} = (-2.50 \pm 0.08) + (-3.06 \pm 0.06) \log P$



Numbers match quite well...
Period distribution not too bad....

Future work

- Refine model (shift IS)
- Ultimately all VMC data of SMC and LMC

- Extend to RR Lyrae (G. Coppola)
- TRILEGAL
  GALACTIC Population synthesis code

  RR Lyrae population in the Bulge (V. Braga)

The END