Baade-Wesselink Method

Madison Markham

ASTR 8400

NASA/ESA

Moving up the Distance Ladder…

Baade–Wesselink method!!

Main Sequence fitting

Secular and statistical parallax

Moving clusters

Trigonometric parallax

Current distance range:
~133 pc to ~50 kpc

Baade & Wesselink

Walter Baade

- Spent most of his career at Mount Wilson Observatory
- Distinguished two different types of Cepheids
- Suggested method of measuring distance to Cepheids in 1929

cambridge.org

Baade & Wesselink

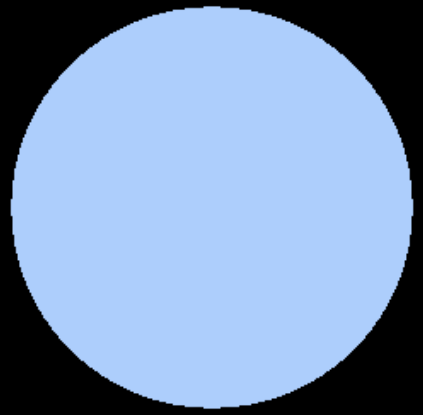
From left to right: A J Wesselink with A D Thackeray and M W Feast, from a staff photograph at Radcliffe Observatory, Pretoria, c. 1963.

Adriaan Wesselink

- Calculated the mean radius of Delta Cephei
- Expanded Baade's methods in 1946
  - Baade–Wesselink Method

Cepheid Variable Stars

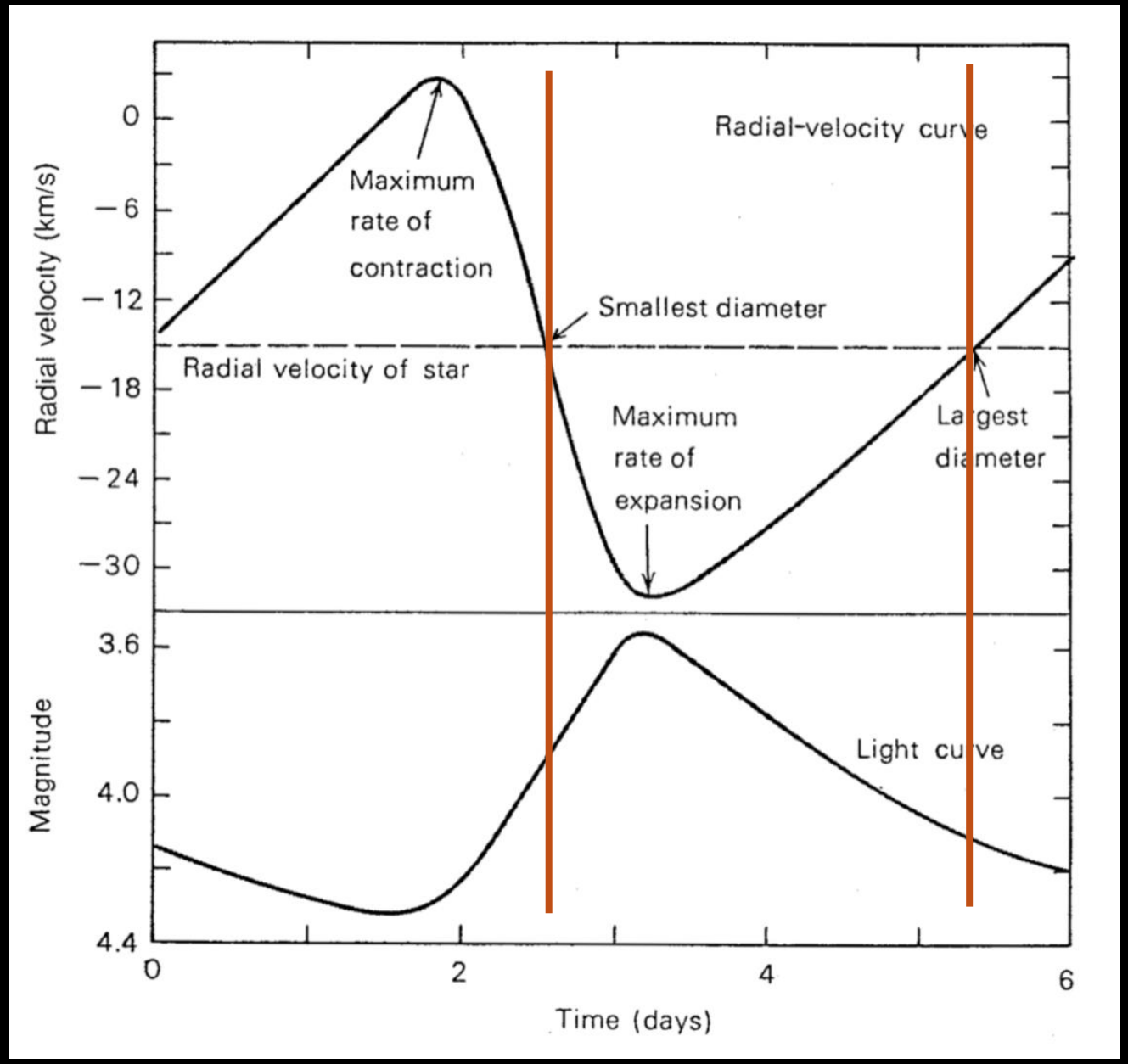
- Classical radial pulsator
- Pulsation driven by κ-mechanism in the partial ionization zone
  - Period depends on timescale to restore equilibrium



