Imaging Stars and Hot Jupiters with the CHARA Interferometer

QuickTime™ and a decompressor are needed to see this picture.

0.5 milli-arcseconds

Ming Zhao

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CHARA + MIRC

- CHARA: 330m baseline => 0.5mas at H
- MIRC:
  - designed for imaging
  - optimized for precision closure phase calibration

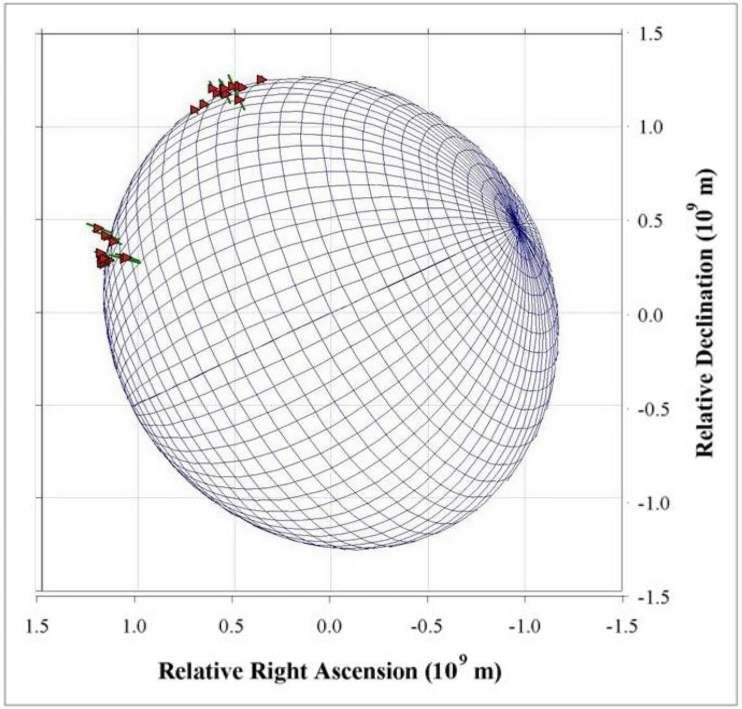
CHARA+MIRC can image and provide new science to:

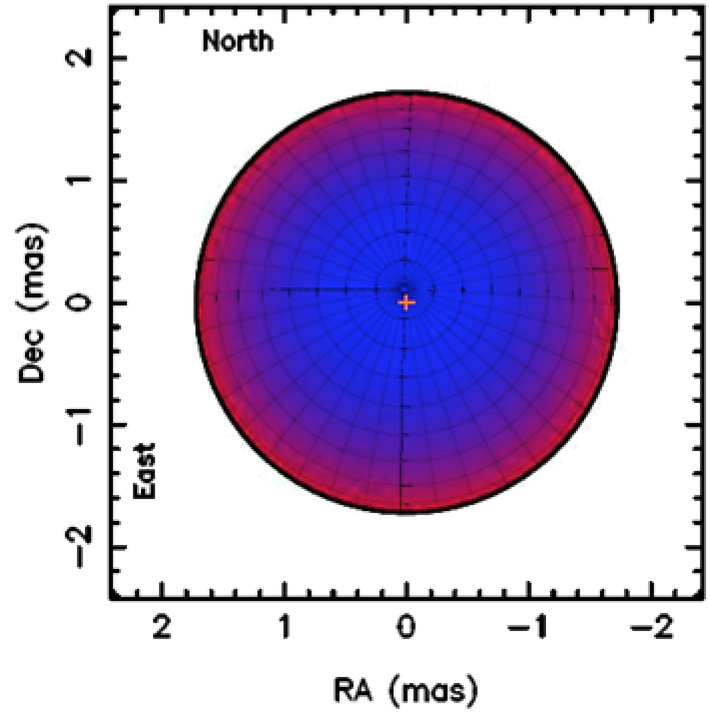
- Stars - e.g., rapid rotators, spotty stars
- Binaries, interacting systems
- Circumstellar disks - Be disks, YSO disks, Debris disks
- Hot Jupiter systems

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)
- Importance in many areas
  - Rotation-induced mixing causing observed abundance anomalies (Pinsonneault 1997, Meynet 2006)
  - Alters H-R diagram and Mass-Luminosity relation (Maeder & Meynet 2000)
  - Affects circum-stellar environments: winds, mass loss
  - Link to Gamma Ray Burst progenitors

Rapid Rotation with Interferometry





- First result: Van Belle (2001), PTI
- Altair (α Aql) is 14% longer in one direction than another

- Vega is rotating at ~91% of breakup and is pole-on!

- Peterson et al. (2005) using NPOI
- Aufdenberg et al. (2006) using CHARA

Rapid Rotation with Interferometry

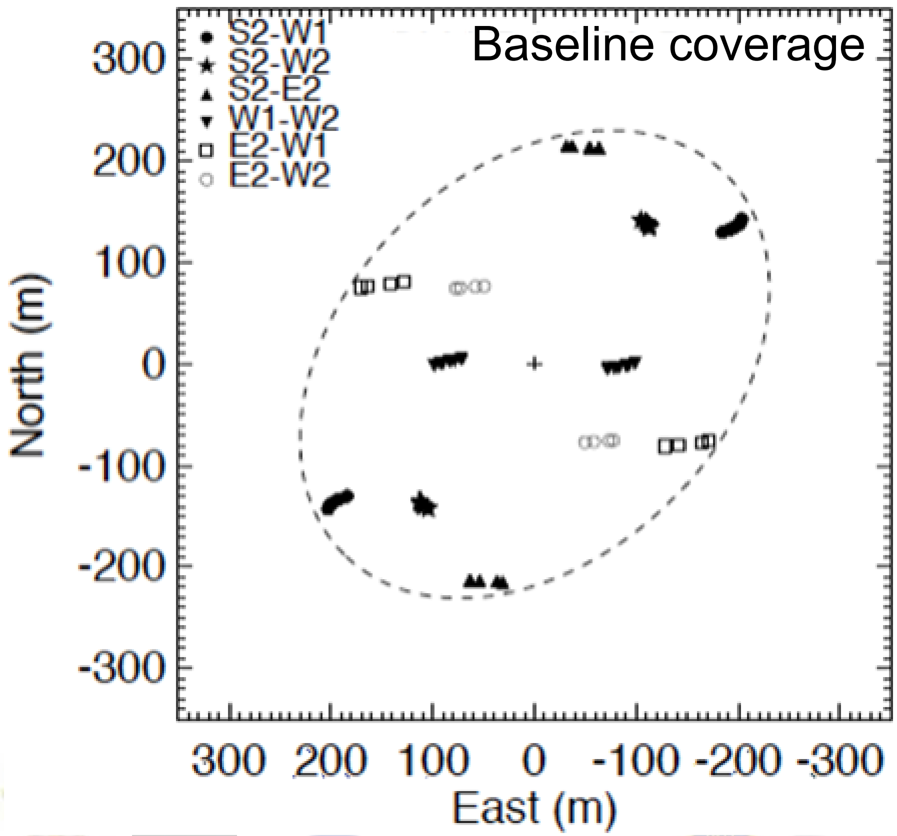
- Many others: Achernar, Regulus, Alderamin

Imaging

- Previous results were based on model-fitting of interferometry data with a few baselines
- Basic model of Von Zeipel (1924a,b)
  - Big assumptions: solid body rotation, point gravity
  - Simple 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)
  - Rapidly rotating (v sin i = 240 km/s, ~90% breakup)



