Imaging Stars and Planets with the CHARA Array

Imaging Stars and Planets with the CHARA Interferometer

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0.5 milliarcseconds
Stars - big or small?

- The nearest star: $\alpha$ Cen (A)
  \[ R = 1.23 \, R_{\text{sun}} , \quad D = 1.34 \, \text{pc} \]
  Angular size = 4.3 milliarcseconds

- The brightest star: Sirius (A)
  \[ R = 1.71 \, R_{\text{sun}} , \quad D = 2.64 \, \text{pc} \]
  Angular size = 3.0 milliarcseconds

<table>
<thead>
<tr>
<th>Observatory</th>
<th>Wavelength</th>
<th>Diameter Or Baseline</th>
<th>Angular Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hubble Space Telescope</td>
<td>500 nm</td>
<td>2.4m</td>
<td>43 milli-arcsecond</td>
</tr>
<tr>
<td>Keck Observatory</td>
<td>1.65 micron</td>
<td>10 m</td>
<td>34 milli-arcsecond</td>
</tr>
</tbody>
</table>

1 milliarcsecond at 1.65 micron => 340 m ! ($\lambda/D$)
MIRC: Michigan Infrared Combiner

Basic Capabilities:

1) Designed for imaging -- currently combines 4 telescopes at once
2) 1.5-2.4 micron wavelength coverage  
   *(in this talk, all results are H band, 1.65 microns)*
3) Spectral modes: R~40,150,400
CHARA+MIRC can image and provide new science to:

- **Stars** - rapid rotators, spotty stars, etc.
- **Binaries** - interacting systems
- **Circumstellar disks** - YSO disks, Be star disks
- **Hot Jupiter systems**
Imaging Stellar Surfaces: Resolving Rapid Rotation

- Rapid rotation of hot stars is expected to
  - Distort stellar photosphere
  - Cause “gravity darkening” along the stellar equator (von Zeipel 1924)
  - Modify interior angular momentum and differential rotation

- Importance in many areas
  - Rotation-induced mixing causing observed abundance anomalies (Pinsonneault 1997)
  - Alters H-R diagram and Mass-Luminosity relation (Maeder & Maynet 2000)
  - Affects circum-stellar environments
  - Link to Gamma Ray Burst progenitors
Imaging

- All previous results were based on model-fitting of interferometry data with a few baselines

- Basic model of Von Zeipel (1924ab)
  - Big assumptions: solid body rotation, point gravity, simplistic radiative transfer model for outer layers

- Hydro models suggest non-solid body rotation, e.g., differential rotation, meridional flows
  - Jackson et al. 2004; MacGregor 2007; Espinosa Lara & Rieutard 2007

- “Model-Independent” imaging with CHARA-MIRC can test wide class of models
First image of a main-sequence star (besides the Sun…)

- Altair (α Aql, V=0.7)
  - Nearby hot star (d=5.1pc, A7V, T=7850 K)
  - Rapidly rotating (v sin i = 240 km/s, ~90% breakup)

Altair Image Reconstruction

Monnier et al. 2007
Modeling Altair

• Construct 3D sphere + apply von Zeipel model ($T \propto g^\beta$) + Kurucz limb darkening
• Fast algorithm: more accurate, faster

Monnier et al. 2007
Model of a fast-spinning star

0.1 revolutions/day
More Results: Alderamin (α Cep)

- A7 IV-V, D = 15pc
- ~93% of break-up, 12.46 hrs/cyc
- $R_{eq}/R_{pol} = 1.26$
- $T_{pol} - T_{eq} = 2000$K
More Results: Rasalhague (α Oph)

- A5IV, d = 14pc
- ~ 89% break-up, 14.6 hrs/cyc
- T_{pol} - T_{eq} = 1850 K
- R_{eq}/R_{pol} = 1.20

Zhao et al. 2009

An edge-on rotator!
Scrutinizing von Zeipel Theory

• Our models prefer non-standard von Zeipel law

• Models show that the polar areas of the stars are radiative and equatorial areas might be convective
  – Other evidence: both stars have strong chromosphere activity

• Images show that equator is cooler than expected
  – Differential Rotation?
  – Spectral line analysis underway
True HR Diagram

Zhao et al. 2009
More Results: 7 rapid rotators in total

<table>
<thead>
<tr>
<th>Star</th>
<th>Spectral Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regulus (α Leo)</td>
<td>B8IV</td>
</tr>
<tr>
<td>Vega (α Lyr)</td>
<td>A0V</td>
</tr>
<tr>
<td>Denebola (β Leo)</td>
<td>A3V</td>
</tr>
<tr>
<td>Rasalhague (α Oph)</td>
<td>A5IV</td>
</tr>
<tr>
<td>Altair (α Aql)</td>
<td>A7V</td>
</tr>
<tr>
<td>Alderamin (α Cep)</td>
<td>A7IV-V</td>
</tr>
<tr>
<td>Caph (β Cas)</td>
<td>F2 IV</td>
</tr>
</tbody>
</table>
A well-known “β Lyrae” system:

