The distance to the Pleiades

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Overview

- Importance of Pleiades as distance indicator
- Previous distances and the Hipparcos controversy
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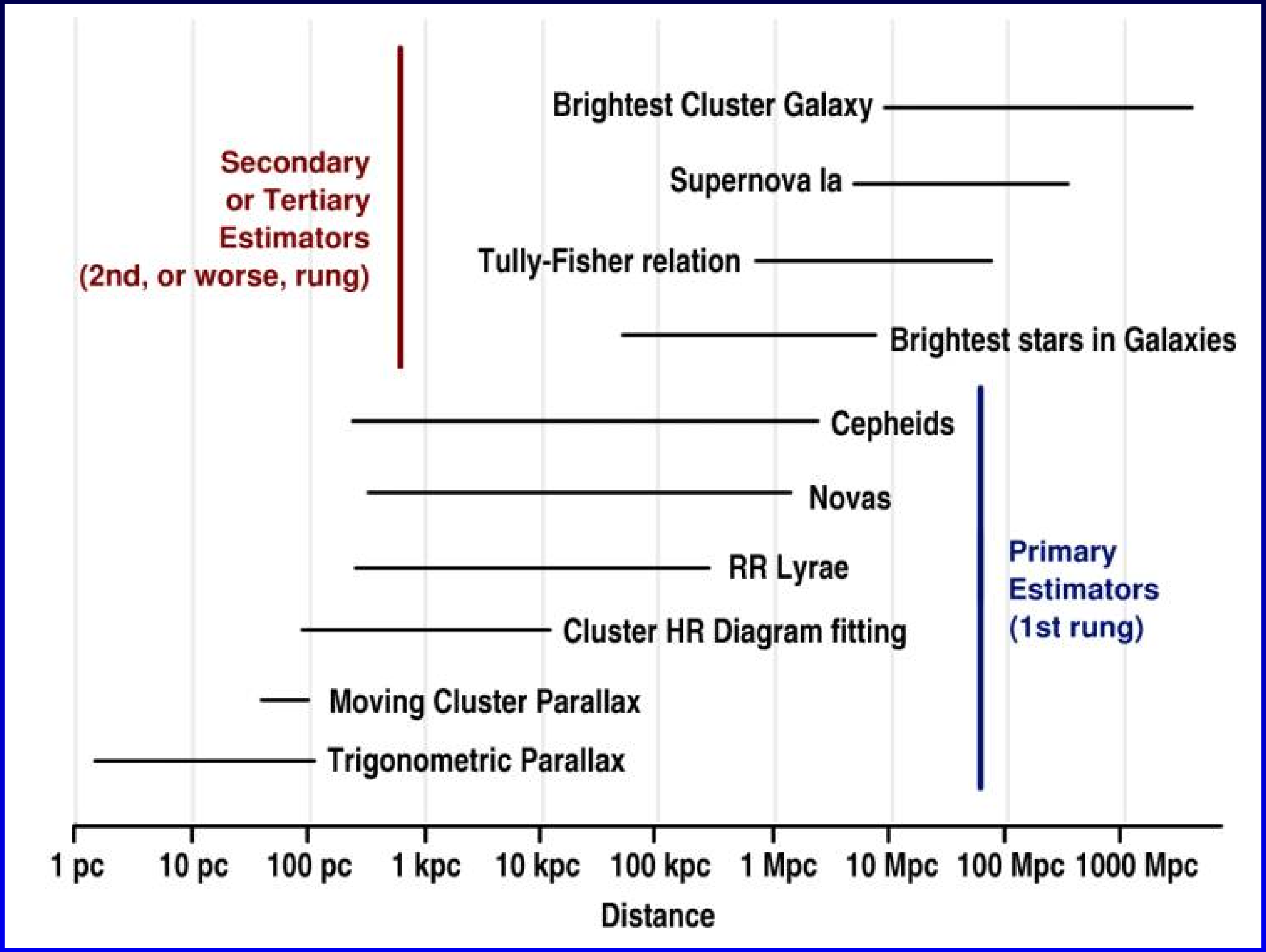
    - Alternative analysis of Hipparcos data
    - Main-Sequence fitting
    - Interferometric binary: Atlas (HD 23850)
    - Parallax using FGS/HST
    - Ground-based Parallax
    - Eclipsing binary: HD 23642
- Conclusions

Distance indicators

- Pleiades (130 pc) and Hyades (46.34 pc) are near.



Previous distances

- Pickering (1918):
  trigonometric parallax, 201 ± 48 pc
- Eggen (1986):
  main-sequence fitting in Strömgren colours,
  135 ± 6 pc (5.65 ± 0.10)
- Gatewood et al. (1990):
  trigonometric parallax, 150 ± 18 pc (5.9 ± 0.26)
- Pinsonneault et al. (1998):
  main-sequence fitting in $(B - V)$ and $(V - I)$,
  131.8 ± 2.5 pc (5.60 ± 0.04)

Previous distances

HIPPARCOS

- van Leeuwen & Hansen Ruiz (1997):
  116.1 $\pm$ 3.0 pc (5.32 $\pm$ 0.06)

  van Leeuwen (1999):
  118.3 $\pm$ 3.4 pc (5.36 $\pm$ 0.07)

- explanations:
  lower metallicity [Fe/H] = -0.25 to -0.45

  large helium content (Y = 0.37)