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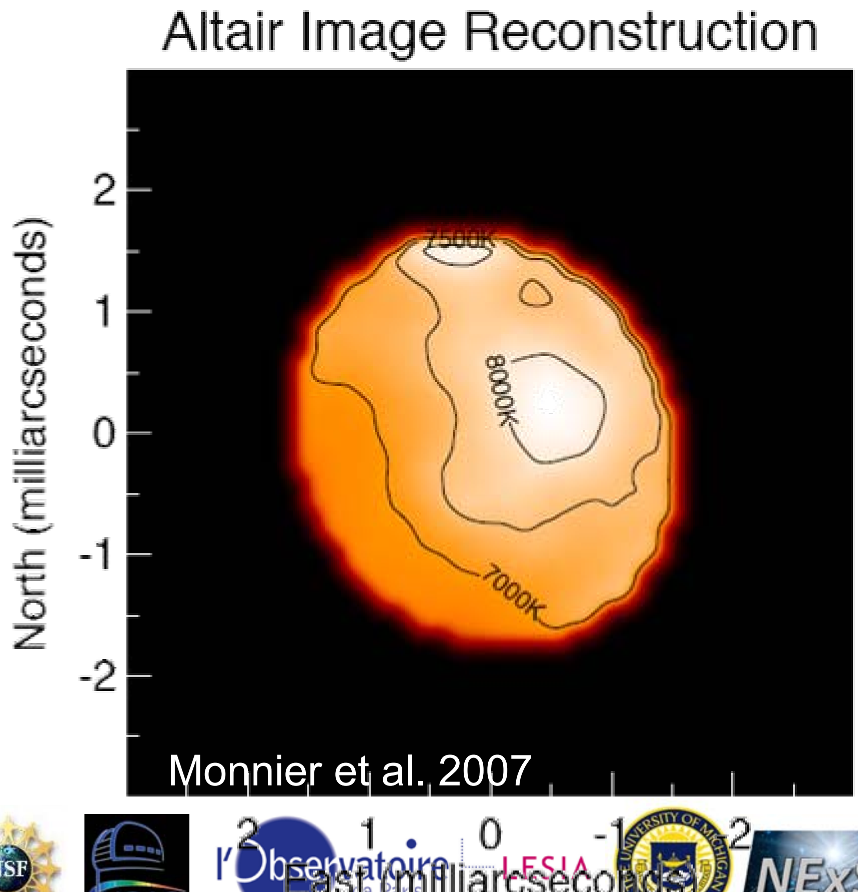
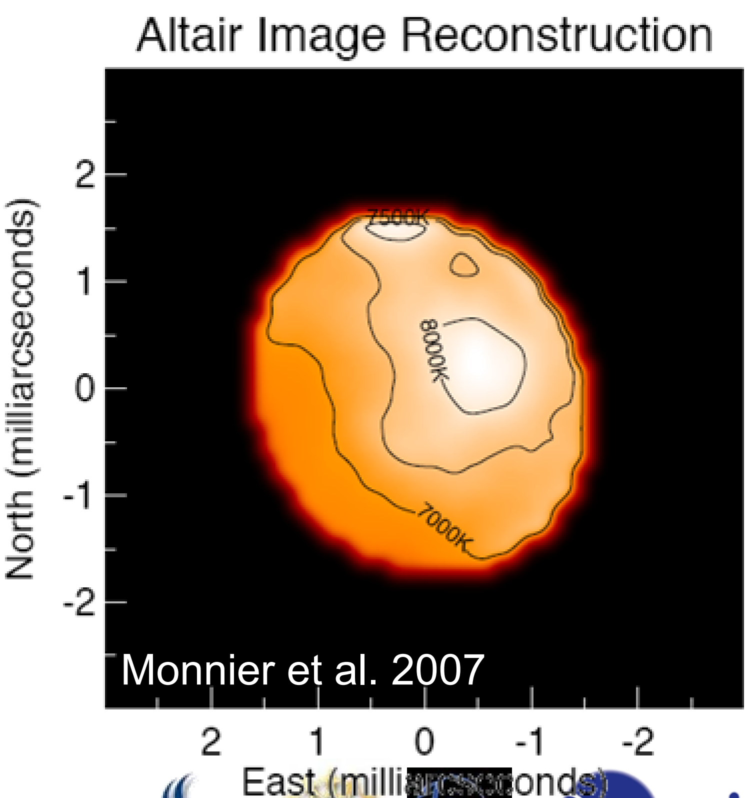
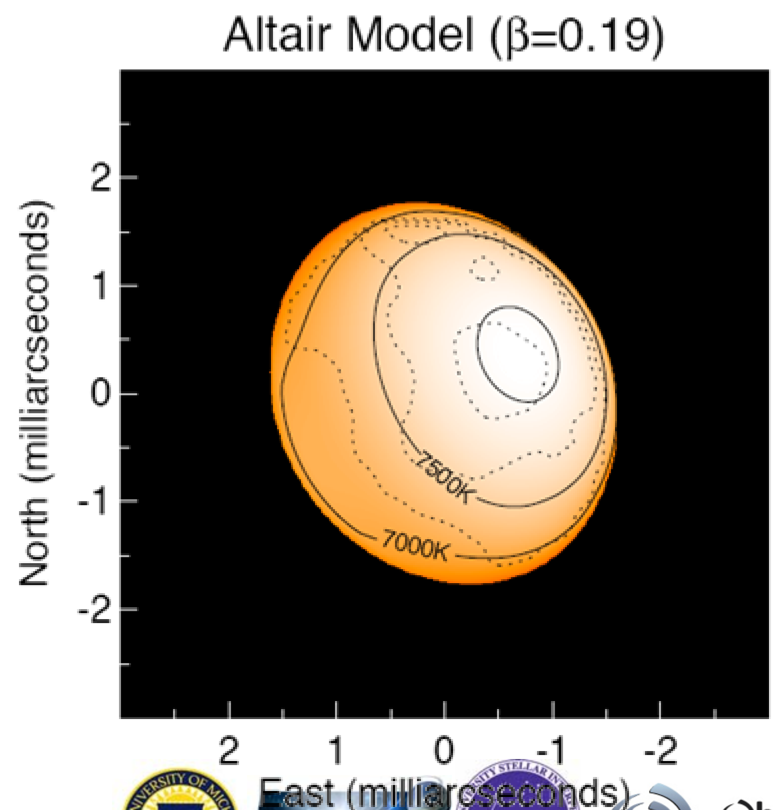


Modeling Altair

- Construct 3D sphere + apply von Zeipel model ($T \propto g^{\beta}$) + Kurucz limb darkening

