Stellar Angular Diameters from CHARA & NPOI Data (Plus Some Other Stuff)

Ellyn Baines
Naval Research Laboratory
ellyn.baines@nrl.navy.mil

The CHARA Array:
Hal McAlister, Theo ten Brummelaar, Nils Turner, Judit Sturmann, Laszlo Sturmann, Christopher Farrington, Norm Vargas, + others

Naval Research Laboratory:
Thomas Armstrong
Henrique Schmitt
Up for discussion:

- HR 8799: final final CHARA results
  This time I mean it!

- CHARA target HR 2582

- NPOI targets ε Eri & κ Oph

- Imaging GEOSats with the NPOI
HR 8799’s Close Up

- Companion type? Star’s age & [Fe/H]? It’s a λ Boo star, so...?
- Observed using the CHARA Array
  - 7 nights, 2010 – 2011
  - 5 calibrators (3 used in the paper)

Companion location if star is young → exoplanets

Companion location if star is older → brown dwarfs

Marois et al. (2008)

Marois et al. (2010)
Our results agree with a young age for the star, so we confirm imaged companions are exoplanets.

If star is contracting onto ZAMS

If star is expanding from ZAMS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_{LD}$</td>
<td>$0.342 \pm 0.008$ mas</td>
</tr>
<tr>
<td>$R$</td>
<td>$1.44 \pm 0.06 , R_\odot$</td>
</tr>
<tr>
<td>$T_{eff}$</td>
<td>$7193 \pm 10$ K</td>
</tr>
<tr>
<td>$L$</td>
<td>$5.05 \pm 0.29 , L_\odot$</td>
</tr>
<tr>
<td>$M_{star}$</td>
<td>$1.52 \pm 0.03 , M_\odot$</td>
</tr>
<tr>
<td>Age</td>
<td>$33^{+7}_{-13.2}$ Myr</td>
</tr>
<tr>
<td>$M_{star}$</td>
<td>$1.51 \pm 0.02 , M_\odot$</td>
</tr>
<tr>
<td>Age</td>
<td>$90^{+381}_{-50}$ Myr</td>
</tr>
</tbody>
</table>
CHARA Target HR 2582

- G6 or K0 III star

- Observed using CoRoT for stellar oscillations
  They found some!

- Observed using the CHARA Array in Dec. 2012
Why it’s interesting

• $M$, $R$, and age are challenging because $L$ and $T_{\text{eff}}$ are poorly constrained.

• HR 2582 appears to be more massive than normal red clump stars $\rightarrow$ implies rapid evolution

• Unknown if star is:
  – H-shell burning on ascending red giant branch?
  – burning He in a later stage?
CoRoT Results

• Observed HR 2582 for 55 days (Baudin et al. 2012)

• Used complementary spectroscopic observations to determine:
  – $T_{\text{eff}} = 4665 \pm 200$ K
  – $\log g = 1.4 \pm 0.3$ cm s$^{-2}$
  – $[\text{Fe/H}] = -0.18 \pm 0.14$
  – $L = 2.70 \pm 0.15 \, L_{\odot}$
  – $R \sim 34 \pm 8 \, R_{\odot}$

$$\nu_{\text{max}} \approx \frac{M/M_{\odot}}{\left(\frac{R}{R_{\odot}}\right)^2 \sqrt{T_{\text{eff}}/T_{\text{eff, Sun}}}}$$

Power density spectrum, $\nu_{\text{max}} = 15 \pm 1 \, \mu\text{Hz}$

$M \sim 5.2 \pm 2.9 \, M_{\odot}$
CHARA Results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta$ (mas)</td>
<td>1.00 ± 0.02</td>
</tr>
<tr>
<td>$R$ ($R_\odot$)</td>
<td>35.8 ± 5.3</td>
</tr>
<tr>
<td>$T_{\text{eff}}$ (K)</td>
<td>4712 ± 151</td>
</tr>
<tr>
<td>$M$ ($M_\odot$)</td>
<td>5.7 ± 0.5</td>
</tr>
<tr>
<td>Age (Myr)</td>
<td>160 ± 20</td>
</tr>
</tbody>
</table>

H-shell burning in 1$^{\text{st}}$ ascending branch: 157 Myr
Core He-burning in 1$^{\text{st}}$ ascending branch: 163 Myr
Core He-burning in 2$^{\text{nd}}$ ascending branch: 180 Myr
Exoplanet Host Star ε Eri