Lamers & Levesque (2018)

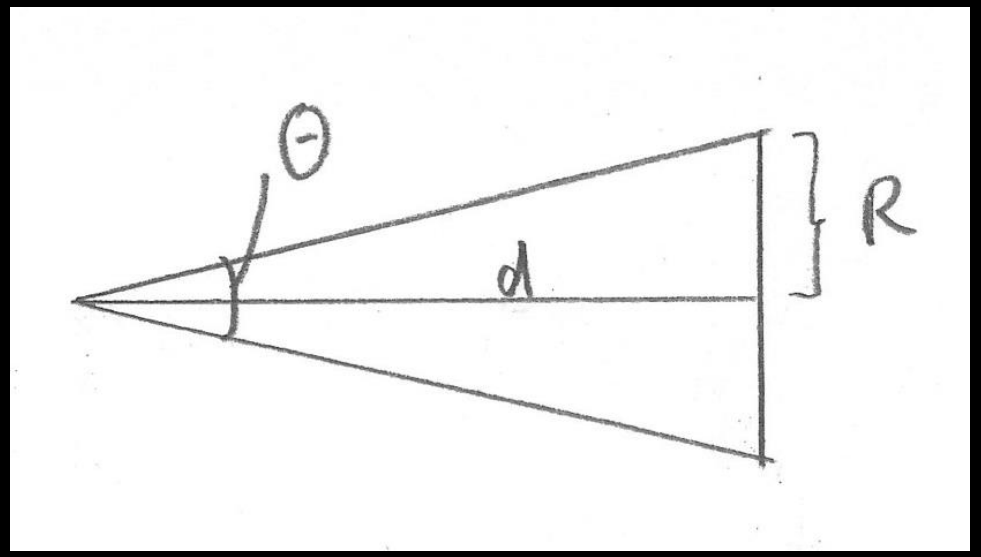
Radial Pulsations

- *R* and *T* are (almost) anti-correlated
  - Minimum *R* occurs just before maximum *T*



Methods

Radius, angular diameter, and distance are related:



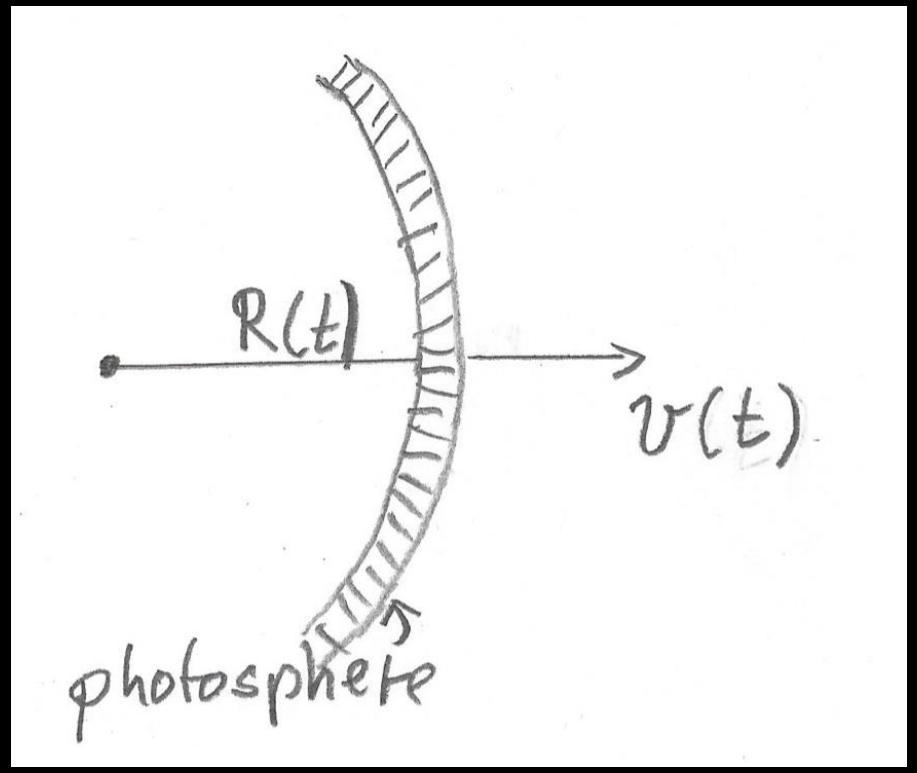
$$\frac{R}{d} = tan\frac{\theta}{2} \approx \frac{\theta}{2}$$