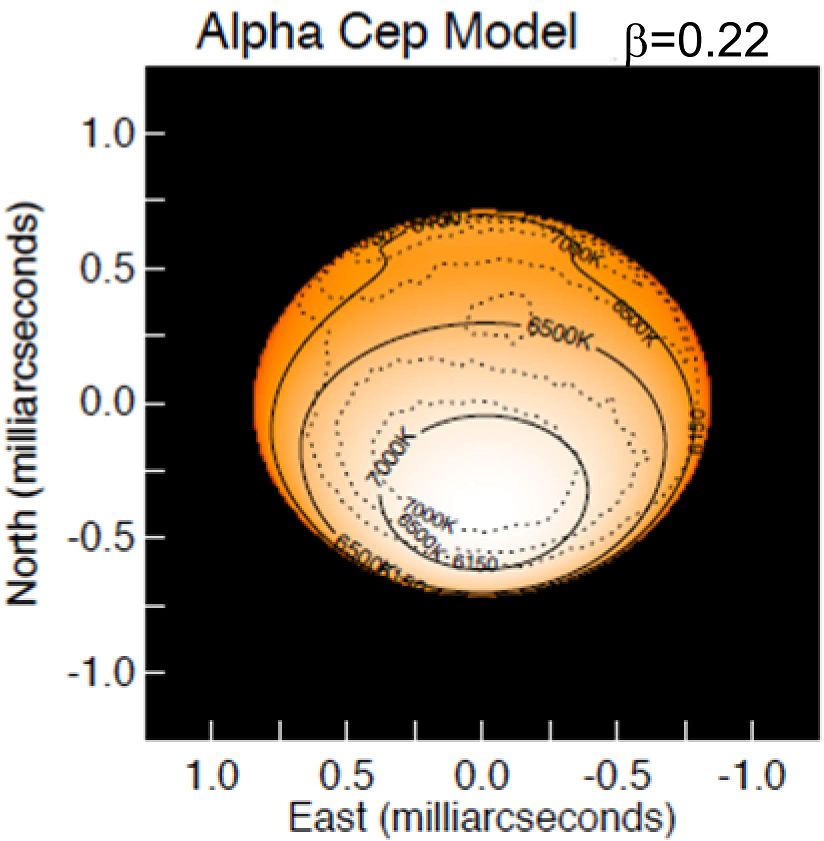




More Results: Alderamin (α Cep)

- Vsini = 245 km/s, 93% break-up

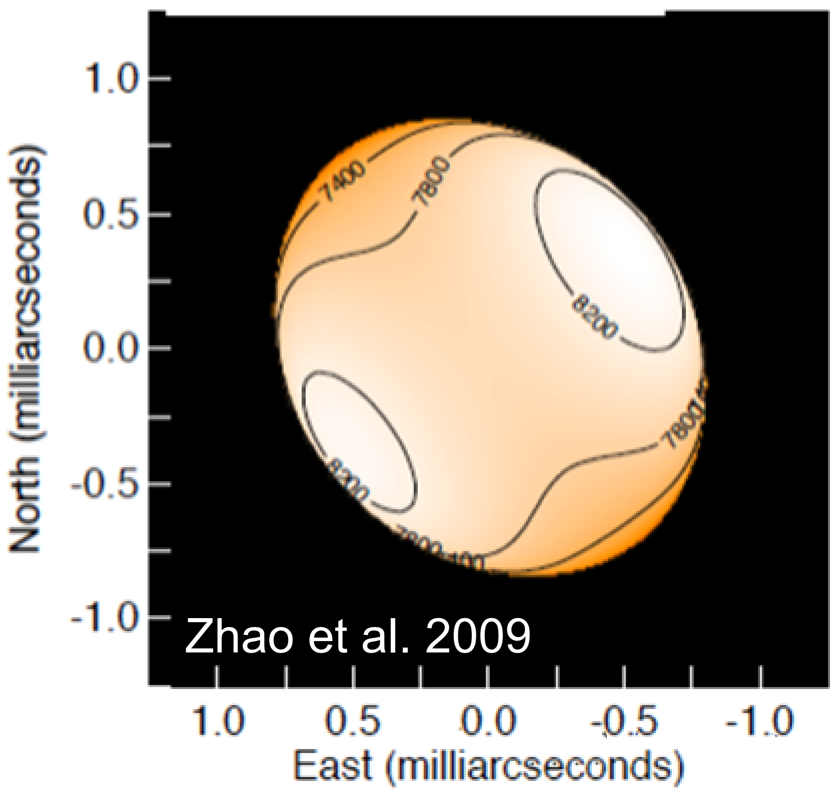
QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

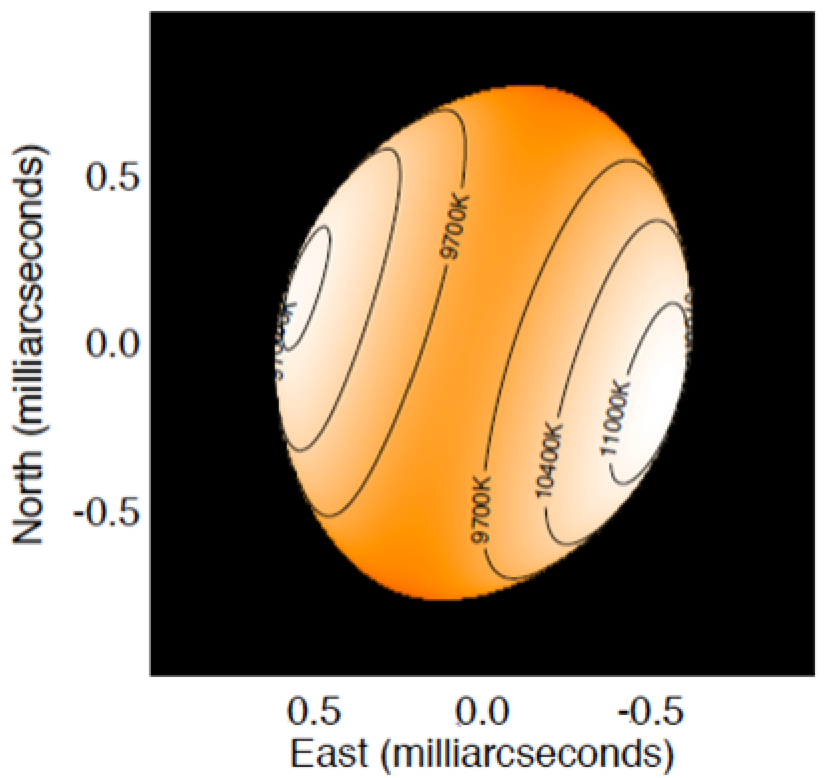


More Results: two edge-on rotators!

- Rasalhague (α Oph)
- A5IV, d = 14pc
- Vsini = 240 km/s, 89% break-up
- i = 88 deg

- Regulus (α Leo)
- B8IV, d = 23.5pc
- Vsini = 317 km/s, 93% break-up
- i = 87 deg

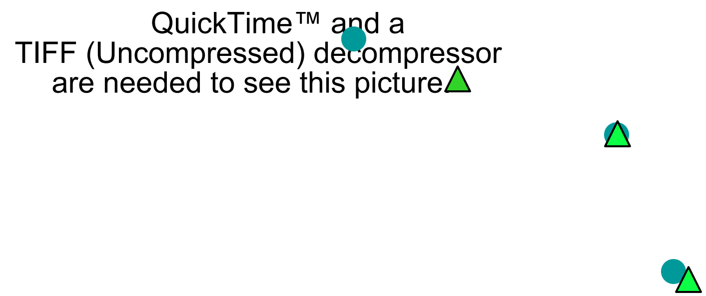




Scrutinizing von Zeipel Theory

- Our models prefer non-standard von Zeipel law
- Models show that the polar areas of the stars are radiative and equatorial areas are convective
- Images show that equator is cooler than expected
  - Differential Rotation?
  - Spectral line analysis underway
  - More confirmations needed!!!

