The impact of micro-lensing surveys on variable star research

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Overview

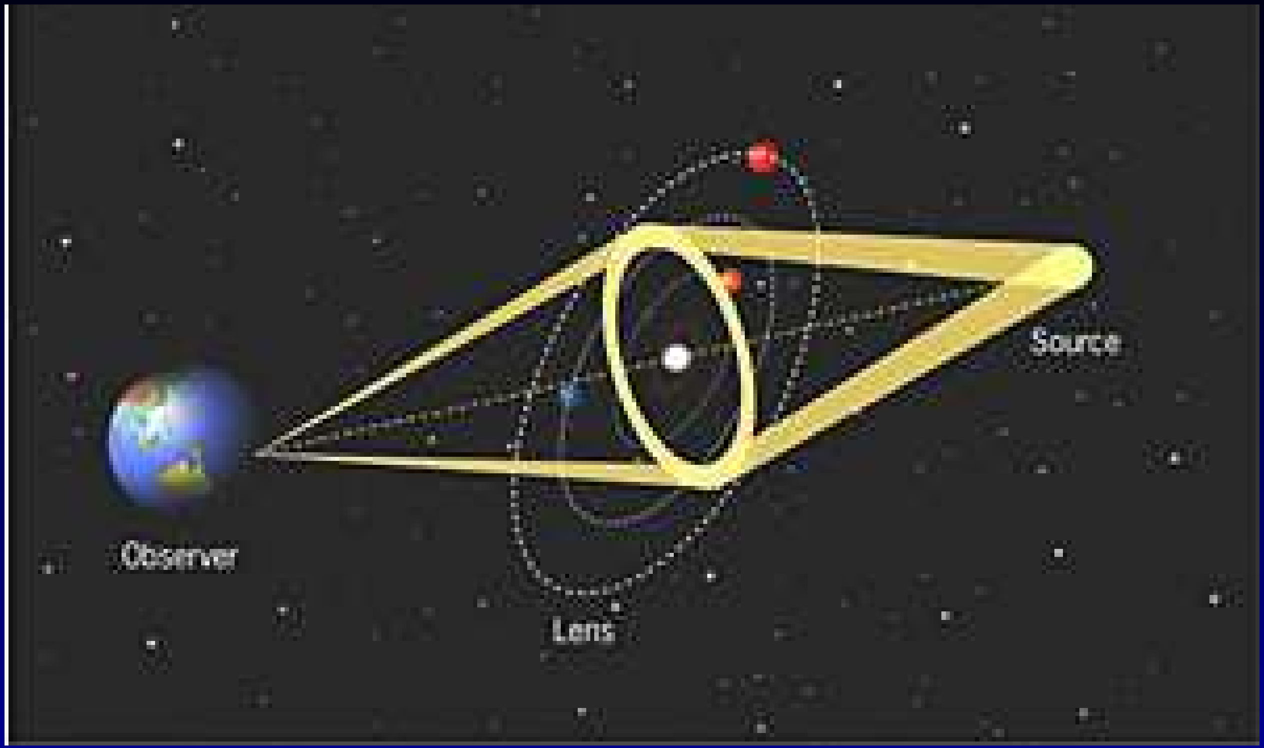
- Micro-lensing surveys
- How to find your variables
- Pulsational variables
  stellar evolution, distance scale, interior structure
- Eclipsing binaries
  fundamental parameters, stellar evolution,
  distance scale
- The future of surveys

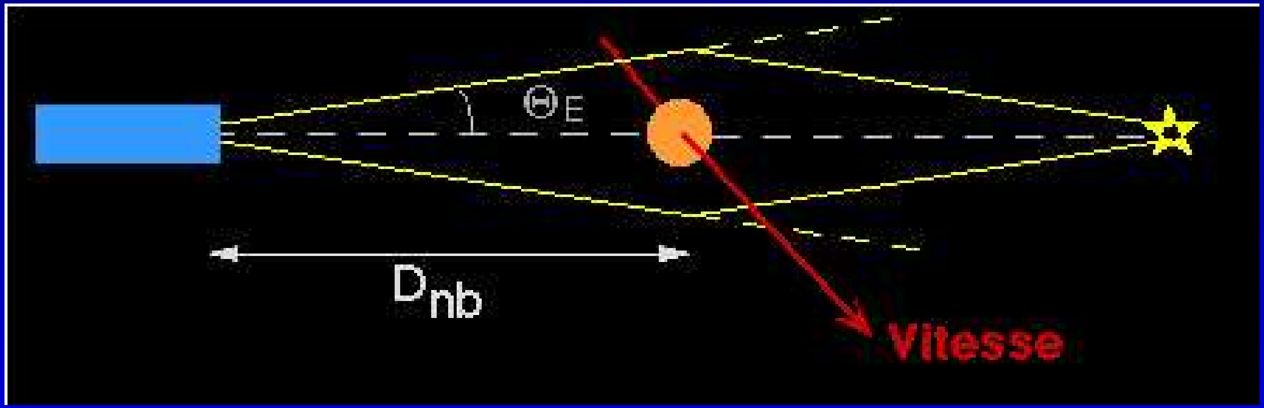
History

- “long-term photometry of variables” (LTPV) 1982-1994, ESO 50cm Danish and SAT, 100 000 observations of 1700 stars
- AAVSO
  (5000 stars – 10^7 observations – 100 years)
  AFOEV
  (8000 stars – 5 10^6 observations – 100 years)
- Hughes (1989): 470 M, 570 SR in LMC; 50 photographic plates
- Lack of areal coverage / time coverage / numbers

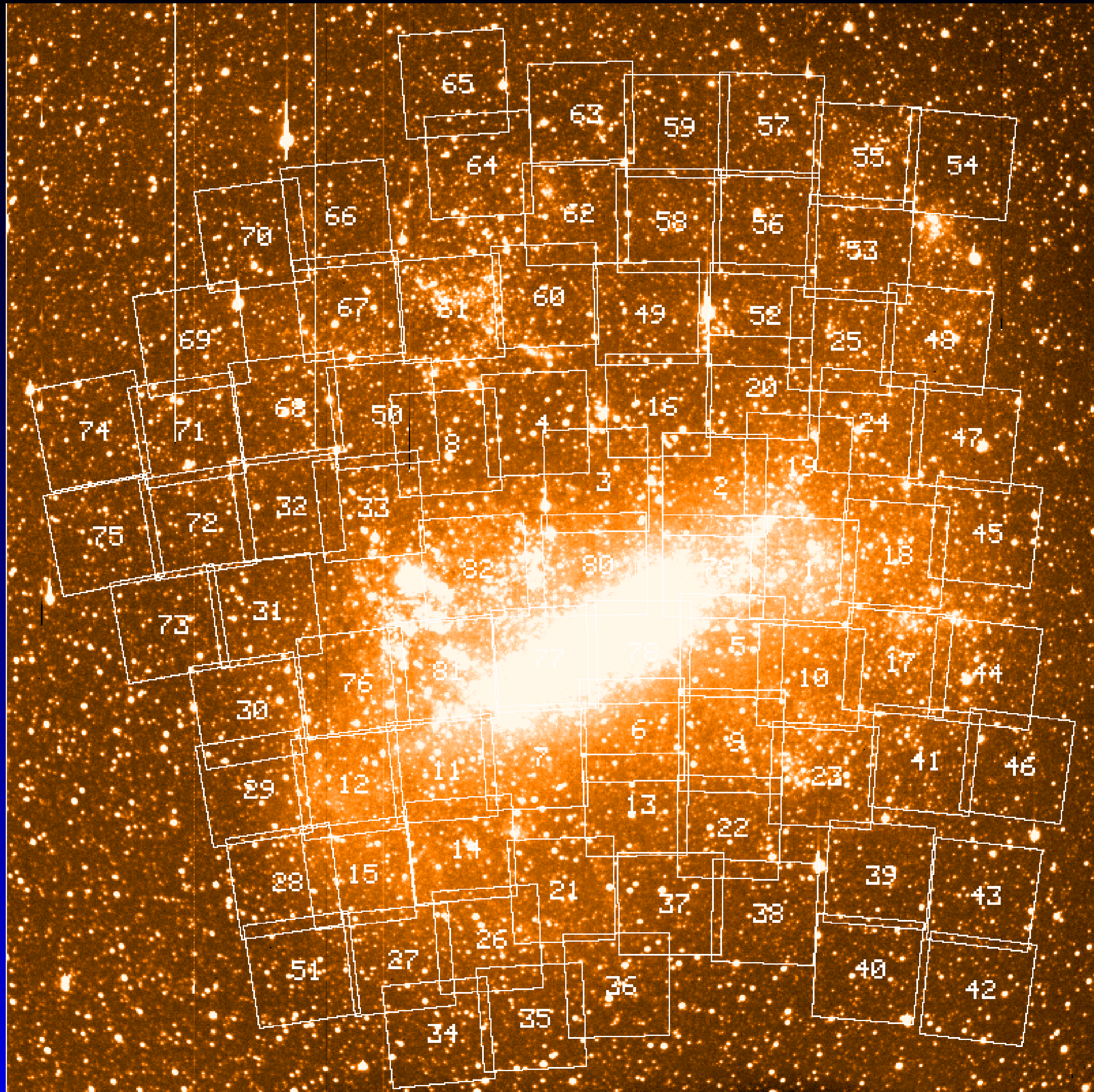
Micro-lensing surveys

- MACHO
  MAssive Compact Halo Objects
- OGLE-I and -II
  Optical Gravitational Lensing Experiment
- EROS-2
  Expérience pour la Recherche d'Objets Sombres
- MOA
  Microlensing Observations in Astrophysics





Principle of micro-lensing



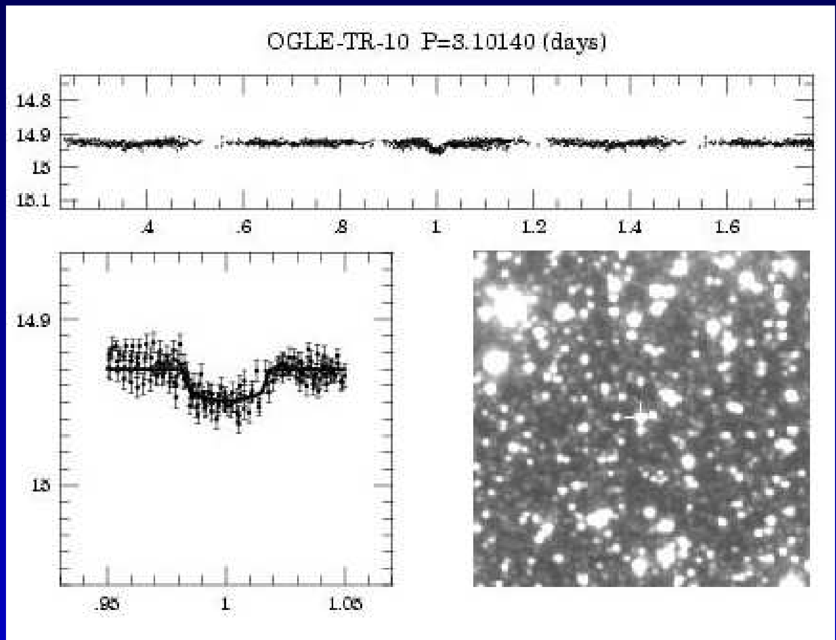
MACHO fields in the LMC

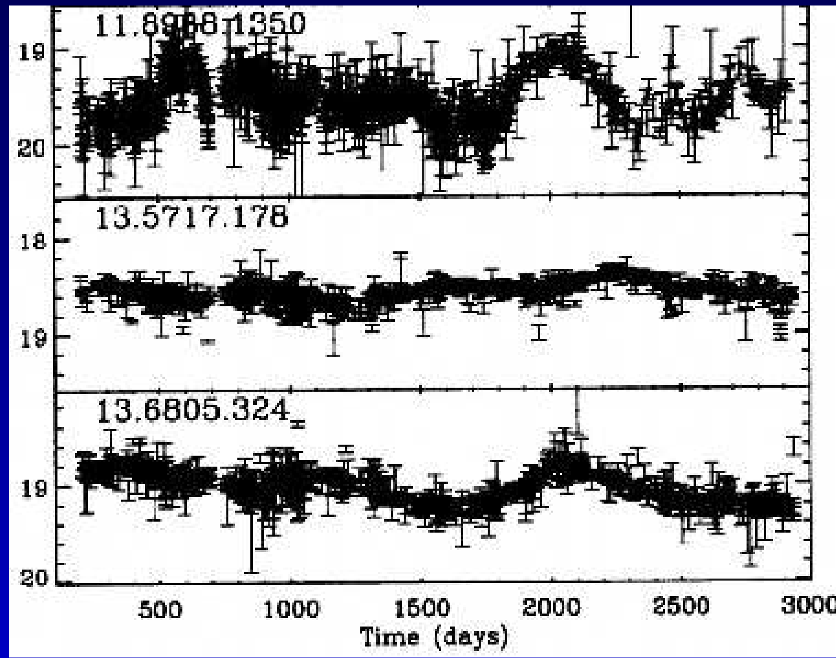
Mirco-lensing surveys

Survey	OGLE-II	MACHO	EROS2	MOA
Time	1997-2000	7/1992-1/2000	7/1996-2/2003	1998-2004
Telescope	1.3m	1.27m	1.0m	0.61m
Area	SMC, LMC, GB	SMC, LMC, GB	SMC, ?	SMC, LMC, GB
Sq.deg.	2.4, 4.5, 11.0	2.5, 35, 35	10	10, 20, 18
Monitored	2, 7, 30 (10^6)	3, 30, 40 (10^6)	6 (10^6)	1.0, 8.0, ? (10^6)
Variables	15, 53, 221 (10^3)	-, -, -	-	-, -, -