$$d = \frac{2\Delta R}{\Delta\theta}$$

Kudritzki (2015)

Methods

Photosphere is approximated as a spherically expanding shell:



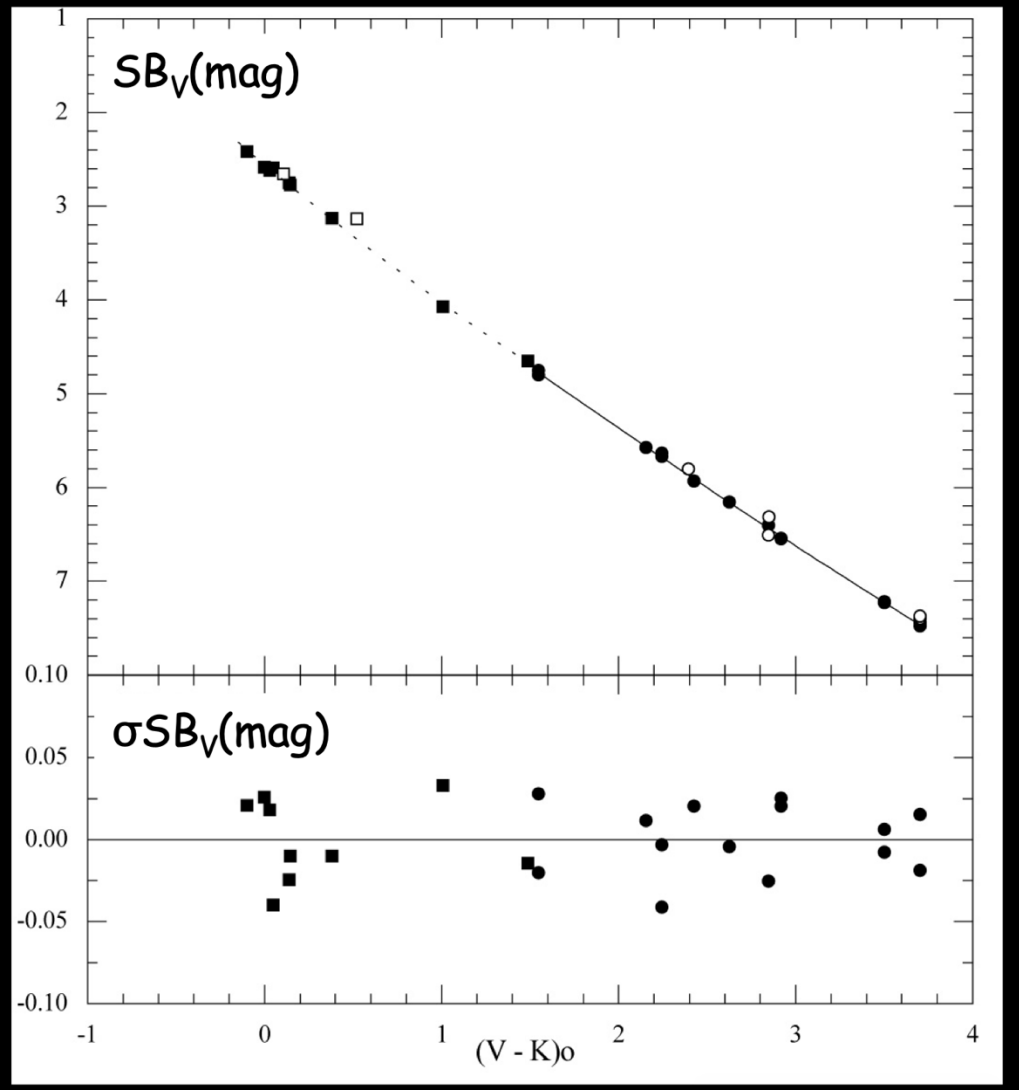
$$\Delta R = R(t) - R(t_0)$$

$$\Delta R = \int_{t_0}^{t} v(t)dt$$

Kudritzki (2015)