- β Lyrae: interacting and eclipsing binary (period 12.9 days)
- B6-8 II donor + B gainer in a thick disk
- V = 3.52, H = 3.35; distance ~300pc
Previous Studies on Beta Lyrae

- Mostly light curves
- NPOI imaging of Hα emission region

(Hutter et al. 2008)
Previous Studies on Beta Lyrae

• Mostly light curves
• NPOI imaging of Hα emission region

However, components unresolved, no astrometric orbit available
First imaging of the 12.9-day eclipsing binary Beta Lyrae

Phase = 0.132
First imaging of the 12.9-day eclipsing binary Beta Lyrae

Phase = 0.210
First imaging of the 12.9-day eclipsing binary Beta Lyrae

CHARA-MIRC Image

Model

Phase = 0.438
First imaging of the 12.9-day eclipsing binary Beta Lyrae

Phase = 0.595
First imaging of the 12.9-day eclipsing binary Beta Lyrae

CHARA-MIRC Image

Model

Phase = 0.828

Zhao et al. 2008
First imaging of the 12.9-day eclipsing binary Beta Lyrae

Zhao et al. 2008
First Astrometric Orbit for β Lyr

- Orbit: $i \sim 92$ degs
- Mass: $M_{\text{donor}} = 12.8 \pm 0.3 \, M_{\sun}$; $M_{\text{gainer}} = 2.8 \pm 0.2 \, M_{\sun}$

Zhao et al. 2008
What’s Next - Direct Imaging of Hot Jupiters?
What can interferometry add to the science of hot Jupiters?

1). Spectral information in the near-IR
   - Estimate global energy budget of hot Jupiters

- IRAC and MIPS cover only a small fraction of SED
What can interferometry add to the science of hot Jupiters?

1). Spectral information in the near-IR
   - Estimate global energy budget of hot Jupiters

2). Day/night flux variation and flux calibration for non-transiting hot Jupiters
   - Break down model degeneracy

3). Obtain inclination and determine accurate mass for non-transiting hot Jupiters
   - Interferometers can see hot Jupiter systems as high contrast binaries
### Best Candidates

Table 1. Hot Jupiter candidates for CHARA-MIRC

<table>
<thead>
<tr>
<th>Star Name</th>
<th>Dist. (pc)</th>
<th>H (mag)</th>
<th>K (mag)</th>
<th>Period (day)</th>
<th>e</th>
<th>Semimajor Axis (AU)</th>
<th>T0 (JD)</th>
<th>R* (mas)</th>
</tr>
</thead>
<tbody>
<tr>
<td>υ And</td>
<td>13.5</td>
<td>2.957</td>
<td>2.859</td>
<td>4.6170</td>
<td>0.034</td>
<td>0.059 (4.42)</td>
<td>2450088.64</td>
<td>0.569</td>
</tr>
<tr>
<td>τ Boo</td>
<td>15.6</td>
<td>3.546</td>
<td>3.507</td>
<td>3.3128</td>
<td>0.018</td>
<td>0.049 (3.13)</td>
<td>2451653.968</td>
<td>0.45</td>
</tr>
<tr>
<td>51 Peg</td>
<td>15.4</td>
<td>4.234</td>
<td>3.911</td>
<td>4.2310</td>
<td>0.01</td>
<td>0.051 (3.31)</td>
<td>2450203.947</td>
<td>0.35</td>
</tr>
</tbody>
</table>

**Ratio:** $\sim 10^4:1$  
(Sudarsky et al. 2003)
Precision requirement: < 0.18° for the highest resolution channel
Observation of \( \nu \) And

Need 6x S/N for 3\( \sigma \) detection!
Improvements

• Analysis Method:

- Orbital parameters: $i$, $\Omega$
- Day/night flux variation: amplitude, phase
- Closure phase offset

⇒ Combined solution of multiple channels and nights
Improvements

- Calibration:
  - closure phase drifts due to polarization or dispersion (under investigation)

Drifts in closure phase

- 2007Nov16

- 2007Nov22
Closure phase as a quadratic surface function of Altitude and Azimuth

\[ a_1 \cdot AZ + a_2 \cdot AZ^2 + a_3 \cdot AZ \cdot Alt + a_4 \cdot Alt + a_5 \cdot Alt^2 \]
After new calibration
Preliminary upper limit for Ups And