  systematic error:
  star-to-star correlations over 2 degree scale

Alternative Hipparcos analysis

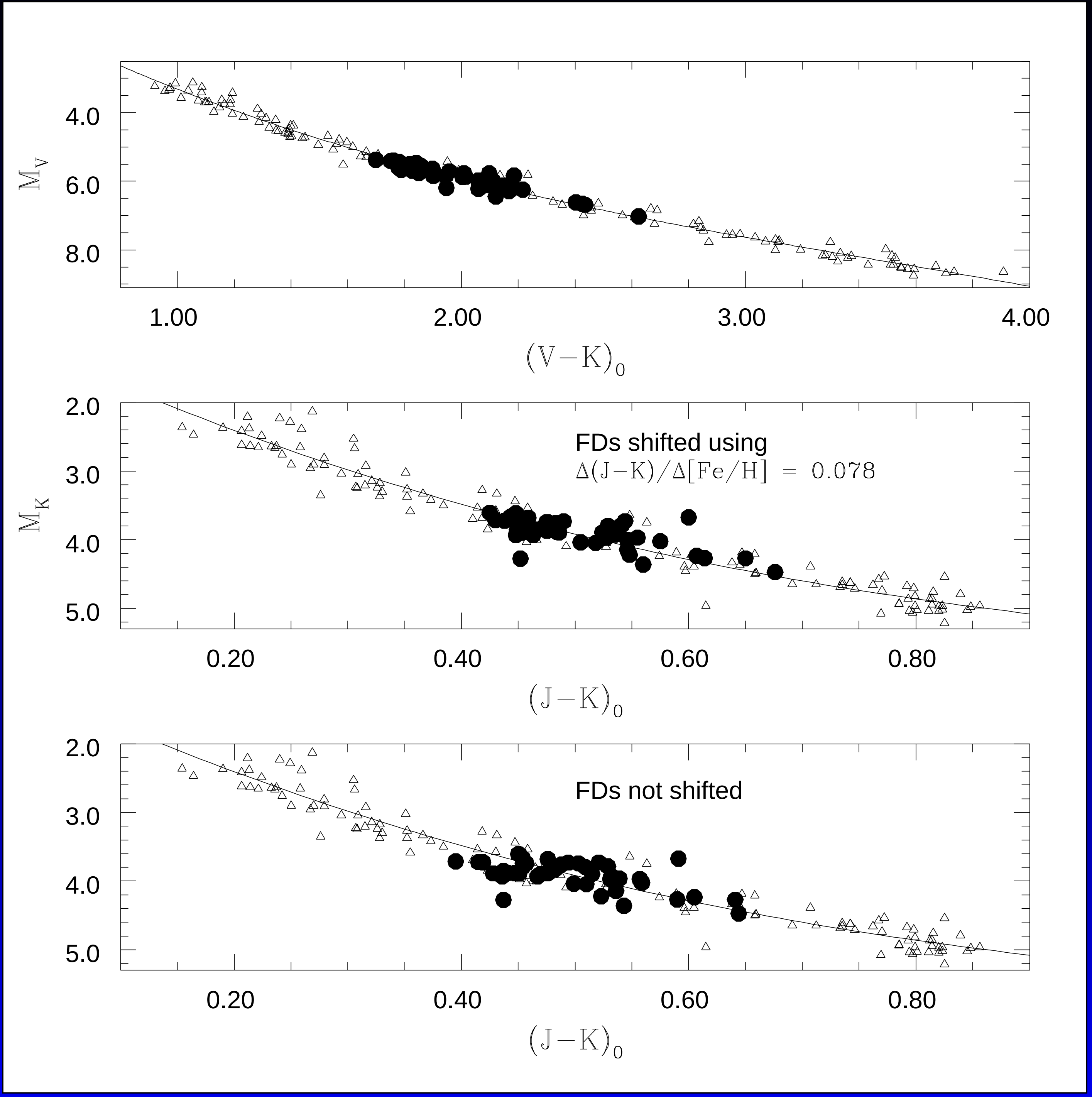
- Narayanan & Gould, 1999, ApJ 523, 328
  used proper motion + RV data
  ("moving cluster method")
  130.7 $\pm$ 11.1 pc (5.58 $\pm$ 0.18)
- Li & Junlian, 1999, ASPC 167, 259
  Similarly, using maximum likelihood method:
  135.56 $\pm$ 0.72 pc (5.66 $\pm$ 0.01)
- Makarov, 2002, AJ 124, 3299
  Hipparcos Intermediate Astrometry Data
  54 cluster members + all other stars within
  58 $\pm$ 0.5 degree
  129.0 $\pm$ 3.2 pc (5.55 $\pm$ 0.05)

Main-sequence fitting

- Percival, Salaris, Groenewegen, 2005, A&A 429, 887
- Main-sequence fitting in the infra-red

  using 54 local sub-dwarfs with accurate Hipparcos parallaxes
- Conclusion: 133.8 ± 3.0 pc (5.63 ± 0.04) (at [Fe/H]= -0.03)

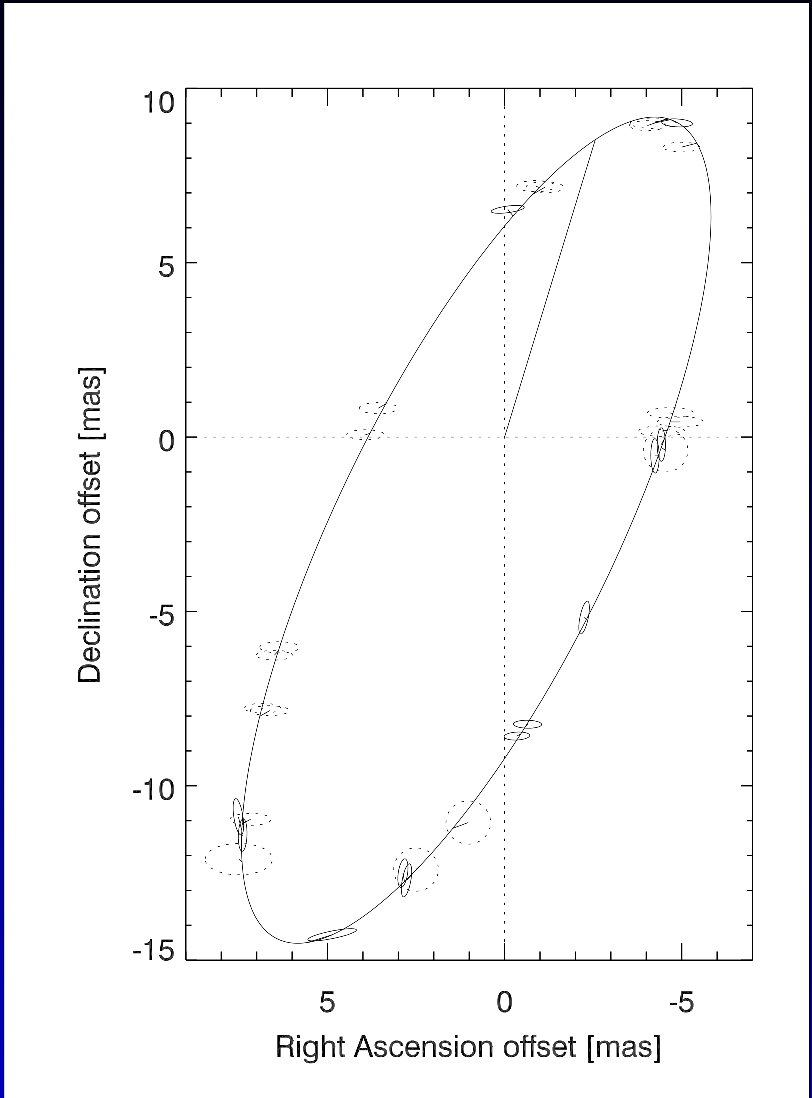
  (at [Fe/H]= -0.4: 126 pc)