Surface Brightness vs. Interferometry

- Two methods to measure $\Delta\theta$:
  - Surface brightness (SB) relationship
  - Interferometry



Kervella et al. (2004)

Surface Brightness vs. Interferometry

- Two methods to measure $\Delta\theta$:
  - Surface brightness (SB) relationship
  - Interferometry

1. Measure the color
2. Use SB–color relationship
3. Solve for angular diameter

$$SB = 2.656 + 1.483(V - K) + 0.44(V - K)^2$$

$$\theta[mas] = 10^{0.2(SB-V)}$$

Kervella et al. (2004)

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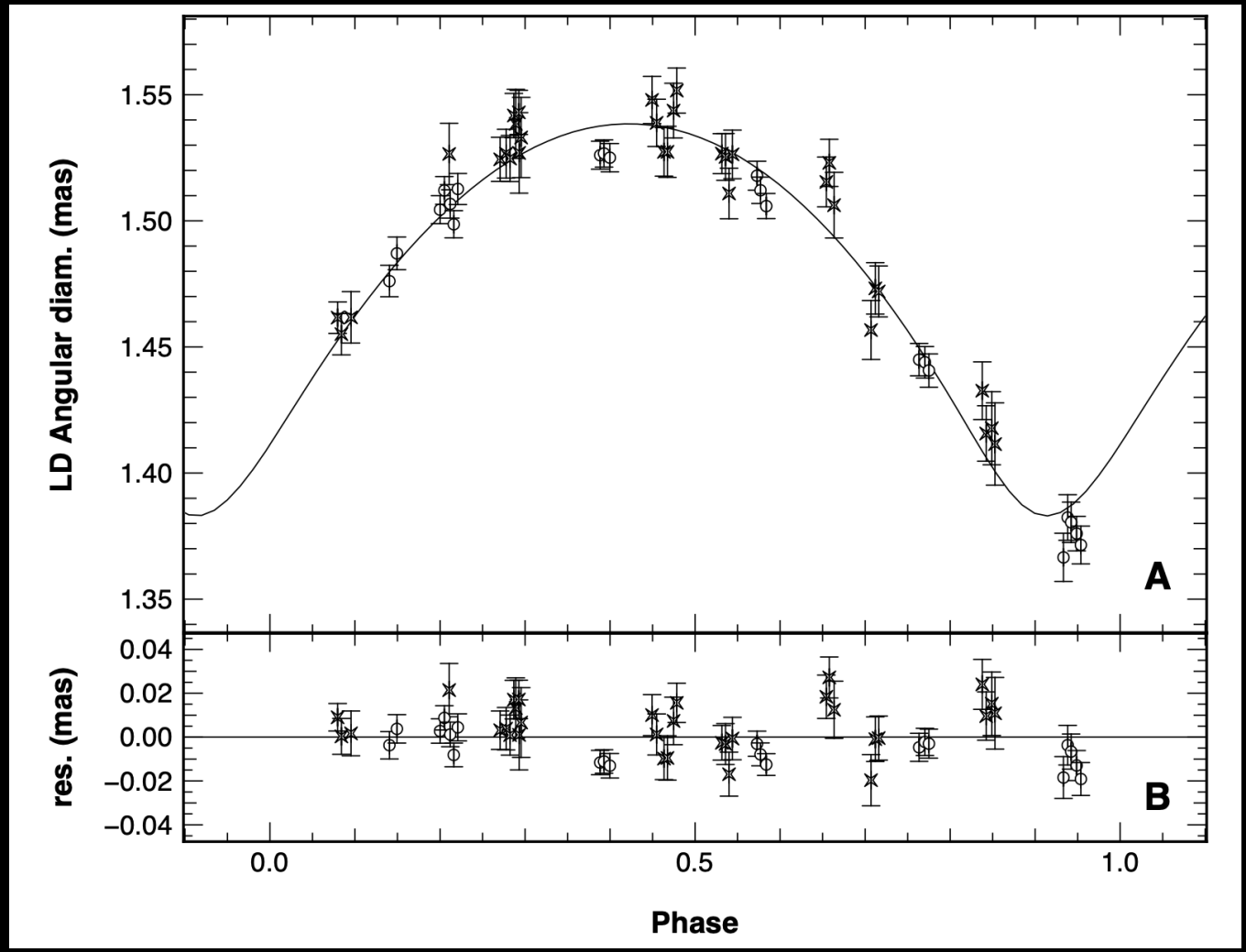
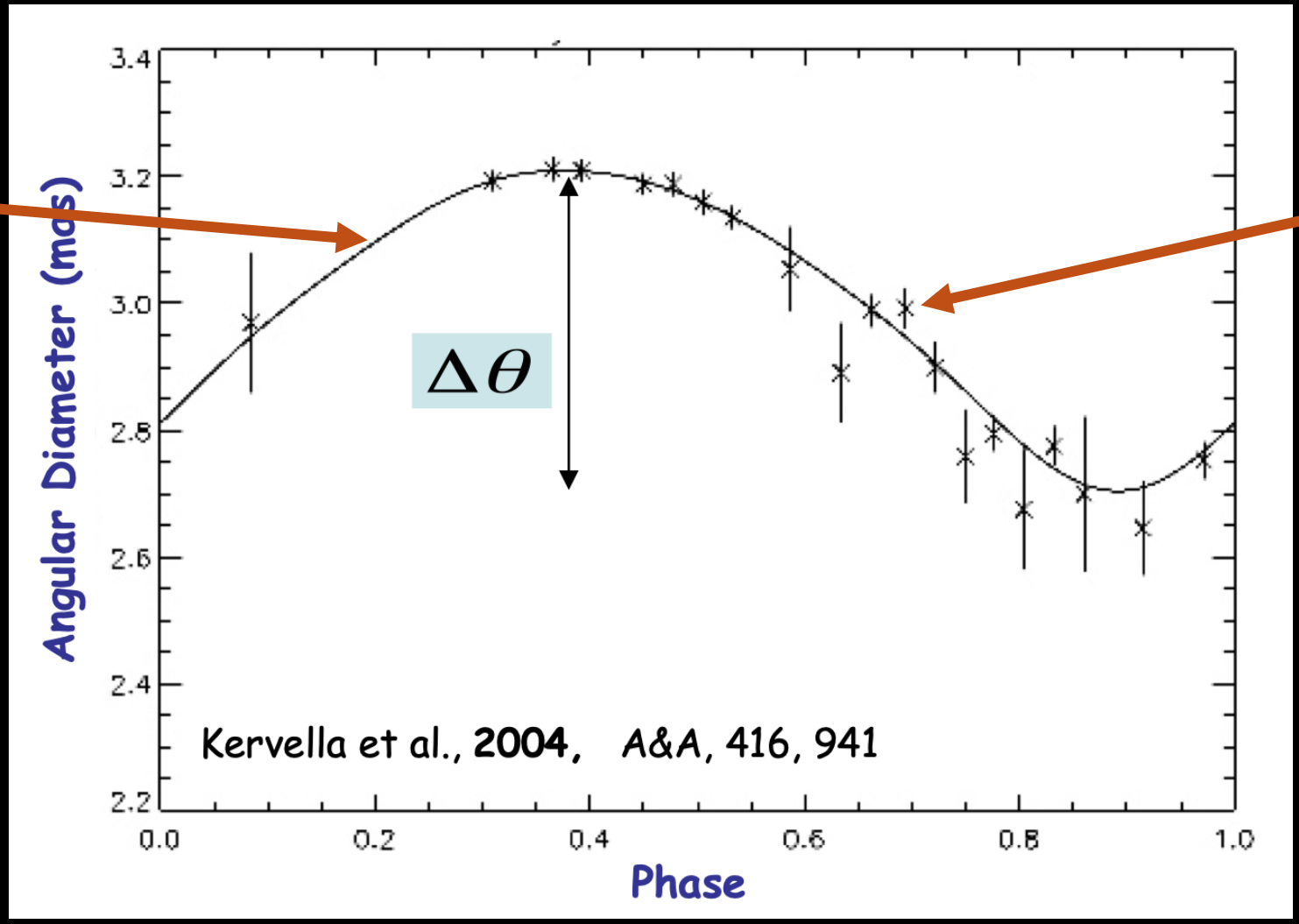


Mérand et al. (2005)