Other results

- MACHOs: $\tau_{\rm smc} \sim (0.5 - 1)\; 10^{-6}$
- Planetary Transits

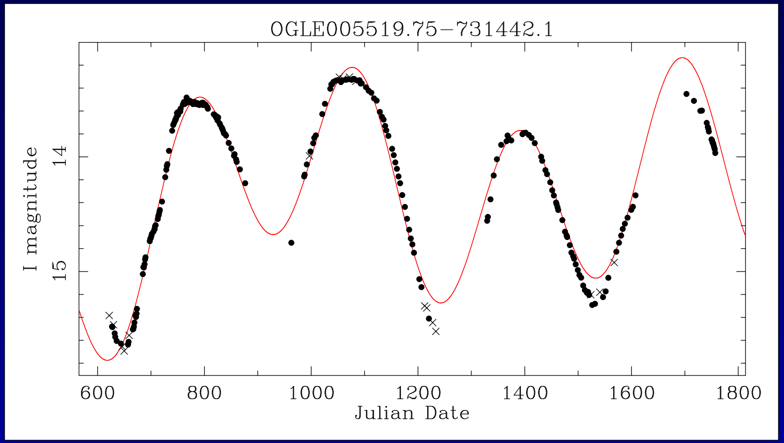


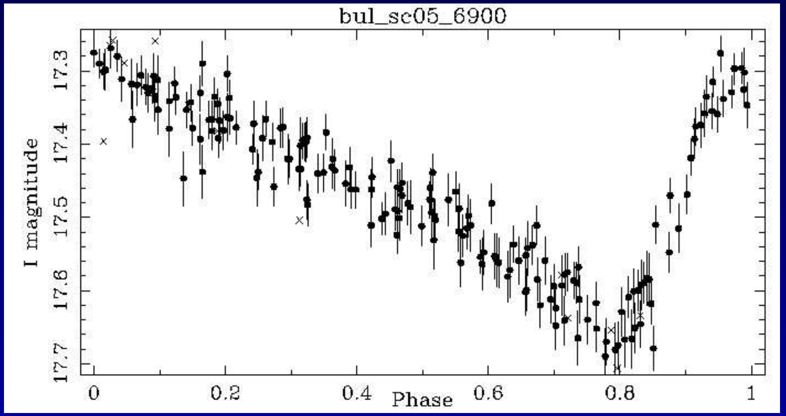


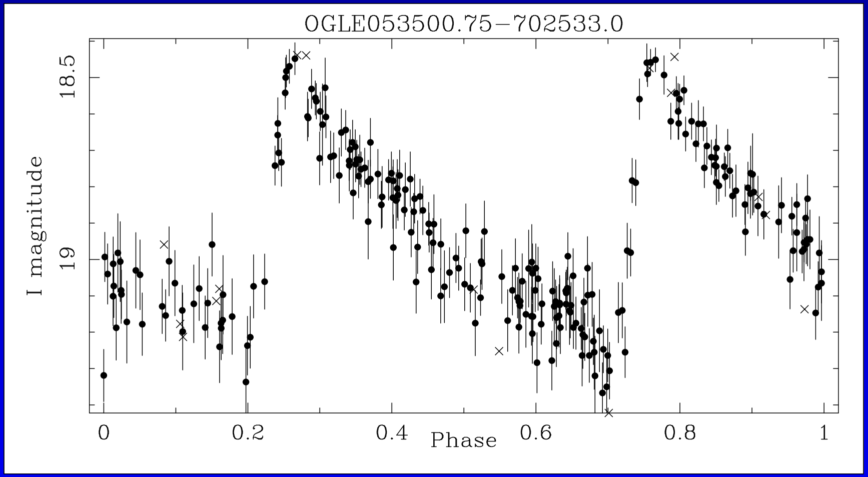
- Quasar variability
- Proper motion
- Extinction maps

Variable star research

- Pulsational variables:
  Miras (LPVs), Cepheids, RR Lyrae

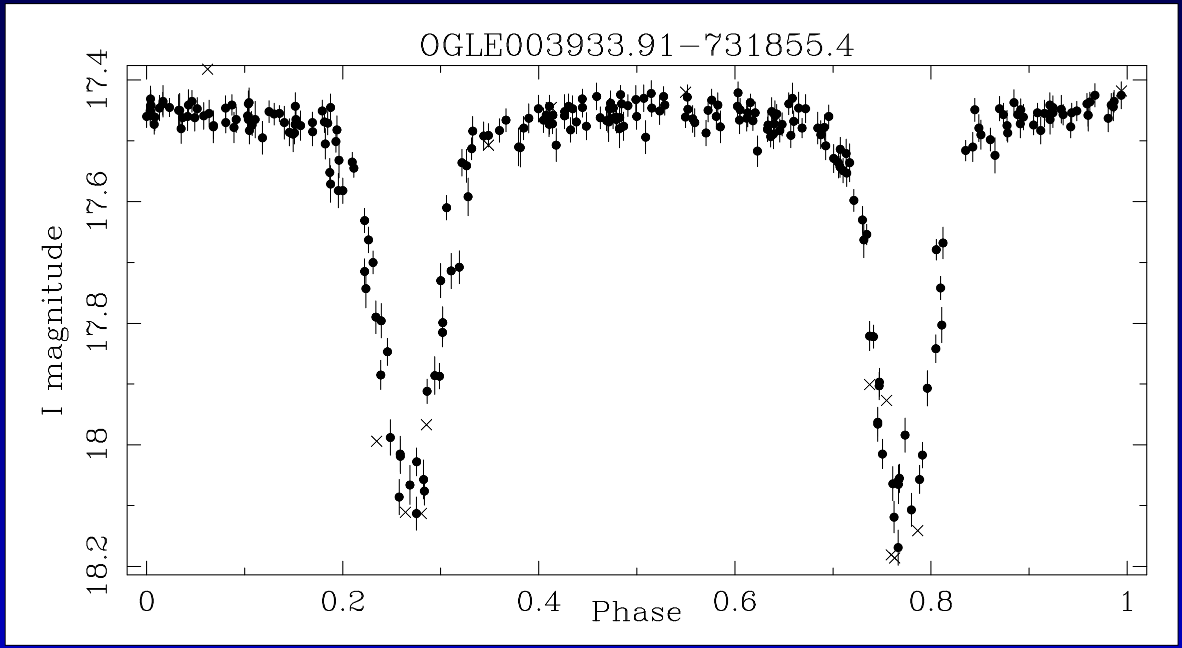






Variable star research

- Eclipsing binaries



- Data analysis system (LPVs and EBs) downloaded 68 000 + 221 0000 OGLE-II *I*-band datafiles

Procedure

Step 1: Fitting LC

- Subtract best fit so far
- Find frequency (FASPER, PDM)
- Linear LSF (MRQMIN)
  $I(t) = I_0$
  $+ \sum_{i=1}^{i=n_{\max}} (A_{\mathrm{i}} \sin(2\pi\ t\ \omega_i) + B_{\mathrm{i}} \cos(2\pi\ t\ \omega_i))$
- Stop: $n = 3$, or no significant frequency

Procedure

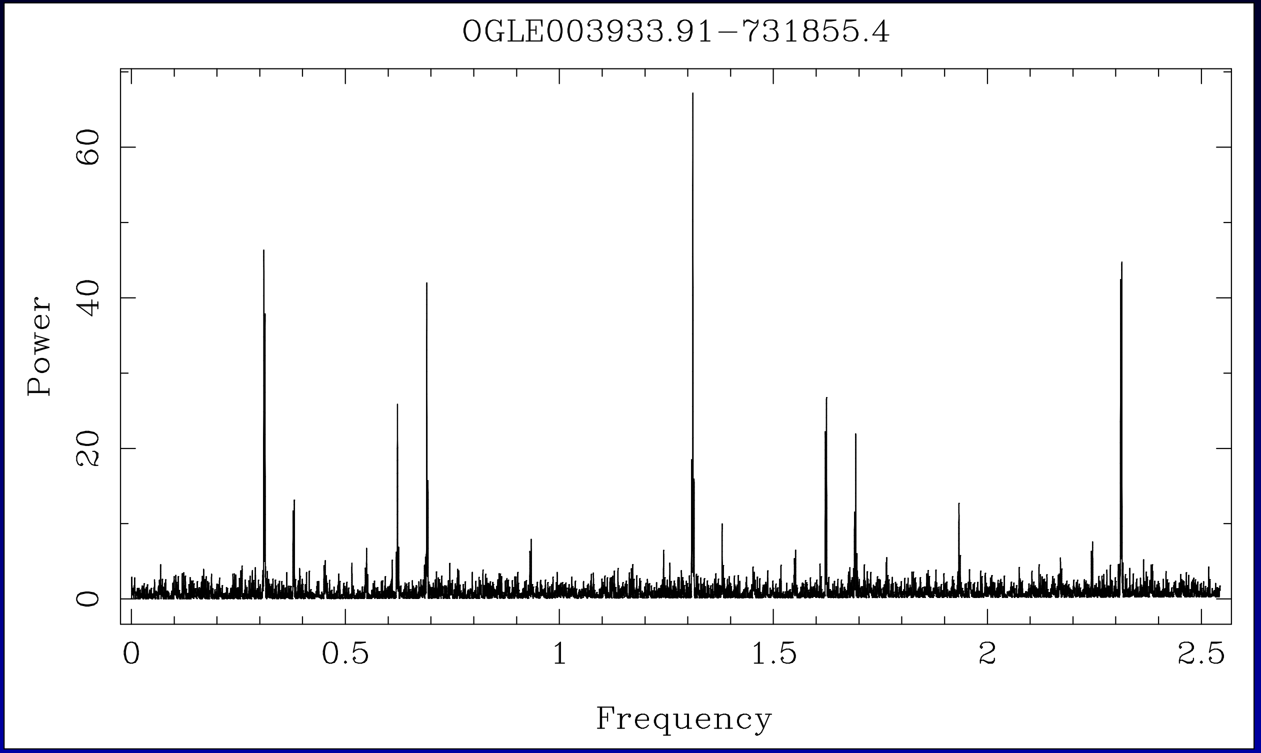
Step 2: Correlation and Selection

- Selection on Magnitude, Amplitude, properties of phased LC (neural networks)
- Correlate:
  221801 OGLE ⇒ 91815 2MASS
  68193 OGLE ⇒ 50129 2MASS & 40793 DENIS

Step 3:

- Visual inspection of fit to LC
- SIMBAD (spectral type)
- Generation of figures and LaTex tables

Frequency finding I



FASPER

INPUT: time, magnitude, ofac, hifac

OUTPUT: ν_{max}, probability

Issues: aliases, harmonics

ofac= 22; hifac= 0.8 (LPVs), 21 (EBs)

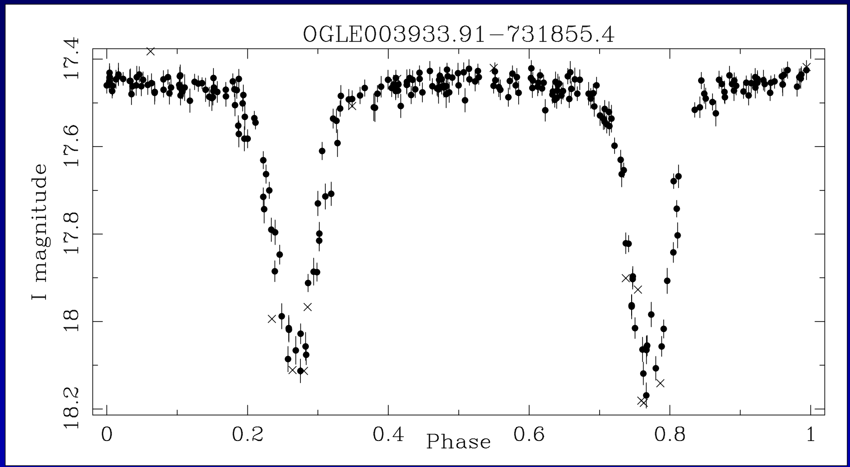
limiting probability= 5.5 10^{-11} (LPVs), 0.05 (EBs)

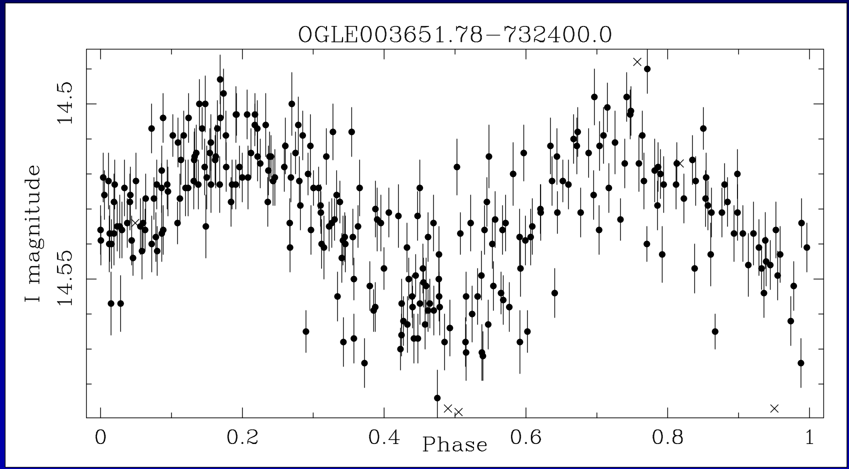
Frequency finding II

- Phase Dispersion Minimisation (θ-statistics; Stellingwerf 1978) at SELECTED frequencies $1, \frac{1}{3}, \frac{1}{2}, 2, 3\ \nu_{\rm max}$, 1-day alias
- Accept frequency if $\theta(\nu) < 0.9\ \theta(\nu_{\rm max})$