True HR Diagram



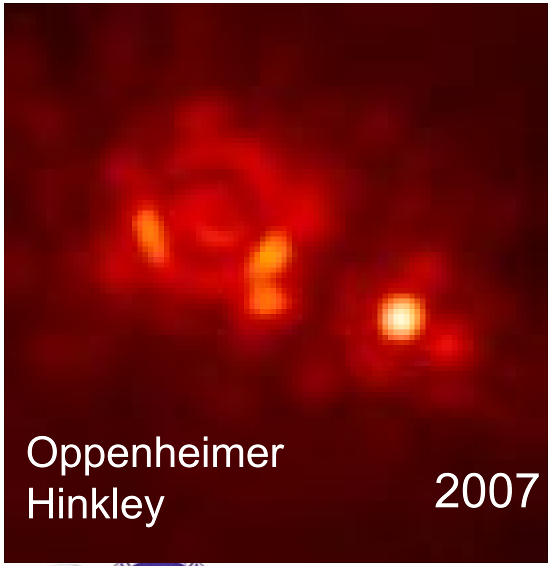
Zhao et al. 2009

New Method to Measure Mass of Single Star

- Interferometer measures star's oblateness & inclination angle
- 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 object: Rasalhague

 - A well-known binary
 - Our results: ~2.1 Msun
 - New AO imaging will determine precise mass as a check
 - in progress

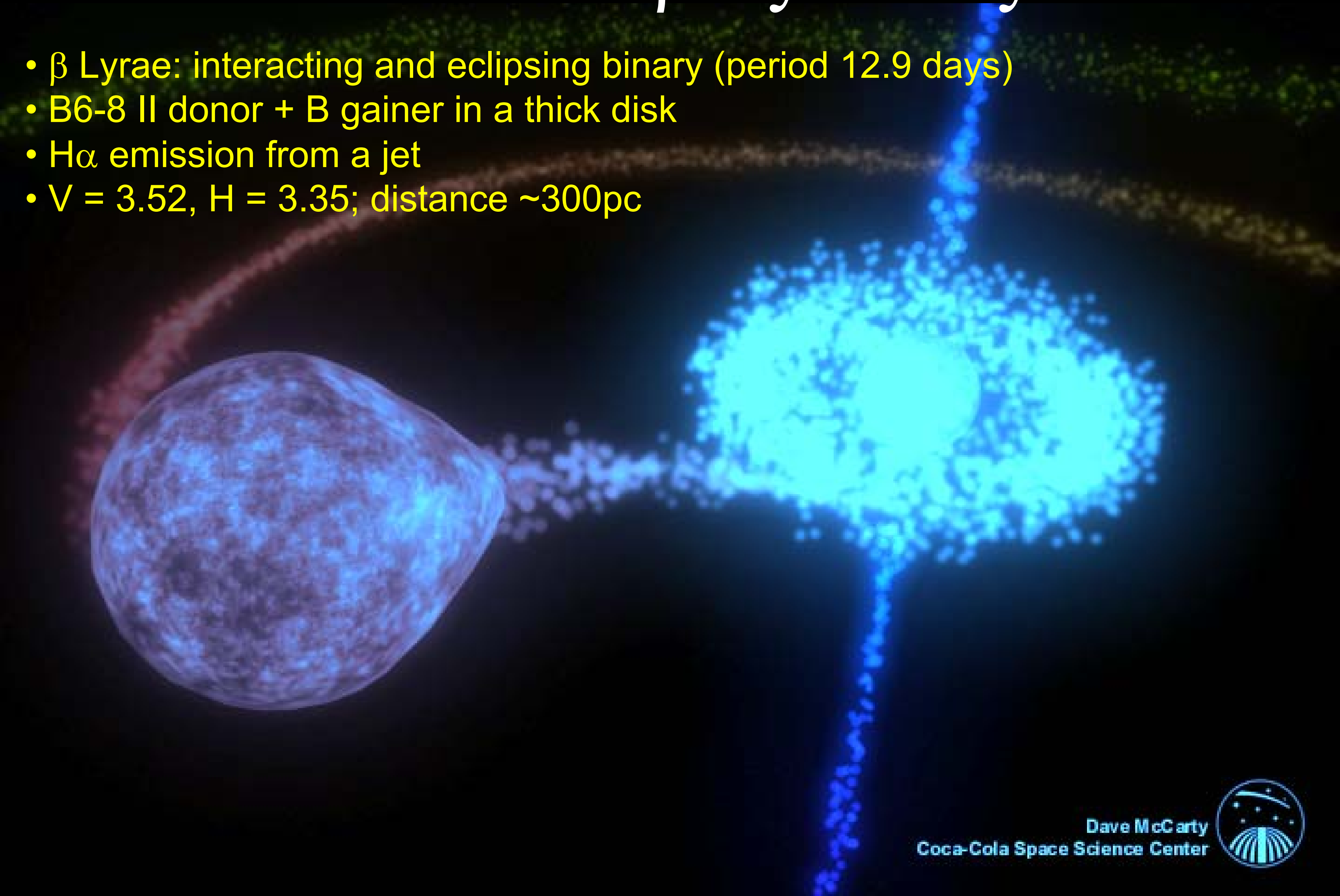


More Results: 7 rapid rotators in total

Star	Spectral Type
Regulus (α Leo)	B8IV
Vega (α Lyr)	A0V
Denebola (β Leo)	A3V
Rasalhague (α Oph)	A5IV
Altair (α Aql)	A7V
Alderamin (α Cep)	A7IV-V
Caph (β Cas)	F2IV

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
- Hα emission from a jet
- V = 3.52, H = 3.35; distance ~300pc



Previous Studies on Beta Lyrae

- Mostly light curves
- NPOI imaging of Ha emission region

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

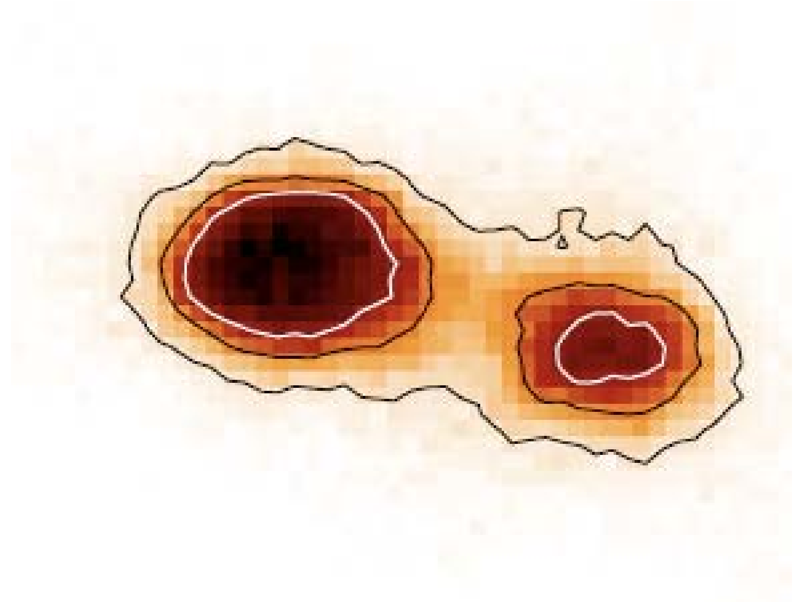
Hutter et al. 2008

Previous Studies on Beta Lyrae

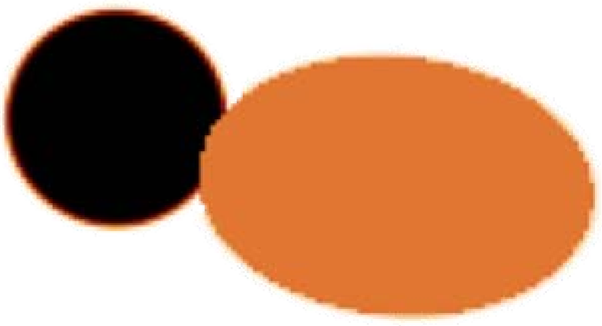
- Mostly light curves
- NPOI imaging of H emission region
- However, components unresolved, no astrometric orbit available