- Measured angular diameter
- Calculated $T_{\text{eff}}$, $R$, $L$
- Used $T_{\text{eff}}$, $R$ with $Y^2$ isochrones to estimate $M_{\text{star}}$
- Combined $M_{\text{star}}$ with $f(m)$ and $i$ to calculate $M_{\text{planet}}$
- Used $T_{\text{eff}}$ to determine HZ (0.5 to 1.0 AU)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_{\text{LD}}$</td>
<td>$2.153 \pm 0.028 \text{ mas}$</td>
</tr>
<tr>
<td>$R$</td>
<td>$0.74 \pm 0.01 \ R_{\odot}$</td>
</tr>
<tr>
<td>$T_{\text{eff}}$</td>
<td>$5039 \pm 126 \ K$</td>
</tr>
<tr>
<td>$L$</td>
<td>$0.32 \pm 0.03 \ L_{\odot}$</td>
</tr>
<tr>
<td>$M_{\text{star}}$</td>
<td>$0.82 \pm 0.05 \ M_{\odot}$</td>
</tr>
<tr>
<td>$M_{\text{planet}}$</td>
<td>$1.55 \pm 0.24 \ M_{\text{Jupiter}}$</td>
</tr>
</tbody>
</table>
Asteroseismology Target κ Oph

- Observed using NPOI Feb. & March 2013
- Used \( \Delta \nu_{\text{max}} \) from Stello et al. (2009) to determine mass:

\[
\Delta \nu_{\text{max}} = \frac{M T^{3.5}}{L}
\]
NPOI Results

This is the only method to measure the mass of a single star.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>% err</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_{LD}$</td>
<td>$3.68 \pm 0.01$ mas</td>
<td>0.3</td>
</tr>
<tr>
<td>$R$</td>
<td>$11.1 \pm 0.1$ $R_\odot$</td>
<td>1</td>
</tr>
<tr>
<td>$T_{eff}$</td>
<td>$4679 \pm 113$ K</td>
<td>2</td>
</tr>
<tr>
<td>$L$</td>
<td>$53.1 \pm 5.1$ $L_\odot$</td>
<td>10</td>
</tr>
<tr>
<td>$M_{star}$</td>
<td>$3.9 \pm 0.5$ $M_\odot$</td>
<td>13</td>
</tr>
</tbody>
</table>

There are 7 other targets with stellar oscillation observations and archival NPOI data:
• $1.32 \leq \theta \leq 3.01$ mas; $0.80 \leq R_{star} \leq 9.98$ $R_\odot$
• $4863 \leq T_{eff} \leq 6349$ K
• $2.8 \leq M_{star} \leq 4.8$ $M_\odot$
And now for “some other stuff”
Imaging GEOsats with the NPOI

• Objective:
  – Address space situational awareness needs by using the NPOI to observe geostationary satellites (GEOsats)
  – Build on previous fringe detection of GEOsat by NPOI to create an image

• We want to answer the questions:
  – What is the GEOsat orientation, configuration?
  – Is there major damage to the GEOsat?
  – Are the GEOsats at risk?
The Challenge

Imaging is difficult because GEOsats are:

• Complex

• Faint, usually $10^{\text{th}}$-$14^{\text{th}}$ magnitude

• Small in apparent size
  – $\sim 40,000$ km away
  – 2 to 50 m in physical size $\Rightarrow$ 10 to 250 mas in angular size
  – Single telescope would need an aperture of 40-60 m

The technology developed to interferometrically image stars is directly applicable to imaging GEOsats.
NPOI Observations During Glint

During glint:
- GEOsats brighten from 10-14<sup>th</sup> magnitude up to 1<sup>st</sup>
- Occurs twice a year
- Lasts ~10 minutes each night for a week
Previous Detection

3 March 2009
Single-baseline detection

Fringe strength vs. Wavelength (nm)

Reduced $\chi^2 = 0.97$

- small, bright element (1 m)
- large, diffuse element ($\geq$3 m)

Artist’s conception:

NPOI stations used:

- W7
- AN
- AW
- E6
- E7
- N7
- AE
- AC

Single-baseline detection

20 60
-20 -20
-60 60
Distance from center (m)
Distance from center (m)
Experiment Approach

1. Observe GEOsats, including NRL’s microsatellite
   - Maneuverable, in sub-GEO track

2. Simulations
   - Develop computer models; learn how much information can be derived from observations

3. Apply observing and data processing techniques
   - Implement multiple baseline measurements
   - Remove atmospheric effects from the data
Applicable Techniques

- **Baseline bootstrapping**
  - Build up to the long $B$ in small increments

- **Phase closure**
  - Remove atmospheric phase effects by summing over a triangle

- **Coherent averaging**
Coherent Averaging

- Ongoing collaboration with A. Jorgensen, New Mexico Tech
- Start with a sequence of fringe measurements
- Fit a function to characterize atmospheric phase effects, compensate, and average
- Result: fringe phase + amplitude with higher SNR

NPOI Observations of υ Oph
GEOsat Image Quality

Simulation with realistic noise...

...apply coherent averaging...

...and assume perfect phase closure