The CHARA/MIRC instrument and first images

10.2 milliarcseconds

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and the CHARA team
CHARA Interferometer
Georgia State University

1 milliarcsecond resolution at K band
CHARA Interferometer

• Built and operated by Georgia State University (PI: Hal McAlister)
  – Funded by State of Georgia, National Science Foundation, Keck Foundation
  – Other collaborators: Paris Observatory, Michigan, Sydney, Universite de Nice, Michelson Science Center, NASA Exoplanet Science Institute

• At visible/IR wavelengths, highest resolution in the world (0.3 to 1 milliarcseconds)

• Milli-arcsecond resolution transforms science of
  – Stars – studies of pulsation, rotation & mass-loss
  – Binaries – precise masses & studies of interacting systems
  – Circumstellar emission from YSO disks, Be, evolved stars

• First results in 2005, so far 25 refereed papers
MIRC: Michigan Infrared Combiner on the CHARA Array

Basic Capabilities:

1) Designed for *imaging* -- currently combines 4 telescopes at once (made for up to 6)
2) 1.5-2.4 micron wavelength coverage *(in this talk, all results are H band, 1.65 microns)*
3) At CHARA, MIRC has ~0.5 milli-arcsecond resolution
4) Spectral modes: R~40,150,400
The CHARA/MIRC instrument and first images

WII09, Goutelas, France, 2009 April 28

Optical Layout

- Steering & Future PZT
- AO: 36.87 μd
- Reflect FT light down 1.5°
- Dichroic angle same 3.5 deg AOI
- Beams 4.5° above table
- Compress 2°
- Fluor BS @ 6° (above FT beams)
- 6-axis vignette adjustment with microlens array
- Plate
- Slit achromatic double
- CM 20mm
- Non-cross prism

Components and layout details are shown in the diagram.
MIRC: an image plane combiner using fibers

- V-groove
- Array of Fibers
- Lenslet Array
“Snapshot” imaging now possible!

Four-Telescope CHARA-MIRC
Fourier Coverage

Configuration:
W1-W2-S2-E2

Single 5-minute Snapshot
for IOTA PEG

Binary Model Fit:
Sep: 10.34 mas
PA: 355.7 degs

Visibility-Squared

Spatial Frequency (Mega-Lambda)
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Imaging Demonstration:

Iota Peg
(period 10.2 days)

First Image with CHARA-MIRC

Monnier et al. 2007
MACIM: Ireland et al. 2006
UV Coverage

• Information Available

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• Examples:
  • Single stars: ud1 -> 1 degree of freedom (DOF)
  • Resolved Binary Star: ud1, ud2, rho, ratio -> 5 DOF
  • Rapid Rotator: major, minor, pa, ld, gradient -> 5+ DOF
  • Spotted Star: ud, nspots X (x, y, flux, size?) ->
    • 1 spot -> 5 DOF
    • 2 spots -> 9 DOF
    • 5 spots -> 21 DOF
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
Rapid Rotators with Interferometry

- Van Belle (2001) used PTI to find that Altair is 14% elongated
- Peterson (2005) and Aufdenberg (2006) found Vega face-on rotating at ~91% of breakup
- Stars now measured to be elongated:
  - Altair (α Aql, van Belle et al. 2001; Peterson et al. 2006)
  - Achernar (α Eri, Domiciano de Souza et al. 2003) — or Be star disk?
  - Regulus (α Leo, McAlister et al. 2005)
  - Alderamin (α Cep, van Belle et al. 2005)
Imaging

• Previous results 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
• “Model-Independent” imaging with CHARA-MIRC can test wide class of models
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The CHARA/MIRC instrument
Completely model-free imaging
Nearly completely model-free imaging + short baseline data

PRIOR

NO PRIOR (+PTI ELLIPSE)
Imaging Method

1. Create elliptical prior
2. Create image using MACIM
3. Calculate ‘entropy’
4. Do this for large grid of elliptical supports
5. Choose image with ‘maximum entropy’
Elliptical Support: too small
Elliptical Support: too big

PRIOR

Bigger +10%
Elliptical Support: wrong angle
Elliptical Support: just right!
Grid of Elliptical Priors:
Find “maximum entropy”
(“objective but arbitrary” regularizer)
First image of a main-sequence star (besides the Sun…)

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

0.1 revolutions/day

Modeling and Animation by Ming Zhao
But wait… there’s more:

Alderamin ($\alpha$ Cep) and Rasalhague ($\alpha$ Oph)

Zhao et al. 2009
Imaging Results

• Basic agreement between imaging and von Zeipel model
  – Centrifugal distortion
  – Gravity darkening
• Imaging suggests equator may be darker than expected
  – Differential Rotation?
  – Convection?
  – Imaging artifact?
• Next:
  – Multiwavelength data (visible + IR)
  – Line profiles fitting (search for differential rotation)
  – Image “on” star – better style of prior
  – Example: enforce symmetry – temperate vs. latitude
Unresolved issues

• Image uniqueness
  – Choice of Prior and regularizer can change result if uv coverage is poor (sadly is often the case)
  – Spots on active stars – complex situation

• Error bars?
  – Statistical
  – UV coverage artifacts (blind modes)
Statistical errors vs artifacts
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
First imaging of the 12.9-day eclipsing binary Beta Lyrae

CHARA-MIRC Image

Model

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

0.5 mas

1 mas

Phase = 0.828

Zhao et al. 2008
First Astrometric Orbit for $\beta$ Lyr

**Masses:**
- $M_{\text{donor}} = 12.8 \pm 0.3 \, M_{\text{sun}}$
- $M_{\text{gainer}} = 2.8 \pm 0.2 \, M_{\text{sun}}$

Zhao et al. 2008
Spotted K giant ζ Andromeda

Doppler Imaging (Kovari et al. 2007)

CHARA-MIRC image (Pedretti et al. 200x)
Review of MIRC Imaging Programs

• Imaging and modeling a wide range of rapid rotators
  – Xiao Che analyzing more stars + line profiles
• Imaging spots and molecular layers in RSG and AGB stars
  – Lazlso Kiss for RSGs, Steve Ridgway for molecular layers
• Imaging and Models of Be star disks
  – Lines: Nathalie Thureau; continuum: Gail Shaefer, Yamina Touhami
• Interacting binaries now accessible
  – Ming Zhao (Bet Lyr), Jason Aufdenberg (SPICA), UM team (ALGOL)
• Studies of magnetic fields and star spots underway
  – Ettore Pedretti combining interferometry + doppler imaging
  – Rob Parks thesis on Lambda Andromeda (+ other RS CVN stars)
• Precision Closure Phases for Exoplanet and faint binary detection
  – Ming Zhao thesis, Fabien Malbet project
• Next: Young Stellar Objects
  – CHAMP fringe tracker + Fabien Baron + Stefan Kraus in 2009!
  – Imaging in Visible using IR fringe tracker
• Collaborations are welcome... Especially with modellers & theorists