First imaging of the 12.9-day eclipsing binary Beta Lyrae

CHARA-MIRC Image



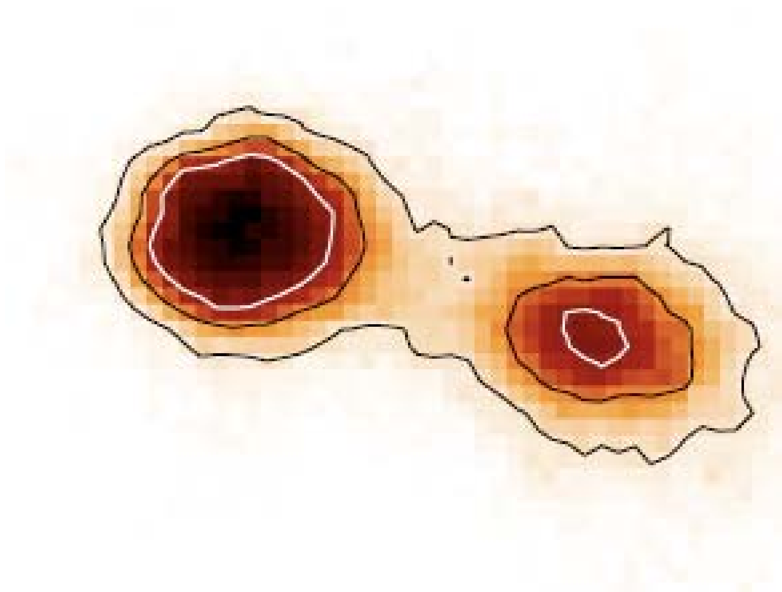
Model



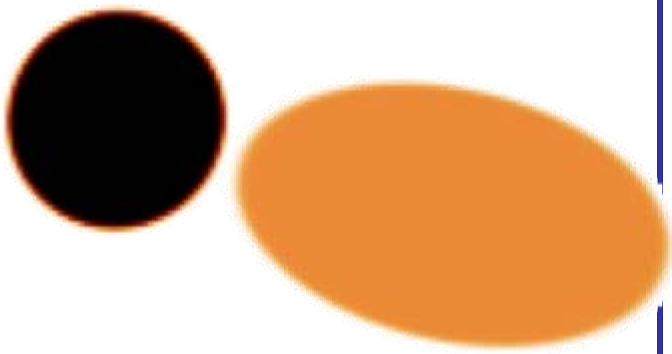
Phase = 0.132

First imaging of the 12.9-day eclipsing binary Beta Lyrae

CHARA-MIRC Image



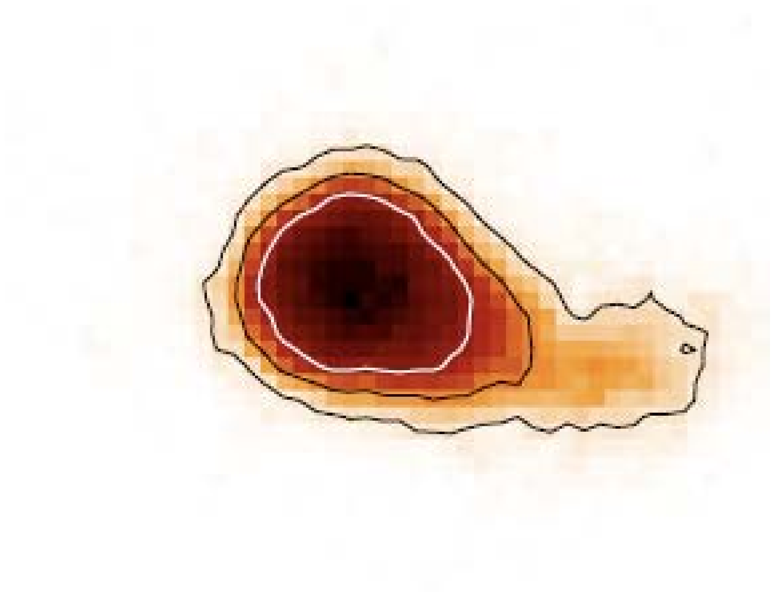
Model



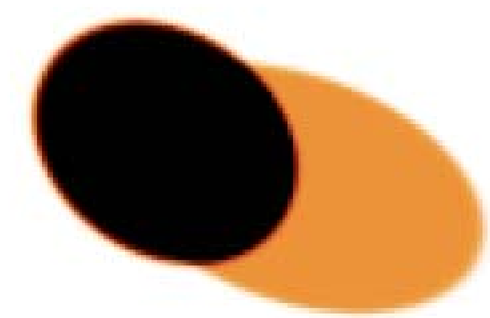
Phase = 0.210

First imaging of the 12.9-day eclipsing binary Beta Lyrae

CHARA-MIRC Image

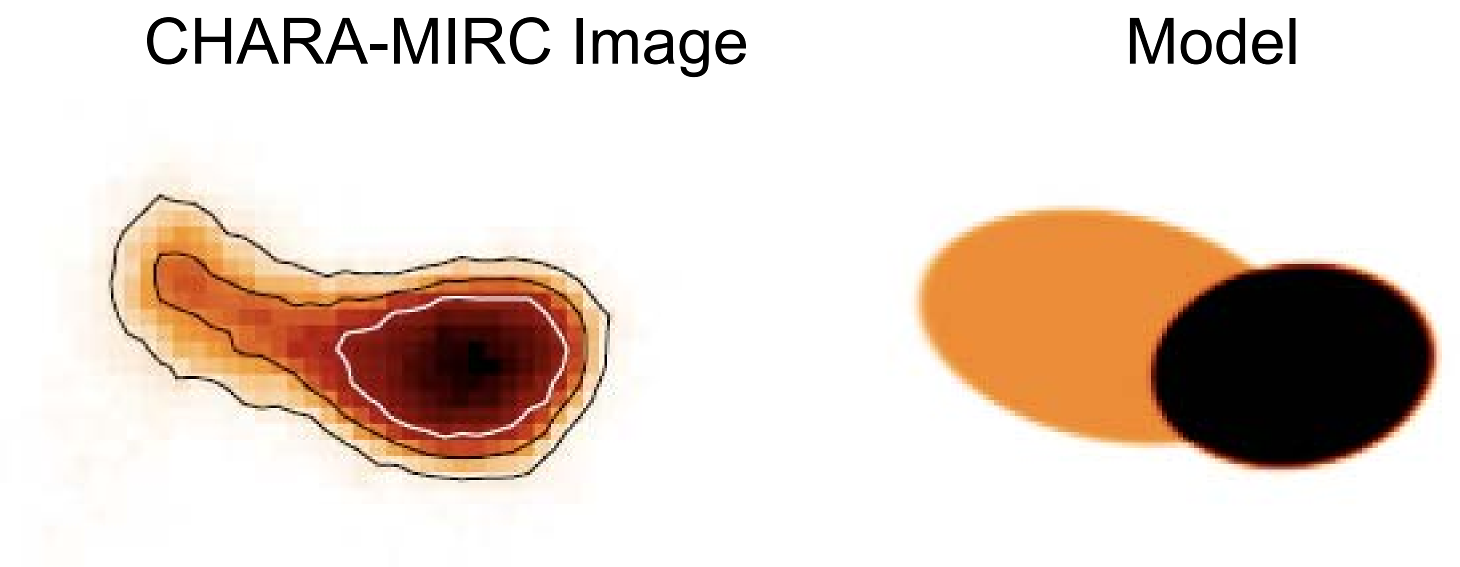


Model



Phase = 0.438