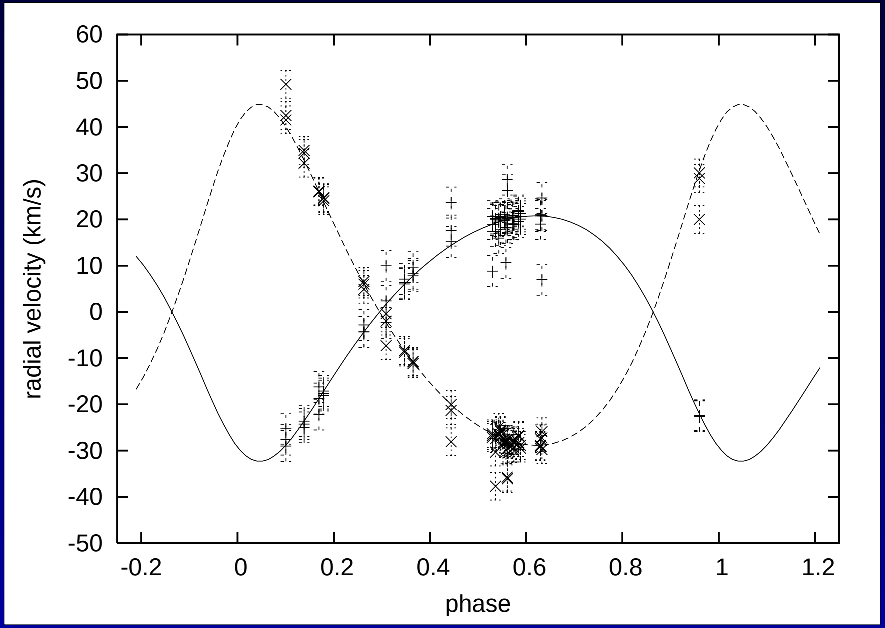


4.0
6.0
8.0
M_V
1.00
2.00
3.00
4.00
$(V-K)_0$
2.0
3.0
4.0
5.0
M_K
FDs shifted using
$\Delta(J-K)/\Delta[Fe/H] = 0.078$
0.20
0.40
0.60
0.80
$(J-K)_0$
2.0
3.0
4.0
5.0
FDs not shifted
0.20
0.40
0.60
0.80
$(J-K)_0$

Interferometric binary: Atlas

- Pan, Shao, Kulkarni, 2004, Nature 427, 326
- Zwahlen, North, Debernardi, Eyer, Gallard, Groenewegen, Hummel, 2004, A&A 425, L45
- V = 3.62. Discovered to be a binary in 1974 by Lunar occulatation
- Pan et al. use interferometry to find a, P, ΔV Adopt an isochrone. With known V and adopt $E(B-V)$ to find 134 - 138 pc
- Zwahlen et al: radial velocity monitoring + more interferometric data
- Conclusion: 132 $\pm$ 4 pc (5.60 $\pm$ 0.06)





4.7 & 3.4 $M_\odot$; a = 13 mas ; P= 290 days

FGS/HST

- Soderblom, Nelan, Benedict, McArthur, Ramirez, Spiesman, Joens, 2005, AJ 129, 1616
- Trigonometric parallaxes for 3 cluster members + 9 reference stars
- 6 epochs over 3.5 yr

  Spectra + colour information to estimate reddening, spectral type and LC $\Rightarrow M_{\rm V} \Rightarrow \pi_{\rm abs}$

  Proper motions

FGS/HST

ID	μ	π	V_t (km/s)
3179	50.36 ± 0.40	7.45 ± 0.16	32
3063	45.30 ± 0.53	7.43 ± 0.16	29
3030	43.20 ± 0.48	7.41 ± 0.18	28

Object	π_{HST} (mas)	π_{HIP} (mas)
Proxima Cen	769.7 ± 0.3	772.33 ± 2.42
Barnard's Star	545.5 ± 0.3	549.3 ± 1.58
Gliese 876	214.6 ± 0.2	212.7 ± 2.10
Feige 24	14.6 ± 0.4	13.44 ± 3.62
Wolf 1062	98.0 ± 0.4	98.56 ± 2.66
Pleiades	7.43 ± 0.17	8.45 ± 0.25
RR Lyrae	3.60 ± 0.20	4.38 ± 0.59
δ Cephei	3.66 ± 0.15	3.32 ± 0.58
HD 213307	3.65 ± 0.15	3.43 ± 0.64

- Conclusion: 134.6 ± 3.1 pc (5.65 ± 0.05)

Ground-based parallax

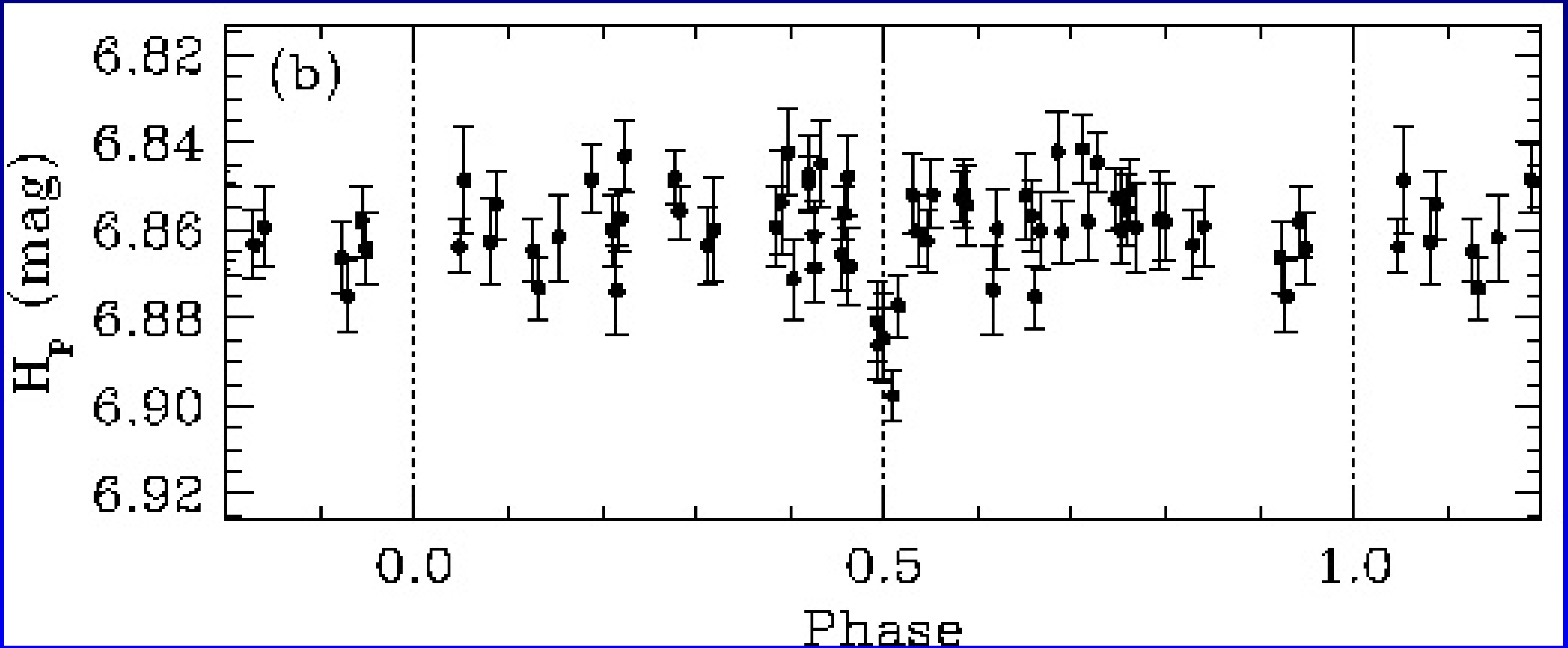
- Gatewood, de Jonge, Han, 2000, ApJ 533, 938
- Ground-based parallax of 7 members
- conclusion: 130.9 ± 7.0 pc (5.59 ± 0.12)

HD 23642

- First known SB2 in the Pleiades (1950s)
- Eclipsing (April 2003)
-
  - Munari, Dallaporta, Siviero, Soubiran, Fiorucci, Girard, 2004, A&A 418, L31
  - Southworth, Maxted, Smalley, 2005, A&A 429, 645
  - Groenewegen, Decin, Salaris, De Cat, 2007, A&A, in press
  - Valls-Gabaud et al., in prep.