Eclipsing Binary specifics

- fitting sine + cosine function is not usefull
- Phase at $\frac{1}{2}\ \nu_{\max}$

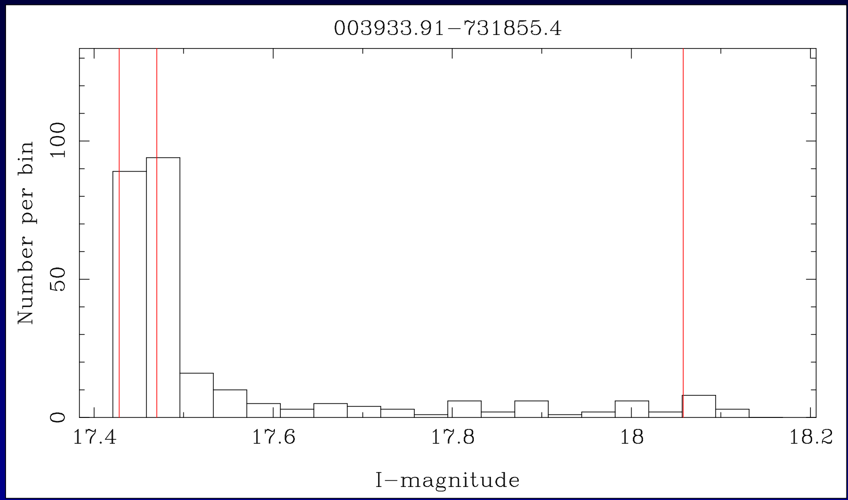


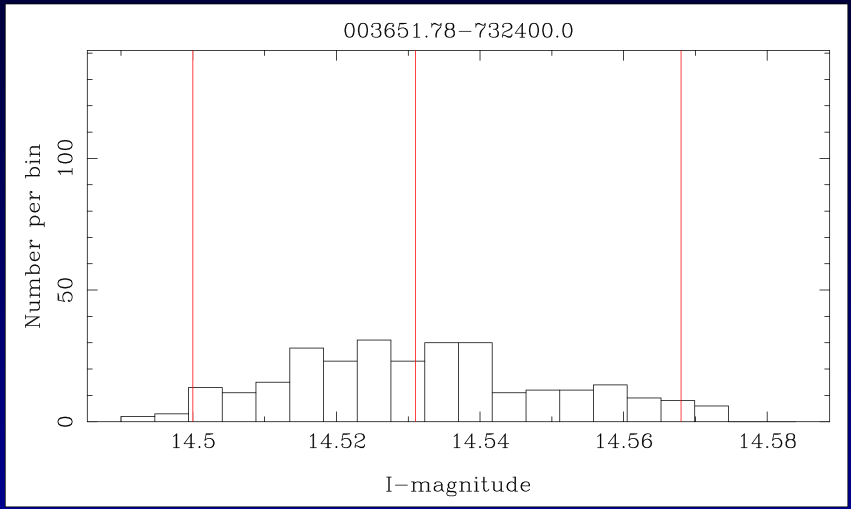


Phased lightcurve of an EB and a LPV

- Statistics at two magnitude levels at deepest eclipse

Eclipsing Binary specifics





Magnitude distribution of an EB and a LPV and 3%, 50%, 97% quantiles.

- Kolmogorov-Smirnof Test against a sinus curve at random phase. probability $< 2.10^{-7}$
- $(m_{97} - m_{50})/(m_{50} - m_3) > 2.1$
- depth of eclipse: $(m_{97} - m_3) < 0.75$

RR Lyrae

- OGLE-II:
  7612 LMC, 571 SMC Soszyński et al. (02, 03)
  MACHO:
  6391/785 FU/FO LMC (Alcock et al. 03, 04)
  MACHO: 1800 Bulge (Alcock et al. 1998)

$$M_{\rm V} = 0.18 \ [{\rm Fe/H}] + 0.67$$

$$M_{\rm K} = -2.33 \ \log P - 1.28$$

- Suggestion for future project:
  OGLE & final MACHO data on Bulge
  Correlate with DENIS and 2MASS IR-data

Cepheids

OGLE: Udalski et al. (1999a,b,c,d): 1335 LMC, 2048 SMC (FU, FO, SO, FU/FO, FO/SO)

OGLE: Kubiak et al. (2003): 54 type-II GB

MACHO: Alcock et al. (1999): 1800 in LMC

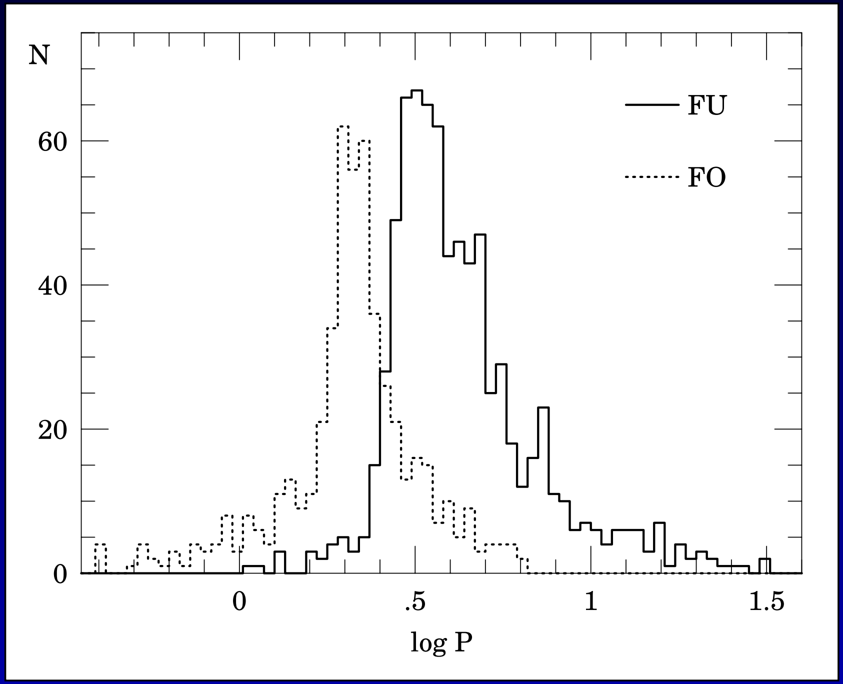
MACHO: Alcock et al. (2002): 3 CEP in EB

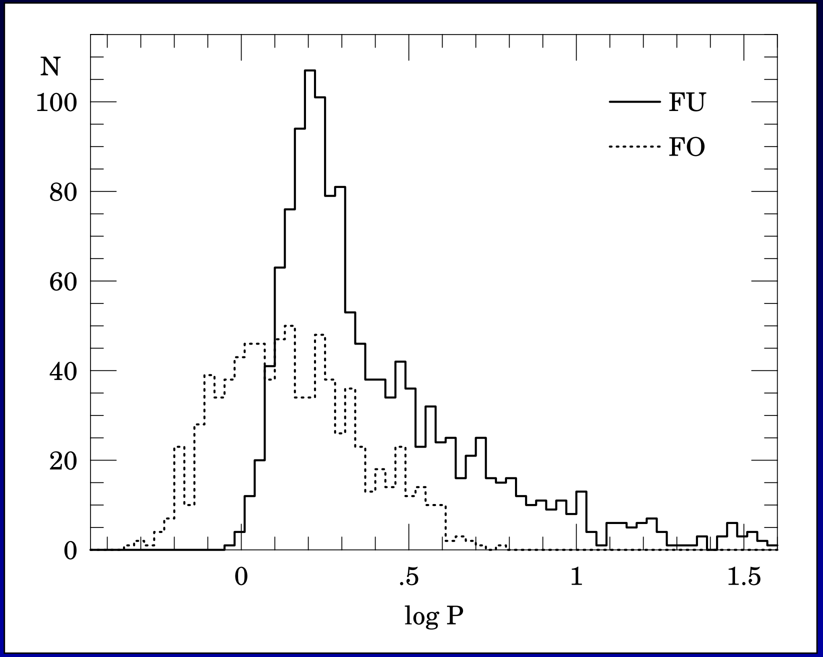
MACHO: Alcock et al. (1998): 30 type-II + RV Tau in LMC

MACHO: Nikolaev et al. (2004): 3000 in LMC

- Tracer of SF (Alcock et al. 1997 for LMC)
- Geometry of LMC and SMC disk
- PL-relations and distances (2MASS)

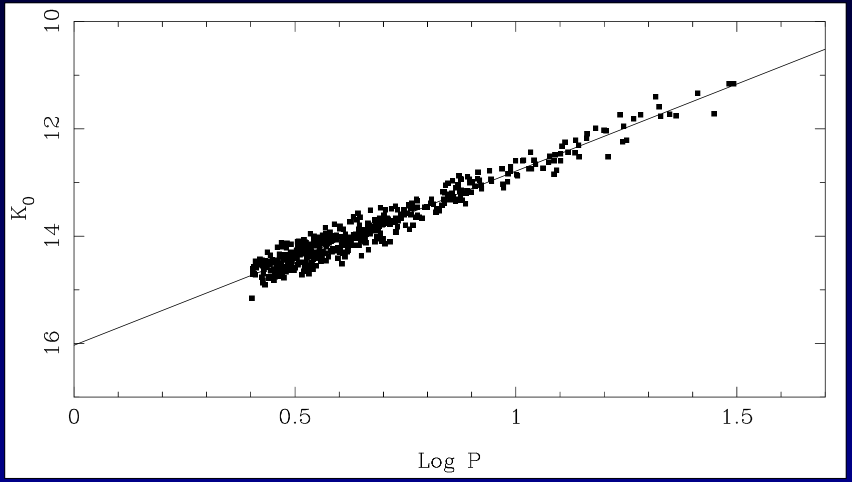
Cepheid Period Distribution

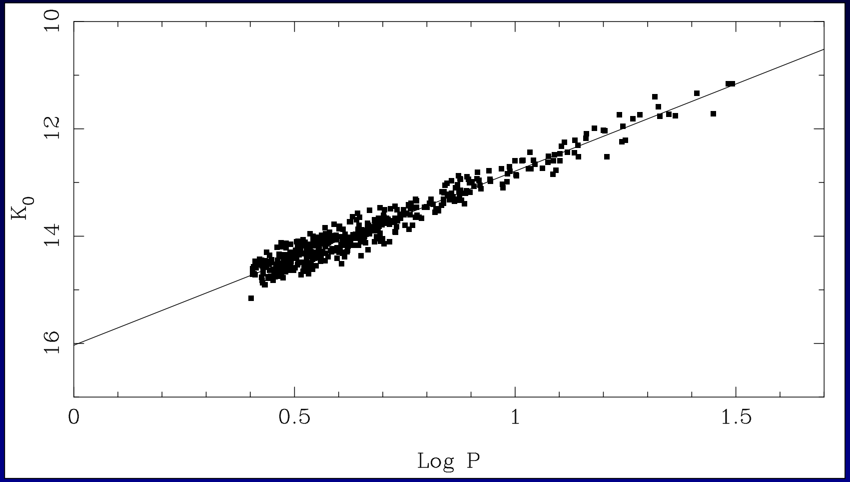




Period distribution of LMC (left) and SMC Cepheids.

Cepheid PL-relation

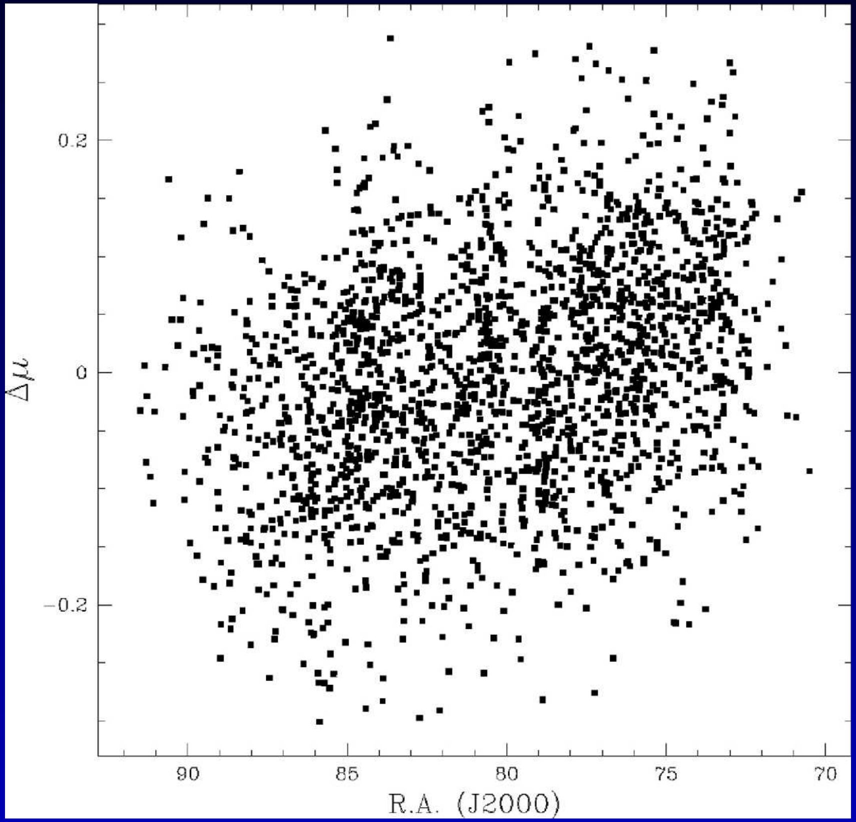




FU K-band PL-relation for LMC (left) and SMC Cepheids (Groenewegen 2000, Nikolaev et al. 2004)

Comparing with Galactic PL-relations:
DM= 18.55 ± 0.17 (LMC), 19.04 ± 0.17 (SMC).