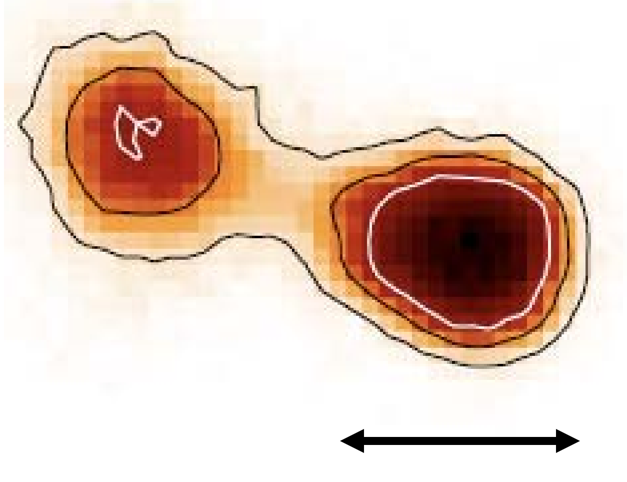
First imaging of the 12.9-day eclipsing binary Beta Lyrae



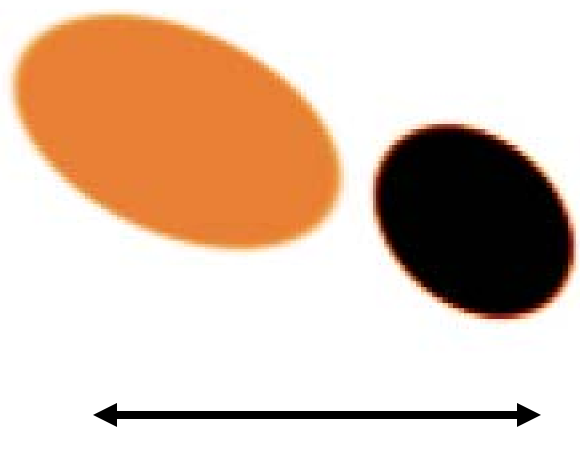
Phase = 0.595

First imaging of the 12.9-day eclipsing binary Beta Lyrae

CHARA-MIRC Image



Model



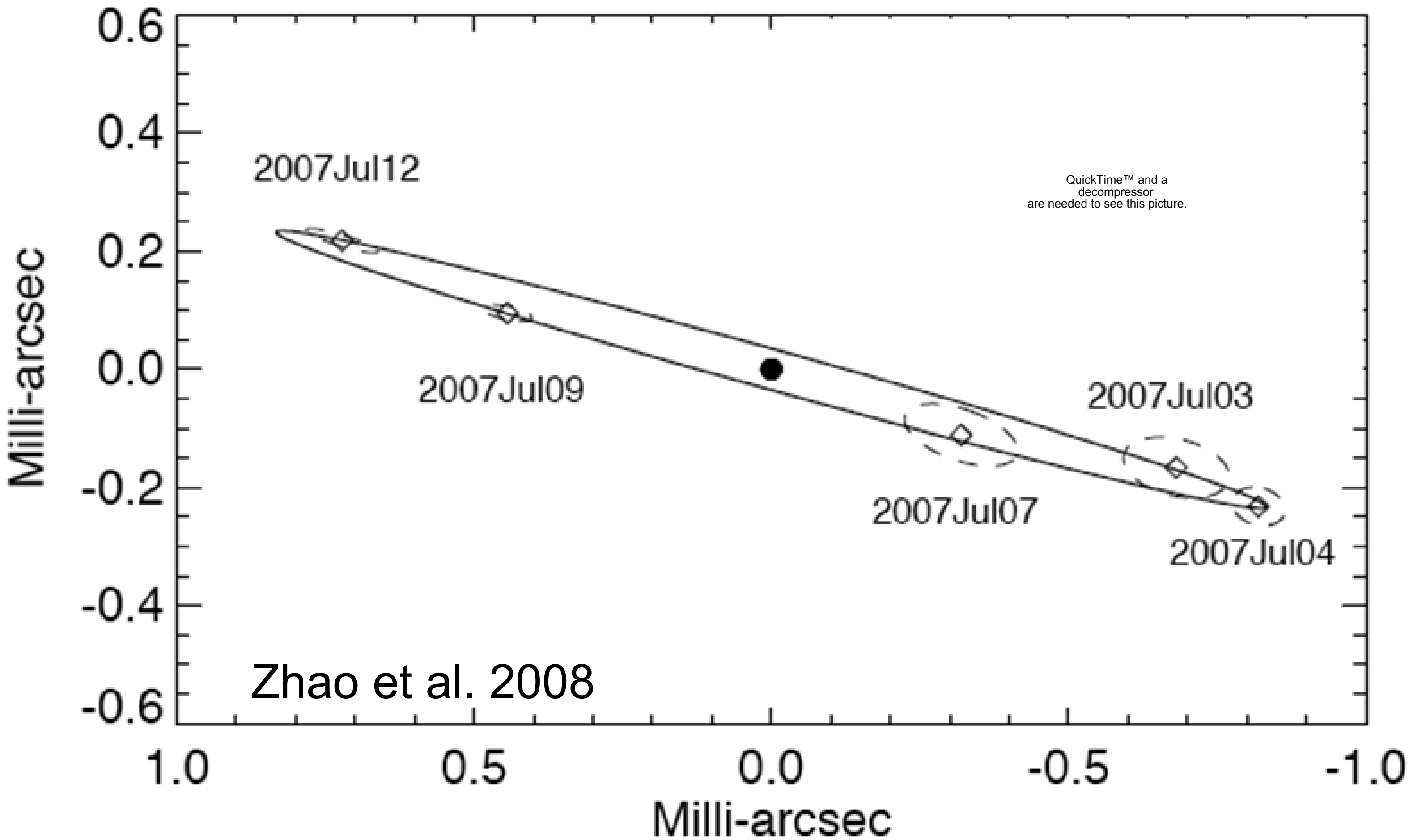
0.5 mas

1 mas

Phase = 0.828

(Zhao et al. 2008)

First Astrometric Orbit for β Lyr

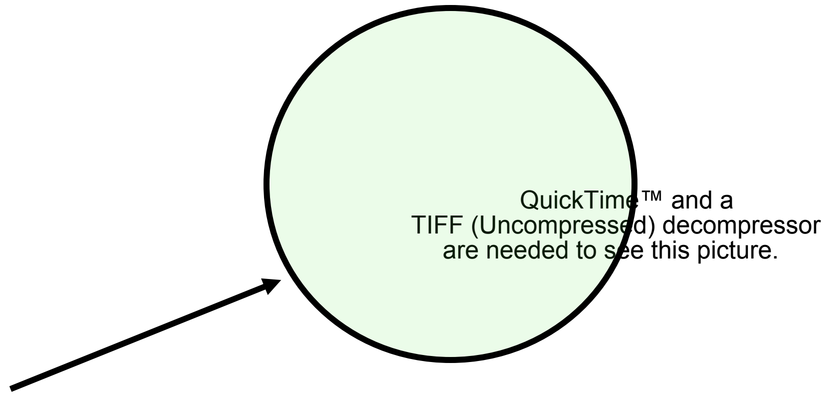


- Orbit: *i* ~ 92 degs
- Mass: M_{donor} = 12.8 +/- 0.3 M_{sun}; M_{gainer} = 2.8 +/- 0.2 M_{sun}

