Polaris - Background

• Nearest and brightest classical Cepheid
  - $V=2.0$, $d = 130$ pc
  - Pulsational period of 3.97 days

• Brightest member of a triple system
  - Visual companion Polaris B: 18'' separation
    $V = 8$, SpT = F3V
  - Polaris A is a single-lined spectroscopic binary:
    $P=30$ yr (e.g. Kamper 1996)

• Resolving the orbit of the close companion would allow us to determine a purely dynamical mass for a classical Cepheid
Spectroscopic Orbital Parameters

Kamper (1996)

Pulsational RV

Lick 1899
DDO 1989
DDO 1993
DDO 1994-95

SB1 RV

Phase from Periastron

Relative Radial Velocity (km s^{-1})

Radial Velocity (km s^{-1})
Spectroscopic Orbital Parameters

Kamper (1996)

\[ P = 29.59 \pm 0.02 \text{ yr} \]
\[ T = 1987.66 \pm 0.13 \]
\[ e = 0.608 \pm 0.005 \]
\[ \omega = 303.01 \pm 0.75^\circ \]
\[ K_{Aa} = 3.72 \pm 0.03 \text{ km/s} \]
**Astrometric Orbital Parameters**

- Wielen et al. (2000)
- Hipparcos proper motion of Polaris Aa
  - Nearly instantaneous in context of 30-yr orbit
- Ground-based proper motion
  - Long-term average proper motion from the FK5
  - Motion of center of mass

<table>
<thead>
<tr>
<th>Prograde:</th>
<th>Retrograde:</th>
</tr>
</thead>
<tbody>
<tr>
<td>$i$</td>
<td>50.1 ± 4.8°</td>
</tr>
<tr>
<td>$\Omega$</td>
<td>276.2 ± 9.5°</td>
</tr>
<tr>
<td>Retrograde:</td>
<td></td>
</tr>
<tr>
<td>$i$</td>
<td>130.2 ± 4.9°</td>
</tr>
<tr>
<td>$\Omega$</td>
<td>167.1 ± 9.4°</td>
</tr>
</tbody>
</table>
HST Observations of Polaris

- Advanced Camera for Surveys (ACS) - High Resolution Channel (0.026 ''/pix)
  - UV F220W filter ($\lambda \sim 2255$ Å)
  - Minimize contrast between Polaris and close companion (anticipated a slightly hotter main sequence star)
- Observed during two epochs (~0.3 sec exposures)
  - 2005 August 2
  - 2006 August 13
- Obtained a longer observation of Polaris B at same location on chip to use a single star PSF (20 sec)
- Results presented in Evans et al. (2008)
ACS-HRC Images of Polaris

ρ ~ 0.170"
PA ~ 226°
Δm = 5.39
Visual Orbital Parameters

- HST measurements establish a retrograde direction of motion
- Fix spectroscopic parameters \( (P, T, e, \omega, K_{Aa}) \)
- Simultaneous fit to HST data and astrometric proper motions

\[
\begin{align*}
i &\quad 128^\circ \pm 21^\circ \\
\Omega &\quad 19^\circ \pm 15^\circ \\
\alpha &\quad 0.133'' \pm 0.015'' \\
M_{\text{tot}} &\quad 5.8^{+2.2}_{-1.3} M_\odot \\
M_{Aa} &\quad 4.5^{+2.2}_{-1.4} M_\odot \\
M_{Ab} &\quad 1.26^{+0.14}_{-0.07} M_\odot 
\end{align*}
\]
Astrophysical Properties

- Archived IUE spectra of standards scaled to the distance of Polaris
  - Polaris Ab
    - Flux ratio consistent with F6V spectral type
    - $M \sim 1.3 \, M_\odot$; $M_{\text{dyn}} = 1.26 \, M_\odot$
  - Polaris B
    - Flux ratio consistent with F3V-F4V
    - Agrees with measured SpT
    - $M \sim 1.35 \, M_\odot$

Magnitude differences at F220W relative to Polaris Aa:
- Polaris Ab: $\Delta m = 5.39$
- Polaris B: $\Delta m = 4.49$
Comparison with Theoretical Masses

- Theoretical evolutionary masses
  - Canonical tracks neglecting core overshoot: \( M_e = 6.1 \pm 0.4 \, M_\odot \)
  - Non-canonical tracks accounting for mild convective core overshoot: \( M_e = 5.6 \pm 0.4 \, M_\odot \)

- Pulsation masses
  - PLC relation (Caputo et al. 2005): \( M_p(\text{PLC}) = 5.1 \pm 0.4 \, M_\odot \)
  - PMR relation (Bono et al. 2001): \( M_p(\text{PMR}) = 4.9 \pm 0.4 \, M_\odot \)
    \( R = 46 \pm 3 \, R_\odot \) (Nordgren et al. 2000)

- Dynamical mass: \( M_{Aa} = 4.5^{+2.2}_{-1.4} \, M_\odot \)
  1\( \sigma \) range: 3.1-6.7 \( M_\odot \)
Conclusions

- We used HST to image the close companion of the classical Cepheid Polaris for the first time.
- Derived dynamical mass of Cepheid Polaris Aa of $4.5 \pm 2.2 \, M_\odot$.
- Dynamical mass is smaller than values estimated from pulsational properties or evolutionary tracks, but error bars are still large.
- Close companion Polaris Ab has a dynamical mass of $1.26 \pm 0.14 \, M_\odot$. The UV brightness is consistent with a spectral type of F6V.
- Continued HST imaging and FGS astrometry will significantly reduce the mass uncertainties, allowing critical tests of evolutionary theories.
The End
Solving for Semi-Major Axis

\[ a = 0.131 \pm 0.04'' \]
Fit to HST Measurements

\[ a = 0.116 \pm 0.01'' \]
\[ i = 155 \pm 16^\circ \]
\[ M_{\text{tot}} = 3.9 \pm 1.0 \, M_\odot \]
PSF Comparisons

GD 71 2002/4/12
GD 71 2004/2/3
HD 150136A 2006/02/12
ACS-HRC Images of Polaris

- Polaris AaAb – 2005
- Polaris AaAb – 2006
- Polaris B – 2006
Polaris B

\[ \Delta \rho = -1.67 \pm 0.19 \text{ mas/yr} \]
- can be reproduced by orbital motion of \( P \sim 100,000 \text{ yr} \), \( M_{\text{tot}} = 7.2 \, M_\odot \), \( d = 130 \, \text{pc} \).

\[ \Delta PA = -0.0035 \pm 0.00094 \text{°/yr} \]
- consistent with no detectable change in position angle
How to Measure Stellar Masses?

- Orbital motion in binary stars

Dynamical Elements:
- $P$: period
- $T$: time of periastron passage
- $e$: orbital eccentricity
- $a$: semi-major axis

Geometric Elements:
- $i$: inclination
- $\Omega$: PA of line of nodes
- $\omega$: angle between node + periastron