Cepheid: orientation of the MCs



DM-offset of the PL-relation versus $R.A.$ for LMC.

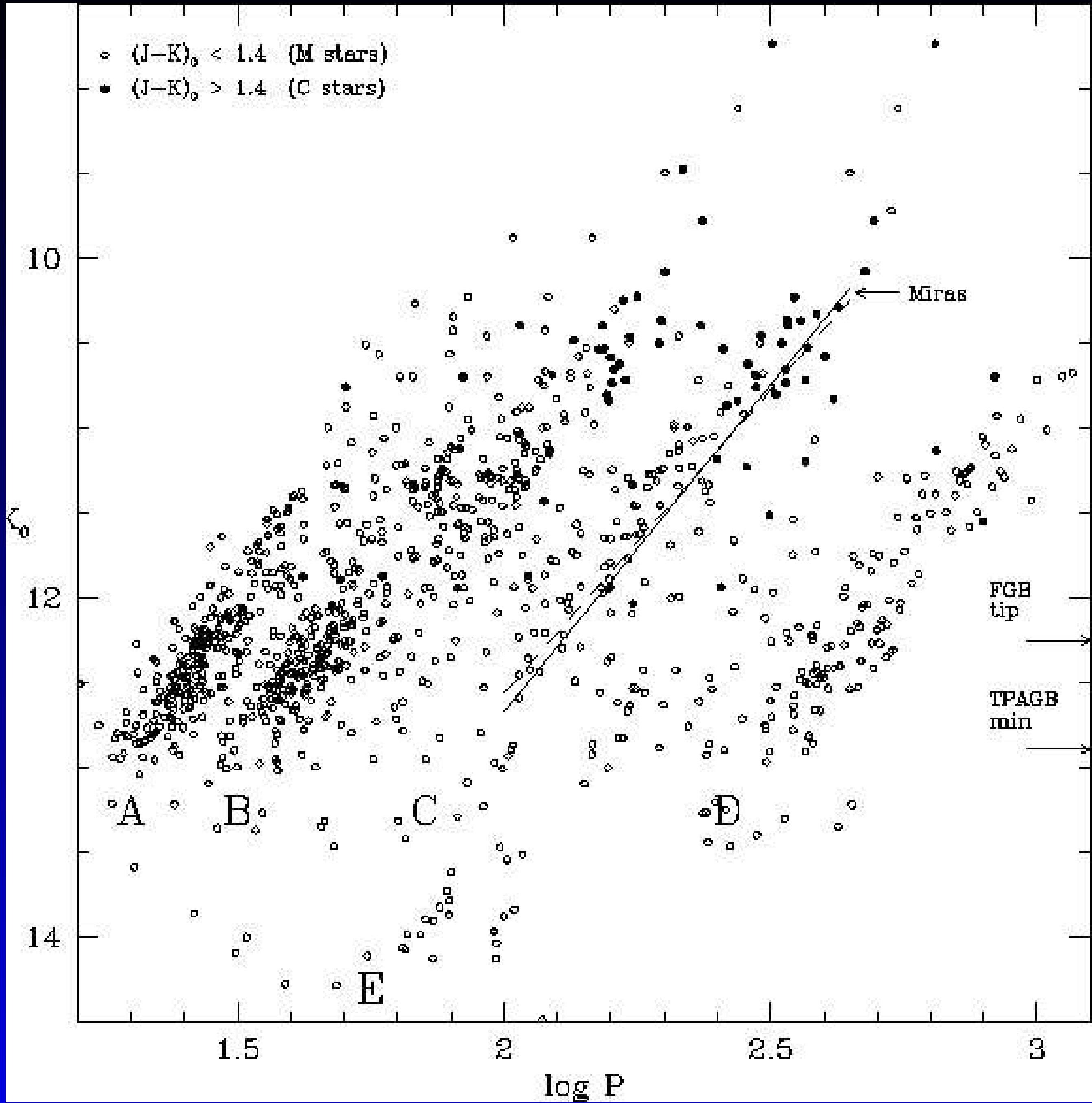
i= 18 $\pm$ 3 (Groenewegen 2000)

i= 30.7 $\pm$ 0.1 (Nikolaev et al. 2004)

i= 68 $\pm$ 2 (SMC, Groenewegen 2000)

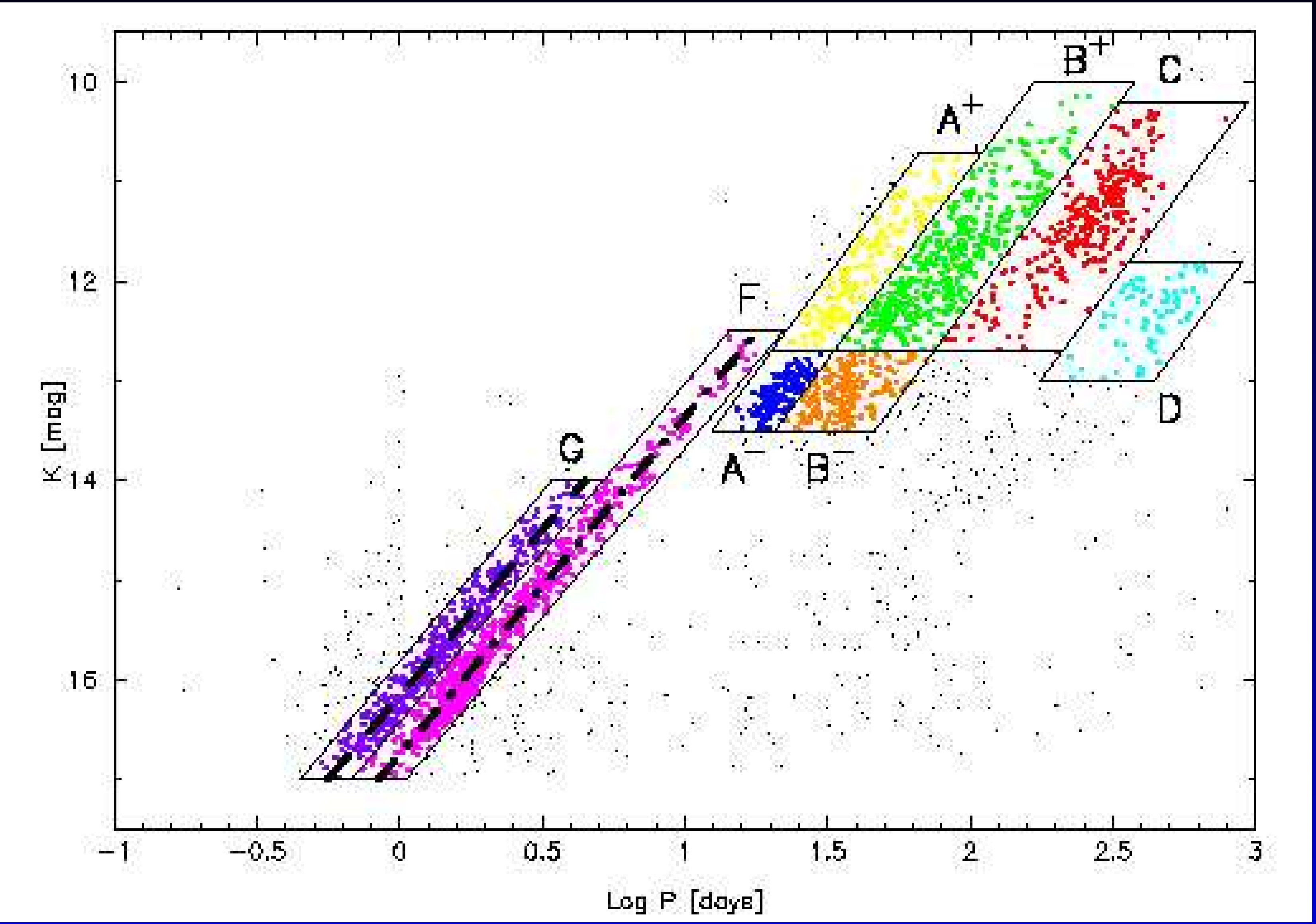
Miras

- Wood et al. 1999, Wood 2000
  (0.25 $\square^2$ LMC-bar; 1430 red variables; MACHO + IR)
- Cioni et al. 2001
  (0.5 $\square^2$ LMC-OC; 240 M+SR; EROS + DENIS)
- Noda et al. 2002
  (14 $\square^2$ LMC; 146 LPV; MOA + DENIS)
- Lebzelter et al. 2002
  (0.25 $\square^2$ LMC-bar; 470 red variables; AGAPEROS + DENIS)
- Cioni et al. 2003
  (0.25 $\square^2$ ISO-sample SMC-bar, 458 red variables; MACHO + DENIS/2MASS)



(J−K)0 < 1.4 (M stars)
(J−K)0 > 1.4 (C stars)
Miras
FGB tip
TPAGB min
A
B
C
D
E
10
12
14
K0
1.5
2
2.5
3
log P

Wood (2000)



Ita et al. (2003)

History

- Wood et al. 1999, Wood 2000
  (0.25 $\square^2$ LMC-bar; 1430 red variables;
  MACHO + IR)
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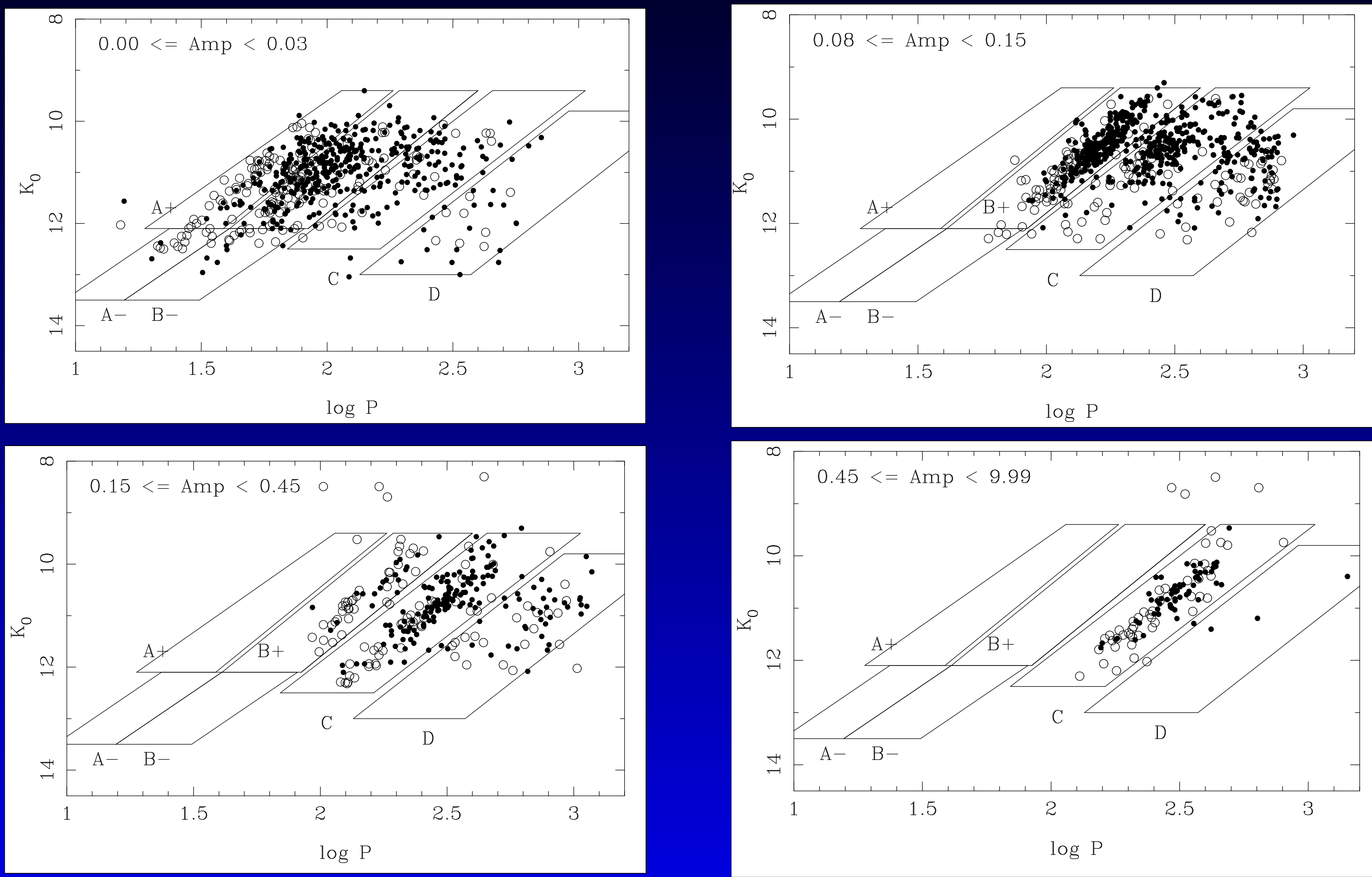
- Cioni et al. 2003
  (0.25 $\square^2$ ISO-sample SMC-bar,
  470 red variables; MACHO + DENIS/2MASS)