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Red: Transiting
Blue: RV

- >300 exoplanets



- ~20% of RV planets;
- >50% of transiting planets

Hot Jupiters

(Ref: The Extrasolar Planets Encyclopaedia)

Hot Jupiters

Molecular Bands & Thermal inversion features

(Burrows et al. 2008)

QuickTime™ and a
TIFF (Uncompressed) decompressor
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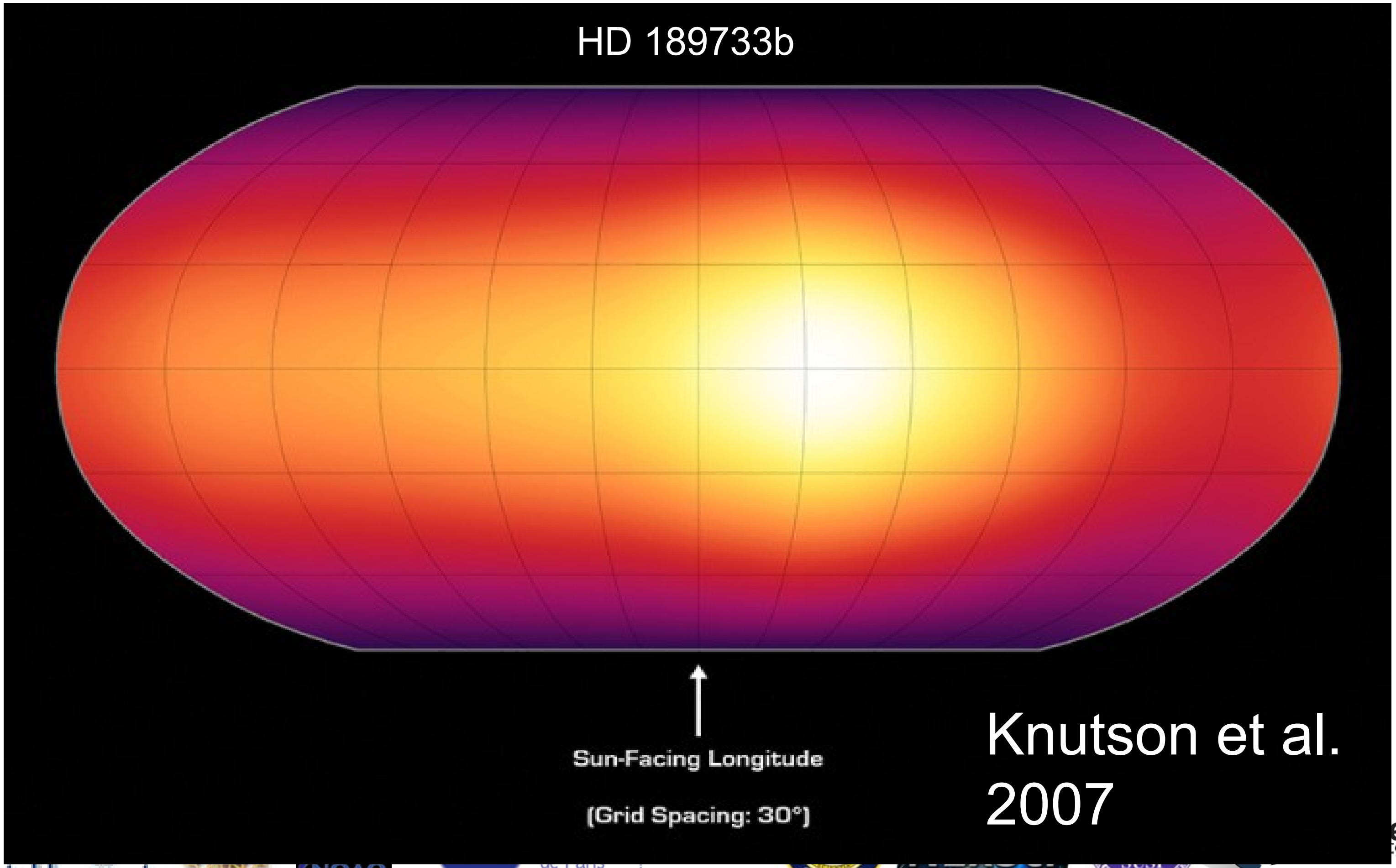
Hot Jupiters

- Day/night flux variation, heat redistribution, etc.



Existing Direct Detections of Hot Jupiters

- 6 were directly detected by Spitzer

  - Secondary transits:

    HD 209458b, HD 189733b, Tres-1, HD 149026b

    (Deming et al. 2005, 2006; Charbonneau et al. 2005; Harrington et al, 2007; Knutson et al., 2007)

  - Non-transiting:

    HD 179949b, Ups And b

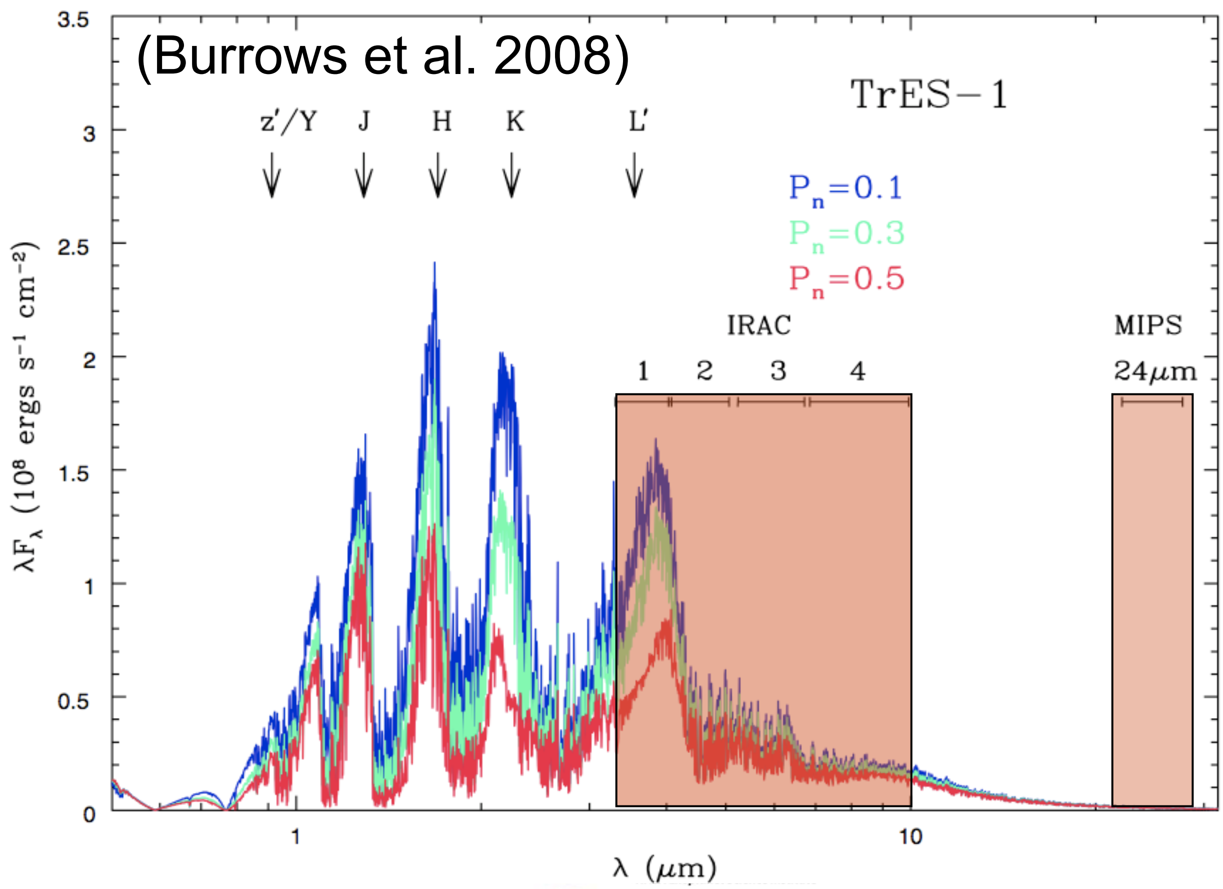
    (Harrington et al. 2006; Cowan et al. 2007)