History of HD 23642

- Pearce (1957), Abt (1958) provide first RV observations
- Torres (2003, IBVS)
  New RV (unpublished)
  66 datapoints of Hipparcos Epoch Photometry



Available data for analysis

- Radial velocities:

  15 measurements from Abt; $\sigma \sim$ 3-15 km/s

  24 measurements from Pearce; $\sigma \sim$ 5-10 km/s

  5 measurements from Munari et al; $\sigma \sim$ 0.5-1.0 km/s (cross-correlation against A-star template)

  11 measurements using Coralie @ Euler

  -17 orders were selected, $\sigma \sim$ 0.9-1.5 km/s

Spectral disentangling: KOREL

$$x = c\ln(\lambda/\lambda_0) \Rightarrow dx = c/\lambda d\lambda = RV$$

$$I(x,t) = \sum_{j=1}^{2} I_j(x - RV_j(t))$$

$$I(x,t) = \sum_{j=1}^{2} I_j(x) \bigotimes \delta(x - RV_j(t))$$

Fourier transform:

$$J(y,t) = \sum_{j=1}^{2} J_j(y)\ \exp(iy\, RV_j(t))$$

$$S = \sum_{i=1}^{k} \int |J(y,t_i) - \sum_{j=1}^{2} J_j(y) \exp(iy\, RV_j(t_i,p))|^2 dy$$

$$RV = f(P, T_0, K_1, q, e, \omega\ )$$

$\Rightarrow$ orbital elements, $RV_j(t_i)$ (relative to the c.o.m.), $I_j(x)$

Stellar parameters: MARCS

- A grid of model atmospheres is calculated

  $\log g$ = 4.0 and 4.3, [Fe/H]= 0.0 and $+0.10$,
  $T_{\rm eff}$ = 9500 and 10500 K, 7250 and 8000 K

- -$T_{\rm eff}$ of primary and secondary (T_1, T_2),
  -Metallicity Z, same for both components,
  -($V_{\rm rot,1} \sin i$) and ($V_{\rm rot,2} \sin i$),
  -The continuum shifts for the two components (s_1, s_2, related to possible shifts in the individual continua after the spectral disentangling),
  -RV of the system (V_γ).
  -($\log g$ is known from masses and radii from LC and RV analysis)

Stellar parameters: MARCS

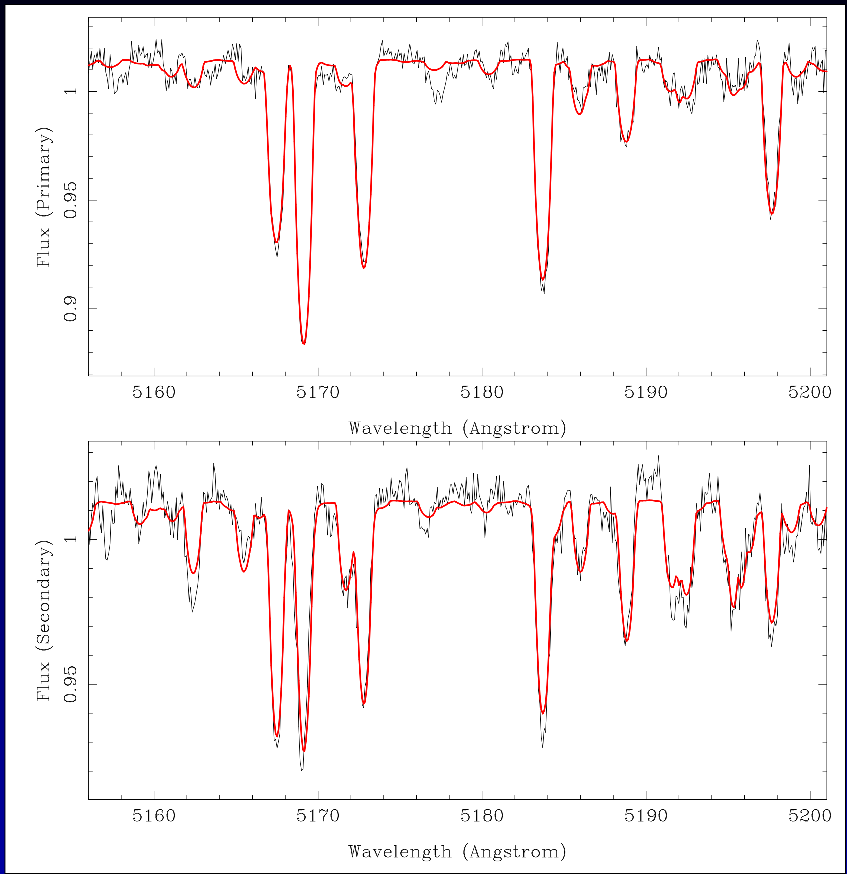
For a given set of parameters,
(1) interpolate the primary and secondary continuum and absolute flux
(2) the wavelength scale is redshifted by the systemic velocity,
(3) the absolute and continuum fluxes are rotationally broadened,
(4) re-binned to the observed wavelength points.
(5)