History

- Ita et al. 2003
  (1.0 $\square^2$ SMC-centre; $\sim$1800 red variables;
  OGLE + SIRIUS)
- Kiss & Bedding 2003
  ($\sim$23000 red variables LMC;
  OGLE + 2MASS with $J - K > 0.9$)
- Fraser et al. (2005)
  (22 000 LMC MACHO + 2MASS)
- Groenewegen (2004)
  SMC+LMC; OGLE + 2MASS/DENIS
  (2277 spectroscopically confirmed M,S,C-stars)
- Groenewegen & Blommaert (2005)
  Galactic Bulge; OGLE + 2MASS/DENIS

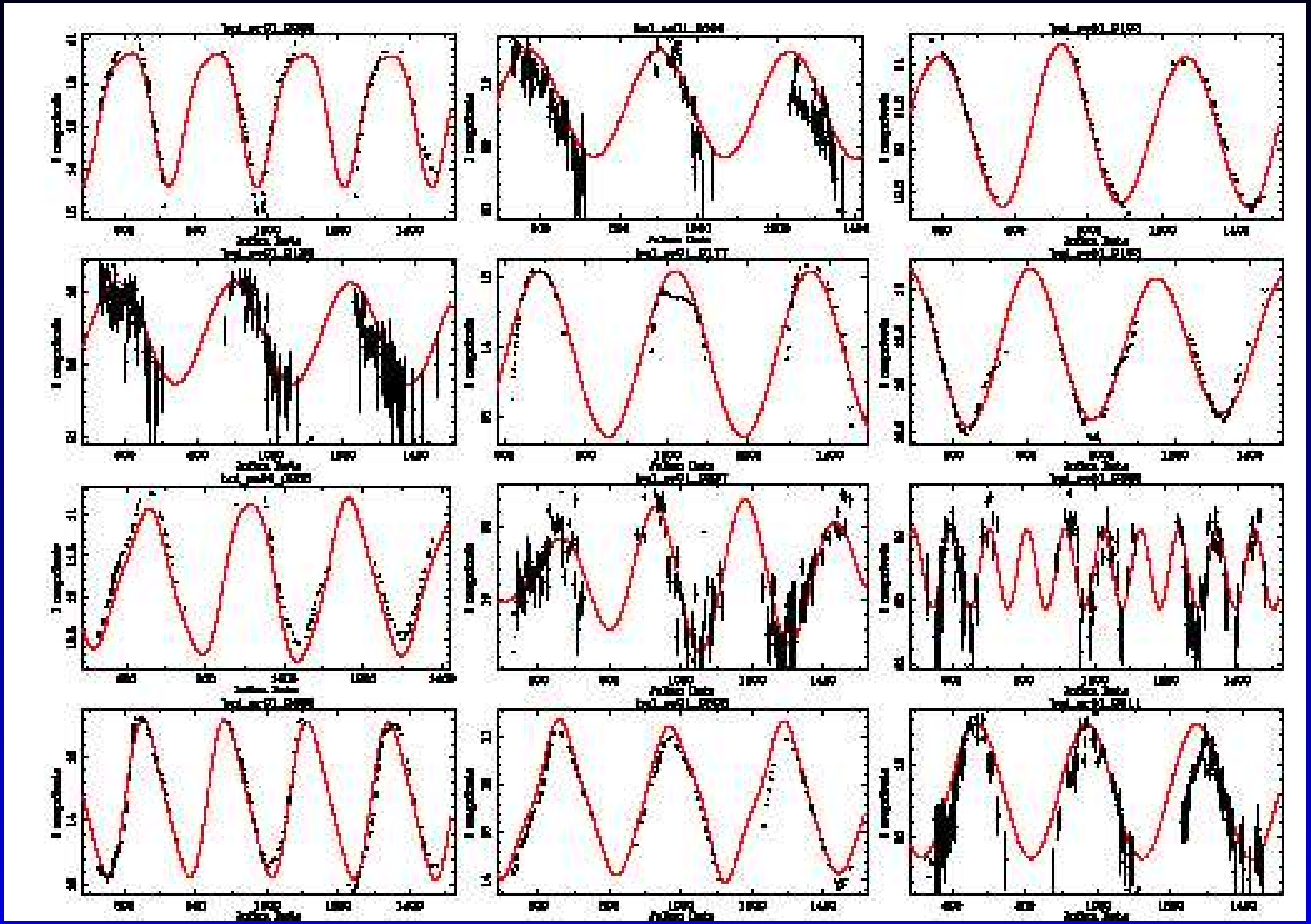
Miras in the LMC



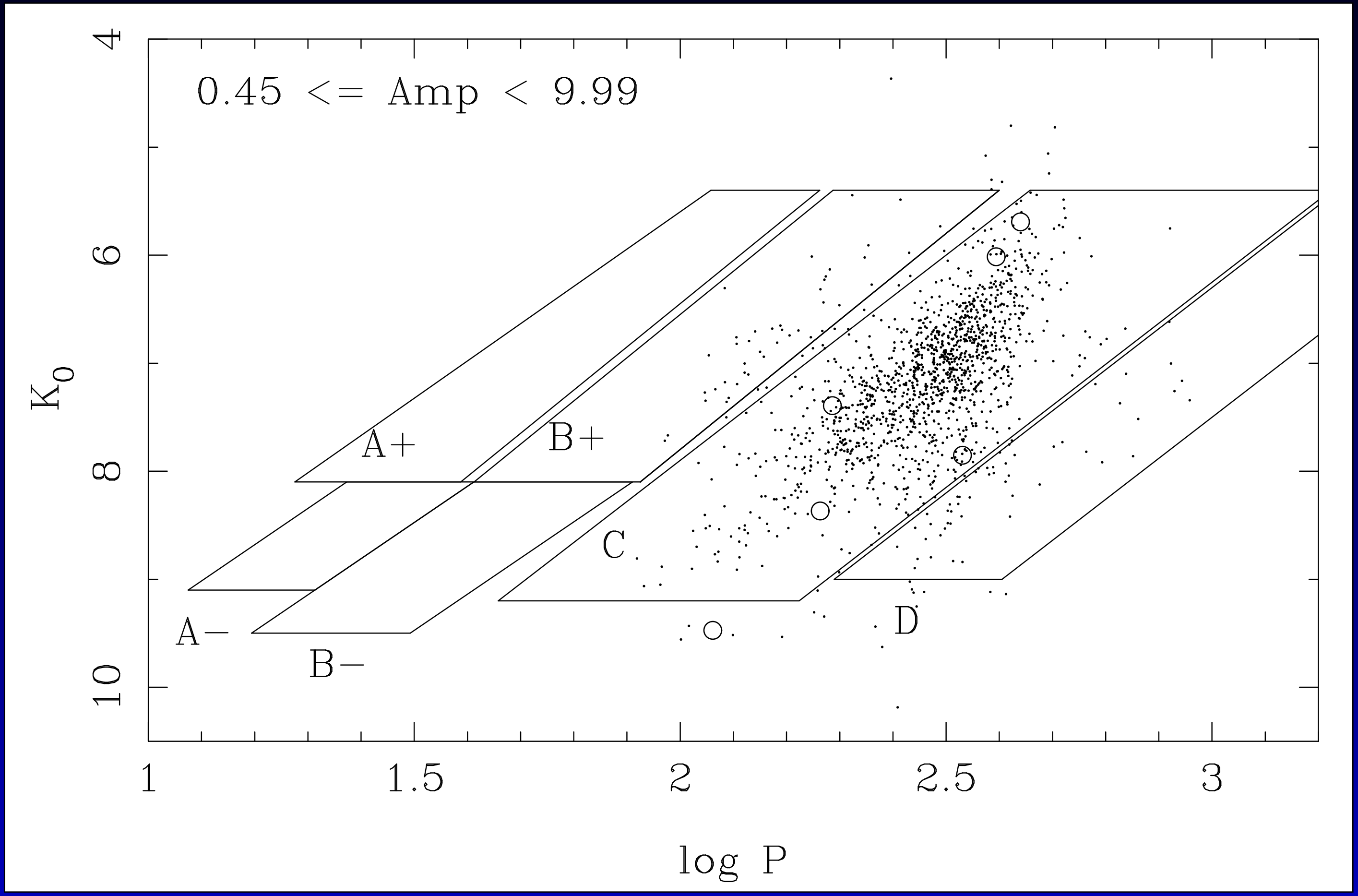
LMC $PL(K)$-relation for different cuts in amplitudes

LPVs in the Galactic Bulge

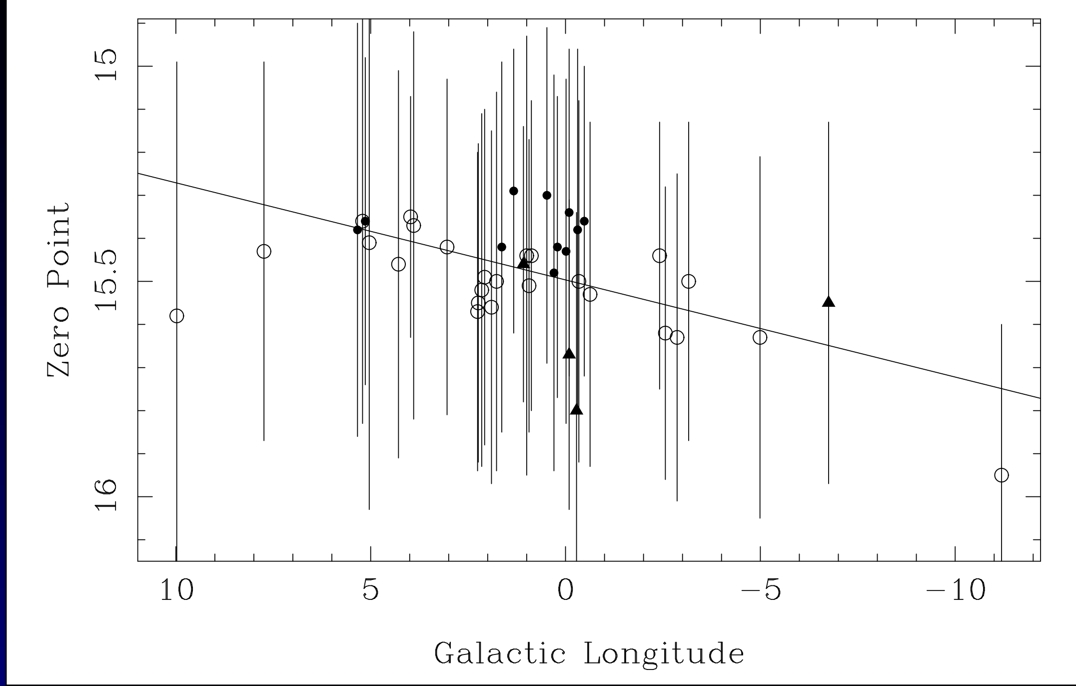
- Groenewegen & Blommaert (2005)
- 2691 Miras:
  $m_{\mathrm{K}} = (-3.37 \pm 0.09) \log P + (15.47 \pm 0.03)$
- Viewing angle of the Bulge: 43 $\pm$ 17 degrees
- Period distribution at various b indicate differences in population
- Distance GC: 8.6 - 9.0 kpc

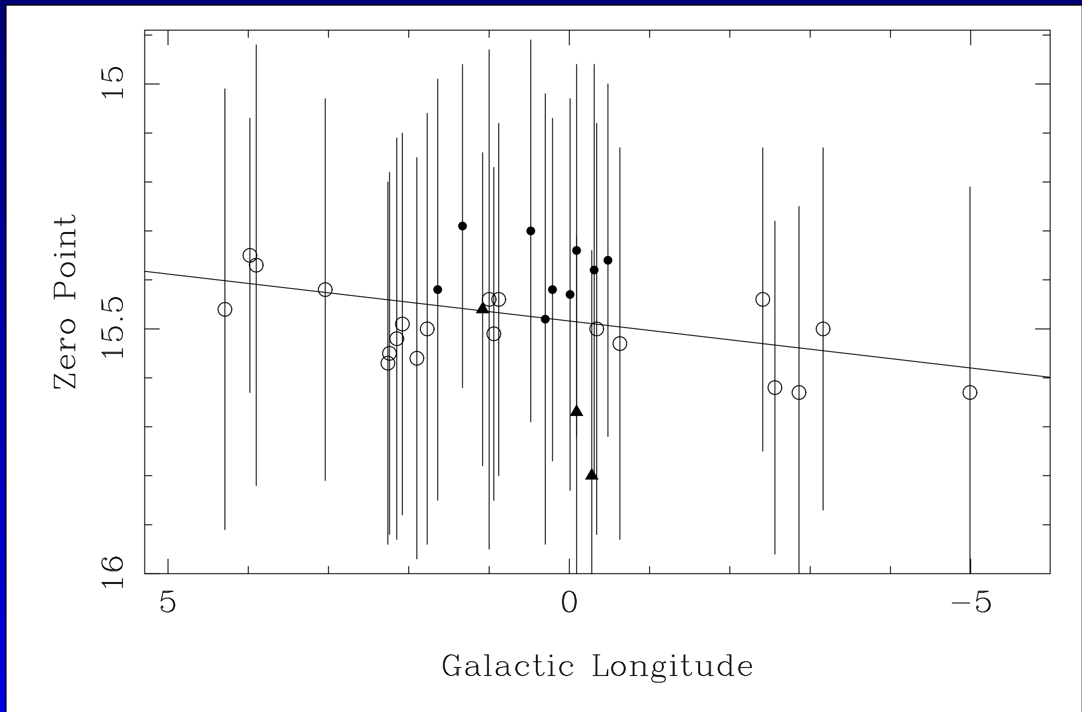


Lightcurves of Bulge Miras



Galactic Bulge Mira *K*-band Period-Luminosity relation





ZP of PL-relation *versus* longitude

Modelling stars in the Bulge

Binney et al. (1997) model of COBE/DIRBE data.

