INTERFEROMETRY AND THE DISTANCE SCALE

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• Long-baseline interferometry can help in different ways:
  1. Baade-Wesselink distances of nearby Cepheids
  2. Surface-brightness-color relations
  3. Cepheids in binary stars
The variables appear to fall into three or four distinct groups. The majority of the light curves have a striking resemblance, in form, to those of cluster variables. As a rule, they are faint during the greater part of the time, the maxima being very brief, while the increase of light usually does not occupy more than from one-sixth to one-tenth of the entire period. It is worthy of notice that in Table VI the brighter variables have the longer periods. It is also noticeable that those having the longest periods appear to be as regular in their variations as those which pass through their changes in a day or two. This is especially striking in the case of No. 821, which has a period of 127 days, as 89 observations with 45 returns of maximum give an average deviation from the light curve of only six hundredths of a magnitude. Six of the sixteen variables are brighter at maximum than the fourteenth magnitude, and have periods longer than eight days. It will be noticed that this proportion is much greater here than in Table II. The number which have been measured up to the present time is 59, and of these the brighter stars were first selected for discussion, as the material for them was more abundant. A few of the fainter variables, selected at random, were then studied, but no attempt has yet been made to determine periods for the remainder. While, therefore, the light curves thus far obtained have characteristics to which the majority of the variables will probably be found to conform, no inference can be drawn with regard to the prevalence of any particular type, until many more of the periods have been obtained.
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Leavitt & Pickering 1912
Fouqué et al. 2007 (Rc)

CALIBRATION

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Parallax of pulsation
Cepheids in binaries

The distance $d$ is given by the relation:

$$d = \frac{2\delta R(T)}{\delta \theta(T)} = \frac{-2 kp \int_0^T v_{rad}(t) \, dt}{\theta_{UD}(T) - \theta_{UD}(0)}$$
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$p = \text{projection factor} = V_{\text{puls}} / V_{\text{rad}} \sim 1.3$
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$p = \text{projection factor} = \frac{V_{\text{puls}}}{V_{\text{rad}}} \sim 1.3$

$k = \text{limb darkening} = \frac{\theta_{\text{UD}}}{\theta_{\text{LD}}} \sim 0.94 \text{ in visible, } 0.98 \text{ in IR}$
The Boade-Wesselink projection factor

- Classical Cepheids
- $\beta$ Cephei star $\alpha$ Lup
- $\delta$ Scuti stars ($\beta$ Cas, DX Cet, Al Vel, $\rho$ Pup)

P-FACTOR
The Boade–Wesselink projection factor


P-FACTOR


P-FACTOR
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$\delta$ CEP: A MEASUREMENT OF $p$

p-factor = 1.27 ± 0.06, with d=274 ± 11 pc from HST-FGS

$\delta$ Cep $E(B-V)=0.104$

$\delta$ Cep

- $V_{JOHNSON}$
- $K_{CTIO}$
- $B_{JOHNSON}-V_{JOHNSON}$
- $K_{CTIO}-K_{CTIO}$
- $I_{CTIO}-K_{CTIO}$

Pulsation velocity (km/s)

Angular diameter (mas)

Effective Temperature (K)

- LD model
- LD, K data
- $T_{eff}$ model
- $T_{eff}$ data
CEPHEID ENVELOPE CONTRIBUTIONS

2.2 µm

8.6 µm

CEPHEIDS OBSERVED BY INTERFEROMETRY

[Polaris] (3.97 d)
δ Cep (5.36 d)
X Sgr (7.01 d)
η Aql (7.17 d)
W Sgr (7.59 d)
β Dor (9.84 d)
L Car (35.6 d)
[RS Pup] (41.4 d)
CEPHEIDS OBSERVED BY INTERFEROMETRY

24 stars, with 22 stars suitable for IBW distance
P93 program with PIONIER (5 stars) + VEGA (5 stars)

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• Up-to-date photometry in the visible and near-IR
SURFACE BRIGHTNESS-COLOR RELATIONS

\[ f \sim L / R^2 \sim T^4 \]

\[ F_B = a \ (B-L) + b \]

\[ F_B = 4.2207 - 0.1B - 0.5\log(LD) \]

Limb darkened angular diameter

\[ \log LD = c \ (B-L) + d - 0.2B \]

Very accurate prediction of angular diameters from photometry
Useful for calibrators and the classical BW technique

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• Similar to dwarf SBC relations for visible-infrared colors
• Calibration is part of our interferometric observing program
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CEPHEIDS IN BINARIES

- Binary systems are very useful to derive masses, distances and \( p\)-factor (when SB2+visual/interferometric orbit available)

- Cepheids are extremely bright \((10^3 - 10^5 \, L_{\text{sun}})\), companions are difficult to detect due to contrast in the IR

- Only a handful discovered using UV spectroscopy (IUE)

- Most systems are unresolved SB1, except Polaris and distant companions on multi-century orbits

- Survey with CHARA/MIRC and VLTI/PIONIER: the companions of V1334 Cyg and AX Cir have been spatially resolved
V1334 CYG (CHARA/MIRC)

Separation = 8 mas, Contrast (H) = 3.1%, Period = 5.3 yr

• HST/FGS astrometry and STIS spectroscopy in Cycle 21 to derive the distance, masses and p-factor to 1%
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Objective: calibration of P-L zero point for Galactic Cepheids to $\sim 1\%$.
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But... Cepheids are relatively complex objects (envelopes, atmosphere dynamics,...)
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New possibilities with the VLTI2 (GRAVITY/MATISSE)