Monnier 2009
Improvements

• Throughput
• Efficiency
• Noise Regime
• Calibration
• Data analysis

All improvements add together:
⇒ 6x - 10x S/N
Summary

• First images of main sequence stars besides Sun
  – Temperatures not consistent with von Zeipel law, suggesting differential rotation
  – Interferometry combined with spectroscopy can weigh stars in new way
  – Knowledge of geometry will allow precise calibration of upper main sequence for first time

• Interacting binaries now accessible
  – Physics of accretion disks in close binaries

• Directly detecting hot Jupiters underway!
Backup slides
Modeling Altair

- Construct 3D sphere + apply Roche- von Zeipel model ($T \propto g^\beta$) + Kurucz limb darkening
- Fast algorithm: more accurate, faster

![Altair Model ($\beta=0.25$)](image1.png)

![Altair Model ($\beta=0.19$)](image2.png)

-Lower $\beta$ is better
New Method to Measure Mass of Single Star

- Interferometer measures star’s oblateness & inclination angle
  - This distortion does not tell us the stellar mass directly
- Spectroscopy can determine projected surface velocities ($v \sin i$)
- Together: we can measure the mass of the star
  - Depends on some assumptions, such as uniform internal rotation, and proper model of spectral line profiles
Test Case: Rasalhague (α Oph)

- A well-known binary
  - Gatewood et al. 2005 determine primary mass 2.8 +/- 0.2 Msun

- Interferometer-determined geometry and $v \sin i$ suggests lower mass ~2.1 Msun

- New AO imaging will determine precise mass as a check of the Oblateness Method
  - Work in progress..
Imaging Stars and Planets with the CHARA Array

Short triangle ~ 0.8 mas resolution

Averaging the whole 1.7 hours => 0.045°
Closure phase simulation

**Short triangle**

**Ups And**  
Telescopes: S2 E2 W1

Maximum = 0.02°

Precision requirement: < 0.02° for the highest resolution channel

Maximum = 0.03°
# Altair

<table>
<thead>
<tr>
<th>Parameters</th>
<th>$\beta$ Fixed</th>
<th>$\beta$ Free</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclination (degs)</td>
<td>62.7 ± 1.6</td>
<td>56.8 ± 2.2</td>
</tr>
<tr>
<td>Position Angle (degs)</td>
<td>-61.7 ± 1.2</td>
<td>-61.9 ± 1.0</td>
</tr>
<tr>
<td>$T_{\text{pole}}$ (K)</td>
<td>8650 ± 150</td>
<td>8370 ± 140</td>
</tr>
<tr>
<td>$R_{\text{pole}}$ ($R_\odot$)</td>
<td>1.662 ± 0.005</td>
<td>1.632 ± 0.011</td>
</tr>
<tr>
<td>(mas)</td>
<td>1.503 ± 0.005</td>
<td>1.476 ± 0.010</td>
</tr>
<tr>
<td>$T_{\text{eq}}$ (K)</td>
<td>6790 ± 110</td>
<td>6810 ± 70</td>
</tr>
<tr>
<td>$R_{\text{eq}}$ ($R_\odot$)</td>
<td>2.023 ± 0.011</td>
<td>2.029 ± 0.009</td>
</tr>
<tr>
<td>(mas)</td>
<td>1.830 ± 0.010</td>
<td>1.835 ± 0.008</td>
</tr>
<tr>
<td>$\omega$</td>
<td>0.902 ± 0.005</td>
<td>0.924 ± 0.005</td>
</tr>
<tr>
<td>$\beta$</td>
<td>0.25 (Fixed)</td>
<td>0.188 ± 0.011</td>
</tr>
<tr>
<td>Model V Mag</td>
<td>0.765</td>
<td>0.765</td>
</tr>
<tr>
<td>Model H Mag</td>
<td>0.221</td>
<td>0.217</td>
</tr>
<tr>
<td>Model $v \sin i$ (km/s)</td>
<td>241</td>
<td>239</td>
</tr>
</tbody>
</table>

**Reduced $\chi^2$:**
- Total: 1.81, 1.35
- Closure Phase: 2.16, 1.70
- $\text{Vis}^2$: 1.50, 1.09
- Triple Amp: 2.12, 1.58
### Table 1: Best-fit parameters for Alp Oph