$$f_{\rm b} = f_0 \exp(-a^2/a_{\rm m}^2) \; / \; (1 + a/a_0)^{\beta}$$

($f_0 = 624$, $a_{\rm m} = 1.9$ kpc, $a_0 = 0.10$ kpc, $\beta = 1.8$)

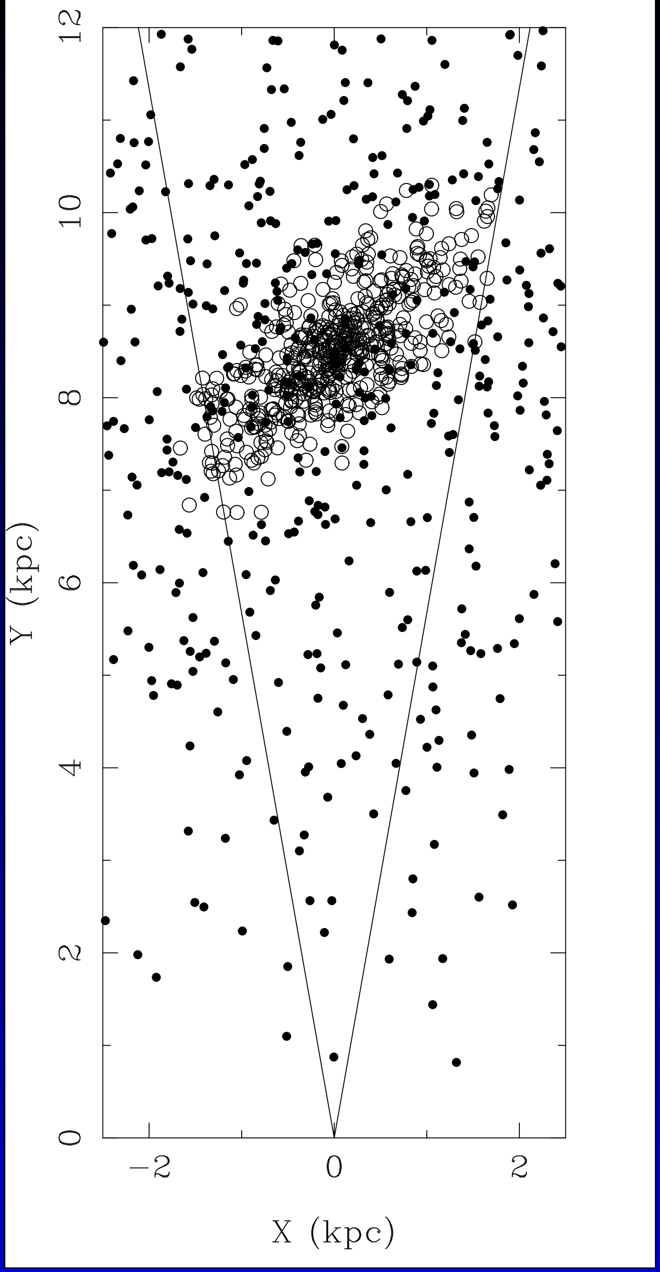
$$a = \sqrt{x^2 + (y/\eta)^2 + (z/\eta)^2}$$

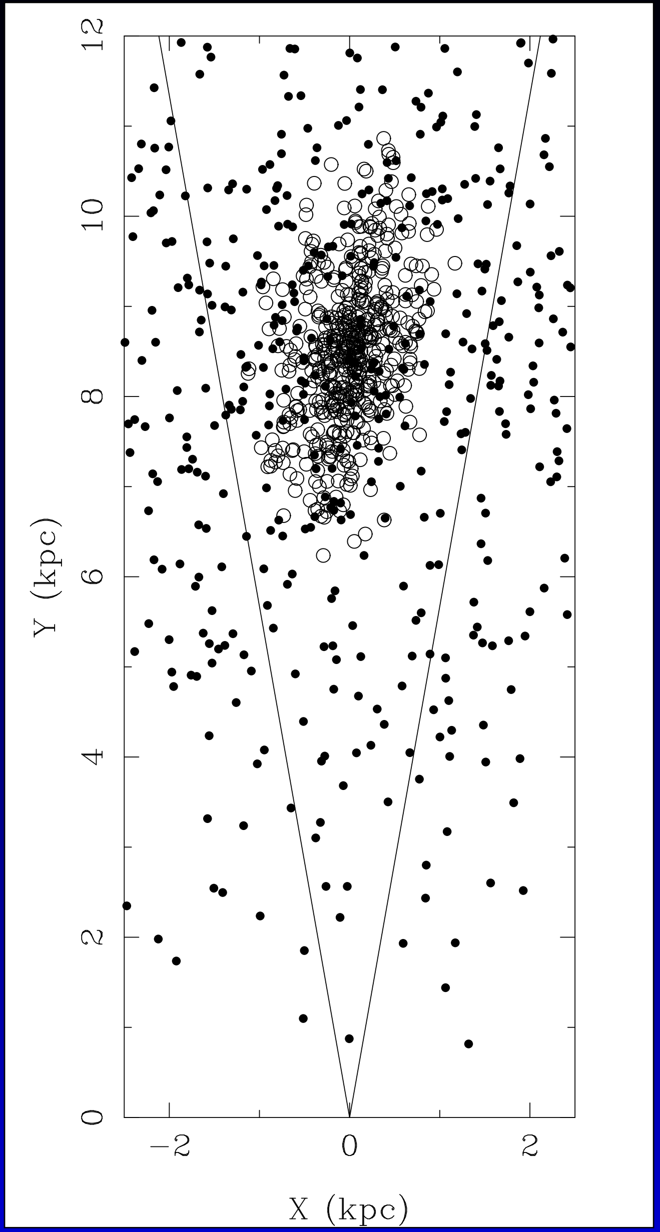
with the value of $\eta = 0.5$

$$f_{\rm d} = (\exp(- \mid z \mid / z_0) + \alpha \exp(- \mid z \mid / z_1)) \; \times$$

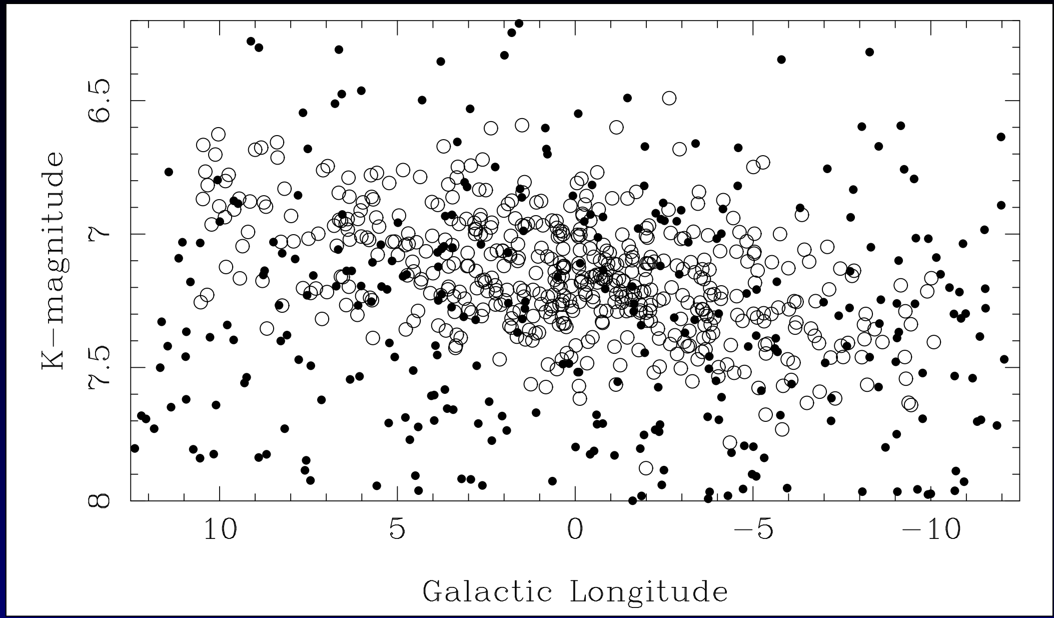
$$R_{\rm d} \; (\exp(-r/R_{\rm d}) - f_{\rm h} \; \exp(-r/R_{\rm h}))$$

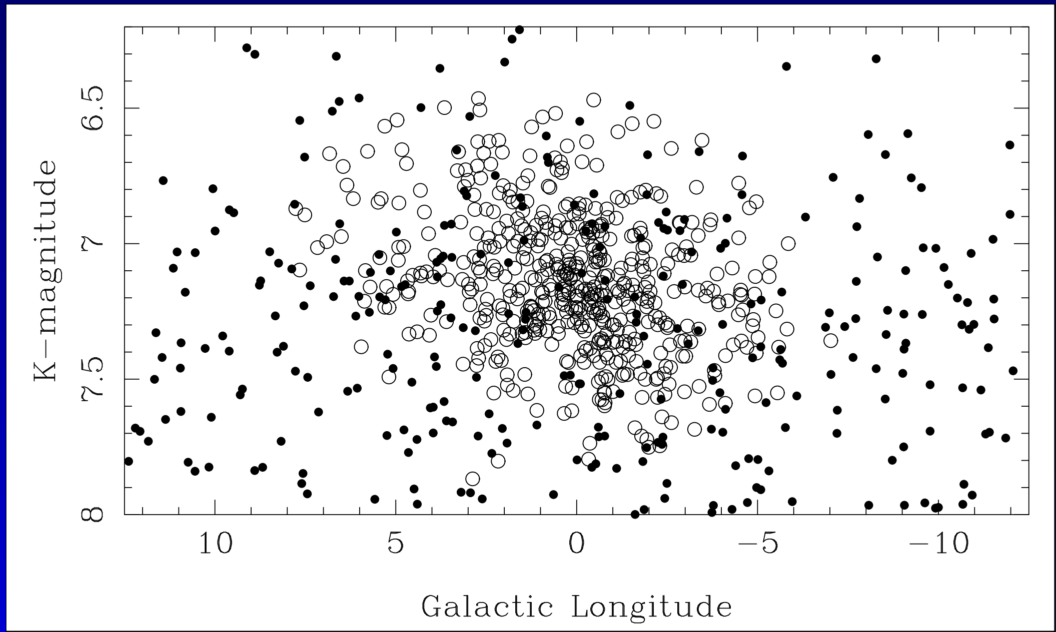
($z_0 = 210$ pc, $z_1 = 42$ pc, $\alpha = 0.27$, $R_{\rm d} = 2.5$ kpc)