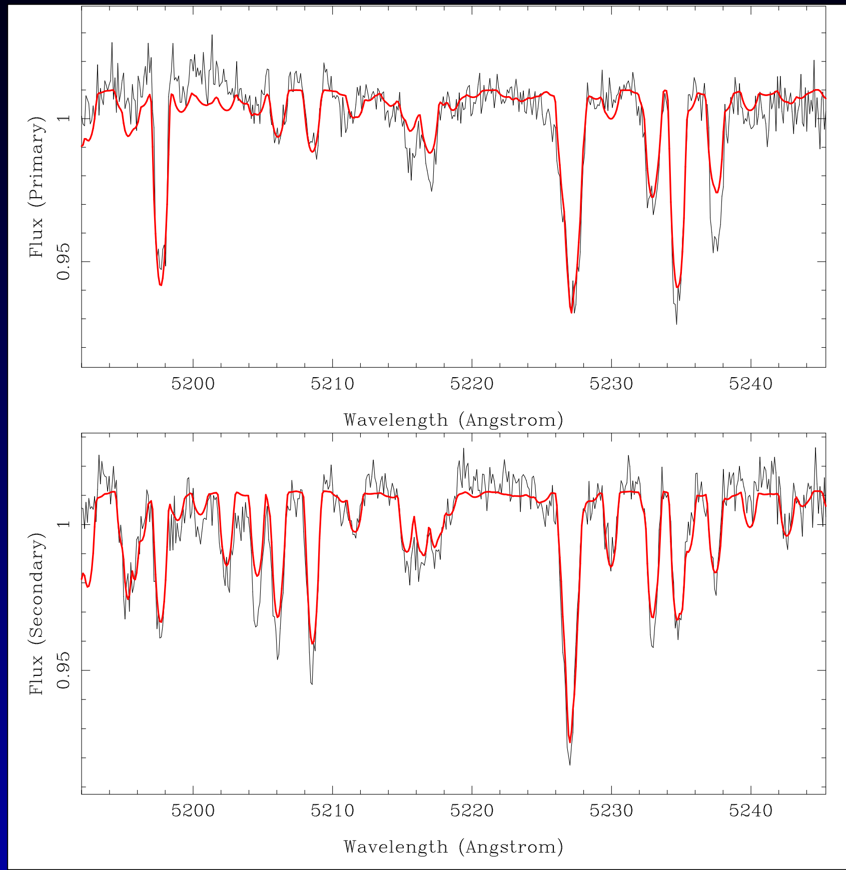
$$C_1(\lambda) = R_1^2\ F_1^{\rm cont}/(R_1^2\ F_1^{\rm cont} + R_2^2\ F_2^{\rm cont})$$

$$NS_1(\lambda) = ((F_1/F_1^{\rm cont}) - 1.0)\ C_1 + 1.0 + s_1,$$

Stellar parameters: MARCS

- Iteration 1: everything left free
  8 parameters per 17 spectral orders
  V_γ = 5.5 ± 1.0 km/s,
  $V_{\mathrm{rot},1} \sin i$ = 36.5 ± 0.8 km/s
  $V_{\mathrm{rot},2} \sin i$ = 31.9 ± 1.2 km/s
- Iteration 2: 5 parameters left free
  $T_1 = 10020 \pm 600$ K
  $T_2 = 7670 \pm 340$ K
  $Z = 1.10 \pm 0.29$ ([Fe/H] = 0.04 ± 0.10)
- Iteration 3: 4 parameters left free
  Fix Z = 1.15
  ([Fe/H] = +0.06 ± 0.02, Boesgaard 2005)
  $T_1 = 9950 \pm 370$ K
  $T_2 = 7640 \pm 380$ K





Fit to two spectral orders

Lightcurve and RV analysis: FOTEL + PHOEBE

$$r_{1,2} = a_{1,2}\,(1 - e^2)/(1 + e\,\cos\nu)$$

$$\nu = 2\arctan\left(\sqrt{\tfrac{1+e}{1-e}}\,\tan(E/2)\right)$$

$$M = E - e\,\sin E$$

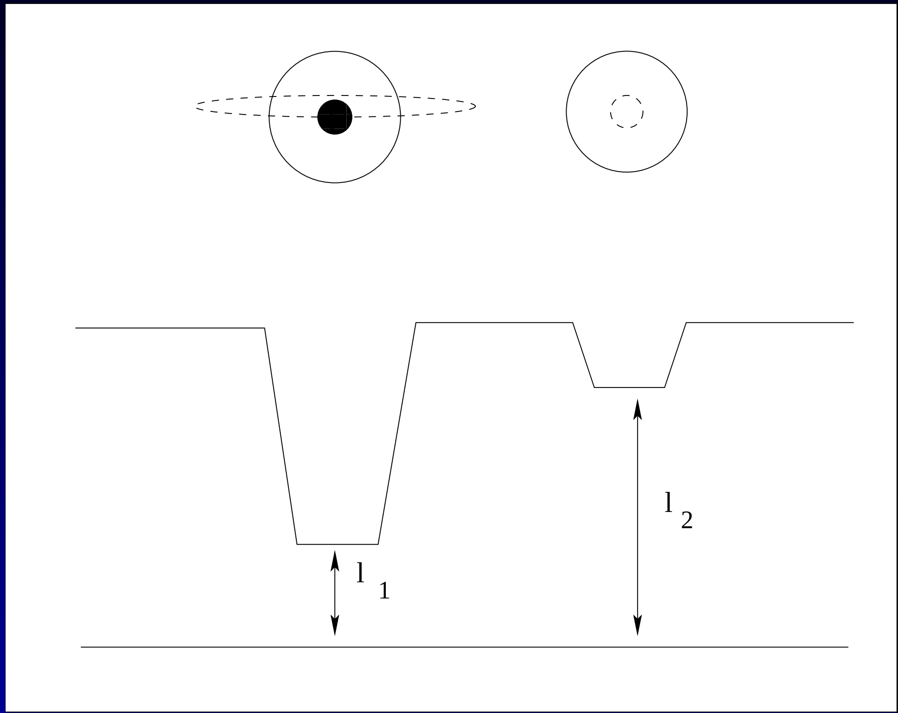
$$a^3 = \tfrac{G}{4\pi^2} P^2 (M_1 + M_2)$$