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Standard model ($\beta = 0.25$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclination (degs)</td>
<td>$87.70 \pm 0.43$</td>
</tr>
<tr>
<td>Position Angle (degs)</td>
<td>$-53.88 \pm 1.23$</td>
</tr>
<tr>
<td>$T_{\text{pol}}$ (K)</td>
<td>$3300 \pm 150$</td>
</tr>
<tr>
<td>$R_{\text{pol}}$ (R$_{\odot}$)</td>
<td>$2.390 \pm 0.014$</td>
</tr>
<tr>
<td>$T_{\text{es}}$ (K)</td>
<td>$7460 \pm 100$</td>
</tr>
<tr>
<td>$R_{\text{es}}$ (R$_{\odot}$)</td>
<td>$2.871 \pm 0.020$</td>
</tr>
<tr>
<td>$\omega$</td>
<td>$0.885 \pm 0.011$</td>
</tr>
<tr>
<td>Model V Magnitude</td>
<td>2.086</td>
</tr>
<tr>
<td>Model II Magnitude</td>
<td>1.66</td>
</tr>
<tr>
<td>Model v sin$i$ (km/s)</td>
<td>275</td>
</tr>
<tr>
<td>Total $\chi^2$</td>
<td>0.91</td>
</tr>
<tr>
<td>CP $\chi^2$</td>
<td>1.33</td>
</tr>
<tr>
<td>Vis$^2$ $\chi^2$</td>
<td>0.72</td>
</tr>
<tr>
<td>T3amp $\chi^2$</td>
<td>0.81</td>
</tr>
</tbody>
</table>

$^a$V magnitude from literature: 2.086 $\pm$ 0.083

$^b$H magnitude from literature: 1.66 $\pm$ 0.03
Alderamin

Table 3.3. Best-fit and physical parameters of α Cep

<table>
<thead>
<tr>
<th>Model Parameters</th>
<th>Standard ($\beta = 0.25$)</th>
<th>Non-standard ($\beta$-free)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclination (degs)</td>
<td>64.91 ± 4.11</td>
<td>55.70 ± 6.23</td>
</tr>
<tr>
<td>Position Angle (degs)</td>
<td>-178.26 ± 4.10</td>
<td>-178.84 ± 4.28</td>
</tr>
<tr>
<td>$T_{pol}$ (K)</td>
<td>8863 ± 260</td>
<td>8588 ± 300</td>
</tr>
<tr>
<td>$R_{pol}$ (R$_\odot$)</td>
<td>2.199 ± 0.035</td>
<td>2.162 ± 0.036</td>
</tr>
<tr>
<td>$T_{eq}$ (K)</td>
<td>6707 ± 200</td>
<td>6574 ± 200</td>
</tr>
<tr>
<td>$R_{eq}$ (R$_\odot$)</td>
<td>2.739 ± 0.040</td>
<td>2.740 ± 0.044</td>
</tr>
<tr>
<td>$\omega$</td>
<td>0.926 ± 0.018</td>
<td>0.941 ± 0.020</td>
</tr>
<tr>
<td>$\beta$</td>
<td>0.25 (fixed)</td>
<td>0.216 ± 0.021</td>
</tr>
<tr>
<td>Model V Magnitude$^a$</td>
<td>2.45</td>
<td>2.45</td>
</tr>
<tr>
<td>Model H Magnitude$^b$</td>
<td>1.92</td>
<td>1.91</td>
</tr>
<tr>
<td>Model $v \sin i$ (km/s)</td>
<td>237</td>
<td>225</td>
</tr>
<tr>
<td>Total $\chi^2_{\nu}$</td>
<td>1.21</td>
<td>1.18</td>
</tr>
<tr>
<td>$\text{Vis}^2 \chi^2_{\nu}$</td>
<td>0.79</td>
<td>0.80</td>
</tr>
<tr>
<td>CP $\chi^2_{\nu}$</td>
<td>1.43</td>
<td>1.27</td>
</tr>
<tr>
<td>T3amp $\chi^2_{\nu}$</td>
<td>1.71</td>
<td>1.76</td>
</tr>
</tbody>
</table>

Other Physical Parameters

<table>
<thead>
<tr>
<th></th>
<th>True $T_{eff}$ (K)</th>
<th>True Luminosity (L$_\odot$)</th>
<th>Apparent $T_{eff}$ (K)</th>
<th>Apparent Luminosity (L$_\odot$)</th>
<th>Mass (M$_\odot$)$^c$</th>
<th>Age (Gyrs)$^c$</th>
<th>[Fe/H]$^d$</th>
<th>Distance (pc)$^e$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>7690 ± 150</td>
<td>20.1 ± 1.6</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.09</td>
<td>14.96</td>
</tr>
</tbody>
</table>

* $\beta$-free models are those where the mass function is not assumed to be Gaussian.
Rapid Rotation with Interferometry

- First measurement: Altair ($\alpha$ Aql) by Van Belle et al. 2001
- 14% longer in one direction than another

- Vega rotating at ~91% of breakup
  - NPOI (Peterson et al 2005)
  - CHARA (Aufdenberg et al 2006)