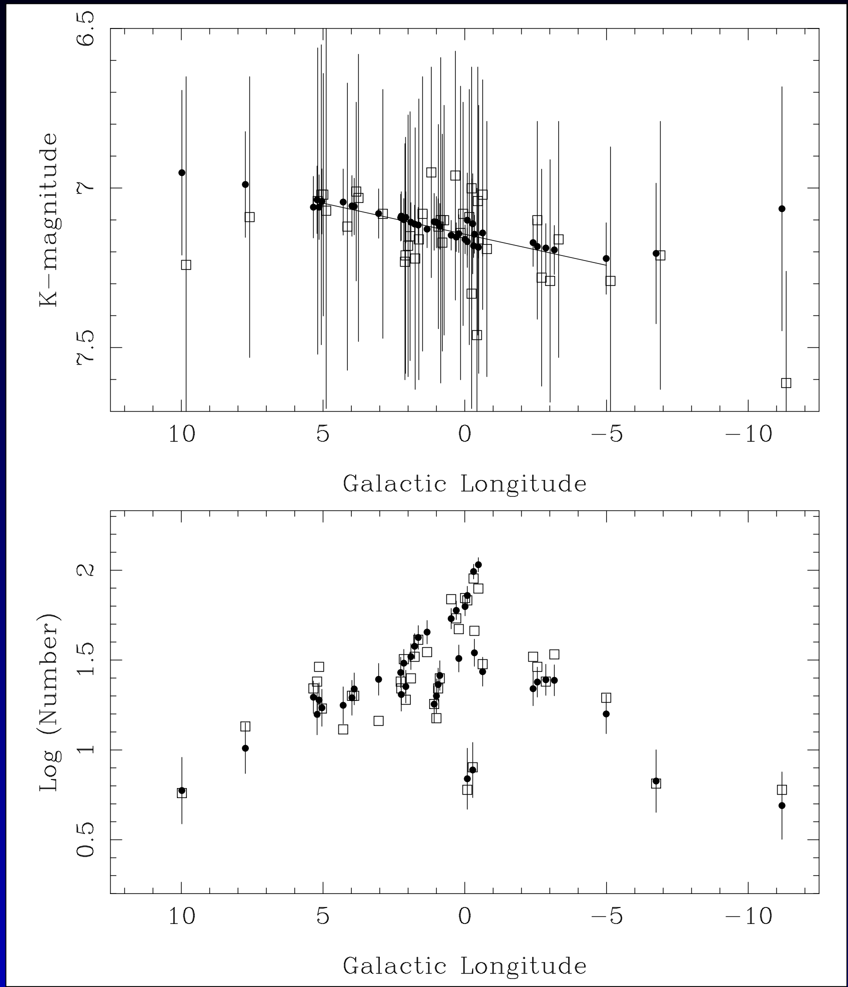


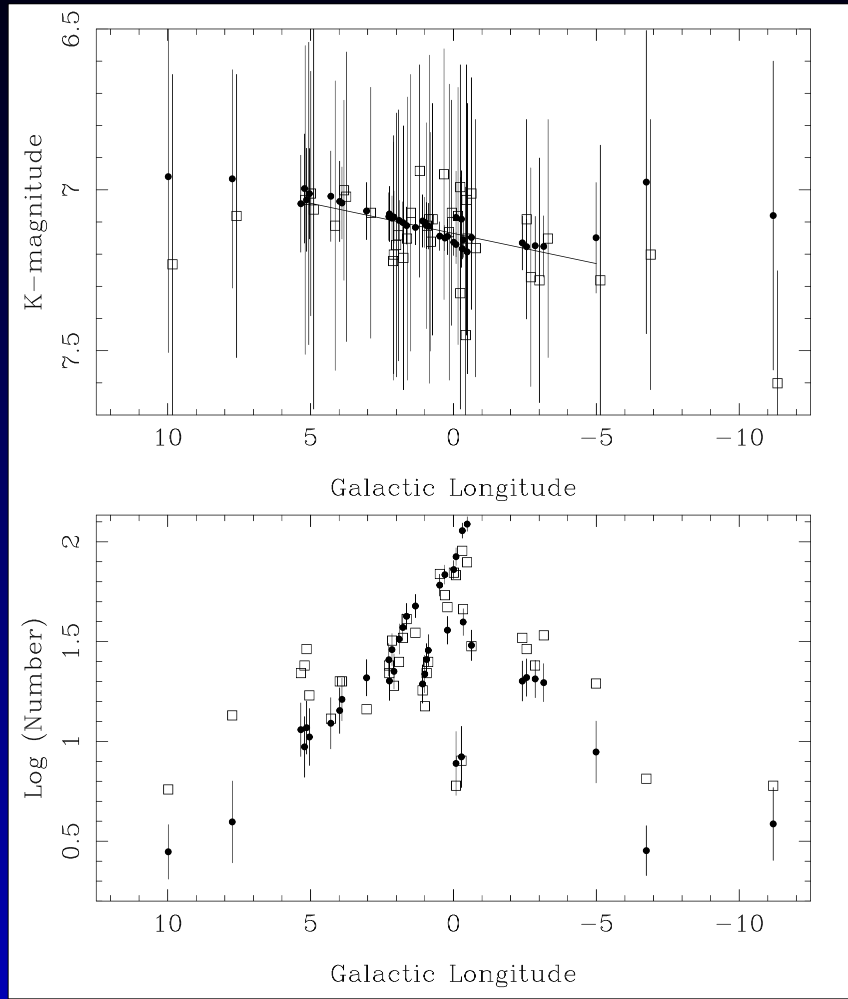
Top view of Bulge (o) and Disc (•) stars for viewing angles of 43 and 79 degrees.



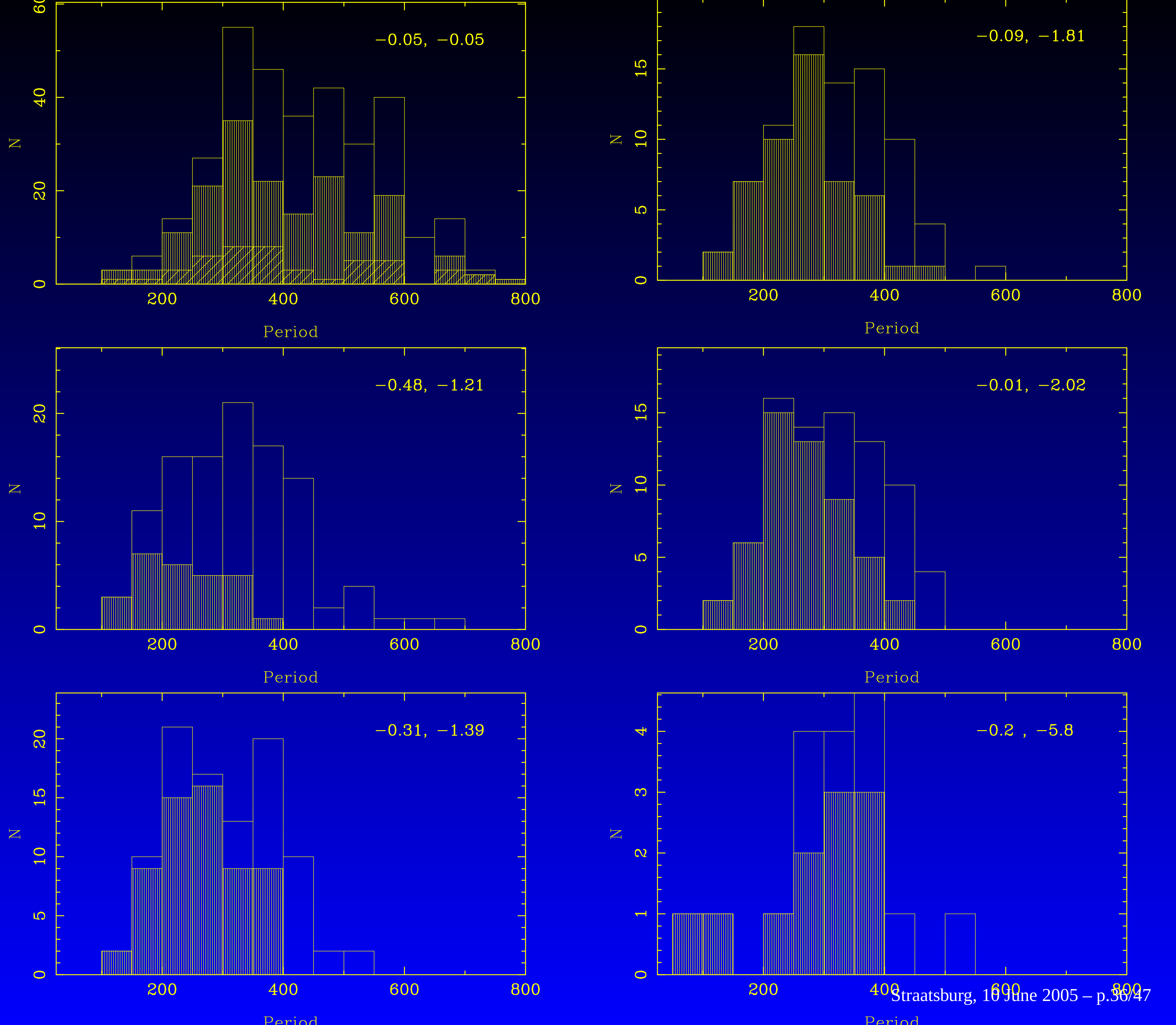


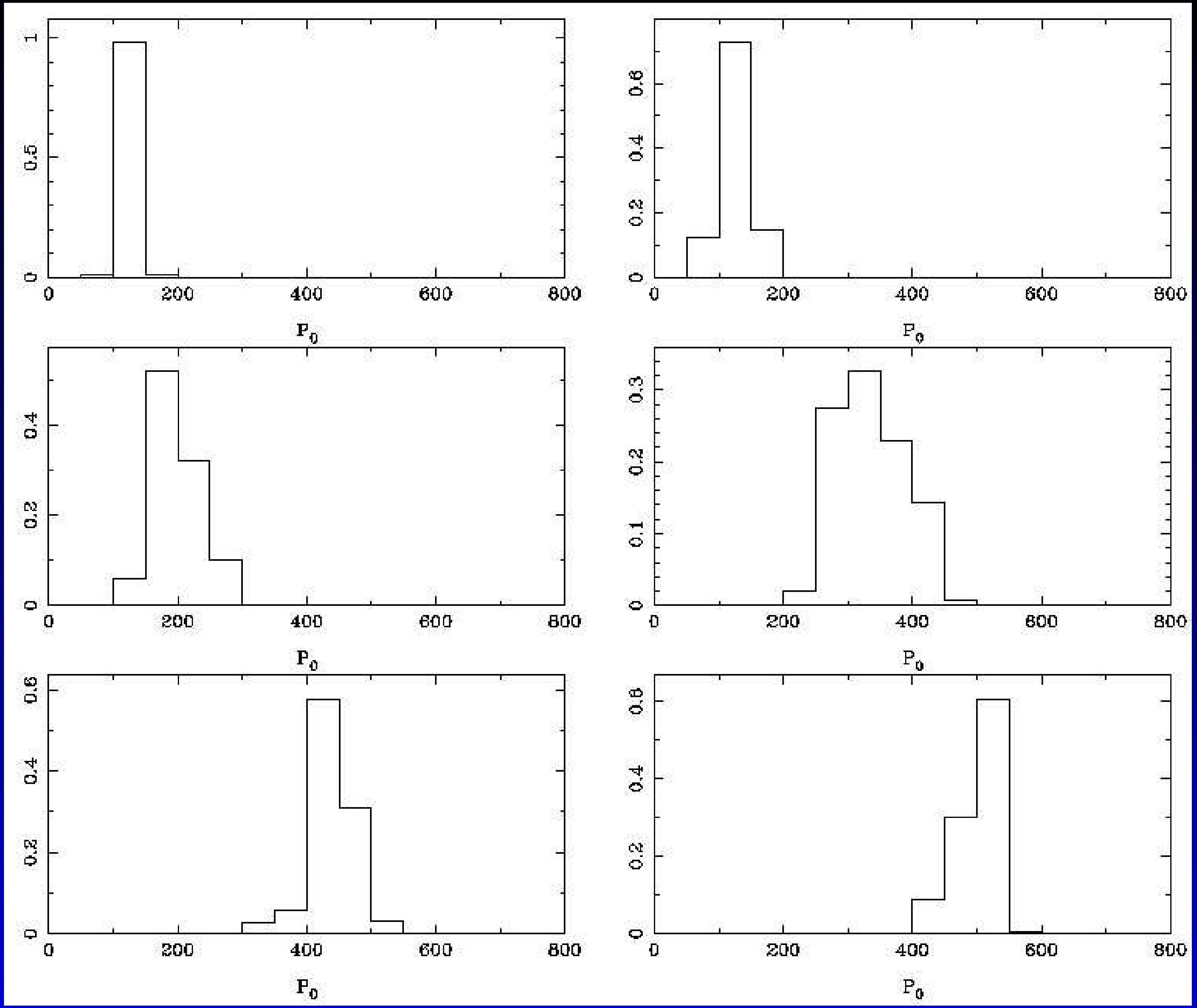
K-magnitude versus longitude for ϕ = 43 (top) and 79^o.





observed (□) and modelled (•) data
Both angles fit slope versus l diagram, but only $\phi = 43^o$ fits the observed numbers

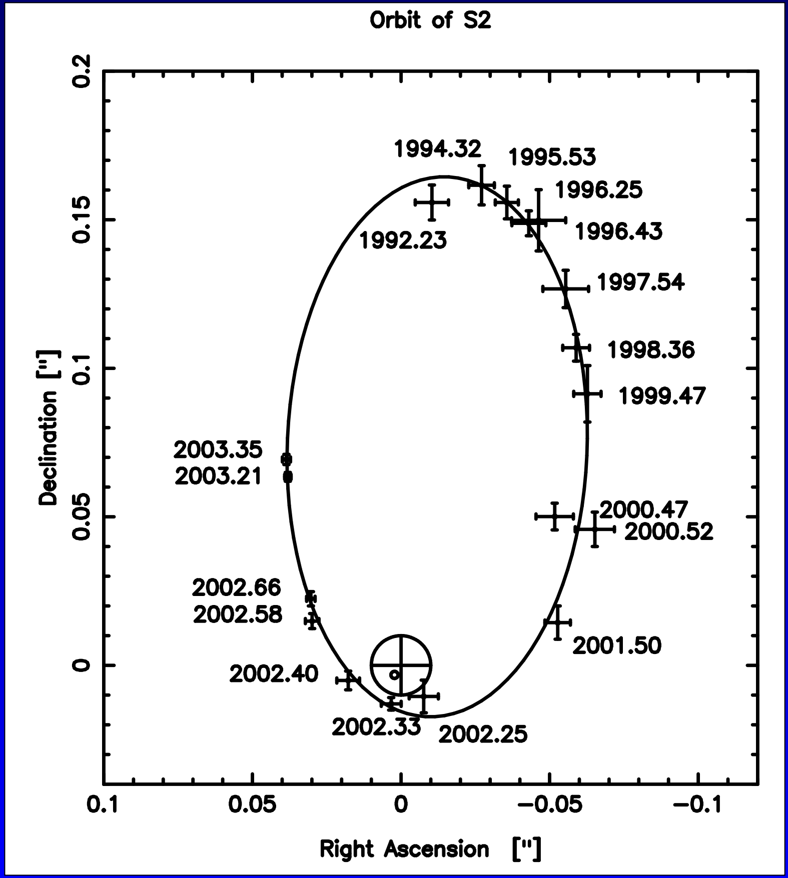

−0.05, −0.05
−0.09, −1.81
−0.48, −1.21
−0.01, −2.02
−0.31, −1.39
−0.2 , −5.8
N
Period



Theoretical period distribution of optically visible stars inside the observed instability strip for masses 1.1, 1.2, 1.5, 2.0 (1.2 Gyr), 2.5, 3.0$M_\odot$ (200 Myr) (left to right, top to bottom)