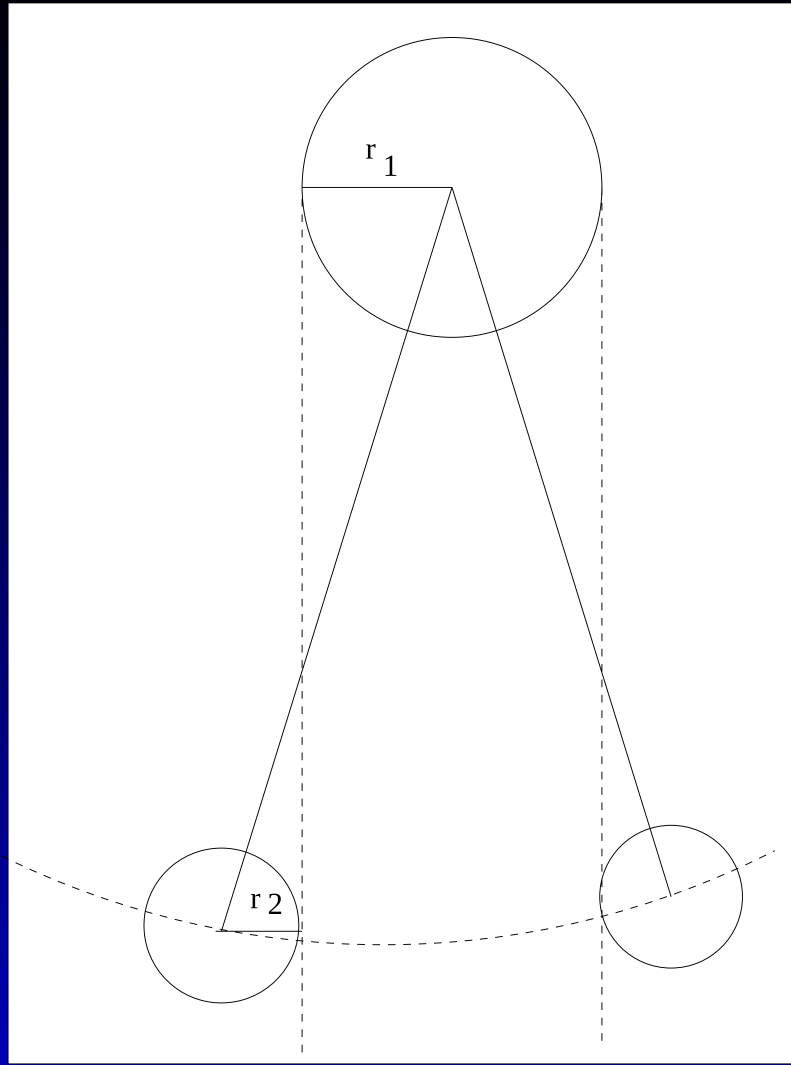
stars are triaxial ellipsoids

eclipses = occulation of two circular disks

reflection

limb-darkening



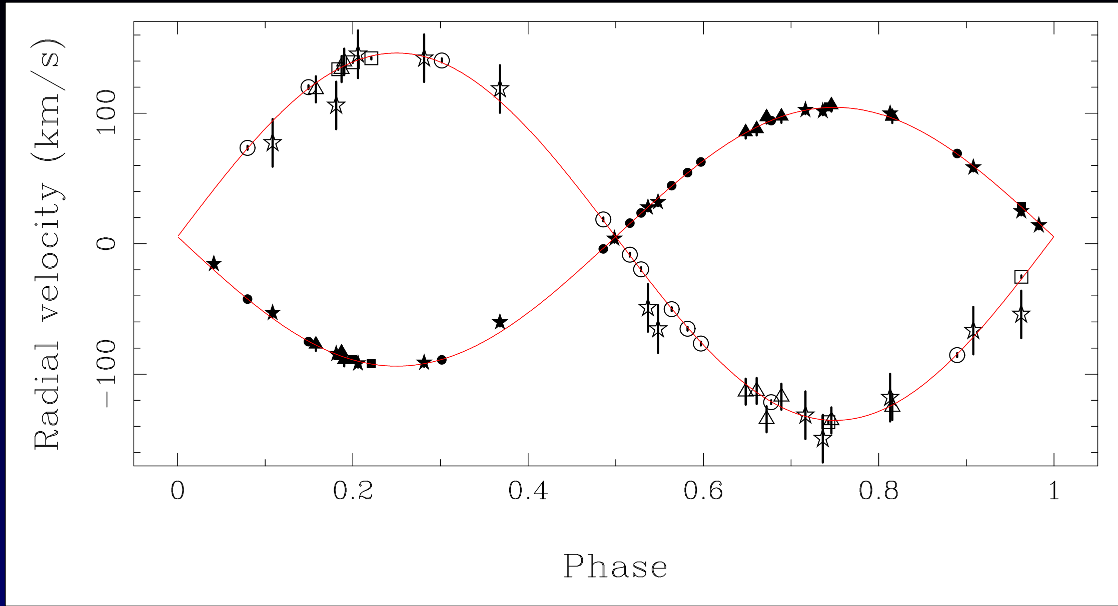


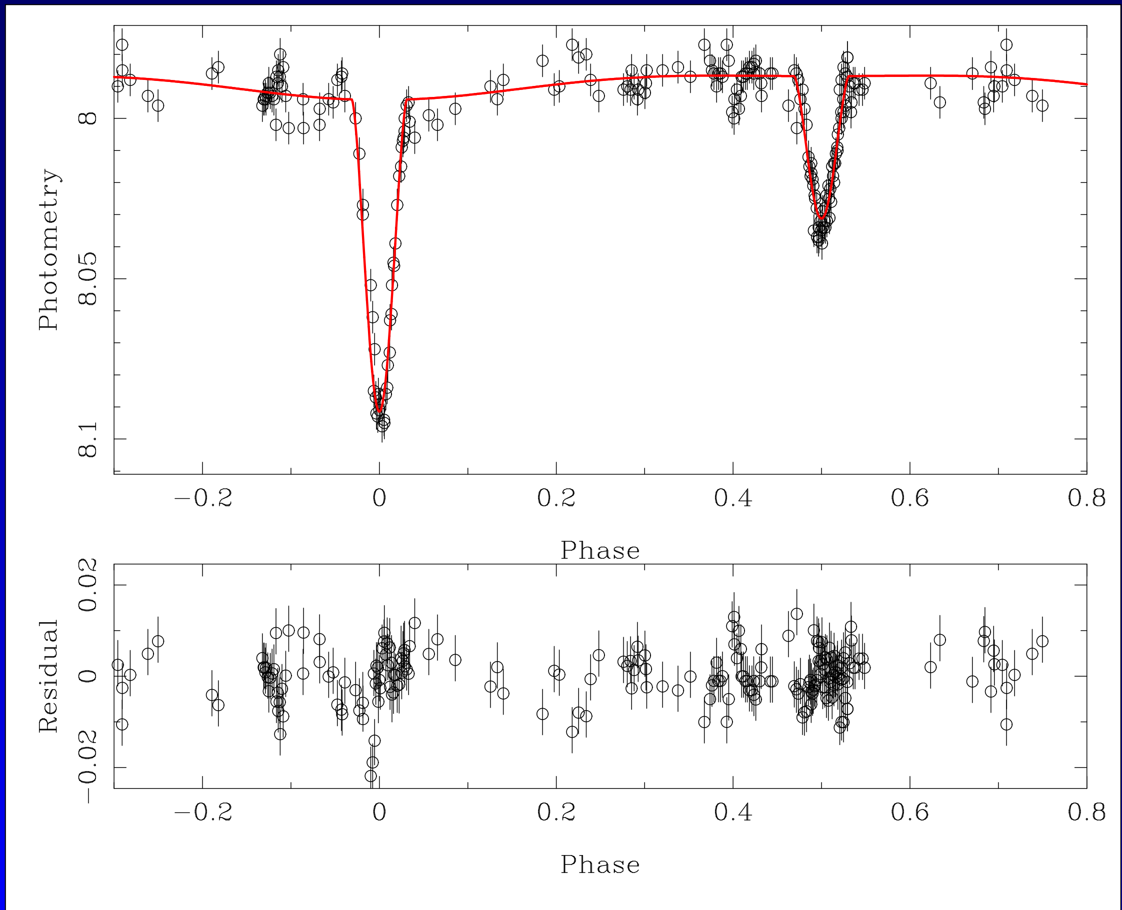
$$(\frac{r_1}{r_2})^2 = \frac{1-l_2}{l_1}\ ;\ i,\ (r/a)$$

