Direct Observations of Rotationally Distorted Stars

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Spectral Inference of Rapid Rotation

- Rapidly rotating stars show line broadening
- Provides an independent check of our interferometric results
- Extreme rapid rotators can be difficult to characterize spectroscopically due to excessive line smearing
The Palomar Testbed Interferometer
PTI is a Near-IR (K & H-band) single-baseline interferometer

- NS and NW baseline combination
- NICMOS array combiner
- Point Src Limiting Mag K ~ 6.5
- Scientific Limiting Mag K ~ 5.7

http://huey.jpl.nasa.gov/palomar

Single and Dual-Beam Interferometry:

- Visibility ($V^2$) measurement $\Rightarrow$ modelling (simple morphology like one or two stars)
- Simultaneous fringe tracking on two nearby stars $\Rightarrow$ differential astrometry

Established as a Technology Testbed for the Keck Interferometer

First Fringe: July 1995
First Sci Pub: August 1998
Ops Through 2002

Palomar Testbed Interferometer (PTI)
Michelson Interferometer

\[ x = D \sin \theta \]

Star is at infinity

Match paths through use of delay lines
Fringe Visibility

- Constructive & destructive interference of light
- Fringe contrast or visibility:
  \[ V = \frac{I^+ - I^-}{I^+ + I^-} \]
- Calibration issues
  - Detector linearity
  - Zero point measurement
  - Noise characterization

*Actual* starlight fringes from IOTA - β And
Photo credit: R.R. Thompson
Visibility Function

- For a ‘uniform disk’, visibility matches:
  \[ V = \frac{J_1(x)}{x} \text{ where } x = \frac{\pi \theta B}{\lambda} \]
  
  - \( B \) is the projected baseline
  - \( \theta \) is the stellar disk size
  - \( \lambda \) is the instrumental wavelength

- Baseline, wavelength known
  - Can solve for \( \theta \)

- Use \( V^2 \) instead of \( V \)
  - Unbiased estimator of visibility
  - See Colavita (1999)
Limb darkening

• Stars are *not* uniform disks
• Gaseous, not solid, sphere
  - End up looking ‘into’ the star
• Good and bad
  - Have to account for this
  - Measuring this can be used to characterize internal structure of star
  - Direct probe of internal temperature structure
Limb darkening. II

- Effects are less striking in the near-IR
- Most of the effects are seen at the higher spatial frequencies
- Acceptable to do a UD fit, and scale
  - Corrections are $\sim 1.5\%$ for main seq.
  - Higher for evolved stars
  - Gives the size of the mean radiating surface

A-type Star Model (Claret et al. 1995)
Initial Indications of Something Interesting with Altair

- Use of the PTI N-S and N-W baselines gave different angular sizes
- Not explainable in terms of limb darkening, spotting

![Graph showing normalized v^2 versus Mλ for different baselines and angular sizes.]

Baseline PA~195°
Baseline PA~245°
3.32 mas UD
3.13 mas UD
3.40 mas UD
Contemporaneous Measurements Appear Normal

- Vega had been observed on the same nights, at the same time
- No apparent $\theta(UD)$ evolution with projection angle
Ellipsoidal Fit to Altair Data

- Measurement of Altair's angular size with PTI's N-S and N-W baselines
  - ~50° between the baselines
- Best fit is an ellipse
  - $a/b = 1.140 \pm 0.029$
  - $a-b = 424 \pm 79 \text{ \mu as}$
- Star is a known rapid rotator
  - Can derive rotational velocity:
    \[ v \sin i = \sqrt{\frac{2GM}{R_b}} \left(1 - \frac{R_b}{R_a}\right) \]
  - $v \sin i = 224 \pm 28 \text{ km s}^{-1}$
The Roche Model

- Shape defined by local radius $R(\theta, \omega)$ of an equipotential surface:

$$\Phi = const = \frac{GM}{R} + \frac{1}{2} \omega^2 R^2 \sin^2 \theta$$

$$= \frac{GM}{R_p(\omega)}$$

where $\theta$ is the colatitude and $R_p(\omega)$ is the polar radius
Solving for the Roche Model

A solution for the colatitude- and rotation speed-dependent radius:

\[ r(\theta, u) = \frac{R(\theta, u)}{R_p} = \frac{3}{u \sin \theta} \cos \left[ \frac{\cos^{-1}(-u \sin \theta) + 4\pi}{3} \right] \]

where \( u \) is the fractional rotation speed and \( r(\theta, \omega) \) is the normalized radius. \( u \) is defined as:

\[ \omega^2 = u^2 \frac{8 \ GM}{27 \ R_p^3(\omega)} \]
Elements of a Roche Model. I

- Four independent parameters define Roche model on the backdrop of the sky
  \( i \) – inclination
  \( \alpha \) – orientation
  \( R_p \) – polar radius
  \( u \) – fractional rotational speed
- Assumes a mass \( M \) and distance \( d \) for the object is known
Noteworthy Assumptions

• Rigid rotation
  – Poor assumption for most stars
  – But actually not bad for A-type stars

• Uniform disk illumination
  – Again, poor assumption for most stars
  – Expected gravity darkening will be low contrast for Altair in near-IR
  – Again, actually not bad for A-type stars

• Working in image space, not Fourier space
  – Downright dangerous assumption
  – Will change the analysis in future experiments
Monte Carlo Fitting

- Can randomly generate values for \( \{i, \alpha, R_p, u\} \) and examine \( \chi^2 \) of fit
- Brute-force examination of \( \chi^2(i, \alpha, R_p, u) \) can reveal global minima in \( \chi^2 \) space
Results of the Minima Search

- No statistically significant global minima found for \( \{i, \alpha, R_p, u\} \)
  - For rich enough interferometric data sets, unique solutions are possible
- However, a minima 'trough' found in \( \{i, u\} \)
  \[
  u = 4.961 \times 10^{-5} (90 - i)^2 + 1.116 \times 10^{-3} (90 - i) + 0.762
  \]
- No inclination less than 30° is allowed, no speed less than 210 km/s

Altair \( \chi^2 \) in \( \{i, u\} \) subspace
Unique Apparent Rotational Velocity

- Family of models appear to fit data
  - A single projected rotation velocity agrees with these models
- Unique solution for $v \sin i = 210 \pm 12$ km/s
  - Independent of, and agrees with, $v \sin i$ from spectra
- Finding not inconsistent with NPOI data

Altair best fit: $u=0.82, i=70^\circ$
Future Directions

• Other large (nearby) rapid rotators
  – eg. Regulus, eps Sgr

• Multiwavelength observations
  – Combine PTI, NPOI data in near-IR, visible
  – Directly probe latitude dependencies of radius and temperature

• Main limitation – resolution, not sensitivity
  – Need 250 or more meters to have a large (10+) sample size
  – New interferometers (CHARA, NPOI) will make this possible
Basic Parameters from Angular Diameters ($\theta$)

- **Direct observation** of fundamental stellar parameters

- Effective temperature is defined as: $L = 4\pi\sigma R^2 T_{\text{EFF}}^4$,
  which can be rewritten as: $T_{\text{EFF}} = 1.316 \times 10^7 \left( \frac{F_{\text{BOL}}}{\theta_R^2} \right)^{1/4}$
  - $F_{\text{BOL}}$ is the bolometric flux (W cm$^{-2}$), $\theta_R$ is the Rosseland mean stellar angular diameter (mas)

- Linear radius is simply: $R = \frac{1}{2} \theta \times d$
  - Hipparcos (Perryman et al. 1997) distances now available
  - Uncertainties in parallax (typically ~15-20%) still largest contribution to error