Distance to Galactic Centre I

- Reid (1993): 8.0 ± 0.5 kpc
- Eisenhauer (2003): O8-B2 star S2 orbiting the BH in 15.5 years ⇒ 7.9 ± 0.4 kpc



Distance to Galactic Centre II

- $M_{\rm K} = \alpha \log P + \beta \qquad (+\, \gamma \log Z)$

  DM (LMC-GB) = 3.71 (for $\gamma = 0$)
  $\Rightarrow$ IF DM(LMC) $\equiv$ 18.50 then d(GB) = 9.0 kpc

  Theory by Wood (1990): γ = 0.25 (in K-band)

  DM (LMC-SMC) = 0.38; "rather small"
  $\Rightarrow$ IF DM(LMC-SMC) $\equiv$ 0.50 THEN γ = 0.40

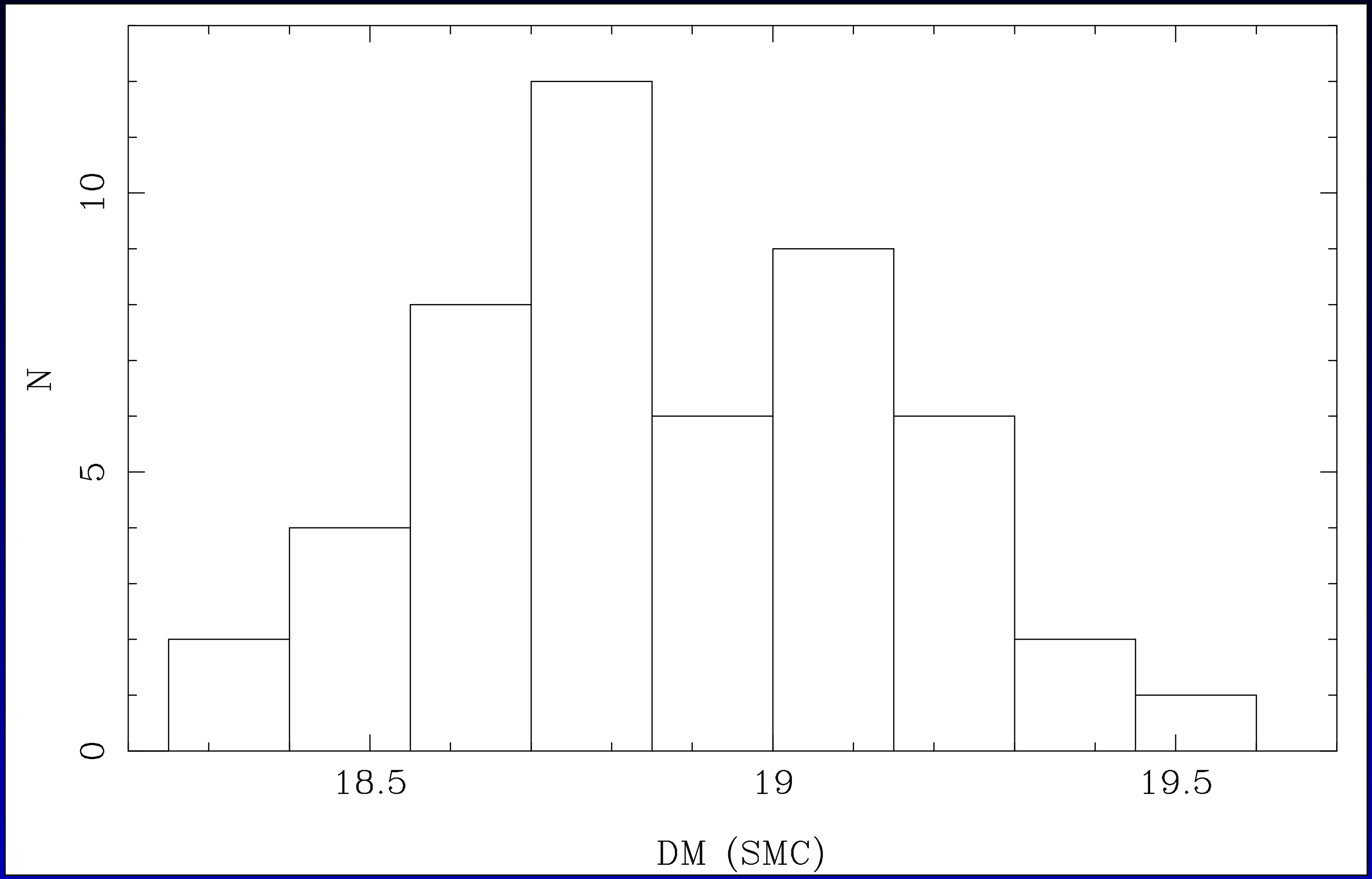
  $\Rightarrow$ IF DM(LMC) $\equiv$ 18.50 then d(GB) = 8.6 kpc

  (DM(LMC) = $-0.10 \Longleftrightarrow d$(GB)= -400pc)

  Using local calibration of Feast (2004):
  d(GB) = 8.8 $\pm$ 0.4 kpc

Eclipsing Binaries

- OGLE: Udalski et al. (1998); 1459 in SMC
  OGLE: Wyrzykowski et al. (2003, 2004);
  2580 in LMC; 1350 in SMC
  MACHO: Alcock et al. (1997); 637 in LMC
  MOA: Bayne et al. (2002); 167 in SMC
  EROS: Grison et al. (1995); 79 in LMC
- RV + Photometry: Harries et al. (2004),
  Hilditch et al (2005)
  (detached, double-lined EB)



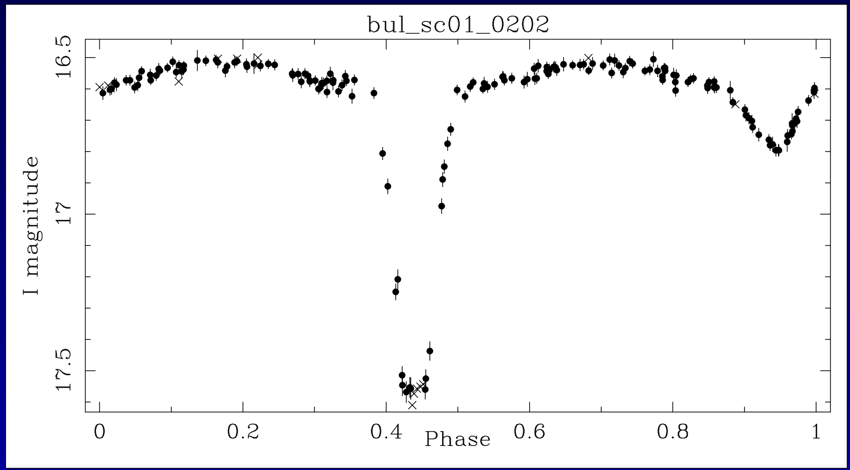
SMC DM based on 50 EB: 18.91 ± 0.03
Harries et al. (2004), Hilditch et al. (2005)

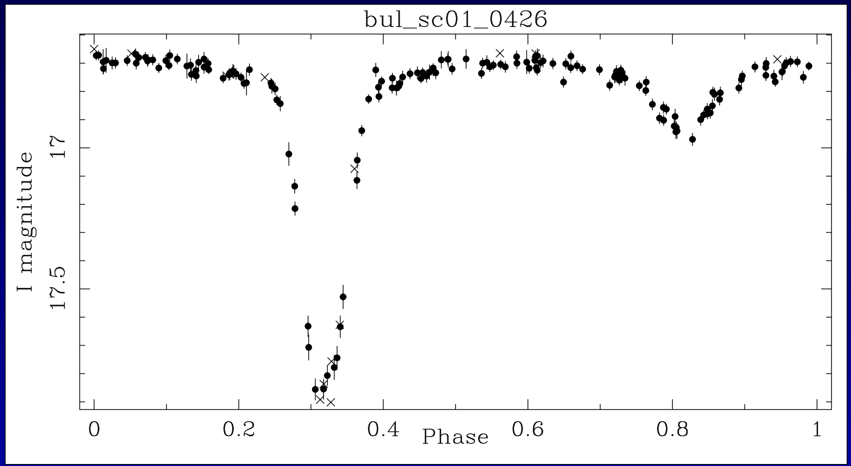
Eclipsing Binaries in MCs

- Groenewegen (2005)
- Test data set of 142 EBs previously claimed in literature to be suitable for distance work.
- Parameters mentioned earlier were finetuned: recovery of 137.
- Run on all MC OGLE-data.
  SMC: 714/752 in Wyrzykowski et al. (2004); 20 wrong (13 known Cepheids); 2 EB by MOA, 16 NEW
  LMC: 1616/1856 in Wyrzykowski et al. (2003); 51 wrong 11 EB by MACHO, 178 NEW
  Complementary to neural network scheme by OGLE: 7.5% new, 2.5% false

Eclipsing Binaries in GB

- Run on all BULGE OGLE-data: 3053 EBs

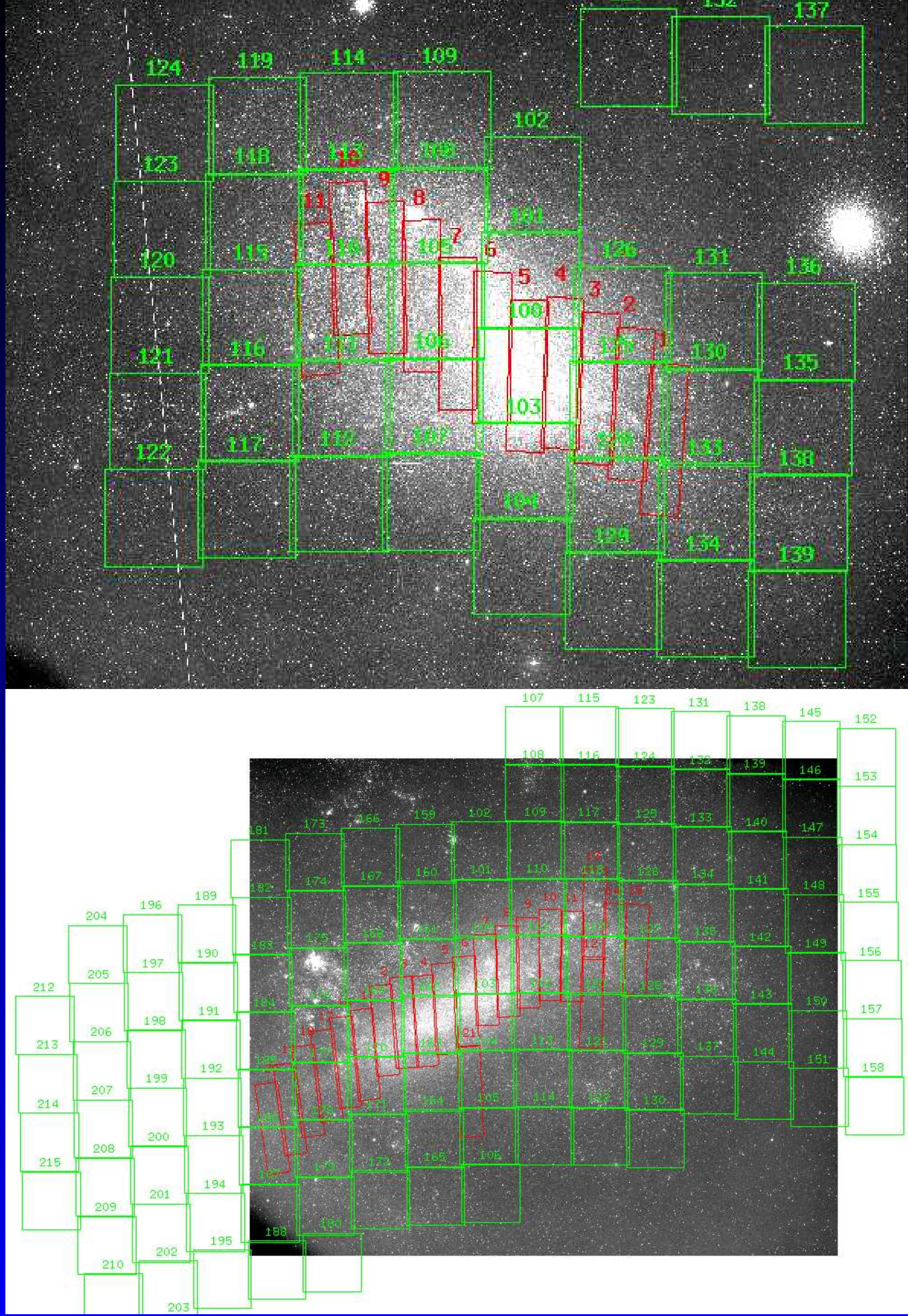




- Future-1: Get 2 RV datapoints for ∼25-50 stars
- Future-2: RV monitoring for sub-sample

Future of surveys

- OGLE-III
  Started June 2001
  Monitoring 170M stars in GB, and 33M in MCs
- super-MACHO
  4m CTIO, LMC, 5 years, 3 months/yr,
  every second d&g night, started 2003
- MOA-II 1.8m since Dec 2004



OGLE-III fields of SMC (top) and LMC

Future of surveys

- Panoramic Survey Telescope & Rapid Response System (Pan-STARRS)
  4x 1.8m, 3 deg FoV, 24th mag, 20x year, 6000 deg^2/n, 2006-2008
- Large Synoptic Survey Telescope (LSST)
  8.4m, 10deg^2 FoV, 24th mag, available sky in 3n (30TB/n), 2012
- GAIA, 2012, 1 billion objects, 80x, 5 years, G= 20, (several million variables)

THE END