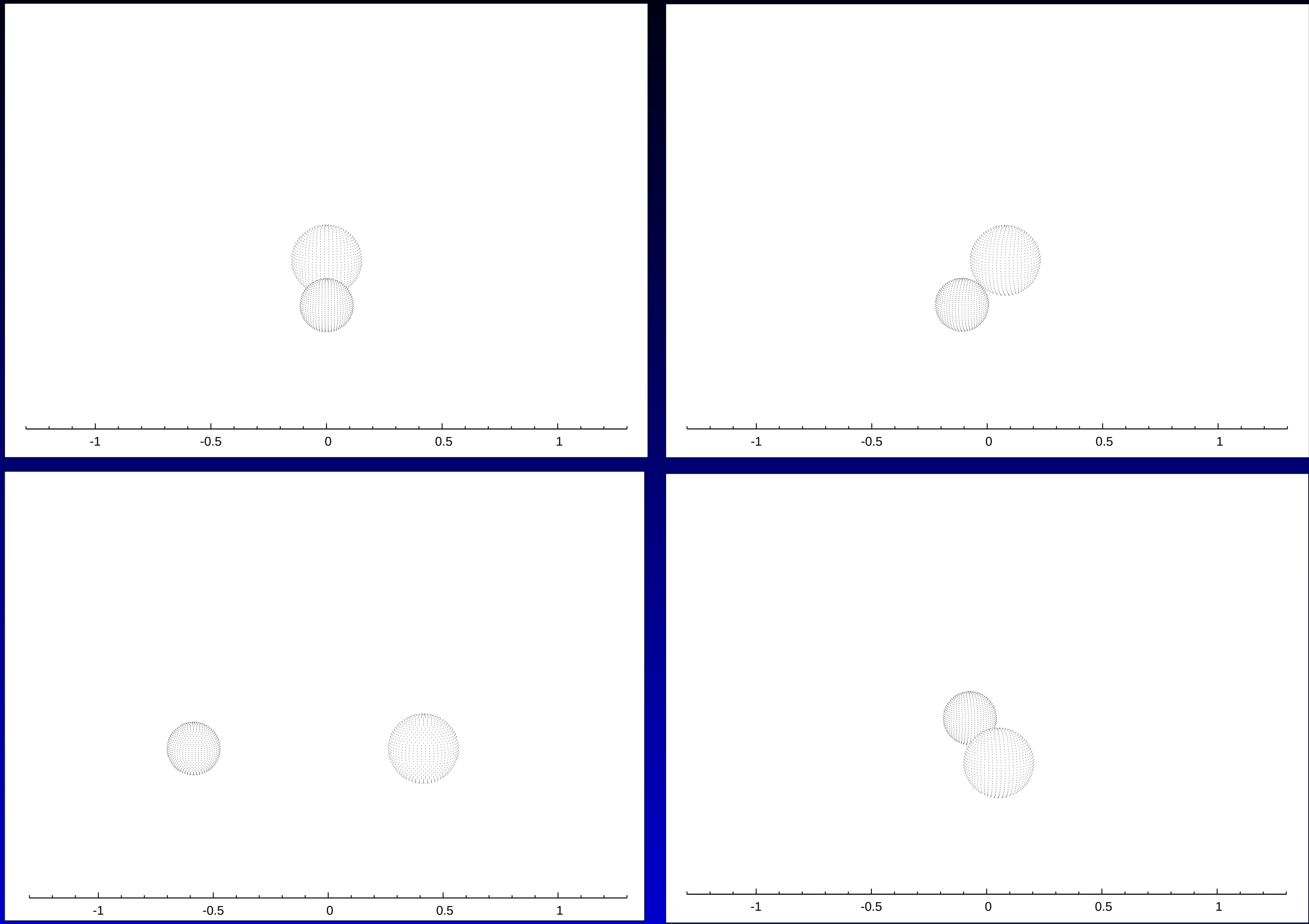
Data: 211 data points Geneva $V, B, U, B1, B2, V1, G$
500 V and 400 B data points from Munari et al.

Lightcurve and RV analysis: FOTEL + PHOEBE

P (d)	$2.46113346 \pm 0.00000069$
$T_{0,prim.min.}$ (HJD)	$2452903.59904 \pm 0.00051$
a ($R_\odot$)	11.954 ± 0.022
V_γ (km/s)	5.42 ± 0.12
q	0.7045 ± 0.0026
i (deg)	77.60 ± 0.15
e	0.0 ± 0.002
K_1 (K)	99.22 ± 0.29
K_2 (K)	140.83 ± 0.32
T_1 (K)	9950 (fixed)
T_2 (K)	7640 ± 40
(r_1/a)	0.1542 ± 0.0031
(r_2/a)	0.1327 ± 0.0035
R_1 ($R_\odot$)	1.843 ± 0.037
R_2 ($R_\odot$)	1.586 ± 0.042
M_1 ($M_\odot$)	2.221 ± 0.027
M_2 ($M_\odot$)	1.565 ± 0.015


Radial velocity (km/s)
100
0
−100
0
0.2
0.4
0.6
0.8
1
Phase


Photometry
8
8.05
8.1
−0.2
0
0.2
0.4
0.6
0.8
Phase
Residual
0.02
0
−0.02
−0.2
0
0.2
0.4
0.6
0.8
Phase



phase 0, -0.03, -0.25, -0.48

Distance and reddening

- Fitting MARCS models to Geneva photometry

  T_1, T_2, ([Fe/H], $\log g$)
  R_1, R_2
  convolution with passbands
  consider a $E(B-V)$ and reddening law
  consider a distance d

