THE VLTI+CHARA CEPHEID PROGRAM

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THE CEPHEID PROGRAM
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• A long-term effort started in 2001 at VLTI (VINCI, then PIONIER) and in 2004 at CHARA
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• Three "sub-programs":

  1. Distances (B-W): FLUOR, PIONIER, VEGA

  2. Circumstellar envelopes: FLUOR, VEGA

  3. Cepheids in binary systems: MIRC, PIONIER
THE INTERFEROMETRIC BAADE-WESSELINK TECHNIQUE (IBW)
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Gives the radius and the distance of a pulsating star
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Based on two types of data:

1. Radial velocity from spectroscopy
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Based on two types of data:

1. Radial velocity from spectroscopy
2. Angular size from interferometry
1. SPECTROSCOPY
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- Expansion
- Max radius
- Contraction
- Min radius
Spectroscopy gives the \textit{variation} in linear radius of the star from:

\[ \delta R(T) = -p \int_0^T v_{\text{rad}}(t) \, dt \]
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\( p = \) projection factor
\( = V_{\text{puls}} / V_{\text{rad}} \)
\( \sim 1.3 \)

measured on \( \delta \) Cep + models
2. INTERFEROMETRY
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Gives the *angular size variation* of the star
The distance $d$ is given by the relation:

$$d = \frac{2\delta R(T)}{\delta \theta(T)} = \frac{-2 kp \int_0^T v_{\text{rad}}(t) \, dt}{\theta_{\text{UD}}(T) - \theta_{\text{UD}}(0)}$$
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The distance $d$ is given by the relation:

$$d = \frac{2\delta R(T)}{\delta \theta(T)} = \frac{-2k \rho \int_{0}^{T} v_{\text{rad}}(t) \, dt}{\theta_{UD}(T) - \theta_{UD}(0)}$$

$k = \text{limb darkening correction (from models)}$

$= \frac{\theta_{UD}}{\theta_{LD}}$

$\sim 0.94 \text{ in visible, } 0.98 \text{ in IR}$
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δ CEP: A MEASUREMENT OF $p$
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$p$-factor = 1.27 ± 0.06, with $d=274 \pm 11$ pc from HST-FGS

Y OPH (CHARA/FLUOR)

Gallenne et al. 2013, in prep.
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Distance: 472 ± 18 pc (4%)

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Y OPH (CHARA/FLUOR)

Distance: $472 \pm 18$ pc (4%) for $p = 1.27$ and $k = 0.983$

Gallenne et al. 2013, in prep.
KAPPA PAV (PIONIER, P91)

Breitfelder et al. (2014, in prep.)
KAPPA PAV (PIONIER, P91)

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KAPPA PAV (PIONIER, P91)

Scheduling was a problem!

Work in progress

Breitfelder et al. (2014, in prep.)
Mérand et al. 2014, in prep.
CEPHEIDS OBSERVED BY INTERFEROMETRY
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[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)
CEPHHEIDS OBSERVED BY INTERFEROMETRY

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


PTI (2001)


Δ Cep

CEPHEIDS IN BINARIES

- Binary systems are very useful to derive masses and distances
- Cepheids are extremely bright ($10^3 - 10^5$ $L_{\text{sun}}$), companions are difficult to detect
- Only a handful discovered using UV spectroscopy (essentially by Nancy Evans et al.)
- 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
**AX CIR (VLTI/PIONIER)**

**Primary:**
- Classical Cepheid
- Puls. $P = 5.27$ days
- $d \approx 500$ pc
- $H = 3.85$

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AX CIR (VLTI/PIONIER)

AX CIR (VLTI/PIONIER)

<table>
<thead>
<tr>
<th></th>
<th>2013-07-11</th>
<th>2012-07-14</th>
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<tbody>
<tr>
<td>Single star model</td>
<td></td>
<td></td>
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<tr>
<td>$\theta_{UD}$ (mas)</td>
<td>$0.770 \pm 0.016$</td>
<td>$0.931 \pm 0.019$</td>
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<tr>
<td>$\theta_{LD}$ (mas)</td>
<td>$0.787 \pm 0.016$</td>
<td>$0.952 \pm 0.020$</td>
</tr>
<tr>
<td>$\chi^2_r$</td>
<td>1.45</td>
<td>1.09</td>
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<tr>
<td>Binary model</td>
<td></td>
<td></td>
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<tr>
<td>$\theta_{UD}$ (mas)</td>
<td>$0.726 \pm 0.020$</td>
<td>$0.821 \pm 0.022$</td>
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<tr>
<td>$\theta_{LD}$ (mas)</td>
<td>$0.742 \pm 0.020$</td>
<td>$0.839 \pm 0.023$</td>
</tr>
<tr>
<td>$f$ (%)</td>
<td>$0.75 \pm 0.17$</td>
<td>$0.90 \pm 0.10$</td>
</tr>
<tr>
<td>$\Delta \alpha$ (mas)</td>
<td>$6.421 \pm 0.198$</td>
<td>$6.153 \pm 0.155$</td>
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<tr>
<td>$\Delta \delta$ (mas)</td>
<td>$-28.366 \pm 0.366$</td>
<td>$-28.584 \pm 0.229$</td>
</tr>
<tr>
<td>$\chi^2_r$</td>
<td>1.17</td>
<td>0.72</td>
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AX CIR (VLTI/PIONIER)

Secondary:
- B6V dwarf
- Orbit 17.9 years
- sep. ~ 30 mas
- $f=0.83 \pm 0.17\%$

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 and masses to 1%