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
- Break down model degeneracy

3). Obtain inclination and determine masses

Method: Precision Closure Phase

- Closure phase is not corrupted by the atmosphere
- Detect star-planet as high contrast binary

Best Candidates:

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Flux Ratio: $\sim 10^4$:1 at H band

Closure Phase Simulation

Maximum= 0.18°

QuickTime
TIFF (Uncompressed)
are needed to see

longest triangle

(Zhao et al. 2008)

Precision requirement: < 0.18° for the highest resolution channel

Observation of υ And

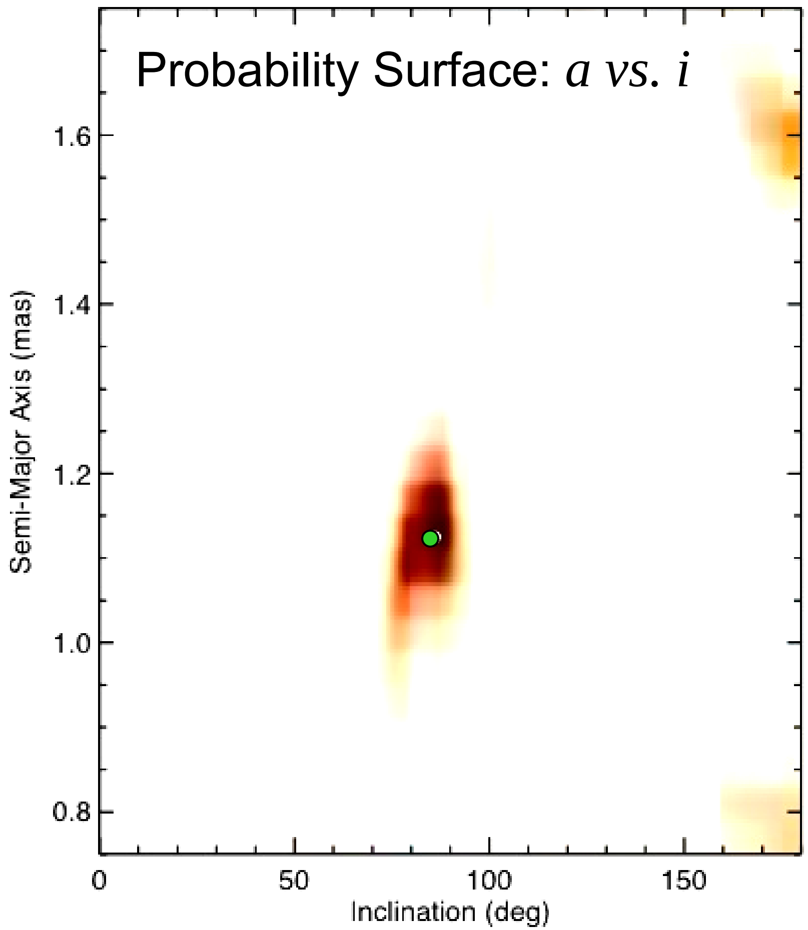
QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

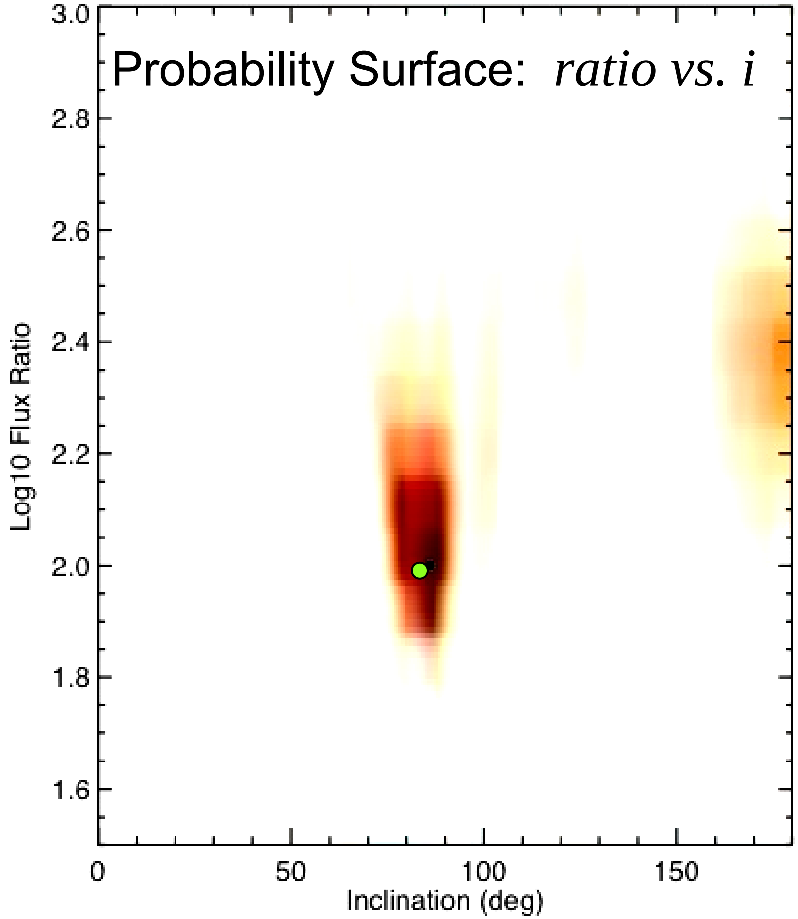
Need 6x S/N for 3σ detection!

Future Improvement

- **Analysis Method:** use the results from RV and combine multiple nights together
  - Orbital parameters: i, Ω
  - Day/night flux variation: amplitude, phase

Test Binary: Eps Per





Multiple nights: 80 mins integration
Inclination ~ 75 degs; Flux ratio ~ 100: 1
Semi-major axis ~ 1.13 mas

Future Improvement

- Calibration:
  - Photometric channel
    => calibrate spectra tilt & internal “fringing”

Drifts in closure phase

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

2007Nov16

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

2007Nov22

Future Improvement

- Analysis Method:
- Calibration
- Efficiency
- Throughput
- Fringe tracker

All improvements add together:
$\Rightarrow$ 6x - 10x S/N
3 σ - 5σ detections!

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 the first time
- Interacting binaries now accessible
  - Physics of accretion disks in close binaries
- Directly detecting hot Jupiters underway!