  $\Rightarrow$ predict out-of-eclips magnitudes

- Surface-brightness relations

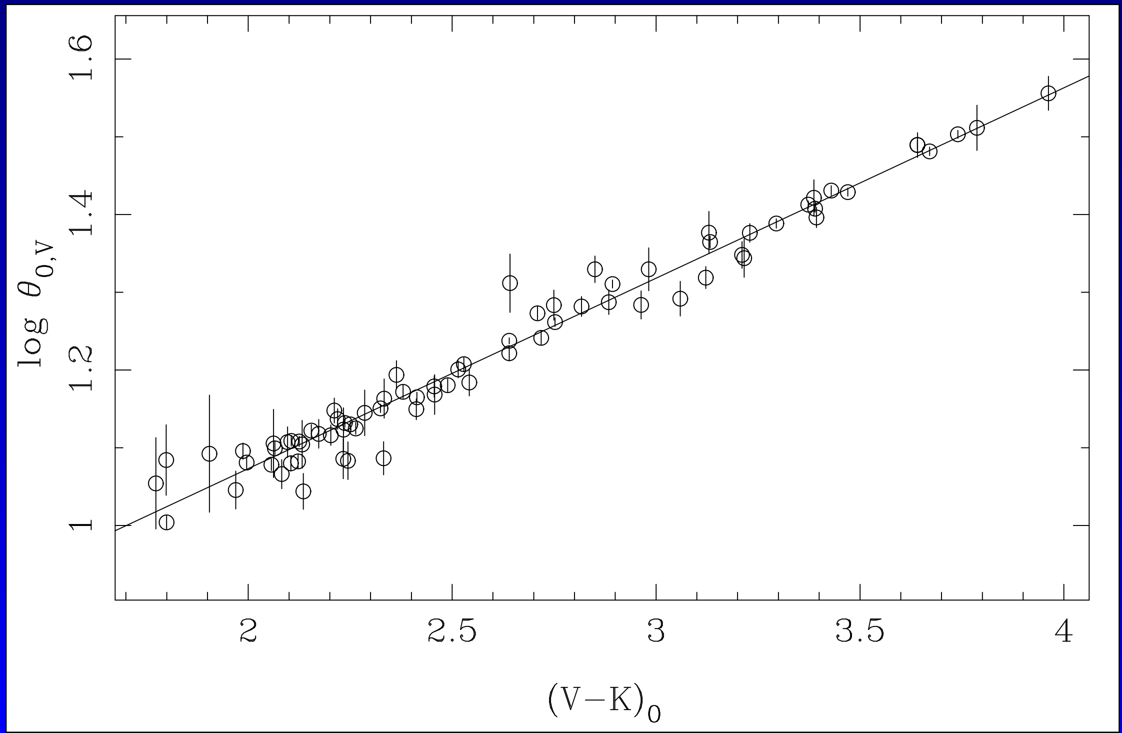
  ($2\,R_{1,2}/d$) versus θ

Intermezzo: SB-relations

Emperically, there exist very tight relations between angular diameter and colour(s)

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

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



Results

Groenewegen et al:
$E(B-V)$ = 0.025 $\pm$ 0.003, d = 138.0 $\pm$ 1.5 pc

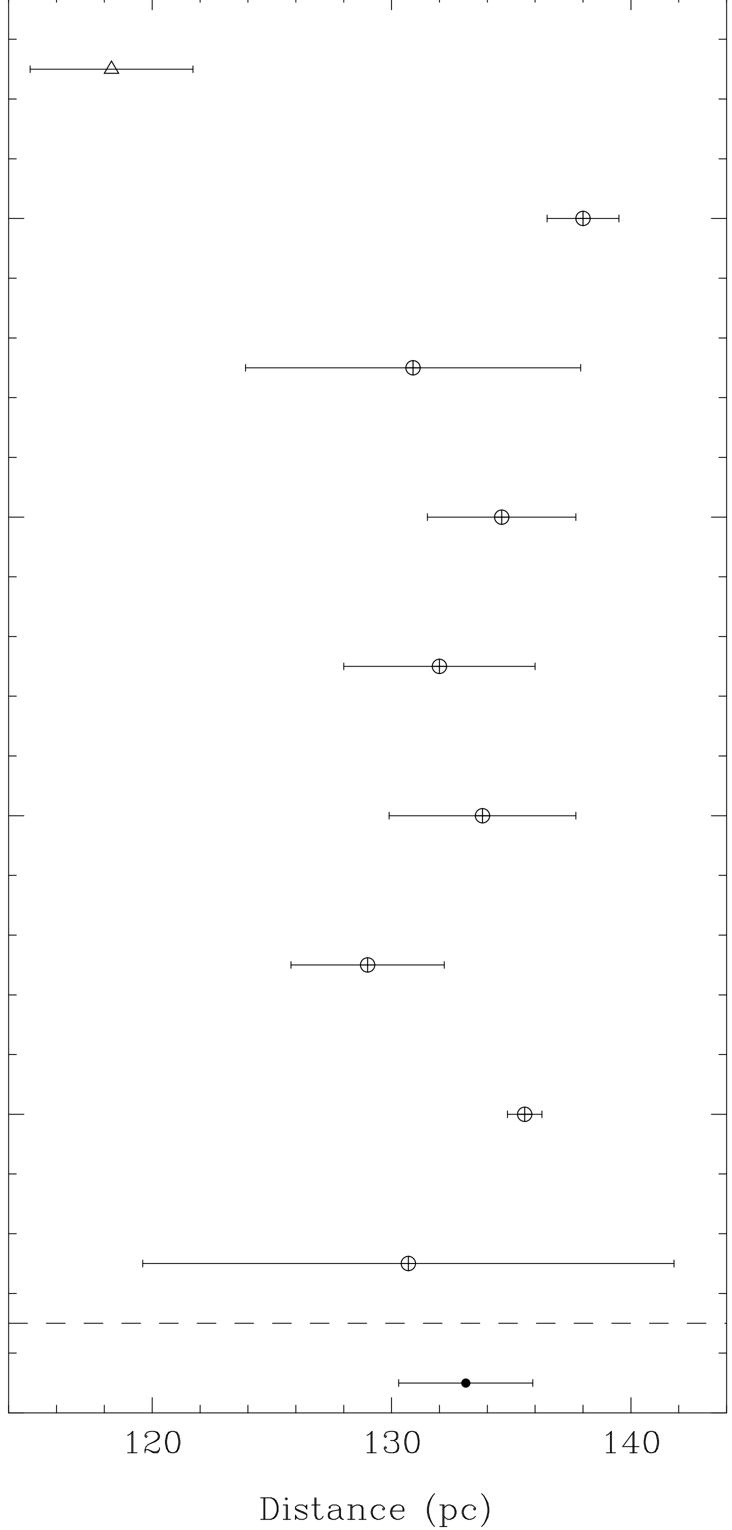
$\theta_{\rm pred,1}$= 0.122 $\pm$ 0.002; $\theta_{\rm SB,(B-V),1}$= 0.119 mas
$\theta_{\rm pred,2}$= 0.111 $\pm$ 0.003; $\theta_{\rm SB,(B-V),2}$= 0.107 mas

Munari et al.:
$E(B-V)$ = 0.012 $\pm$ 0.004, d = 131.9 $\pm$ 2.1 pc

Southworth et al:
$E(B-V)$ = 0.012 (adopted), d = 139.1 $\pm$ 3.5 pc
(SB in K)
(correct Munari et al. to 135.5 $\pm$ 2.3 pc)

Conclusions

Hipparcos parallax	118.3 ± 3.4 pc
	±
Moving cluster method	130.7 ± 11.1
Moving cluster method	135.6 ± 0.7
HIAD	129.0 ± 3.2
Infra-red Main-Sequence fitting	133.8 ± 3.9
Astrometric binary HD 23850	132 ± 4
HST parallaxes of three Pleiades stars	134.6 ± 3.1
Ground-based parallaxes	130.9 ± 7.0
Eclipsing binary HD 23642	138.0 ± 1.5
	±
MEAN	133.1 ± 2.8


120
130
140
Distance (pc)

THE END