Comparing the Two Methods

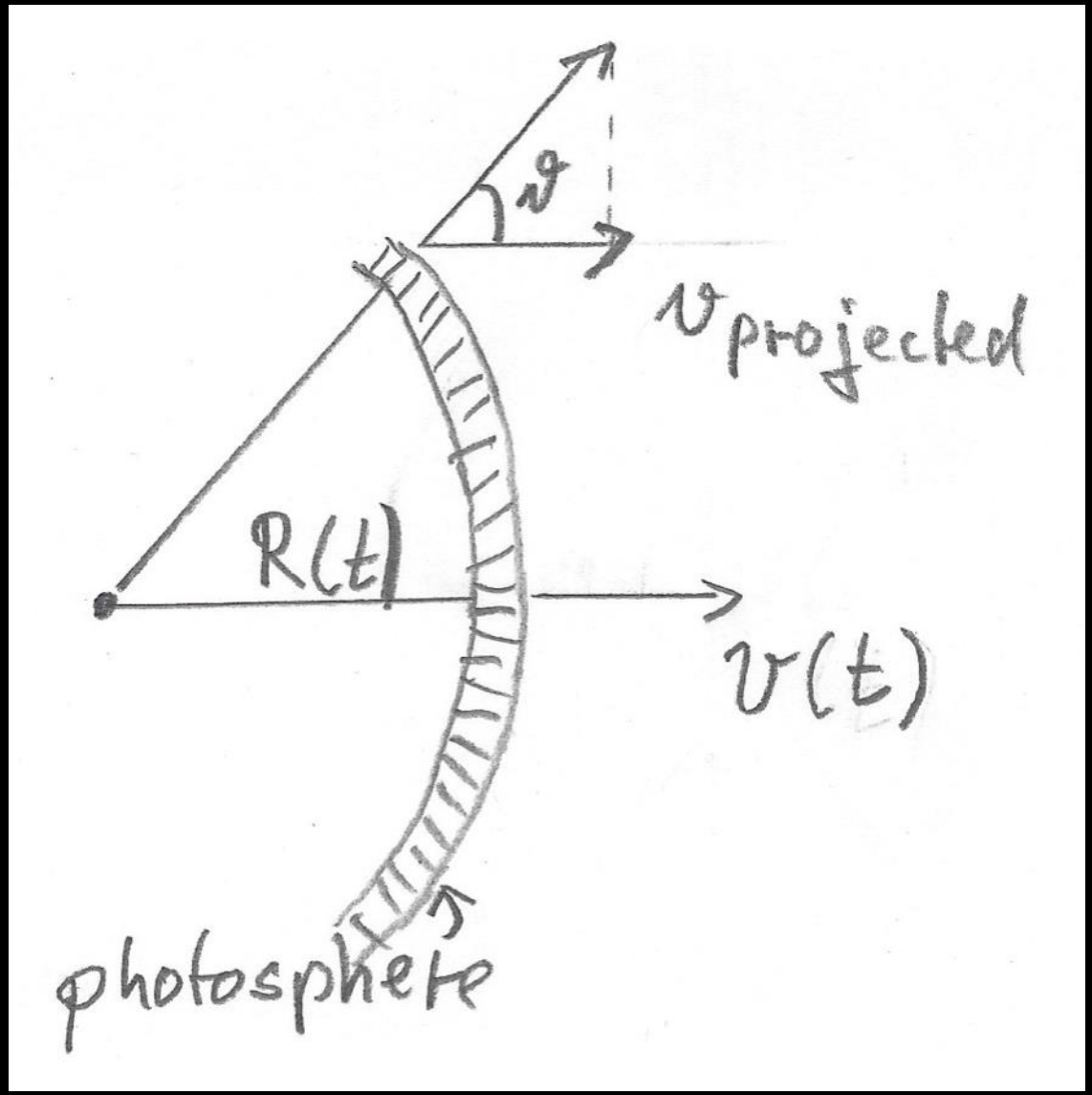
Line: SB–color relationship



Points: Interferometric observations

Measuring ΔR

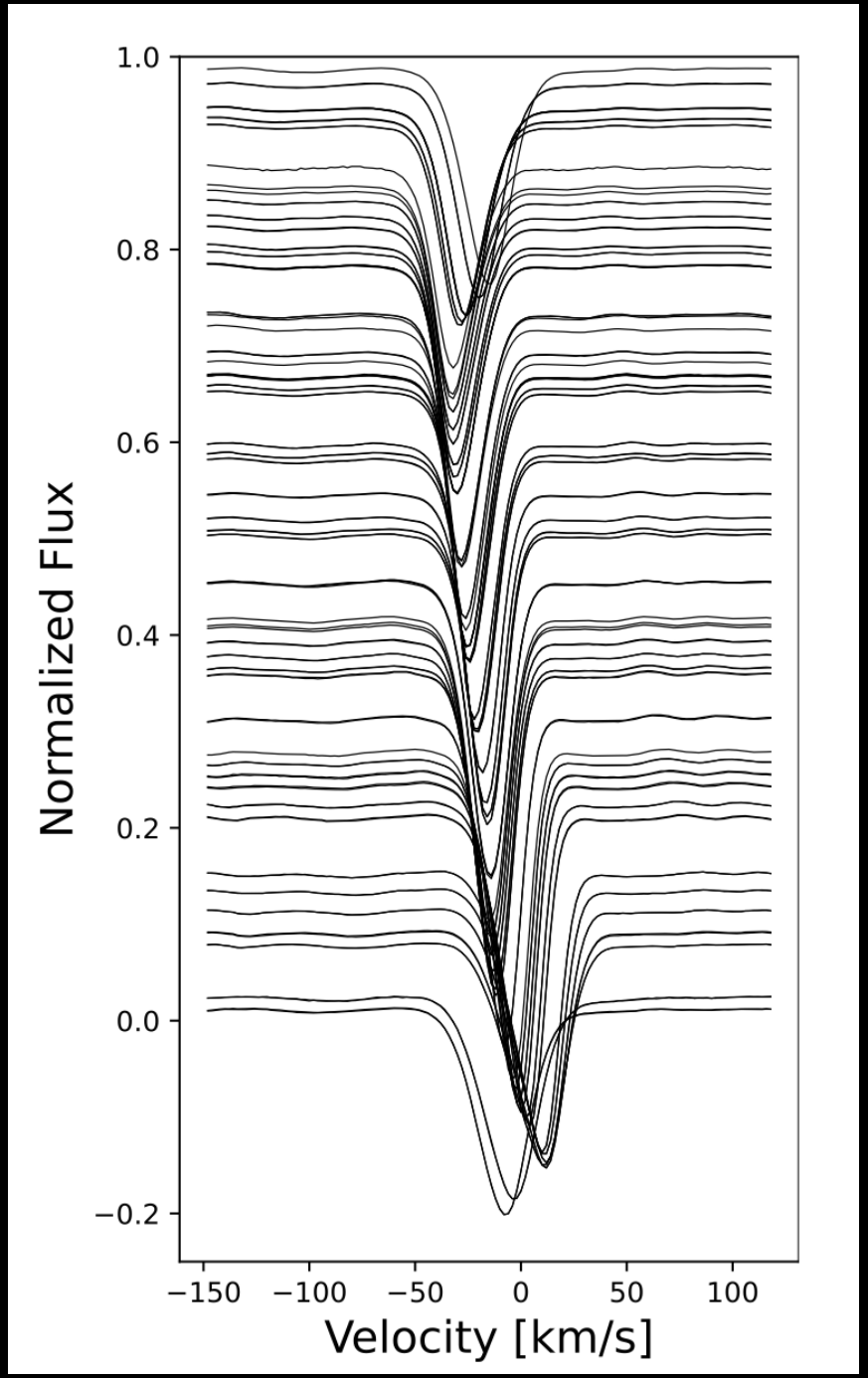
- Determining the expansion velocity is more complicated
  - Radial velocity from spectral lines is not equal to radial expansion velocity
  - Also need to account for limb-darkening
- Solution: adopt a projection factor
  - $1 < p < 1.5$



Kudritzki (2015)

Current Research

- Nardetto et al. (2023) obtained high spectral resolution observations of Cepheids
  - Aimed to quantify the impact of SB–color relationship on projection factor



Nardetto et al. (2023)

Current Research

- Often used as a calibrator for other distance methods
  - Particularly used in the 2000's-2010's for determining an independent distance to the Magellanic Clouds

Benedetto (2008)

Current Research

Table 5. Calibration of luminosity relations of the form $M' = D'(\log P - 1.0) + \beta\, C_O + Z'_O$ by FU LMC Cepheids and distance to the LMC.

Relation	N	Band	D'	β	Z'_O ($\log P = 1.0$)	σ (mag)	μ_O (mag)
PL	662[a]	B	-2.439 ± 0.046	0.0	14.929 ± 0.031	0.240	18.266 ± 0.031
PL	650[a]	V	-2.779 ± 0.031	0.0	14.287 ± 0.021	0.160	18.363 ± 0.021
PL	662[a]	I	-2.979 ± 0.021	0.0	13.615 ± 0.014	0.107	18.431 ± 0.014
PL	472[b]	K	-3.246 ± 0.036	0.0	12.795 ± 0.008	0.168	18.515 ± 0.008
W	657[c]	$(V, V-I)$	-3.285 ± 0.013	2.45	12.641 ± 0.003	0.068	18.530 ± 0.003
BW	657[c]	$(V, V-I)$	-3.387 ± 0.014	2.918	12.323 ± 0.003	0.074	18.559 ± 0.003
BW	472[b]	$(V, V-K)$	-3.393	1.315	12.325		18.562
BW	657[c]	$(V, B-V)$	-3.425 ± 0.022	2.067	12.979 ± 0.004	0.115	18.555 ± 0.004

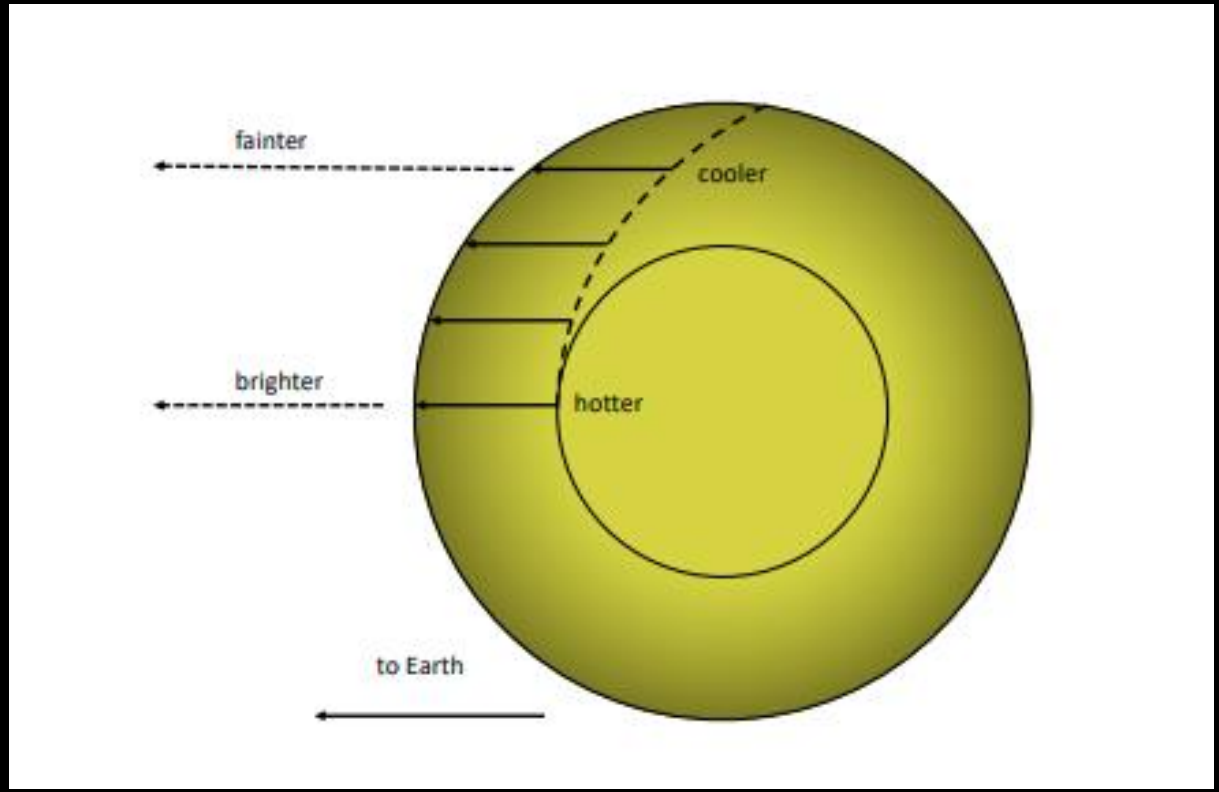
[a]From Udalski et al. (1999).
[b]From Groenewegen (2000).
[c]From the present work.

Current: $\mu = 18.476 \pm 0.002$

Benedetto (2008)

Limitations

- Instrumental limitations in photometric and radial velocity measurements
- Limb-darkening effects
- Calibration of *p*-factor



Summary

- Baade–Wesselink method relates the changing radius and angular size of a Cepheid to its distance
  - Valid for distances around 133 pc (Polaris) to 50 kpc (LMC)
- Angular size can be determined photometrically or interferometrically
- Calibrations to SB–color relationships and *p*-factors are still being made

Thank you!